REPORTS OF THE CCIR, 1990
(Also Decisions)

Annex to Volume II

Space Research
And Radioastronomy Services

CCIR International Radio Consultative Committee

Geneva, 1990
REPORTS OF THE CCIR, 1990
(ALSO DECISIONS)

ANNEX TO VOLUME II

SPACE RESEARCH
AND RADIOASTRONOMY SERVICES
## ANNEX TO VOLUME II

**SPACE RESEARCH AND RADIOASTRONOMY SERVICES**

*(Study Group 2)*

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1. **Introduction**

During 1975 the United States National Aeronautics and Space Administration conducted a planning study entitled "Outlook for Space". An important aspect of this study was a forecast of advances in space technology which could be expected to occur between 1980 and 2000 [NASA, 1976].

2. **The forecasts**

Between now and the year 2000 a great number of advances are expected to occur in technology applicable to space activities. These advances will bring about the feasibility of complex missions and systems of benefit to mankind. The more important areas where advances are expected, and should be encouraged, are listed below, and the expected advances are summarized in the remainder of this Report.

These advances will not occur spontaneously, but will be achieved by deliberate emphasis on research and development in particular areas where advances will have the greatest impact on space capabilities. Therefore, the summary in this Report covers both needs and anticipated advances.

- Instruments and sensors
- Data interpretation
- Precision navigation
- End-to-end information management
- Communication elements
- Space energy converters
- Very-long-life components and systems
- Large-scale, reliable microcomponent utilization
- Large, controllable lightweight structures
- Low-cost Earth-to-orbit transportation
- Nuclear space power and propulsion
- Advanced propulsion
- Autonomous spacecraft and vehicles
- Lunar resource recovery, processing and space manufacturing
- Planetary environmental engineering
- Closed ecological life-support systems
- Long-flight physio-psycho-socio implications

2.1 **Instruments and sensors**

The requirement for increasing the effectiveness and capacity of remote sensing systems stems both from the global nature of the measurements, and from the extraordinary difficulty of achieving some of the required measurement parameters.
Particle, optical and microwave sensing systems, both active and passive, will continue to be developed with particular emphasis on frequency selection and low-cost designs. Instrument capabilities may be greatly enhanced by technological advancement in space cryogenics, large lightweight optical systems, and large space-erectible antennae.

Lightweight optical systems, employing continuously adaptable optical surfaces formed of multiple elements, will permit extraordinary growth in the light-gathering capacity for both astronomical and remote sensing applications.

Due to increased sensor system capability, data handling needs will grow substantially. For example, by the year 2000, imaging devices on Earth application satellites will be capable of returning a thousand times more data than in 1975, that is, an increase from about $10^{10}$ bits/day to about $10^{13}$ bits/day.

2.2 Data interpretation

The level and sophistication of theoretical models for the design and interpretation of remote sensing techniques needs to be upgraded. As an example, the capabilities of radar and microwave radiometry to measure desired quantities are only understood with any precision in a small number of areas and, even in those, there are requirements for enhancement of modelling precision (e.g., temperature sounding).

Upgrading measurement conception, data interpretation, and modelling are necessary in order to permit quantitative interpretation of remote sensing data in terms of quantities, and phenomena of interest to the user.

2.3 Precision navigation

High accuracy, in-orbit, position knowledge is intrinsic to many missions. Order of magnitude improvements are required in gravity models, station location accuracies, and in atmospheric density effects, with companion efforts in multilateration techniques for Earth orbit determination.

For interplanetary navigation, very-long-baseline-interferometry techniques will be utilized with extragalactic radio sources, eventually permitting angle measurements to spacecraft of 0.01 second of arc.

2.4 End-to-end information management

The steady and rapid growth in the amount of data collected in space and returned to the Earth will necessitate radical improvements in the technology for acquiring, processing and disseminating this information at low cost.

Satellites dedicated to the relaying of data at high rates will use laser or microwave beams to reduce on-board storage requirements in other satellites.

Many Earth-oriented activities, for example, those involving meteorological, agricultural, and marine observations, will require major advances in information management systems to be put into operation on a global scale. Future space information systems devoted to these applications will benefit significantly from the miniaturization of processing and storing capabilities; from more sophisticated on-board software systems; from more economical and efficient data distribution facilities; and from advanced methods for human-machine interaction.

There will be a need for very advanced, reliable, economical, and high-capacity systems capable of transferring information at gigabit/second rates, processing it as received, or as needed, preserving it in large memories in flight or Earth-based systems, or making it available to users in a form that enables them to make timely and effective use of it on a national scale.
2.5 Communication elements

Low-cost, large antenna apertures will be developed for use on Earth and in Earth orbit. These antenna apertures will be required for a wide spectrum of space missions, ranging from radio instrument sensing at high resolution, and spacecraft tracking throughout the solar system, to interstellar communication and the search for extra-terrestrial intelligent life.

In addition to employment of classical large-dish reflector antenna techniques, development of low-cost methods of arraying integrated elements for achieving the required antenna aperture size will be pursued in light of continued advances in LSI and monolithic microwave integrated circuit (MMIC) technology, fibre optic links and microprocessors. In addition to the need for large-aperture antennas, special antenna designs will be developed (in Bands 9 and 10) for radio sensing and satellite communications. These designs will emphasize special coverage patterns, side lobe control, multiple frequency and polarization operation, and beam scanning. Lens antenna technology and small-element array technology will be used to a large degree to provide these classes of antennas.

Large scale integrated circuit and MMIC technology will be exploited to develop compact, integrated communication systems composed of receiver amplifiers and transmitter power amplifier elements connected to their respective antenna dipole array elements.

Development of complex, high-data-volume, real-time digital processors is contemplated for a number of information transfer applications such as radar imaging, random access satellite communications, and detection of interstellar microwave signals in a search for extra-terrestrial intelligence (SETI). For SETI applications, spectral resolution to 0.1 Hz is necessary to detect weak, highly monochromatic signals.

2.6 Space energy converters

The attractiveness of collecting solar power in space and beaming it back to Earth depends on the development of either low-cost photovoltaic solar arrays or solar energy concentrators with thermal converters deployed on extremely lightweight structures. In the case of photovoltaic arrays, the high voltages and multi-gigawatt power levels imply that the structural array must have extraordinary insulating properties. The complete structure should be adaptable to space assembly and subsequent maintenance-free operation for many years. Considerations of efficiency, radiation susceptibility, temperature, weight reduction and cost reduction; all present challenges for new technology. In the case of the concentrators with thermal converters, the problems of orientation, shape, thermal stability, and rigidity of large-scale structures are keys to the development of space energy conversion.

2.7 Very-long life components and systems

Many candidate objectives warrant the utilization of space techniques only if the capitalization cost of the missions or systems can be amortized over a long period of time, requiring little maintenance or resupply. For example, a solar-power station in space might achieve a competitive position with alternative stations on Earth, not only as a consequence of a reduction in the cost of the energy conversion system and the space transportation costs to orbit, but also simply through the station's operation over many maintenance-free years in space.

Systems properly designed for the environment of space often find space to be a benign environment. Thus, the unique environment of space itself offers the opportunity for space application systems to compete with Earth-based systems. Concomitantly, deep space missions, by the very nature of their long flights to their targets, demand long-life systems lasting for decades. Some will require systems resistant to radiation effects.

2.8 Large-scale, reliable microcomponent utilization

The miniaturization of components will continue, altering the whole architecture of space and Earth information systems leading, for example, to distributed systems with balanced use of standardized and customized processor elements, arrayed in optimum fashion for their tasks.
Ultra-high-density microelectronics for information storage is an example of a necessary prerequisite to an expanded and enhanced information management capability. Mass memory of $10^7$ bits will be stored on a silicon chip less than one square cm in area; present devices can hold less than $10^4$ bits/chip.

The potential use of such large quantities of active devices places extraordinary demands on designing reliable systems. These must be either component fault-free, heavily redundant, self-repairing, or a combination of all of these attributes.

2.9 Controllable lightweight large-scale structures

A complete new technology is required for such structures so that they can be delivered into space, unpacked, assembled, and maintained with the required precision in orientation, shape, thermal stability and rigidity. Some of these structures will have dimensions of the order of kilometres and in many cases the shapes of their surfaces will have to be controlled by servo-mechanisms to within centimetres or millimetres. Examples of such structures include very large microwave reflectors, microwave antennae, solar-energy collectors, radiators, solar sails, telescopes and enclosures for farms and habitats.

In additional to structural integrity and shape control, the dynamic interactions involved in the pointing control of such structures are unprecedented.

Large structure flexing will necessitate integral antenna pointing systems providing attitude sensing in addition to the craft attitude sensing.

2.10 Earth-to-orbit transportation-larger scale, lower cost

Space transportation technology advancement continues as a dominant need for certain missions to make them cost-effective. The Shuttle transportation system can be expanded to full capability to give both improved flexibility and lower cost for a variety of missions envisioned for the next 10 to 15 years. For more advanced missions such as large orbital power plants, nuclear waste disposal, and assembly and processing operations in space, and eventually bases or outposts in space, a new heavy lift vehicle can provide a factor of three or more reduction in the cost of lifting massive quantities of material to low Earth-orbit. Other options include a number of heavy lift vehicles which could prove feasible, such as a winged, single-stage-to-orbit vehicle or vertical takeoff vertical landing vehicle. These designs could potentially lower launch costs to 50 dollars per kilogram.

2.11 Nuclear space power and propulsion

High levels of operational power must be supplied for long durations for missions where solar energy is not available in sufficient quantities. One cost-effective solution is the employment of nuclear energy storage converted to tens of kilowatts to megawatts of electric power in space. The shielding, safety and waste disposal aspects of nuclear power in space are amenable to solution.

Radioisotopes provide a very efficient mechanism for storing energy. When used at power levels below 10 kW$_e^*$, in conjunction with thermoelectric or thermionic conversion, radioisotopes provide electrical energy on a mass-per-unit energy basis three to four orders of magnitude more favourable than electrochemical batteries. Projected improvements in thermoelectric or thermionic converters and in isotopic fuel will significantly reduce costs from today's levels.

For higher powers, 100 kW$_e$ to multi-megawatt, nuclear fission reactors will hold the same level of mass-per-unit energy stored and reduce energy storage costs one to two orders of magnitude below that possible with radio-isotopes. A fission nuclear power system of 100 to 500 kW$_e$ could be developed in the last decade of the century. If nuclear propulsion is to be used for high-load transportation such as placement of solar power stations in synchronous orbit, multi-megawatt systems must be developed.

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$^*$ kW$_e$ refers to electrical Watt.
2.12 Advanced propulsion

Storing and use of energy for propulsive purposes is a major cost factor in missions requiring high energy provision (i.e., to the edge of the solar system and beyond, out of the ecliptic plane, to landings and returns from extra-terrestrial bodies) and missions requiring transportation of very large amounts of matter (i.e., nuclear waste disposal, solar or nuclear power stations in space and bases in orbit or on the Moon).

The high costs associated with heavy loads and long flight durations can be dramatically reduced by the use of systems which accelerate the exhaust mass to very high velocity by electric or magnetic means, and which employ energy stored in the nuclear states of matter or collected from the solar radiation in space. The development of solar and nuclear-fission electric propulsion is expected in the next 20 years.

Even more advanced propulsion concepts, which would be brought into operation after the turn of the century, offer the prospect of system mass per unit power levels two to three orders of magnitude less than solar and nuclear electric propulsion. Systems utilizing gas core nuclear fission, fusion microexplosion and metastable hydrogen rockets could provide such propulsion.

2.13 Autonomous spacecraft and vehicles

Already, we have seen the early steps in a technology to develop remote, adaptive human supervisory control of space machines having some degree of autonomy. The use of semi-autonomous robots will require on-board capabilities approximating those of present-day minicomputers, plus visual, manipulative and analytical instrumentation, sufficient to permit a real-time (except for propagation delay) and high-level interaction between humans and machines. These capabilities imply kHz to MHz channel rates, megabit on-board storage, microsecond operation times, and four- to ten-level hierarchical command structure. The high-density data storage and end-to-end data management technologies mentioned earlier contribute to achieving these capabilities in semi-autonomous spacecraft. To perform even the simplest tasks autonomously, machines must be given the ability to acquire data from their environment, build models of them that incorporate prior knowledge, physical laws and "common sense", and use these models for task execution and problem solving.

In deep space, on missions requiring fast reaction time, round trip propagation times make Earth-based navigation and control impractical. As such remote locations, machine autonomy is required to move safely from one location to another, determine present location, implement control sequences and provide a desired set of dynamic states independent of unexpected internal or external forces, equipment failures or other unexpected occurrences.

2.14 Lunar resource recovery, processing and space manufacturing

At some point in the future, it is estimated that it will become cost effective to process some minerals into products on the Moon and transport them to facilities in Earth orbit or possibly on Earth. The obtaining of such resources from space would ease the pressure on the demand for energy and minerals obtainable on the Earth.

Materials present on the Moon are: oxygen for life support and propulsion; metals (e.g., Al, Mg, Fe, Ti) for structural materials and propulsion; ceramics and glasses for construction; silicon for photovoltaic devices and thorium for nuclear breeder reactor fuels. The manufacturing and assembly of small components or modules into large structures in orbit could become a reality by using lunar materials. The special requirements of resource recovery and processing in the lunar environment need to be examined now and developed over the next one or two decades to prepare for potential opportunities near the turn of the century.
2.15 Planetary environmental engineering

Much of the monitoring of our environment's subtle changes is available only through space activities. Efforts to control future damage to the environment, and repair the damage already done, will be greatly enhanced by the availability of global environmental information gathered from space. This enhancement may well become crucial for the successful preservation of our environment.

Ultimately, once we have learned to preserve our own biosphere, the ability to shape nearby planet biospheres as benign environments for human beings could become a reality.

2.16 Closed ecological life-support systems

At a certain crew size and duration in space, the cost, mass and complexity associated with a closed life-support system become less than that of resupplying expendables from Earth. A number of attractive space objectives will ultimately reach this trade-off point and, since the development lead time is very long, it is advocated that this general technology advancement begin with the last quarter of this century.

Even though it might not be possible to guarantee long-term fully closed operation, a vigorous pursuit of this technology will permit substantial reductions in resupply.

Monitoring and control systems need to be developed for temperature, humidity and probably for CO₂, particulate and bacterial matter, and trace contaminants, even if major recycling is accomplished biologically.

2.17 Long-flight physio-psycho-socio implications

As human beings in greater numbers spend more time in space, the physiological implications must be understood and dealt with.

Consideration has to be given also to the appropriate forms of social order for large space ventures. Though the form that this order might take in a small and isolated community is now unknown, its components include communications, aesthetics, education, law, entertainment, work products and other such elements that are recognized as the hallmarks of successful human communities on Earth.

It will be necessary to translate our knowledge of social and political science to the space environment and to understand the special problems and opportunities provided by this environment.

3. Conclusion

The next 25 years will find mankind reaching further into space for not only purely scientific investigations, but also for Earth-oriented applications such as solar energy production, space processing and space mining.

The growth and variety of future space operations is a precursor of the diversity of the frequency-use needs of the space services.

REFERENCES

1. Introduction

The determination and maintenance of proper spacecraft orientation is essential to the fulfilment of nearly all space research and other missions. The accuracy and reliability of a spacecraft’s attitude control system (ACS) affects many other satellite subsystems: above all, narrow beam antennas must be properly aimed in order to function effectively; solar panels will operate most efficiently when oriented normal to the sun line and sensors must be precisely pointed to fulfil their proper functions. Earth-oriented satellites, with continuous orientation of narrow beams toward specific locations on Earth require precise attitude stabilization.

This Report describes various techniques for attitude control and discusses some of the factors that affect the accuracy of control systems.

2. Background

The majority of satellites must be attitude oriented with respect to the Earth. Some experimental communication satellites make use of high-gain narrow beam antennas which must be directed toward and "locked" onto specific areas of the surface of the Earth. The Communication Technology Satellite (a joint United States and Canadian project), for example, makes use of two steerable spot-beam antennas which can, on command, be pointed independently anywhere within the field of view of the satellite. To point either of these 2.5° beams effectively, the attitude of the spacecraft must be determined and maintained to an accuracy of better than 0.1°.

Earth exploration satellites and meteorological satellites using imaging sensors must function as extremely stable platforms to prevent small satellite-motions from distorting or blurring the sensor images, while keeping the Earth-viewing side of the spacecraft pointed at the nadir. Thus, the attitude control system on an Earth-oriented spacecraft must rotate the Earth-pointing section of the spacecraft about its pitch axis (Fig. 1) precisely once each orbit and simultaneously remove the effects of any perturbing torques in pitch, roll or yaw.

Some spacecraft use the Earth as one of the principal reference bodies. The primary limitations of this type of system arise from the Earth’s optically indistinct periphery which contributes to attitude-sensor error. Another effect is the Earth’s oblateness or ellipticity which, if not allowed for, may induce errors in local vertical determination.

* This Report is brought to the attention of Study Groups 4, 7, 8, 10 and 11.
Other space research missions require that the spacecraft attitude control reference be obtained from astronomical bodies other than the Earth. United States spacecraft, such as the Orbiting Astronomical Observatory (OAO), Orbiting Solar Observatory and the MARINER and VIKING planetary missions, use the Sun or other stars as references. Inertial reference systems such as that on the orbiting astronomical observatory, OAO-3, using gyros, four gimbaled star trackers (providing data to control momentum wheels), and a fine star-sensor which operates through the experimental telescope, have reduced pointing errors with respect to the target bodies, to less than 1 arcsecond.

The intrinsic accuracy of an attitude control system is limited by the physical alignment of the sensors, the structural and thermal stability of the platforms and the resolvability of the reference point used. The haziness of the edge of the Earth and, to a lesser extent, the haziness of the apparent disc of the Sun, limits the accuracy of any attitude control system which uses either of these two bodies as a reference. The use of point sources, such as stars, for attitude reference permits more accurate attitude sensing. This is true to an even greater extent for a satellite for which the primary attitude reference system is an integral part of the experimental observation system (e.g., a star telescope).

3. **Perturbing torques**

The existence of perturbing torques on a spacecraft as a result of its interaction with the space environment, makes constant adjustment of the spacecraft attitude a necessity. Thus, detailed information concerning the perturbing torques is a basic prerequisite for the design of an attitude control system. The relative importance of the particular torque depends upon the configuration and orbit parameters of the specific spacecraft. The major sources of disturbance torques are the gravity gradient, the Earth's magnetic field, solar radiation pressure, aerodynamic pressure, meteoritic impacts, internal mass shifts and the flexibility of the spacecraft. Each of these is discussed briefly in the following paragraphs.

3.1 **Gravity gradient**

A body of finite size in orbit in a gravitation field will experience a gravity gradient torque. In a passive satellite this torque will cause the spacecraft to oscillate, which is usually undesirable, but through deliberate design the gravity gradient can be used to provide coarse passive attitude control.
3.2 The Earth’s magnetic field

The torques due to the coupling of the magnetic field generated by a spacecraft, and the magnetic field due to external sources (primarily, the Earth’s magnetic field) can also disturb spacecraft attitude. Proper shielding on the spacecraft can reduce these effects considerably; or, in some cases, the effect may be used as a counter-torque for the momentum wheel, or as a primary torque.

3.3 Solar radiation pressure

The torque caused by solar radiation and the solar ionic "wind" pressure can also perturb the spacecraft attitude. The magnitude of this torque, which is cyclic if the spacecraft is Earth oriented, will be a maximum for complete reflective surfaces and smaller in the case of an absorbent body.

In the case of a geostationary satellite, the solar radiation torque is dominant. Its magnitude depends on the shape and the surface material of the satellite and has seasonal variation due to the variations of Sun angle and the received solar radiation intensity.

By using measured solar radiation torque data, attitude prediction and correction planning of a spin-stabilized satellite are possible by calculation based on a simple model of the satellite attitude dynamics as shown in Annex II. Other perturbing torques of this nature also exist, for example, torques caused by cosmic rays, but the magnitude is usually small compared with that due to the Sun.

3.4 Aerodynamic pressure

Aerodynamic forces become significant or dominant for spacecraft in low-altitude circular orbits or in eccentric orbits with low perigees. The effect of aerodynamic pressure can usually be minimized through careful design of the configuration and shape of the spacecraft to minimize and equalize drag; and by the use of a higher nominal spacecraft orbital altitude.

3.5 Impact by meteorites

The angular momentum imparted by the impact of meteorites upon the spacecraft can usually be estimated statistically, that is to say, by determining the probability of meteorites of various masses striking a given satellite and the resulting magnitude of momentum transfer.

3.6 Internal mass shift and structural flexibility

The relative movement of antennas, cameras, solar panels, live occupants and fuel will result in torques on the main body of the spacecraft, and these torques are difficult to analyse. Because these moving parts must first be accelerated and then decelerated to obtain a new position, some of these torques are cyclic in nature. Structural flexibility may cause false attitude error signals and could resonate at the frequency of the attitude control system (ACS). Such problems are becoming more common with large solar array configurations. Outgassing and gas leaks can also cause disturbance torques.

4. Attitude sensing

The principles and devices which can be used to establish attitude reference systems (to sense the attitude or angular velocity of a vehicle) are of prime importance in today’s high accuracy control systems. Since the accuracies of attitude control systems are bounded by the ability to sense attitude errors, much effort has been directed toward attitude sensing instrumentation. The following sections briefly describe some of the techniques which are employed in this fundamental and essential aspect of satellite attitude control.
4.1 Sensing with reference to the Earth or the Sun

It is a natural advantage to use as a reference target the celestial body of experimental interest. This is the case with most near-Earth satellites which use the Earth's line of maximum atmospheric gradient (tropopause) as a means of locating the centre of the Earth. The sensors may operate in response to the Earth's far infra-red radiation (> 8 µm) with such devices as thermistor bolometers, pyroelectric detectors, or thermopiles or the sensors may use the scattering of reflected sunlight (Earth's albedo) as an indicator (e.g. by means of silicon photocells, or photo transistors). The most widely used spectral band for defining the Earth's disc has been the 14.0 to 16.3 µm band which is associated with CO₂ absorption.

The factors which contribute the largest error in this determination of the local vertical with earth sensors are the resolution limit at the tropopause and the local and random atmospheric variations in infrared radiation.

Infrared sensors detect the "centre" of the Earth's infrared image: this "centre" is virtually the same as the sub-satellite point, so that these sensors give no information on satellite movements around the yaw axis. However, the yaw can be estimated by means of these sensors combined with other means, e.g.: gyrometric measurements.

In the case of present geostationary satellites which have sufficient kinetic moment, yaw is detected indirectly every six hours by the exchanges between the roll and yaw axis.

The irreducible bias introduced by the infrared sensors is 0.02°: this is the minimum intrinsic contribution of the infrared sensor to the total pointing error balance. At present, the intrinsic infrared sensor error has a random component of between 0.01° and 0.05° at 3σ.

Solar reference sensing is conceptually similar to earth sensing with reference to the Earth. Although higher pointing accuracies with respect to the Sun may be achieved (a few seconds of arc); due to the Sun's more readily defined apparent disk, additional errors are introduced in co-ordinate transformation of this data to an Earth-pointing mode.

4.2 Sensing with respect to celestial bodies

The use of point sightings on distant stars such as Canopus or Polaris has indicated that stellar reference systems can offer more accurate attitude determination capabilities than earth sensors because of a star's low and predictable relative motion over long periods of time and its high angular resolvability.

If star sightings are used to establish an earth-centred local vertical, the computation of the reference system co-ordinate transformation involves knowledge of the "true" geographical location of the spacecraft which may be obtained only within the limits of present-day abilities in orbit determination.

Star sensors may operate on a tracking or mapping principle. Star trackers usually sense in two axes to enable versatile pointing. Either mechanical gimbals or electronic offset may be used. Servo-mechanisms mounted on each axis drive the trackers to acquisition, and the offset angles provide measurement data in a code suitable for use in the computer.

Sensors which operate on a star mapping principle have received attention recently because of their mechanical simplicity. They do not involve servo loops, encoders, or a gimbal axis. A computerized star catalogue and pattern recognition system identifies star fields and determines the relative position.
Considering the accuracies usually obtained with star mapping sensors, launch and orbit thermal stresses are a major design consideration and necessitate periodic tracker misalignment corrections. For example, the OAO-2A star tracker misalignment errors with respect to the spacecraft, were from two to five times larger than the desired pointing accuracy and were the results of both thermal distortions and misalignments arising from vibration during the powered phase of the launching. This necessitated calibration and compensation of the sensors after launching, to achieve the desired pointing accuracy.

OAO-3 uses gimballed star trackers to adjust momentum wheels for coarse stellar reference, to bring the star telescope into its field-of-view of four minutes of arc, and also uses a body-fixed star sensing system which operates through the experiment telescope. Since the sensor optical axis is that of the experiment, and is body-fixed, the system has enabled the OAO-3 spacecraft to point to its experimental target to within about 0.01 arc seconds of jitter. The variations in pointing error are primarily due to thermal stresses (day-night operation) and to orbital position.

For the astronomy satellite HIPPARCOS, a novel solution has been adopted whereby the attitude measurement (star measurement) is carried out in the actual focal plane of the instrument; the accuracy of the subsequent attitude reconstruction (i.e., after ground processing) should be within about 0.001 arc second.

4.3 Inertial sensors

Inertial systems use the gyroscope as the prime sensing device. The simplest, a set of three orthogonal body-mounted rate integrating gyros, is capable of high accuracy error sensing. Another application of the gyroscope is as a gyrocompass for the detection of yaw deviation out of the orbit plane, assuming that the direction of the local vertical has been independently established. Inertial sensing may also take on the form of a rate gyroscope which measures the velocity of the body and resolves it into body-fixed co-ordinates, and thus acts as an indicator of the damping required. The main drawback with body-mounted rate-integrating gyro sensors is that the motion of the reference frame, which is not a measure of attitude, must be taken into account. Gyro drift must be continually accounted for.

An attitude estimation based on inertia alone is suitable only for launcher-type vehicles with missions of less than a few hours. For longer missions (satellites), optical sighting correction (earth, sun, stars) is required to prevent inaccuracy which increases with time due to the unknown part of gyroscopic drift. The optico-inertial systems used for attitude estimation provide very high levels of accuracy for both attitude and spin velocity.

4.4 Radio-frequency sensing

An alternative to earth sensing is provided by radio-frequency (RF) sensing, where antennas and circuitry aboard a satellite determine the orientation of an RF signal arriving from a ground based beacon. This class of sensor seems a natural one for communications satellites since communications equipment will already be on board and many perturbations affecting the attitude signal will also modify the communications transmission in a like manner.

RF sensors include monopulse and interferometer types, both of which operate on the general principles of monopulse radar tracking systems, processing phase or amplitude information from either single or multiple antennas [Skolnik, 1970].
With RF sensors it is easier to determine the off-boresight angle of the signal, (i.e. azimuth and elevation, or in spacecraft co-ordinates, roll and pitch) while rotation about the boresight (the yaw angle) is more difficult to measure accurately. Yaw may be calculated by measuring rotation of a polarized signal from a single beacon, by processing roll and pitch from each of two beacons separated by the maximum baseline possible, or by processing additional information from Earth, Sun or star sensors. There are drawbacks to each of these yaw measuring options. The polarization orientation is affected by Faraday rotation and orbital parameters, as well as by differential rotation and phase shift caused by weather conditions. Yaw calculation from two earth stations suffers from the relatively narrow angle subtended at the spacecraft by the Earth, while yaw estimation from Earth, Sun or star sensor information entails the inclusion of an additional sensor aboard the spacecraft.

Despite these undesirable effects on yaw computation, RF attitude sensing is still a viable and promising approach, especially since for synchronous communications satellites, the yaw angle error affects beam pointing less than either roll or pitch errors. Indeed, RF attitude sensors have been flown and more are being selected for projected missions, having accuracies of the order of ± 0.05° for roll and pitch, and about ± 0.5° for yaw. The basic sensor is capable of considerably greater accuracy, but a disproportionate degree of compensation for the various perturbations becomes necessary. [Mamen, 1973; CCIR, 1974-78.]

4.5 Attitude determination using a laser

Some new methods using lasers are available for the orientation of antennas or detectors on spacecraft toward specific locations on the Earth. An Earth laser beacon sensor for Earth-oriented geosynchronous satellites has been proposed [Sepp, 1975], and in [Aruga and Igarashi, 1977] a new attitude-determination method has been proposed. The latter system consists of a transmitter of a linearly-polarized laser beam on the Earth, and receiving equipment on a satellite. The distinctive feature of this method is its complete attitude determination (the three elementary angles can be determined) using the laser and its polarization. The accuracies of determination are estimated to be $10^{-4}$ radians (0.006°) or better for the angles corresponding to roll and pitch, and about $10^{-2}$ radian (0.6°) for the angle corresponding to yaw. The ground-based laser beacon technique is applicable to absolute location calibration in earth observations from space as well as to spacecraft attitude determination and antenna orientation. This technique is especially useful for geostationary satellites since the ground laser station observed from the geostationary spacecraft stays fixed in the geocentric coordinates. The accuracy limitation of the earth laser beacon as a reference point is finally decided by the effect of the terrestrial atmosphere. A recent experiment [Aruga et al., 1985] shows that the limitation is smaller than 30 μrad (=0.002°) for geostationary satellites.

4.6 Other considerations (geostationary-satellite orbit)

In normal mode, the kinetic moment of the satellite is high enough to maintain a quasi-inertial pitch axis and to provide adequate satellite rigidity in its movements around the yaw axis.

In positional corrections on orbit, torque effects are applied by the working jets. Since the pitch axis can no longer be considered as quasi-inertial, its movement has to be detected during these operations by measuring the yaw angle.

Several types of sensor are used for this purpose: solar sensors, integrating gyrometers or possibly, stellar sensors.
5. **Attitude control elements**

The achievement of the desired satellite attitude may be accomplished by the use of active or passive devices. The following two sections briefly describe these two categories of attitude control elements.

5.1 **Passive devices**

Of the perturbing torques described in § 3, the gravity gradient, magnetic field and solar pressure may be used constructively as primary or secondary attitude control elements. Although these may produce only low-amplitude torques such passive devices have the obvious advantage that they do not consume spacecraft resources.

5.2 **Active devices**

Active control devices, unlike passive devices, use spacecraft power for attitude control. The most common types are angular momentum-exchange devices (flywheels, control moment gyros) and momentum-elimination devices (reaction jets, magnetic coils).

Techniques which use fixed-axis variable-speed flywheels have long been considered more desirable than passive devices because of the higher degree of pointing accuracy attainable with their use. Their operation is based on the principle that an external torque applied to a spacecraft may be countered by an appropriate change in the rate of angular momentum of the vehicle (torque being the first derivative, with respect to time, of angular momentum). Essentially, perturbing torques on a spacecraft may be countered by varying the angular speed of the flywheel about its axis or through gyroscopic precession.

Control moment gyros (CMG's) operate on the same momentum exchange principle as the variable-speed flywheel. A CMG is a constant-speed flywheel which is gimbaled about one or two axes in such a way as to allow the angular momentum axis to be skewed through an angle which may attain, theoretically, 90°.

In considering perturbation torques which are cyclic, for example, the oblateness effect of the Earth, or the gravitational cycle of the Sun, flywheels and CMG's may, in some cases, be designed to "absorb", (for example by limited control of their speed and/or orientation), these cyclic perturbations, the cumulative effects of which are essentially zero over one complete cycle. Otherwise, for the case of secular torque, such as solar pressure, these devices must be desaturated periodically so that wheel speed or gimbal angle limits are not exceeded. For this reason, flywheels and CMG's are usually best suited to inertially oriented payloads, rather than earth pointing satellites. Reaction wheels, particularly those using magnetic bearings, produce very low friction torques allowing very precise stability control in angular velocity and a long service life.

Mass expulsion control systems (reaction jets) differ from flywheel and CMG control in that momentum is disposed of rather than stored. Of the various techniques of mass expulsion the most common are cold gas systems, which employ the escaping stored gas to produce the restoring force, and monopropellant and hypergolic systems, in which momentum is produced by chemical reaction. Since reaction jet systems use expendable propellants, the momentum required to perform the various mission functions must be determined and provided for beforehand. This contrasts with on-board closed-loop null-seeking systems, such as momentum wheels and CMG's. This is an obvious disadvantage of the use of reaction jets as the primary attitude control subsystem. Another point of consideration is that regardless of the smallness of the impulse required to re-orient the spacecraft, a precisely equal and opposite impulse needs be provided to arrest the resultant angular motion of the spacecraft at the appropriate point.

6. **Attitude control systems**

6.1 **Passive systems**

When pointing accuracies are not stringent and when long satellite lifetimes are desired, passive attitude control systems may be employed. Some of the perturbation torques can be used for satellite attitude control, for example, gravity gradient, the Earth's magnetic field or the solar radiation pressure. A typical method of passive attitude control is the gravity gradient method. The Dodge satellite, for example, made use of a gravity-gradient effect by means of extendable booms.
The basic principle of attitude control by gravity gradient is that a satellite in a gravitational field, having a moment of inertia about one axis which is less than those about the other two axes, will experience a torque which will tend to align the axis of least inertia with the local gravity gradient vector. In this system, an undamped oscillation about the control axis would result from the action of external torque disturbances. A passive device is usually used to damp out these oscillations. The pointing accuracies which can be achieved by this means are generally no better than a few degrees.

6.2 Spin stabilization

Spin stabilization is an accepted means of maintaining spacecraft attitude because a spinning body has an inherent resistance to torques tending to disturb the spin axis. As a result of internal and external disturbances, the spin stabilized satellite will generally exhibit wobble or coning of its spin axis. A damper performs the function of dissipating the energy associated with this motion, eventually causing the spin axis to align itself in the desired attitude within preset limits. Generally, the spin axis is the axis of greatest moment of inertia (nutationally stable axis). Due to the effect of non-zero external torques, the kinetic momentum tends to deviate from its original orientation. This precession movement must be corrected by an active device.

6.3 Dual-spin stabilization

Dual-spin stabilization uses the same basic principle to achieve attitude control system; a part of the satellite rotates about its spin axis at a predetermined rate. The momentum caused by the spinning portion of the spacecraft tends to lend gyroscopic stability to the attitude of the vehicle. The remainder of the spacecraft is freely mounted about a shaft passing through the spin-axis of the spacecraft, and is rotated with a very low angular velocity, in the opposite direction to the spinning body. The velocity, typically one revolution per spacecraft orbit, is maintained by active control loops so that the de-spun platform points to the Earth or other reference within the limits of preset errors.

The alignment of the de-spun platform shaft and the main spin axis is critical to the performance of the dual-spin system. Any misalignment will tend to make the de-spun platform unstable and thus degrade the accuracy of the system. The coning motion caused by the misalignment is termed "wobble". Wobble can be eliminated by adjusting the position of two or three masses on a satellite spinning body [Nakatani and Izumisawa, 1977; Wright, 1974]. Also, as in passive-spin stabilization, damping of spacecraft nutation is necessary, especially if the spin axis is the axis of minimum moment of inertia.

An example of advances in the development of dual-spin technology is demonstrated by Intelsat-IV. Developments in bearing and power transfer assemblies, which form an interface between the spun and de-spun platforms, allow the realization of the advantages of mechanically de-spun antennas; as compared with electronically de-spun antennas having an equivalent number of elements and in which the ferrite phasing networks incur an insertion loss of 2 dB or more. The bearing and power transfer assembly incorporates a motor with permanent magnet armature and a field coil to produce the torque to counterbalance friction effects on the bearings and slip rings. A labyrinth seal, a polymer elastic reservoir, and an impregnated bearing retainer ensure a lubricant lifetime of an order of magnitude greater than anticipated mission life of seven years.

An important feature of Intelsat-IV's stabilization is the fact that rather than being spun about its axis of greatest moment of inertia, in which case energy dissipation within the rotor would not tend to destabilize the satellite, it was arranged to take as the spin axis, the axis about which the moment of inertia was the least (this depending on spacecraft volume and mass distribution design considerations). To counteract the destabilizing force associated with the choice of spin axis, an active nutation damper system was required on the non-spinning platform for dissipation of the energy.
6.4 Three-axis stabilization

Generally, three-axis orientation for an earth orbit is such that the spacecraft pitch axis is parallel to the normal to the orbit, the roll axis is parallel to the local horizontal, and the yaw axis is maintained parallel to the local vertical. This set of orthogonal co-ordinates makes one revolution about the pitch axis in one orbit period thus maintaining an Earth-pointing yaw axis. Three-axis stabilization may be desirable to point an experiment, or may be necessary when spacecraft power considerations necessitate a constant, or nearly constant, orientation of the solar panel to the Earth-Sun line; this cannot be achieved in a spin stabilized vehicle where effective solar array area is limited to the geometrical projection of the spacecraft surface area.

Three-axis stabilization may be achieved by mass expulsion techniques or, in appropriate instances, by passive environmental effects employed solely as the momentum-correction devices. Typically, however, these techniques are used in conjunction with reaction or momentum wheels which provide primary control in attitude. An external torque applied to the spacecraft may be countered by means of control loops which feed attitude-error signals from sensors to the momentum wheels to produce a time rate of change in the wheel momentum. Since momentum devices have limited momentum storage, this type of attitude control system must be augmented with reaction jets or with a magnetic torquing system so that the increasing wheel momentum may be reduced periodically.

Techniques of using flywheels and CMG's in conjunction with reaction jets or some passive means of reducing wheel momentum vary widely and their design depends primarily on mission requirements.

The earth observation satellite SPOT applies the principle of long-term attitude detection based on earth and sun sensors, coupled with gyrometric measurements for short-term reference.

It is activated by a system of magnetic bearing reaction wheels kept desaturated by the torque generated by magnetic coils. This type of control is effective in the presence of disturbances caused by the flexibility of appendages (solar generator). The pointing values obtained are better than 0.07° at 3σ, with an angular velocity stability of some 10⁻⁴ degree/s. [ANSTETT, 1981]

The medium-scale broadcasting satellite for experimental purposes (BSE) of Japan uses the zero-momentum three-axis method of stabilization as the attitude control system. The attitude errors are fed from the three types of sensors: the Earth sensor, the radio-frequency sensor (both fixed to the body) and the Sun sensor on the solar paddles. This system realized dynamic errors of the attitude control within ± 0.03° for pitch and roll by the use of an Earth sensor, and generally within ± 0.3° for yaw by the use of a combination of a radio-frequency sensor and an Earth sensor. It was noted that for short duration periods the errors exceeded these values due to the zero-crossing of angular velocity of the wheel and the interference of the Sun to the Earth sensor [Shimizu, 1980].

Through the multipurpose use of a single, speed-modulated, double-gimballed, control-moment gyroscope, the Molnya-I communication satellite, has achieved three-axis stabilization which alternates between solar orientation for solar panel efficiency and Earth orientation for communications. Speed modulation is needed to counter the effects of the satellite's highly eccentric orbit.

A dual-spin technique, known as “Stabilité”, employs a single reaction wheel as the only moving part of the attitude control system to maintain pitch axis orientation. Roll and yaw control in this system is maintained by the stored momentum and precessed by torque produced by the Earth's magnetic field. If magnetic torque is not applicable because the altitude is high and therefore the magnetic field is weak (and variable), reaction jets may be necessary to supply roll and yaw control. Pointing accuracies of ± 0.1° may be attained about all three axes, and with more advanced attitude sensing instrumentation this accuracy may be improved.
The Communication Technology Satellite (CTS, also known as Hermes), a geostationary satellite, uses a system with a momentum wheel and offset thrusters for three-axis stabilization. The primary components of the system were an Earth sensor, a momentum wheel with axis parallel to the pitch axis, offset thrusters having a torque vector in the roll-yaw plane and control electronics. The Earth sensor provided pitch and roll error signals to the control electronics. The gyroscopic properties of the wheel coupled the roll and yaw dynamics and eliminated the need to sense yaw error directly. Pitch control was obtained by accelerating or decelerating the wheel about its nominal speed in response to a control signal derived from the pitch error. Roll and yaw were stabilized by the gyroscopic stiffness of the momentum wheel. Small roll and yaw errors were corrected by automatic firing of the offset thrusters in response to a control signal derived from the roll errors. The performance and flight operations experience are outlined in [Vigneron and Millar, 1978]. The system successfully stabilized Hermes for the four-year duration of the mission. It performed as designed, except for occasional minor temporary malfunctions of an Earth sensor, and a minor occasional transient associated with the bearings of the momentum wheel. The pointing error of the communications antenna was deduced from flight measurements to be $\pm 0.09^\circ$ in pitch, $\pm 0.1^\circ$ in roll, and $\pm 0.5^\circ$ in yaw during the normal operating mode. In the de-saturation mode the pointing errors were within $\pm 0.6^\circ$, $\pm 0.11^\circ$, and $\pm 0.5^\circ$ in pitch, roll, and yaw respectively. Numerous geostationary satellites, for example, telecommunication satellites such as TELECOM 1, apply the CTS principle. A system using two momentum wheels (the two momenta being in the pitch-yaw plane on both sides of the pitch axis) allows, inter alia, flexibility in matching the variations in orbital inclination (attitude control system with one degree of freedom). This system was adopted for the MARECS, ECS, ARABSAT, INSAT and SKYNET satellites.

A new generation of telecommunication satellites, such as the INMARSAT II satellites, uses solar pressure torques generated by flaps fitted to the solar panels for normal mode roll and yaw attitude control; adequate torques are obtained by modulating the orientation of the panels around the nominal position.

Skylab had primary (solar and Earth), as well as secondary, (celestial) space targets necessitating the use of three-axis stabilization provided by sensing rate gyroscopes, a Sun seeker, a star seeker and a control moment gyro-system which consisted of three mutually perpendicular CMG's for primary attitude control. Desaturation of the control moment gyroscopes was provided by reaction thrusters.

Spacecraft designed to view celestial objects will in general require three-axis stabilization for multi-target viewing. For example, the inertially-referenced OAO-3 is equipped with gimbaled star-trackers for coarse attitude sensing and a fine error sensor operating integrally with the astronomical telescope. Error signals derived from equal outputs of the starlight passing through a diffraction slit are processed to drive fine adjustment inertia wheels on the appropriate axes. Continuous wheel desaturation is provided by magnetic torquing. This system has provided stellar pointing to the order of milliseconds of arc.

6.5 Orbit parameter corrections

6.5.1 Geostationary satellite

In addition to the sensing of and reduction or elimination of attitude errors, it is necessary from time to time to correct the orbital position of a geostationary satellite. During these position corrections, the attitude stability of the satellite may be temporarily degraded.

In the case of a spin-stabilized satellite, pointing accuracy may be temporarily degraded due to the spin axis nutation which is induced when an axial thruster is fired for the purpose of corrections of the attitude or the orbital inclination.

In the case of a three-axis stabilized satellite, attitude control systems use servo devices with an error detector in normal mode in the form of either an infrared sensor or an RF sensor. During orbital position corrections, these sensors are backed up by a yaw sensor.
The actual orbital correction phase may last less than an hour with conventional high-thrust propellants (hydrazine) or several hours with very low-thrust propellants (ionic drive). It is followed by a residual oscillation phase, particularly on direct TV broadcasting satellites using large solar generators, which always have a degree of mechanical flexibility.

With the conventional hydrazine systems in current use (high-thrust), corrections have to be made at intervals of about two months; with low-thrust ionic propulsion, corrections will be carried out almost daily.

The time of day, or night, exactly twelve hours later, at which these manoeuvres have to be performed, varies throughout the year, since it is linked to the orbital precession, so that the inclination may be corrected either on the ascending or the descending node.

With regard to pointing accuracy during orbital corrections, Table I sums up the main factors involved for telecommunication satellites (solar generator power of less than 2.5 kW, satellite weight 700 kg).

6.5.2 Heliosynchronous observation satellite

Heliosynchronous observation satellites require large orbit parameter correction manoeuvres with a periodicity of about one year and small corrections typically carried out every 15-30 days to maintain attitude and the phasing of ground passes. Generally, during an orbital manoeuvre, the pointing is degraded.

7. Prospects and limitations

The importance of precise attitude control increases as the beamwidth of a satellite antenna decreases, with a corresponding decrease in the service area of the satellite on the Earth. The relationship between attitude control perturbations and displacement of the aiming point of a geostationary satellite antenna are discussed in Annex I, for the attitude frame of reference given in Fig. 1.

<table>
<thead>
<tr>
<th>TABLE 1 - Effect of thrust level on accuracy of attitude control loops during orbital position correction</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Correction time (hours)</strong></td>
</tr>
<tr>
<td>AOCS without degree of freedom (1)</td>
</tr>
<tr>
<td>Thrust (mN)</td>
</tr>
<tr>
<td>1500</td>
</tr>
<tr>
<td>Control accuracy (2)</td>
</tr>
<tr>
<td>0.08°</td>
</tr>
<tr>
<td>Correction time margin (3)</td>
</tr>
</tbody>
</table>

AOCS: Attitude and Orbital Control System.

(1) The direction of the kinetic moment is fixed in a trihedral system tied to the spacecraft.
(2) The direction of the kinetic moment is variable in a plane containing the pitch axis of the spacecraft.
(3) The normal correction time varies with time. A time of day or night may be selected depending on whether correction is made on the ascending or descending node of the orbit.
Since the ultimate accuracy of any attitude control system is a function of attitude-error determination, both the sensors and the sensed targets chosen as references are important. Systems design must be based upon basic mission requirements, weight, cost and reliability.

Earth-oriented systems employing the Earth as the prime attitude reference body are orientation-limited to about 0.1°. Removal of atmospheric and oblateness effects by the use of an on-board computer will allow the pointing accuracy to be improved to about 0.05° in the near future.

The likelihood of improving low Earth-oriented, Earth-sensing systems to better than 0.05° is small. If higher Earth-pointing accuracies are required, the use of Sun or star sensors is indicated. In Earth-oriented stellar tracking systems, transformation of stellar-reference co-ordinates is limited by the present-day abilities of orbit determination with respect to the Earth. The first National Aeronautics and Space Administration attitude control system of this type will be used on the Earth Observation Satellite (EOS). The EOS is expected to be capable of providing a 0.001° pointing accuracy with respect to the Earth, by means of both a gimbaled star-tracking system and an on-board computer system, which will provide orbit determination errors of less than about five metres.

Inertially referenced spacecraft such as OAO have shown that extremely accurate pointing with respect to astronomical bodies may be achieved (within milliseconds of arc). Such accuracies are possible through the use of experiment sensors and attitude sensors operating in co-ordination.

With angular pointing requirements of a few seconds of arc, design control of structural and thermal deformation of the spacecraft is extremely important. Very slight deformation in the spacecraft, especially if in the neighbourhood of an attitude sensor, may result in relatively large errors in the spacecraft’s attitude-keeping capability. Also, when considering attitude control errors of the order of 0.001°, the overall ability of a satellite to point to a particular location on the surface of the Earth is no longer primarily a function of the attitude control system. Rather, an equivalent contribution of pointing error can be caused by uncertainties in ephemeris data. For example, a pointing uncertainty of 0.001° will produce a pointing error of about ± 9 m from a 500 km orbit. This is of the same magnitude as the orbit determination accuracy expected in the near future.

REFERENCES


Communications Research Centre, Dept. of Communications, Ottawa, Ontario, Canada.


CCIR Documents

[1974-78]: 2/234 (10/330; 11/413) (France).
BIBLIOGRAPHY


ANNEX I

IMPACT OF ATTITUDE CONTROL ERROR ON THE COVERAGE AREA OF A GEOSTATIONARY SATELLITE

1. Introduction

The purpose of this Annex is to describe the impact of errors in a geostationary-satellite attitude control system on the service area of the satellite. Although the importance of this effect is highly mission dependent, this Annex presents a simplified description of the impact of rotational errors in geostationary-satellite pitch, roll and yaw axes.

2. Attitude frame of reference

Figure 2 presents the orientation of the pitch, roll and yaw axes, described in Cartesian co-ordinates, of a typical geostationary-satellite. The figure also shows the desired boresight of the satellite antenna (point P) and the sub-satellite point S. The displacement of point P for small rotational errors about each of the three orthogonal spacecraft axes are described in the following sections.

2.1 Pitch axis

Figure 3 presents the effect of rotation about the satellite pitch or Y axis. Such a rotation would cause the satellite Z axis to be displaced east or west on the equator.
The displacement of point P in km is a function of the pointing angles measured at the spacecraft. For pointing locations near the equator (or satellite pointing azimuth of 90° measured from North) the boresight displacement is approximately:

\[ d_y = R_e \left[ \sin^{-1} \left( k \sin (\alpha + \Delta y) \right) - \Delta y - \sin^{-1} (k \sin \alpha) \right] \frac{\pi}{180} \text{ km} \]  

where:

- \( R_e \): equatorial radius of Earth (km)
- \( k = (R_e + h)/R_e \)
- \( h \): geostationary altitude (km)
- \( \alpha \): elevation angle from satellite to point P (measured from nadir in degrees), and
- \( \Delta y \): rotational error about pitch or Y axis in degrees.
Figure 4 presents the sensitivity of antenna boresight point displacement as a function of pitch error ($\Delta y$) and elevation angle ($\alpha$) for pointing locations on or near the equator.

For Earth pointing locations on or near the satellite meridian (satellite pointing azimuth of 0° measured from North), the elevation angle $\alpha$ does not significantly impact the displacement error, and the boresight displacement is given by:

$$d_y = h \cdot \Delta y \cdot \frac{\pi}{180} \text{ km} \quad (2)$$

Figure 5 presents the sensitivity of antenna boresight displacement error to pitch errors for Earth pointing locations on or near the satellite meridian.

Figure 6 is presented as an example of the sensitivity of boresight displacement error to pitch or roll errors at 45° pointing azimuth (in any quadrant).
2.2 Roll axis

Figure 7 presents the effect of rotation about the satellite roll axis. The distance that the boresight of the antenna would shift is derived similarly to that in § 2.1 of this Annex. The figures in § 2.1 presenting the results of pitch error (Figs. 4, 5 and 6) apply also to roll errors in the following manner. Figure 4, which shows displacement due to pitch errors for a pointing azimuth of 90°, also shows the displacement due to roll errors for a pointing azimuth of 0°. Likewise Fig. 5, showing boresight displacement due to pitch errors for a pointing azimuth of 0°, also shows the displacement due to roll errors for a satellite pointing azimuth of 90°.
2.3 Yaw axis

Figure 8 presents the effect of rotational errors of the satellite about the yaw, or Z axis. As can be seen, point P would be displaced both in latitude and longitude.

![Diagram of satellite yaw axis error](image)

**Figure 8 – Pointing error due to yaw axis error**

Errors in the satellite yaw axis produce corresponding one to one errors in the azimuth pointing direction of the satellite. Therefore, in order to determine the location of point P' as a function of yaw errors, it is necessary to determine the changes in latitude and longitude of P as a function of changes in pointing azimuth. The latitude of point P ($\Phi$) is related to the azimuth and elevation pointing angles of the satellite as follows:

$$\Phi = \sin^{-1} \left[ \cos(A_z) \sin \left( \sin^{-1}(k \sin(\alpha)) - \alpha \right) \right]$$  \hspace{1cm} (3)

where:

- $A_z$: pointing azimuth of the satellite (degrees measured from North)

The change longitude ($\Psi$) of point P (from the sub-satellite point S) is given by:

$$\Psi = \tan^{-1} \left[ \sin(A_z) \tan \left( \sin^{-1}(k \sin(\alpha)) - \alpha \right) \right]$$  \hspace{1cm} (4)

The sensitivities of $\Phi$ and $\Psi$ to small changes in azimuth are given by:

$$\frac{d\Phi}{dA_z} = \frac{-\sin(A_z)}{\sqrt{1-a^2 \cos(A_z)^2}}$$  \hspace{1cm} (5)

where:

$$a = \sin \left[ \sin^{-1}(k \sin(\alpha)) - \alpha \right]$$
and,

\[
\frac{d\Psi}{dA_z} = \frac{b \cos (A_z)}{1 - [b \sin (A_z)]^2}
\]

where:

\[b = \tan [\sin^{-1} |k \sin (\alpha)| - \alpha]\]

For a given elevation angle, \(a\) and \(b\) are constant.

Figure 9 presents the distance from P to P' based on the above changes in latitude and longitude of the antenna boresight. The distances are presented as a function of the error in yaw (Z axis) and parametrically for various satellite antenna elevation angles (measured from nadir). As can be seen, at high elevation angles (i.e., especially approaching the Earth's limb at 8.5°), the maximum error induced by a 1° error in yaw control is of the order of 90 km.

An approximation of the allowable error in yaw rotation (\(\Delta z\)), such that the displacement of point P does not exceed that induced by errors of \(\Delta y\) or \(\Delta x\) in pitch or roll respectively, is derived below:

\[d_z = R_z \Delta z [\sin^{-1} (k \sin \alpha) - \alpha] \frac{\pi}{180} \text{ km} \quad (7)\]

and,

\[d_x \text{ or } d_y = R_x [\sin^{-1} (k \sin (\alpha + \Delta y)) - \Delta y - \sin^{-1} (k \sin \alpha)] \frac{\pi}{180} \text{ km} \quad (8)\]

where:

- \(d_z\): distance traversed by point P due to a rotation about the yaw axis of \(\Delta z\)
- \(d_x\) or \(d_y\): distance traversed by point P due to a rotation about pitch or roll axis of \(\Delta x\) or \(\Delta y\).

Equating \(d_z\) and \(d_x\) or \(d_y\) and solving for \(\Delta z\) yields:

\[\Delta z = \frac{[\sin^{-1} (k \sin (\alpha + \Delta y)) - \Delta y - \sin^{-1} (k \sin \alpha)]}{\sin \{\sin^{-1} (k \sin \alpha) - \alpha\}}\]

(9)

For small values of \(\alpha\) and \(\Delta y\), the expression can be simplified to:

\[\Delta z = \frac{\Delta y \text{ or } \Delta x}{\sin \alpha}\]

(10)

where \(\Delta y\), \(\Delta x\), \(\Delta z\) and \(\alpha\) are expressed in degrees.

It should be noted that this expression is an approximation, valid only for small angles (\(\alpha = 2^\circ\), \(\Delta x\) or \(\Delta y = 0.1^\circ\) results in 3% error). For larger angles, the unsimplified relationship should be used.
2.4 Conclusions

To sum up, displacements due to a given pitch error are relatively insensitive to pointing direction on or near the satellite's meridian (see Fig. 5) and are proportional to offset on or near the equator (see Fig. 4). Conversely, displacements due to a given roll error are relatively insensitive to pointing direction on or near the equator, and are proportional to offset on or near the satellite's meridian. For the worst case, small errors (≈ 0.1°) in pitch or roll cause displacements equal to or greater than yaw errors of the order of 2°.
Many geostationary communication satellites have axis-symmetrical bodies and de-spun antennas. The spin axis of such a satellite is drifted mainly by the solar radiation torque. The magnitude of the torque depends on the shape and the surface material of the satellite and has seasonal variation due to the variations of the sun angle and the receiving intensity of the solar radiation.

The drift rate of the spin axis is in proportion to the solar radiation torque. Figure 10 shows the actual drift rate data of Japan's experimental satellite CS (the medium-capacity communication satellite for experimental purpose).

The variation of attitude due to disturbing torques can be theoretically calculated, but the process is rather complicated. On the other hand, by using actual data of the drift rate of spin axis it is possible to predict the attitude by solving the equation:

$$\frac{d\vec{r}^*}{dt} = D (\vec{s}^* \times \vec{r}^*)$$

where:

- $\vec{r}^*$: unit vector along the spin axis,
- $\vec{s}^*$: unit vector toward the Sun,
- $D$: drift rate of the spin axis.

These vectors and the coordinate system are shown in Fig. 11.

Using the drift rate data in Fig. 10, equation (11) is solved and the attitude predictions of the CS are obtained. An example of the predictions is shown in Fig. 12. They are found to agree well with the actual attitude calculated from the telemetry data.

In order to keep the attitude of a satellite within a given allowable error, periodic corrections are necessary. The period is in proportion to the magnitude of the allowable error and in inverse proportion to the attitude drift rate. As regards a satellite which has the same drift rate as that shown in Fig. 10, the correction periods are shown in Fig. 13 for three different allowable errors 0.2, 0.1 and 0.05°.

![Graph](https://via.placeholder.com/150)

**FIGURE 10 — Drift rate of the spin axis of the CS satellite**

- ● 1978
- ○ 1979
- — Fitting curve for 1978
FIGURE 11 — Coordinates for the equation of spin axis drift

FIGURE 12 — Attitude predictions of the CS

- Attitude obtained by telemetry data
- Prediction
- Initial attitude
FIGURE 13 — Attitude correction period of a satellite with the drift rate shown in Fig. 10

A: allowable attitude error
REPORT 673-3

ELECTRICAL POWER SYSTEMS FOR SPACECRAFT

(Question 15/2)


1. Introduction

The purpose of this Report is to provide information on past, current, and future (to 1990) satellite electrical power systems. The Report is confined to those systems which have received extensive study and which are considered feasible for application in space during the time frame to 1990.

2. Background

In general, the requirements for on-board electrical power have increased in the past, and are expected to continue to increase in the future.

Present requirements have reached 1.5-3 kW for large capacity communication satellites and are increasing to 3.5-6 kW during non-eclipse period for direct television broadcasting satellites. Power at this level is or will be delivered by photovoltaic conversion systems in combination with chemical storage battery systems which supply power when the satellites are eclipsed by the Earth. In the case of broadcasting satellites, a large storage battery capacity will allow more freedom in selecting orbit positions instead of the current practice of placing them west of the service area.

Space flights to the outer parts of the solar system, where solar electrical conversion becomes impractical, and certain other space missions, have necessitated the development and implementation of radioisotope power systems in the range of a few hundred watts. The application and development of nuclear power systems will only be possible insofar as safety problems have been thoroughly understood. Lithium cells may be used in the case of deep space probes whose active mission is limited in time (from a few days to about 10 days).

3. Current technology

The following sections discuss the current technology of satellite prime power generation.

3.1 Solar array/electrochemical storage battery systems

Solar cells (photocells) may be mounted directly on the main body of the satellite (spin-stabilized satellite) or on deployable (rigid or flexible substrate) Sun-oriented arrays (3-axis momentum wheel satellite), in which case an electric motor is required to rotate the arrays. Although each type of satellite has its own specific advantages, given equal characteristics a spin-stabilized satellite requires roughly twice as many solar cells as a 3-axis satellite.
The launch volumes offered by new launchers such as STS and ARIANE have raised the electrical power of spin-stabilized satellites to 2.2 kW (INTELSAT 6) and of 3-axis stabilized satellites to 3.7 kW (TVSAT/TDF1) or even 5 to 7 kW (OLYMPUS) at the beginning of life.

In the case of manned space stations, arrays mounted on paddles deployed from the spacecraft after launch can increase the power level of photovoltaic systems to many kilowatts. These arrays usually track the Sun continuously in order to optimize their efficiency. Large, deployable rigid, Sun-oriented arrays having a power capability as high as 16 kW have been built and successfully used in space (Skylab).

A disadvantage of the rigid high-power solar arrays needed for supplying future space stations is the relatively large stowage volume needed in the shroud of the launch vehicle. Deployable flexible solar arrays (solar cells mounted on flexible substrates) allow a higher packing density during launch when the flexible solar array blankets are folded or rolled-up. These can also be designed for folding by telecommand (ESA's recoverable EUREKA platform).

An experimental roll-up solar array was flown in 1971 [Wolff and Wittman, 1972]. A flexible fold-up array was flown in 1974 on the British Miranda (X4) technology spacecraft. A flexible fold-up array of 1.2 kW was incorporated in the Canadian communication technology satellite [Harrison et al., 1976].

The SPOT 1 remote sensing satellite launched by France in 1986 is fitted with a 1.2 kW photocell generator mounted on a flexible substrate and folded for launching. A more powerful version (2.2 kW) will be fitted to the European ERS 1 remote sensing satellite to be launched in 1989. ESA's large European OLYMPUS 1 experimental satellite is equipped with a flexible concertina-folding generator capable of supplying 3.6 kW at end of life (this generator is optimized for powers of 5 to 7 kW).

Research on the solar array systems of telecommunication satellites is aimed chiefly at increasing the power-to-mass and power-to-surface ratios with a view to reducing the launching cost or enabling the propellant mass to be increased for longer life. In the case of large 15 kW solar generators, such as those designed for space station COLUMBUS, research is also aimed at decreasing the stowage volume during launch.

Research in solar array power systems is aimed at increasing the power-to-mass ratio of solar arrays in space and decreasing the stowage volume during launch. A major part of the research is still directed toward further improvements of solar cells and cover glasses. Following the development of silicon solar cells with a higher sensitivity in the blue and violet part of the spectrum and of cells with a reduced reflection loss (BSR solar cell) in the mid-seventies, further improvements were achieved [Scott-Monck, 1978] by the development of cells with a back surface field and back surface reflector (BSFR solar cell). The back surface field cell has a built-in electrical field near the rear contact which reduces the electrical losses at the rear contact. A combination of the back surface field technology with new etching methods for silicon has led to the development of experimental ultra-thin cells with a thickness as low as 50 μm (compared to the presently-used thickness of 200-250 μm) and a correspondingly low mass without a significant reduction of the electrical performance after several years of operation in space. A new range of solar cell cover glasses, which are now used on most spacecraft arrays, has been developed in the United Kingdom [Taylor et al., 1982]. They have superior transmission and better stopping power to particle radiations and can be produced in thicknesses down to 50 μm, thus matching the thin solar cell. Back surface reflector layers in silicon cells lead to a lower operating temperature in space and to a further improvement of the effective conversion efficiency since it increases with decreasing cell temperature. In total, the beginning of life efficiency of space silicon solar cells has increased from 10% to about 14% during 1970-1980.
So far, all operational solar arrays on spacecraft have used silicon solar cells. Other solar cell materials have been extensively studied, but in the near future only gallium-aluminium-arsenide solar cells appear to be a potential alternative for certain applications. Laboratory cells [Knechtli et al., 1980] of this type have shown a very high efficiency (18%) and lower sensitivity to space radiation. GaAs solar cells with typical efficiency of 17.5% have been developed and are routinely produced in Japan [Matsuda, S. et al., 1986]. These cells are used for Japanese Communications Satellites CS3a and CS3b which have been launched in 1988. None of the other solar cell types presently investigated, e.g. cadmium sulphide, amorphous silicon or multi-band-gap cells, have so far reached the efficiency and reliability of present space silicon solar cells. So far, the results of the current large effort in terrestrial photovoltaic power research have not yet had a strong impact on the evolution of space solar cells.

The technological advancements both in solar cells and in structures have led to significant improvements of the power-to-weight ratio of solar arrays during the period 1970-1980 (the following data refers to the initial performance in space and the weight includes both the solar cells and the supporting structure). Body-mounted solar arrays have provided up to 7-8 W/kg at a specific mass of 4 to 5 kg/m$^2$. The performance of deployable arrays with a power level of 0.5-2 kW has increased from 10 to 30 W/kg, with the specific mass decreasing from 7 to 3.6 kg/m$^2$.

Between 1980 and 1986, a considerable improvement was achieved in Europe [Mamode et al., 1986] in the performance of the deployable solar arrays intended for the 3-axis stabilized telecommunication satellites to be launched from 1989 onwards.

The performance index in W/kg for a power calculated after seven years in geostationary orbit, including deployment devices, has risen from 23 W/kg for the ARABSAT satellites (1.5 kW at end of life) to 39 W/kg for the EUTELSAT 2 satellites to be launched in 1989 (3 kW at end of life).

Advances have been made in BSR silicon cells, in better cell cooling and lighter rigid panel structure and mechanical/pyrotechnic deployment devices.

The reliability and the total weight of a combined solar array storage battery system are strongly affected by the characteristics of the chemical storage batteries. Battery systems are of particular importance for high power geostationary communication and broadcasting satellites if continuous operation is needed during the semi-annual 45-day periods of daily eclipse. At present, battery lifetime appears to be the most critical factor in the design of long-life power systems (limitation of the number of charging-discharging cycles).

So far, nickel-cadmium batteries have been used in most space missions. Since the mass of nickel-cadmium batteries in high power communication satellites may represent 10-20% of the satellite dry mass, metal-hydrogen - in particular, nickel-hydrogen cells [Young, 1979] - are being developed as a lighter alternative. Experimental nickel-hydrogen batteries have been successfully flown on the NTS-2 spacecraft [Dunlop and Stokel, 1978] and are used on several of the INTELSAT-V type spacecraft. The change from nickel-cadmium to metal-hydrogen batteries raises the usable specific energy from 20 Wh/kg to 33 Wh/kg or more. It is also assumed that nickel-hydrogen batteries will have a considerably higher life expectancy than nickel-cadmium batteries.\footnote{For a 100% discharge and capacities of the order of 20 Ah, specific energy levels of 35 Wh/kg and 60 Wh/kg can be achieved for nickel-cadmium and nickel-hydrogen storage batteries respectively.}
The EUTELSAT 2 satellites will be the first European telecommunication satellites to be fitted with Ni-H$_2$ storage batteries which will enable all 16 50-W channels to be used throughout eclipses.

Ni-H$_2$ storage battery technology has now been mastered in the United States and is being developed in France, in Japan and in the United Kingdom.

Although no experiments have been conducted in space, the United States and France are contemplating the use of momentum wheels for energy storage as an alternative to chemical storage batteries. Experiments are in progress on reversible lithium pairs and lithium storage batteries such as Li-V$_2$O$_5$ or Li-TiS$_2$ [Otzinger, 1985] and the possibility of using a hot sodium-sulphur storage battery is also being explored [Dueber et al., 1985].

3.2 Solar collectors

Where several dozen kilowatts are required, e.g. for large orbital stations, solar collector (heat trap) systems may provide useful mass and volume characteristics. The devices at present being studied include solar concentrators, a one-cycle power conversion system of the Brayton or Rankine-type and a turbo-alternator. This type of generator may be combined with an electrochemical, mechanical or thermal power storage device.

3.3 Nuclear systems

The application of nuclear technology to the generation of electrical power in space has shown distinct potential in terms of power levels, long lifetimes and high reliability. However, a great deal of effort [Stadter and Weiss, 1975] has been required to assure safety in the implementation of these systems. The following sections discuss some of the power source and energy conversion techniques which have been the subject of extensive study to date.

3.3.1 Radioisotopes

The use of radioisotopes as energy sources for space electrical power has been recognized since the early 1960s, and the systems derived therefrom have been described in many published references.

Nuclear electric power for space application was first achieved in 1961 when a 2.7 W plutonium-238 fueled generator was orbited by the United States. More recent missions using radioisotope thermoelectric generators (RTGs) in five Apollo Lunar Surface Experiment Packages (ALSEP) on the lunar surface, and four RTGs aboard each of the Pioneer 10 and 11 interplanetary satellites (exploration past Jupiter and Saturn), attest to their inherent reliability.

Radioisotope thermoelectric generator technology growth has reached the point where kilowatt levels of electric power for spacecraft can be considered as practical. Through extensive research, efficiencies can now be doubled by application of new Si Ge thermoelectric materials. Specific powers of these systems are expected to increase to 9 to 11 W per kilogram. These improvements, coupled with the projections of a 50% reduction in the cost of long-lived plutonium-238, indicate that, for some specific missions, RTG space power systems could be nearly competitive.
It should be stressed that a considerable quantity of highly toxic and therefore dangerous radioactive material (in this case plutonium 238) is carried. This raises the problem of accidental re-entry of the material into the atmosphere where, at the power levels envisaged, its dispersal would cause a planet-wide disaster. Studies are in progress on the replacement of the thermo-element conversion system by thermodynamic engines.

Perhaps the most significant conversion means are the Brayton, Rankine and Stirling dynamic cycles. These conversion cycles are thermodynamic engines typically consisting of the nuclear heat source which transfers energy to a working fluid which in turn drives a turbine, electrical generator and compressor. Typically, these conversion systems deliver 2 to 3 times the energy conversion efficiency of thermoelectric materials. However, present-day cost and weight factors are also higher.

3.3.2 **Fission reactors**

Several generic types of nuclear fission reactors have undergone study for space applications. An operational system might be developed in the next ten years under the United States SP-100 research programme [Truscello and Davis, 1984]. Such a system will possibly employ uranium dioxide fuel clad in molybdenum with heat removal by lithium heat pipes.

4. **Prospects and limitations**

Table I presents estimated performance parameters of the three prime systems for electrical power generation for spacecraft. Although many other power generation and conversion technologies exist and have been studied, the three generic systems listed in Table I are considered the most likely to be realized in space qualified hardware within the foreseeable future.

The immediate future space power generation systems will probably continue to be comprised of advanced solar cell/chemical battery systems due to recent technological advancements and their proven space qualified performance in the low multi-kilowatt range. Deep space and interplanetary missions at distances of several AU's from the Sun will continue to require advanced RTG technology energy conversion systems. Very high power (5 to 20 kW) Earth-oriented communications or broadcasting-satellites may realize the advantages of utilizing nuclear power systems (continuous power independent of sunlight) once the inherent safety and weight/cost restrictions are overcome. The critical safety factors associated with spaceborne nuclear power systems which must be studied are fairly numerous. In addition to special handling and disposal requirements of long-lived nuclear reactor by-products, spaceborne nuclear power systems have associated critical accident potentials such as launch booster failure and detonation, shrapnel dispersion, fire immersion, aerodynamic heating during re-entry, high velocity terrestrial impact and potential post-impact burial and oxidation. Each of these failure modes require extensive materials research and development to ensure that the radioactive heat source (some of whose half-lives may be of the order of 100 years or more) does not contaminate the Earth's atmosphere or water resources.

5. **Summary**

The selection of a power system for space applications depends on a number of factors, in addition to the amount of on-board electrical power that is required. The estimated performance and cost parameters for the most likely systems are listed in Table I.

Solar array/battery subsystem characteristics are mission dependent, and the number of integrated subsystem elements such as the arrays orientation mechanisms, sensors, storage units and power conditioning circuitry must all be included in an overall power system evaluation.

Nuclear radioisotope and reactor system performance capabilities have not yet been fully explored in a mission operations context, and safety and cost considerations require further evaluation.
The continuing evolution in the performance and in the achievable power level of solar array/battery systems will probably ensure that this system will continue to remain the dominant power source for space missions, at least in the 1980-1990 period. Nuclear systems may replace solar array/chemical battery systems in some applications at a later stage, provided the potential safety problems can be solved.

**TABLE I — Estimated power system performance parameters of some US power units**

<table>
<thead>
<tr>
<th>System</th>
<th>Technology status</th>
<th>Year of availability</th>
<th>Performance and cost parameters (')</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>kg/W</td>
</tr>
<tr>
<td>Photovoltaic cells</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt; 2 kW units (I)</td>
<td>In use</td>
<td>—</td>
<td>$3 \times 10^{-2}$</td>
</tr>
<tr>
<td>2 to 100 kW units</td>
<td>In use</td>
<td>1980–1985.</td>
<td>$2 \times 10^{-2}$</td>
</tr>
<tr>
<td>&gt; 100 kW units (low cost)</td>
<td>Future development</td>
<td>1985–1990.</td>
<td>$5 \times 10^{-3}$</td>
</tr>
<tr>
<td>Radioisotopes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermoelectric conversion</td>
<td>In use</td>
<td>—</td>
<td>$3 \times 10^{-1}$</td>
</tr>
<tr>
<td>0.1 to 1 kW unit</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brayton conversion</td>
<td>In development</td>
<td>1985</td>
<td>$1.5 \times 10^{-1}$</td>
</tr>
<tr>
<td>0.5 to 5 kW units</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reactors</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermoelectric conversion</td>
<td>In development</td>
<td>—</td>
<td>$2.5 \times 10^{-1}$</td>
</tr>
<tr>
<td>100 kW units</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(') Estimated performance parameter uncertainty, ± 20 to 100%.

(1) In special applications such as Skylab this number has been exceeded.

**REFERENCES**


BIBLIOGRAPHY


1. **Introduction**

The manufacture and launching of satellites is an expensive enterprise which is something of a 'high risk' business. It is therefore important that, once successfully injected into orbit, spacecraft continue to operate correctly until the end of their planned life. However, the space environment is hostile and experience has taught us that trouble-free operation will not be attained unless rigorous attention is paid to the potentially hazardous interactions of ambient particles / radiation with spacecraft materials and systems. There is now an extensive chronicle of in-orbit 'anomalies' or malfunctions but it is usually impossible to positively identify their cause. A prime candidate for the source of many of these is electrostatic discharge (ESD), resulting from a local build up of charge to such an extent that a breakdown threshold is exceeded. This process, termed spacecraft charging, occurs readily at exposed surfaces but also within dielectric materials close to an unprotected surface. Similar effects (e.g. single event upsets) due to penetrating radiation, such as cosmic ray and Van Allen belt particles, complicate the issue but these are treated separately because the protection strategies are very different.

2. **Operational Problems**

Unmanned satellites are complex engineering systems which rely on internal emf supplies (usually solar powered), telecommand and telemetry radio links, and onboard computer control; they must function under conditions of high vacuum, zero gravity and variable thermal balance; requiring long life expectation without servicing. The overall record has been remarkably good, largely due to an appreciation of the need for thorough pre-launch testing and stringent quality control procedures. Given that all the flight systems die sooner or later and that failure analysis is often a matter of conjecture, the recognition of spacecraft charging related anomalies is far from easy. In recent years, many spacecraft managers have been all too ready to blame charging for transient operational effects. The problem is that few of the satellites experiencing anomalies carry instruments which can detect charging events, while the scientific satellites, equipped to study charging, have been carefully designed to be immune to ESD. Exceptionally, ATS (DeForest, 1972), METEOSAT (Wrenn and Johnstone, 1987), DMSP (Gusenhoven et al., 1985) and SCATHA (Mullen et al., 1986, Li and Whipple, 1988) have produced important evidence for charging, but still failed to establish a conclusive pattern of cause and effect. However, there are many good correlations between the frequency and timing of anomalies and such variables as local time and geomagnetic activity indices which classify charging levels.

* This Report should be brought to the attention of Study Groups 4, 8, 10 and 11.
The National Geophysical Data Center at Boulder, Colorado, has assembled a Spacecraft Anomaly data base (Allen and Wilkinson, 1986) with over 2000 entries; the number between midnight and 06 h is 64% above the average for the other 6 hour intervals. On 2 June 1973, DCSC-9431 suffered a catastrophic surge on its power system (Pike and Bunn, 1976); on 27 February 1982, MARECS-A switched from Earth pointing to emergency Sun re-acquisition mode (Capart and Dumesnil, 1983); on 26 November 1982, GOES-4 was fatally crippled (Allen and Wilkinson, 1986); on 8 March 1985, control of ANIK-D2 was lost when the antenna platform suddenly spun up (Vadham, 1987). These are some reported examples of serious anomalies which have been related to geomagnetic disturbances; undoubtedly, there have been many others. Most of the problems have occurred on satellites in geosynchronous orbit (GEO) where the conditions are very often suitable for severe charging; detailed studies of the capricious environment and charging physics have been carried out on GEOS-2 and SCATHA. The most common anomalies are phantom commands, logic upsets, spurious mode switching and erroneous status indications but random part failures do occur. It is fortunate that almost all of these malfunctions are overcome by controller action but not without some cost in terms of loss of data, reliability and mission life; increased staffing and vigilance also have a price.

3. **Charging Mechanisms**

The potentials of surfaces in space has been excellently reviewed by Whipple (1981). The equilibrium potential of a surface is established when the net current to the surface is zero. The sources of current are: charged particles from the environment - electrons and positive ions, (predominantly protons above 1000 km); secondary electrons and photoelectrons emitted from the surface; and leakage to or from any underlying substrate. The potential difference between the surface and the substrate controls the latter component which is not always negligible, even for relatively good insulators. The surface currents are complex functions of their potentials; negative feedback limits the currents and tends to induce a dynamic equilibrium. A satellite structure ('ground') will float to an equilibrium potential, -19 kV was observed on ATS-6 (Olsen and Purvis, 1983), but such absolute charging represents no real hazard. Differential charging is much more dangerous, it can occur between surface elements and also within dielectric materials; the consequent breakdown produces a discharge current transient which can propagate through all the sensitive electronics systems on the spacecraft.

3.1 **Absolute charging**

In low-Earth orbit (LEO), within the plasmapause, potentials reach only a few volts negative or positive, depending upon the concentration of cold plasma and whether the surface is in shadow or sunlight. At higher altitudes, where Ne < 10^2 cm^-3, photoemission usually keeps the spacecraft frame potential near zero except when the effects of high energy particles become important. Plasmasheet fluxes, greatly enhanced in the midnight and early morning sectors at sub-storm injection, drive a spacecraft near GEO to large negative potentials. Until an equilibrium state is reached the flux of electrons, of a few keV to a few tens of keV, always exceeds that of any ions that can be attracted. In eclipse (< 75 min about local midnight in GEO), spacecraft potential can approach the -19 kV reported, but in sunlight it is limited to a few hundred volts [Mullen et al., 1986]. In these situations the level of absolute charging is largely dependent upon the mean temperature of environmental plasma. In eclipse, the equilibrium potential is largely dependent upon the secondary electron yield characteristics of the satellite surfaces [Katz et al., 1986]. The rate of charging dV/dt, inversely proportional to capacitance (ε1ε0 Ro) is typically several hundred volts per second. In sunlight photoemission limits the potential and the rate of charging at lower, but still critical, values. Outside the midnight to dawn quadrant, in local time, (which in some circumstances could extend from 8 p.m. to 8 a.m.), the environment never seems able to induce conditions of high level absolute charging.
3.2 Differential Charging

Given that spacecraft surfaces are not all conducting and electrically connected, it is clear that large potential differences can develop between isolated surface elements, and between these and substrates or structure. Spacecraft ground still floats to minimise the net current and conducting surfaces are effectively tied to this. The level of charging depends upon the energy spectra of the incident particles, material properties, surface geometry and configuration as well as satellite orbit and attitude. Conductivity, relative permittivity and the yield coefficients for secondary and photo-emission are critical. Since the capacitances associated with differential charging can be high, the charge times are relatively long (many minutes) and spatial constraints, e.g. satellite spin, are important. Sunlight with shadowing probably introduces the greatest contrast but other asymmetries rise from satellite motion (ram and wake perturbations), the geomagnetic field (the energetic electron fluxes are field-aligned) and the \( \mathbf{v} \times \mathbf{B} \) induced electric fields. The process is complicated by the fact that surfaces are coupled via the plasma, space charge sheaths develop and the local electric field is complex; secondary emitted electrons from one surface can be attracted to another and potential barriers can reflect incident or emitted fluxes (Purvis, 1983).

There is little doubt that this mechanism is responsible for many ESD problems on GEO missions. 90% of MARECS-A anomalies were between 00.30 and 06.30 LT but not during eclipse; they were usually at geomagnetically active times (Capart and Dumesnil, 1983). Since the energetic electrons are regularly precipitated to low altitudes in the auroral zones, the ingredients exist for similar problems to occur at LEO for high inclination (POLAR) orbits. Significant charging has been observed (Gussenhoven et al., 1985) but there is no history of related anomalies; the increased dimensions of proposed polar spacecraft will make these more susceptible (Katz and Parks, 1983).

3.3 Deep dielectric charging

More energetic electrons, hundred of keV to several MeV, can penetrate to considerable depth in a dielectric and deposit charge within the bulk material. If the rate of deposition exceeds the rate at which charge leaks away due to the intrinsic conductivity, potential differences can reach the threshold for breakdown, resulting in a discharge [Vampola, 1987]. Such fluxes of electrons do appear in the outer magnetosphere and many day-side anomalies are attributed to this mechanism [Baker et al., 1987]. It is envisaged that this type of charging is slow, taking hours or days; total fluence (integrated flux) becomes the critical parameter. Unshielded components close to a spacecraft surface, e.g. cables, present the principal problem; 2 mm of aluminium, or equivalent, will stop most of the offending electrons i.e. those below 1 MeV.

4. Modes of breakdown

Isolated charged surfaces, either dielectric or conducting, will lose charge slowly by conduction to the substrate. They will discharge to space if they become sunlit or encounter higher concentrations of cold ions, (plasma clouds are not uncommon at GEO) but such transients are not directly conducted to the rest of the spacecraft. Output from an earth sensor aboard ANIK-A gives a neat demonstration of periodic discharging of a metal lens barrel by photoemission [Wadham, 1987]. More usual and dangerous are breakdown discharges. Those involving a conductor electrically connected to the structure are likely to be more damaging because large current spikes (many amperes) can be conducted or inductively coupled into any sensitive circuit. Floating conductors (e.g. metallized coating of thermal blankets) break down more readily than dielectrics, but the latter can support a greater build up and the discharge,
propagating from a source point, will still sweep across the entire surface. Discharge produces strong electric field and space charge modification (blow-off) around the satellite and a sudden drop in absolute potential, these can cause additional radiated effects. Breakdown is an event lasting not more than a few hundred nanoseconds but a burst of such events might occupy several tens of microseconds. If the many anomalies occurring at geomagnetically quiet times or on the day-side, remote from the enhanced electron fluxes, are due to ESD then there seem to be only two explanations. Either they are caused by energetic electrons or there is a long delay, up to many hours, between charge and a triggered discharge. Local intensification of electric field, fulfilling arcing conditions, can occur on an initially charged spacecraft, paradoxically due to photoemission (off-shadowing, eclipse output) or to cold plasma (day-side environment).

5. Guidelines for protection

The principle of prevention of ESD due to surface charging is well known - eliminate all exposed dielectrics and isolated conductors; unfortunately this tends to be either impossible or prohibitively expensive. Deep dielectric charging will be effectively suppressed by shielding (~2 mm of aluminium) but it is not feasible to stop electrons with very high energy (several MeV). "Design guidelines for assessing and controlling spacecraft charging effects" have been issued by NASA [Purvis et al., 1984]; these should be adopted wherever possible.

5.1 Limitation of Charge Build-up

Adequate grounding (<1MΩ) of conductors is usually not a difficult exercise and is strongly recommended. This includes all structural or mechanical strength components, metallic coatings of plastic films used for thermal control, cable screens, printed circuit trays, etc. The use of excessively insulating materials, e.g. fluoropolymers such as teflon, epoxy-fibreglass composites mylar, should be avoided. Now available are "leakage" dielectric materials such as are carbon-filled teflon and thin-layer kapton polyimides, and also a range of conducting paints. Indium tin oxide (ITO) coatings are transparent and have been used successfully where thermo-optical properties must be retained, e.g. large area solar arrays, second surface mirrors and kapton blankets; progress has been made on the ion implantation of solar cell cover glasses.

5.2 Circuit Protection

Designers of satellite electronics have always had to meet high standards in respect of electromagnetic interference suppression, and rules of good practice have evolved. Since the susceptibility of components continues to increase, there is no room for complacency and new devices must be rigorously tested. Cable forms and grounding schemes must be considered critically; it is often possible to introduce filters for the fast discharge transients. In some cases, actuators or memories have unnecessarily high speeds and these can be desensitized by adding delay components (Lechte, 1987) without degrading the response. The cables most likely to be affected by radiation from ESD are those located on the outside of the main frame. Thermal insulation foils, even grounded, do not constitute a protection against the electromagnetic field produced by the discharge. All cables not inside the main structure should be screened.
5.3 Modelling and Qualification

A better understanding of spacecraft charging has been achieved with the help of computer modelling programs. NASCAP (Katz et al., 1983) is a 3D code which permits a dynamic simulation of the electrostatic charging processes; it is a valuable tool for assessing the likelihood of problems and quantitatively evaluating possible solutions. Similar codes for low-Earth orbit and polar applications are being developed. It is not normally practicable to place a spacecraft in a vacuum chamber and study the effects of electron irradiation but special tests at subsystem level might be contemplated. Alternatively, simulated signatures of discharges can be injected during the programme of qualification, and testing on the integrated spacecraft. At the present time it cannot be claimed that any standard procedure exists to guarantee satisfactory in-flight operation.

5.4 In-flight Monitoring

There is still a need for data specific to operational satellites which exhibit peculiar charging characteristics; it would be very desirable if each could carry some suitable monitors, such as electron or ion spectrometers, surface potential probes and transient analyzers. A simple Langmuir probe, with fixed negative bias to detect thermal ions, would be particularly valuable. Small instruments with minimal mission constraint could solve the outstanding questions far more reliably than any simulations which may be carried out on the ground. As example the charging characteristics of surface materials were obtained by the electric potential monitor (POM) of the Japanese geostationary Engineering Test Satellite-V (ETS-V) [Nishimoto et al., 1989].

6. Conclusions

Experience suggests that even if all the recommended procedures are followed, geosynchronous spacecraft will continue to suffer malfunctions as a consequence of charging. There is still no complete explanation for numerous day-side anomalies. It appears that energetic electron fluxes are seldom high enough to yield the fluences necessary for discharges in thick dielectrics. On the other hand, it is rare that cold plasmaspheric ions are totally absent around the orbit, and thus surface elements seem unlikely to remain highly charged for many hours.

Recently there has been much interest in proposals for large polar platforms in low-Earth orbit and possible charging hazards have now been identified; the coincidence of wake, shadow and sub-storm could be ominous. Astronaut EVA's above auroral arcs are certainly to be discouraged for the time being.
REFERENCES


BIBLIOGRAPHY


I. Introduction and background

Report 556 discusses the factors affecting station-keeping of geostationary satellites, and provides some information on both the magnitudes of these factors as well as on station-keeping accuracies of some spacecraft. The purpose of this Report is to provide general information on current technologies available or projected for use in geostationary-satellite station-keeping systems.

Current and future geostationary spacecraft with multiple narrow antenna beams directed at specific locations on the surface of the Earth may require orbital determination and maintenance to within ± 0.1°. This level of station-keeping will allow the use of earth-station antennas with fixed pointing. Additionally, the maintaining of close tolerance on spacecraft position will enhance geostationary orbit and spectrum utilization. The station-keeping systems described in this Report are capable of providing accuracies of location within the orbit of the order of ± 0.1° for 7 to 10 year satellite lifetimes.

The factors affecting the orbital elements of a geostationary satellite (see Report 556) are:

- the gravitational effect of the Sun and Moon: the primary effects of these bodies is to change the inclination of the satellite orbital plane, causing the satellite to follow a figure-of-eight path relative to the surface of the Earth;
- the non-uniformity of the Earth's gravitational field: this non-uniformity causes an increase or decrease in a geostationary satellite velocity and, hence, orbital period. Consequently, the satellite tends to drift east or west at a rate proportional to the magnitude of the local gravitational acceleration. Figure 1 illustrates spacecraft drift directions as a result of the non-uniformity of the Earth's gravitational field along various longitudes;
- solar radiation pressure: this secondary effect can change the eccentricity of the satellite orbit, and hence cause a cyclic east or westward motion of a satellite.

Early communication-satellite station-keeping systems, such as those of Intelsat-I and II and Syncom, employed pulsed jet systems on spin-stabilized platforms. The primary choice of propulsion fluid was hydrogen peroxide, due to its relatively high specific impulse ($I_{sp} = 155$ s)* and its acceptable performance over limited periods ($\approx 1$ year).

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* This Report should be brought to the attention of Study Group 4.
** A performance measure of a rocket propellant, expressed in seconds, equal to the thrust $F$ divided by the propellant mass flow rate $w$: ($I_{sp} = F/w$).
FIGURE 1 — Easterly component of gravitational acceleration

Spacecraft drift direction under the influence of the Earth’s gravitational field

A: 155° west longitude
1.64 x 10^{-3} degrees/day^2
2.86 x 10^{-5} rad/day^2

B: 105.5° west longitude
Stable equilibrium point (gravity valley)

C: 56° west longitude
- 1.42 x 10^{-3} degrees/day^2
- 2.47 x 10^{-5} rad/day^2

D: 11.5° west longitude
Unstable equilibrium point (gravity peak)

E: 34° east longitude
1.80 x 10^{-3} degrees/day^2
3.14 x 10^{-5} rad/day^2

F: 75° east longitude
Stable equilibrium point (gravity valley)

G: 117° east longitude
- 1.98 x 10^{-3} degrees/day^2
- 3.45 x 10^{-5} rad/day^2

H: 161.8° east longitude
Unstable equilibrium point (gravity peak)
2. Current systems technologies

Current communications satellite systems require lifetimes of about 7 years, and future satellites will be designed for lifetimes up to 10 years. Additionally, the mass of a communications satellite is continually increasing. For instance, Intelsat-V weighs more than 900 kg. Consequently, greater station-keeping energy requirements are being placed upon communications and other types of satellites in order to maintain a given orbital position within the necessary limits. As a general rule, north-south station-keeping requires an average of 50 m/s per year velocity increment capability, while east-west station-keeping requires about 2 to 5 m/s per year. (The exact value for E-W station-keeping depends on the longitude of the satellite.)

Much effort has been directed toward light weight, efficient* station-keeping control systems. Basically, all of these systems involve the expulsion of mass at a desired velocity and direction relative to the satellite centre of mass. Spin-stabilized, as well as three-axis stabilized satellites, employ axial (along the spin axis or north-south) thrusters and radial (in the plane normal to north-south axis) thrusters. The axial thrusters control the orientation of the north-south axis, as well as latitude excursions of the spacecraft. The radial thrusters control the east-west satellite position.

Ideally, station-keeping manoeuvres are accomplished by applying an impulse each time the spacecraft crosses the line-of-nodes between the actual orbit and the geostationary orbit. Since "impulse" or zero time interval thrusting is, in general not possible, thrusters must fire for a finite period of time in order to impart the necessary velocity increment. In this connection, it is noted that the quantity of propellant required to maintain the position of a satellite (of given mass) is essentially independent of the "duty cycle" employed, except in those cases where the efficiency of the propellant varies with the duration of valving or pulsing, or when thrusting has to be carried out for hours around the nodes.

The bulk of current and expected future technology for station-keeping systems is confined to chemical and electric engines. Additionally, these systems are often used for initial orbit insertion, as well as to "dump" momentum stored in attitude control devices such as momentum wheels. The following sections discuss the chemical and electrical propulsion systems.

2.1 Chemical engines

A great deal of effort has been directed toward development of improved propulsion systems employing a variety of propellants. Intelsat-III introduced the first United States-built production spacecraft for which station-keeping was accomplished through the use of hydrazine thrusters [Meredith, 1972]. The flight history provided by five Intelsat-III spacecraft indicated the inherent high reliability and performance characteristics of these systems. Since that time, nearly all geostationary satellites have employed thruster jets using hydrazine fuel. Hydrazine typically has a specific impulse of 220 s and supplies thrust in the range of a newton.

Perhaps the greatest amount of experience in the use of mono-propellant** systems has been gained by Intelsat [Owens, 1976]. Intelsat-I through IV-A have all used a mono-propellant of either hydrogen peroxide (for Intelsat-I and II) or hydrazine (for Intelsat-III, IV, and IV-A). Tables I and II list the technical and performance specifications of the onboard propulsion systems of these five satellites. As can be seen from Table I, each propulsion sub-system total weight equals approximately 1/5 of the total initial in-orbit satellite weight. The sum (175 kg) of propellant weight and dry weight, for instance, of Intelsat-IV-A is the satellite's heaviest sub-system (9 kg heavier than the total communications sub-system). Table III lists the velocity requirements (ΔV) budget for Intelsat IV-A.

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Dry weight (kg) (*)</th>
<th>Propellant weight (kg)</th>
<th>Number of tanks</th>
<th>Number of thrusters</th>
<th>Initial orbit satellite weight (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intelsat-I</td>
<td>3.7</td>
<td>5.0</td>
<td>4</td>
<td>4</td>
<td>39.5</td>
</tr>
<tr>
<td>Intelsat-II</td>
<td>7.0</td>
<td>9.6</td>
<td>4</td>
<td>4</td>
<td>86.3</td>
</tr>
<tr>
<td>Intelsat-III</td>
<td>5.6</td>
<td>21.8</td>
<td>4</td>
<td>4</td>
<td>133.0</td>
</tr>
<tr>
<td>Intelsat-IV</td>
<td>16.8</td>
<td>136.4</td>
<td>4</td>
<td>6</td>
<td>732.0</td>
</tr>
<tr>
<td>Intelsat-IV-A</td>
<td>16.8</td>
<td>158.2</td>
<td>4</td>
<td>6</td>
<td>828.0</td>
</tr>
</tbody>
</table>

(*) Tanks, thrusters, valves and associated piping.

* That is, high specific impulse.

** Single propellant systems not requiring an oxidizer.
TABLE II — Intelsat satellite on-board propulsion system performance

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Propellant</th>
<th>$\Delta V$ (m/s)</th>
<th>Design life (years)</th>
<th>Thrust level (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intelsat-I</td>
<td>Hydrogen peroxide</td>
<td>190</td>
<td>1.5</td>
<td>14-5.5</td>
</tr>
<tr>
<td>Intelsat-II</td>
<td>Hydrogen peroxide</td>
<td>200</td>
<td>3</td>
<td>14-5.5</td>
</tr>
<tr>
<td>Intelsat-III</td>
<td>Hydrazine</td>
<td>320</td>
<td>5</td>
<td>16-7</td>
</tr>
<tr>
<td>Intelsat-IV</td>
<td>Hydrazine</td>
<td>432</td>
<td>7</td>
<td>26-13</td>
</tr>
<tr>
<td>Intelsat-IV-A</td>
<td>Hydrazine</td>
<td>432</td>
<td>7</td>
<td>26-9</td>
</tr>
</tbody>
</table>

TABLE III — $\Delta V$ budget for Intelsat-IV and IV-A

<table>
<thead>
<tr>
<th>Manoeuvre</th>
<th>$\Delta V$ (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Attitude correction</td>
<td>0.305</td>
</tr>
<tr>
<td>Spin-up</td>
<td>0.61</td>
</tr>
<tr>
<td>Spin speed control</td>
<td>4.17</td>
</tr>
<tr>
<td>E-W and station repositioning</td>
<td>14.6</td>
</tr>
<tr>
<td>Initial orbit correction</td>
<td>54.9</td>
</tr>
<tr>
<td>N-S station-keeping</td>
<td>358.4</td>
</tr>
</tbody>
</table>

Due to the weight requirements associated with the use of hydrazine, efforts have been directed toward other liquid propellants which may provide higher overall performance characteristics. These studies have included different blends of hydrazine azide and hydrazine which resulted in an increase in the specific impulse. However, due to a higher combustion temperature, problems have been encountered with thruster lifetimes.

Two other candidate systems are considered feasible for future communication satellite station-keeping systems. These are bipropellants, and electrically-augmented hydrazine. Both of these systems offer advantages in weight and specific impulse.

An advanced bipropellant system has been designed and successfully flown by Germany (Federal Republic of) in the Symphonie programme [Pfeiffer and Viellard, 1970]. This bipropellant system used mono-methyl hydrazine for the fuel and nitrogen tetroxide for the oxidizer. This type of system offers a substantial weight saving to station-keeping systems.

The electrically-augmented hydrazine systems [Free, 1978] add electrical energy to the hydrazine flow, thus increasing the system gas temperature and specific impulse (up to 300 s). Pursuit of this technology has resulted in selection of the augmented hydrazine thruster for north-south station-keeping on Intelsat-V. To perform N-S station-keeping of a 1000 kg satellite for 10 years, two high performance hydrazine thrusters (HIPEHT) could be fired simultaneously for about 0.5 h once each week. Hydrazine can be stored for years, if sealed properly and kept in a cool, dark place. Table IV lists HIPEHT specifications for the Intelsat-V configurations.

2.2 Electric propulsion

In an electric propulsion system, an ionized or electrically charged propellant is accelerated to a high velocity by an electrostatic field or by the interaction of a discharge-current with a magnetic field. With two exceptions, all devices require the propellant to be in a gaseous form, and therefore liquids are usually vapourised and solids ablated via electric discharges prior to ionization and acceleration. The exceptions are colloid and field emission thrusters; in the former, charged liquid droplets are accelerated, and in the latter, a film of propellant covering a sharp point or edge emits ions under the influence of a strong electric field.
### TABLE IV — High performance hydrazine thruster (HIPEHT) specifications, Intelsat-V configuration

<table>
<thead>
<tr>
<th>Description, thruster assembly</th>
<th>Series redundant seats</th>
<th>Redundant coils</th>
<th>Redundant valve heaters</th>
<th>Redundant heaters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solenoid propellant valve</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal decomposition chamber</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vortex heat exchanger with nozzle</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature sensors</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Propellant</td>
<td>Low-carbon hydrazine</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Performance</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inlet pressure range</td>
<td>1725–830 kPa</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extended range</td>
<td>1860–760 kPa</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thrust</td>
<td>0.45–0.18 N</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total impulse (qualification)</td>
<td>240 000 Ns</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specific impulse</td>
<td>&gt; 285–305 s</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cyclic life</td>
<td>&gt; 450 starts</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aggregate thrusting life</td>
<td>&gt; 214 h</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal</td>
<td>Similar to 1.3-N catalytic hydrazine thruster interfaces</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Environments</td>
<td>Typical of Atlas-Centaur and shuttle-launched geosynchronous spacecraft</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weight (without mounting bracket)</td>
<td>0.4 kg</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Although thrust levels from these devices are usually low, being in the one to several hundred mN range, exhaust velocities are very high, since they are limited only by the available electrical energy. Consequently, large values of specific impulse are readily attainable, currently reaching to nearly 10 000 s, while 20 000 s should be feasible in the near future. Thus the propellant masses required for a given mission can be reduced very considerably by the use of electric propulsion systems.

Over the past 25 years or so, many different electric propulsion systems have been developed. The characteristics of some of the more significant of these are summarized in Table V [Fearn, 1982], in which the values quoted are from typical experimental data. It will be noted that only the ion thrusters and pulsed plasma rail gun have so far achieved flight status in the West. Very little has been published regarding the extensive Soviet flight experience, so the table does not take that into account [Zhurin et al., 1983].

In Table V, the first three main columns refer to ion thrusters. In these, a propellant in gaseous form is ionized in a discharge chamber. The positive ions are then extracted and accelerated by high electric fields between sets of perforated grids at one end of the discharge chamber, thus forming an ion beam which produces thrust. In the Kaufman thruster, also known as the electron bombardment thruster, a d.c. discharge is employed to produce the required ionization. The magnetic field used to assist in this process has a modified form in the magneto-electrostatic containment (MESC) thruster. A radio-frequency discharge is utilized in an RF thruster, which has been developed in the Federal Republic of Germany.
### TABLE V — Comparison of typical parameters of ion and plasma thrusters

<table>
<thead>
<tr>
<th>Type</th>
<th>Kaufman ion</th>
<th>RF ion</th>
<th>MESC</th>
<th>Colloid</th>
<th>Field emission</th>
<th>Contact ionization</th>
<th>Rail gun</th>
<th>MDP arc</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Acceleration mechanism</strong></td>
<td>ES SS</td>
<td>ES SS</td>
<td>ES SS</td>
<td>ES SS</td>
<td>ES SS</td>
<td>ES SS</td>
<td>EM Pulsed</td>
<td>EM Pulsed</td>
</tr>
<tr>
<td><strong>Usual propellants</strong></td>
<td>Hg Argon, Xenon</td>
<td>Hg Argon, Xenon</td>
<td>Cs Hg, Argon</td>
<td>Glycerol ('1)</td>
<td>Cs</td>
<td>Cs</td>
<td>Teflon Argon N₂</td>
<td></td>
</tr>
<tr>
<td><strong>Spacecraft acceptability</strong></td>
<td>Good</td>
<td>Good</td>
<td>Poor (Cs)</td>
<td>Good</td>
<td>Poor</td>
<td>Poor</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td><strong>Exhaust exit dimensions (cm)</strong></td>
<td>8 dia</td>
<td>30 dia</td>
<td>10 dia</td>
<td>35 dia</td>
<td>12 dia</td>
<td>3 dia annulus</td>
<td>3 cm linear</td>
<td>5 x 0.6 rectangle</td>
</tr>
<tr>
<td><strong>Potential:</strong></td>
<td>1.2 kV (A)</td>
<td>1.1 to 5.0 kV (A)</td>
<td>1.5 kV (A)</td>
<td>~ 3.7 kV (A)</td>
<td>760 V (A)</td>
<td>10-16 kV (A)</td>
<td>2.4 kV (A)</td>
<td>4 kV (A)</td>
</tr>
<tr>
<td><strong>Power (kW)</strong></td>
<td>0.13</td>
<td>2.6 to 10.4</td>
<td>0.3</td>
<td>3.6</td>
<td>0.34</td>
<td>~ 0.01</td>
<td>~ 0.16</td>
<td>~ 0.12</td>
</tr>
<tr>
<td><strong>SI (s)</strong></td>
<td>2800</td>
<td>2000 to 6300</td>
<td>3100</td>
<td>3400</td>
<td>3300 to 4000</td>
<td>1000 to 2000</td>
<td>9000</td>
<td>6700</td>
</tr>
<tr>
<td><strong>Electrical efficiency</strong></td>
<td>0.69</td>
<td>0.84 to 0.96</td>
<td>0.64</td>
<td>0.79</td>
<td>0.81</td>
<td>0.7</td>
<td>~ 0.9</td>
<td>~ 0.4</td>
</tr>
<tr>
<td><strong>Mass efficiency</strong></td>
<td>0.84</td>
<td>0.89 to 0.95</td>
<td>0.80</td>
<td>0.88</td>
<td>0.97</td>
<td>0.2 to 0.8</td>
<td>~ 0.7</td>
<td>0.99</td>
</tr>
<tr>
<td><strong>Thrust (mN)</strong></td>
<td>5 to 18</td>
<td>130 to 290</td>
<td>10</td>
<td>160</td>
<td>17 to 63</td>
<td>0.5 (²)</td>
<td>~ 2.5 (²)</td>
<td>1.5</td>
</tr>
<tr>
<td><strong>Life test (h)</strong></td>
<td>15 000</td>
<td>10 000</td>
<td>8000</td>
<td>None</td>
<td>600 (³)</td>
<td>475 (⁴)</td>
<td>Few 100</td>
<td>None (³)</td>
</tr>
<tr>
<td><strong>Development status</strong></td>
<td>Flight ready</td>
<td>Flight ready</td>
<td>Flight ready</td>
<td>Medium</td>
<td>Medium</td>
<td>Good</td>
<td>Fair</td>
<td>Fair</td>
</tr>
</tbody>
</table>

(¹) Doped with NaI.
(²) Easily stacked to give increase by a factor of 10 to 100.
(³) But 2600 h on smaller device.
(⁴) But 6500 h on multiple needle thruster.
(⁵) Components up to 5000 h.

ES: electrostatic
EM: electromagnetic
SS: steady state
SI: specific impulse
MESC: magneto-electrostatic containment
MDP: magnetoplasma-dynamic
The principles of operation of the colloid and field-emission thrusters have already been mentioned; both rely on electrostatic phenomena. The contact ionization device incorporates a heated, porous tungsten emitter, through which gaseous caesium is passed. The caesium becomes ionized upon emerging from the tungsten emitter, and the ions are then accelerated by high voltages applied to a multi-element electrode system.

Many different types of pulsed plasma thruster have been studied, but most have not reached an advanced state of development. In these devices, the propellant is often vapourized from the solid or liquid storage phase by an auxiliary discharge, but gaseous propellants are frequently chosen, especially in larger, high thrust variants. A high voltage, high current discharge then ionizes the propellant, and the interaction between this current and a magnetic field expels the plasma at the desired velocity, giving a very large specific impulse. The magnetic field can be that induced by the discharge current itself, or it can be provided by some other means.

In the rail gun, the discharge occurs between a pair of rail electrodes, and the resulting plasma is accelerated along these rails until it emerges from the muzzle of the thruster. Power is provided from a high voltage capacitor, and frequent operation can give a quasi steady-state thrust.

The much larger and more powerful magnetoplasma-dynamic (MPD) arc thruster requires instantaneous power levels in the MW regime to achieve acceptable efficiencies. This device is coaxial or conical in form, with a stud-shaped or rod cathode and a tubular or ring anode. Gaseous propellants are usually employed, and thrust levels can be high, although there are very serious problems with limited lifetimes. Operation can be pulsed or in a quasi-d.c. mode.

Only the rail gun has been used operationally in space, but several ion thrusters of various types have been flown experimentally. These include the very successful SERT II thrusters, placed into orbit by NASA in 1970 and operated at intervals for the next 11 years. These two 15 cm diameter Kaufman thrusters were run for an aggregate time of over 6000 h, including a total of nearly 400 starts. The ion thrusters mounted on ATS-6 were not so successful, the use of caesium causing the electrical breakdown of high voltage insulators and leading to total system failure. More recently, there has been a flight test of a Japanese ion thruster, and several other similar experiments are planned. In addition, a great deal of ground testing has been carried out, particularly on Kaufman and RF thrusters, which has provided most of the information needed for spacecraft integration purposes and has given a high level of confidence of mission success, particularly for North-South station-keeping.

Early work in the United States of America [Free and Huson, 1972] suggested that the weight of a mercury ion thruster system would be equivalent to only 27% of the weight of a comparable hydrazine system for 7 years of North-South station-keeping. This study assumed thrust levels of the order of 5 mN, with the thrusters fired for many hours on a daily basis around the equatorial crossing nodes. To reduce both operating times and the number of starts, higher thrust levels are attractive, a possibility made more feasible by the advent of the lightweight nickel-hydrogen battery [Hyman and Dulgeroff, 1978].

Several mercury ion thruster systems are now available for the North-South station-keeping mission [Bassner and Klein, 1979; Fearn and Hughes, 1978; Murakami et al., 1984; Power, 1984]. These are suitable for medium to large geostationary satellites (over 500 kg) having lifetimes of 7 to 10 years, provided that adequate electrical power can be made available. The low overall mass resulting from the use of such a system will increase considerably payload capability within a given mass budget, and thrust vectoring will also allow some attitude control functions to be undertaken. Very extensive ground testing suggests that there should be no spacecraft-thruster compatibility problems, and that proven thruster lifetime is fully adequate for these missions [Fearn, 1982].

3. Collision in the geostationary-satellite orbit and removal of unwanted satellites

When fuel is near exhaustion, with impending loss of satellite control, consideration should be given to the possibility of removal of the satellite from the geostationary-satellite orbit to reduce the probability of collision with operational satellites. Some relevant aspects are addressed in Report 1004 of Volume IV-I.
Conclusion

The Radio Regulations (1982) require the following station-keeping accuracies for geostationary spacecraft.

"Satellites in the fixed-satellite service or broadcasting-satellite service shall maintain their positions within ± 0.1° of longitude, but experimental stations on geostationary satellites and space stations on geostationary satellites which do not use any frequency band allocated to the fixed-satellite service or the broadcasting-satellite service shall maintain their position within ± 0.5° longitude."

However, space stations need not comply with the above limitations as long as the satellite network to which the space station belongs does not cause unacceptable interference to any other satellite network which does comply with the above limitations.

Several operational satellites have demonstrated for extended periods of time the capability to maintain orbit location within the limits of ± 0.1°. For satellites having narrow antenna beamwidths, precise station-keeping could reduce the spacing between adjacent satellites servicing different, non-contiguous service areas.

Conventional hydrazine thrusters have proven high reliability and performance characteristics for long lifetime (7 years) operations. However, a hydrazine system comprises about 20% of total spacecraft weight. Advanced technologies, using propellants of a higher specific impulse, may offer weight savings. Electric engines, already used in space, offer a substantial weight saving, and it is expected that their use will increase in the future.

These weight savings are achieved at the expense of added complexity, which may affect reliability and lifetime. Consequently, the value of such weight saving technology, after the advent of the Space Transportation System (Shuttle-tug), will require further study.

Control in the North/South position requires a considerable amount of propellant.

The development of a stabilization concept known as "on-board angular momentum with one degree of freedom" offers the possibility of having an attitude control system which is not dependent upon the orbital plane control (see Report 546, section 6.4).

REFERENCES


BIBLIOGRAPHY


1. Introduction

The performance of a space radiocommunication system is highly dependent on the characteristics of the spacecraft antenna. One important aspect of this matter is the technology for minimizing the side lobe response of antennas. Another factor in some applications is the generation of asymmetrically shaped beams for spacecraft antennas. Asymmetrically shaped beams are designed to optimize coverage of particular geographical areas while minimizing power flux-density in adjacent areas. This coverage can be obtained by the use of a single shaped beam or by combining multiple beams to obtain the desired pattern.

2. Beam shaping techniques

The following sections discuss beam shaping techniques as applied to reflector, lens and array antennas. Contoured beams may also be formed by shaping of reflector surfaces.

2.1 Reflectors

The parabolic antenna is the most widely used for beam shaping. A combination of two techniques is usually involved, the shaping of the illumination pattern of the parabolic reflectors, and the shaping of the parabolic reflectors themselves. Profiling of reflector surfaces can now be applied to both main and sub-reflectors, providing another method of coverage contour control.

The first technique, illumination tapering, is a process by which the amplitude and phase of the illumination across the aperture is varied in order to match the pattern required. Due to the fact that curvature of the phase front reduces the total effective aperture available thus leading to a reduction of contribution in the direction of maximum gain, tapering can be accomplished only at the expense of a broadening of the main lobe, and so reducing the directivity of the antenna [Radio Spectrum Utilization, 1965; Silver, 1949].

Practical means by which illumination tapering can be achieved include the use of single feeds designed with limited beam patterns to produce under illumination, offsetting of feeds from focus, and the employment of array type feed structures.

* This Report should be brought to the attention of Study Groups 4, 10 and 11.
The second technique used in the control of side lobes and the shaping of the beam involves a direct modification of the reflector, and is usually supplementary to the tapering of the illumination. Reflector modifications for symmetrically shaped beams can include squaring the edges of the antenna for a square-ended sector beam, cutting the paraboloid so that the centre is elevated relative to the periphery for a normal sector shaped beam; flaring the edge of the reflector for a flared beam and so on. Modified reflector designs have also been used successfully to obtain asymmetrically shaped beams. These are usually accomplished by the use of an extended feed in conjunction with reflector modifications [Silver, 1949].

A basic problem common to reflector systems is aperture blockage. Many designs and techniques have been evolved with regard to this problem. One particularly satisfactory technique is to offset the feed. This technique is increasingly effective with increasing offset and there is a consequent decrease of directly reflected energy into the feed. However, where the asymmetry of the offset configuration creates unacceptable electrical performance or problems of a mechanical nature in some applications, the use of a Cassegrain antenna is preferred. In Cassegrain antennas the feed is located behind the main paraboloid reflector, and radiates the energy through a small aperture in the main reflector, to a secondary sub-reflector which reflects the energy to the main reflector from which the final collimated beam is radiated. Other techniques include active compensation for the blockage by use of a single radiator at the feed, as discussed in Report 558, and zone suppression techniques which can involve either stepping of the reflector or the installation of a ring of radiating elements around the periphery.

Several antennas utilizing a combination of shaped reflector structure and tapered illumination have been built or are currently under development. Examples are given in Reports 558 and 810.

2.2 Lenses

Lenses, like reflectors, enable a satellite to serve a number of separate regions on the Earth simultaneously through a single antenna aperture and a common band of radio frequencies. Desirable properties of lenses for production of shaped beams include the ease of shaping the lens surfaces and the ability to maintain precise surface tolerances [Collins and Zucker, 1969]. Certain techniques such as zoning of the lens elements contribute to reduction in chromatic aberration and therefore side lobe levels as described in Report 810. Lenses are a promising alternative for providing multibeam operations [Ricardi, 1977]. They have an advantage over reflectors as the feed is located behind the aperture, thus eliminating aperture blockage.

2.3 Arrays

Satellite borne multi-element arrays have been determined in many studies to be well suited for multiple beam and shaped beam operations. This is discussed in further detail in Report 810. There are limitations to the use of arrays based on weight, but their performance with respect to weight and cost, improves considerably at higher frequencies.

Side lobe control for array antennas can consist of null-placing techniques in which the directly radiating elements of the array are properly excited to form a multiple beam system, with beam peaks and nulls in specified angular positions. This technique is applicable to spacecraft antennas operating in higher frequency bands where the size and mass of the array is reduced to reasonable values [Atia and DiFonzo, 1975].

Developments [Phelan, 1976] such as “Spiraphase” have led to lower cost, lower loss, and lighter weight phased arrays. “Spiraphase” involves a different technique for obtaining phase shift control in an array aperture. It is based on the fact that as a circularly polarized antenna is rotated, the phase shift of the radiated field from the antenna changes proportionally to the rotation of the antenna. Utilizing a completely symmetrical radiation pattern, the phase shift of the “Spiraphase” is frequency independent and limited in bandwidth only by the bandwidth of the antenna used. To obtain the phase shift, it would be necessary to rotate the circularly polarized antenna mechanically. This method would not apply to linear polarization.

3. Conclusions

It is possible to develop shaped beams by the use of reflector, lens and array type antennas. Each of the three antenna types offer particular advantages for certain applications.
Many applications require highly irregular beam shapes. In many cases, complex structures using a combination of several techniques to provide the desired amplitude and phase distribution across an aperture are needed.

REFERENCES AND BIBLIOGRAPHY


1. Introduction

The antenna gain of an interfered-with or interfering source in the direction of the unwanted signal is of prime importance in determining the levels of interference. Thus, there exists a need for a generalized antenna pattern for space research earth stations which could be used in situations where adequate measured data do not exist.

It is also useful to consider the performance characteristics of offset reflector antennas with very low side lobes, which may be suitable for space research earth stations. For information regarding low side-lobe antennas of axisymmetrical type, see Report 663 (Volume I) and Reports 390 and 391 (Volume IV - Part 1).

2. Representation of measured data by a reference radiation diagram

Values of side lobe radiation may be represented for antennas of diameter greater than 100 wavelengths by (Report 391):

\[ G \text{ (gain relative to isotropic antenna)} = 32 - 25 \log \varphi \quad \text{dB} \]

where

\[ \varphi \text{ is the angle in degrees between the main beam axis and the direction in question and is limited to } \varphi > 1^\circ. \text{ The equation is valid for } G > -10 \text{ dBi. At larger angles } G \text{ is constant at } -10 \text{ dBi.} \]

Measurements of patterns of earth station antennas used in the Space Research Service have been made using collimation towers and in one case (64 m antenna), using a Surveyor spacecraft transmitting from the Moon [Levy et al., 1967]. The difference between these measured data and the above reference radiation pattern is small. A more recent set of measurements at 11.5 and 34.5 GHz were obtained with a 10 m Cassegrain antenna used in the Japanese space programme. In most cases the space research antenna side lobe levels are lower. This is to be expected since there has been an emphasis on minimizing antenna temperature in the design of the large antennas used in space research.

It is therefore considered that in situations which require interference calculations, and for which actual antenna patterns for space research earth stations do not exist, the reference radiation pattern of \[ G \text{ (dBi)} = 32 - 25 \log \varphi \text{ may be used as a representation of the envelope of the side lobes of these antennas.} \]

* This Report includes text from Report 675 which is hereby cancelled.
3. **Side-lobe characteristics of offset reflector antennas**

Various configurations of offset reflector antennas are shown in Figure 1. Side-lobe levels of the horn reflector antenna are lower than those of the offset paraboloidal antenna because of the shielding structure of the feed horn. However, the horn reflector antenna has disadvantages in size and weight compared to the offset paraboloidal antenna. The offset paraboloidal antenna has side lobes due to spill-over in the side and backward regions. Side lobes of offset multiple reflector antenna can be reduced by controlling the aperture distribution over the main reflector, since these antennas have high freedom in choosing the antenna parameters. In order to achieve an optimum amplitude and phase distribution of the aperture of the main reflector, the sub-reflector and main reflector surfaces can be modified.

Figure 2 shows an offset Cassegrain antenna fed by three beam-waveguide reflectors [Ogawa et al., 1978]. In this antenna, the wind load on the antenna base is reduced by the use of a flat and nearly horizontal main reflector. The antenna can be applied to earth stations in space research systems. Figure 3 shows the measured side-lobe characteristics (peak value) of an offset Gregorian antenna [Mizugutch et al., 1976], the offset Cassegrain antenna and a symmetrical Cassegrain antenna compared with the reference radiation diagram presented in section 2.

4. **Side-lobe reduction by microwave absorbers and effect on antenna noise temperature**

Though offset Gregorian antennas have very low side lobes as explained above, much lower side lobes may be required in some cases. It is very effective to attach microwave absorbers around the outer edge of reflectors for suppressing the spill-over rays. Figure 4 shows the comparison of the measured side-lobe patterns with and without microwave absorbers. The measured efficiency of this antenna was about 70%.

![Figure 1: Various offset reflector antennas](image)

**FIGURE 1 — Various offset reflector antennas**

A: main reflector
B: sub-reflector
C: primary horn

<table>
<thead>
<tr>
<th>Offset single reflector type</th>
<th>Offset multiple reflector type</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>A</td>
</tr>
<tr>
<td>C</td>
<td>C</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Offset paraboloidal antenna</th>
<th>Horn-reflector antenna</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Offset Cassegrain antenna</th>
<th>Offset Gregorian antenna</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>A</td>
</tr>
<tr>
<td>C</td>
<td>C</td>
</tr>
<tr>
<td>B</td>
<td>B</td>
</tr>
</tbody>
</table>
FIGURE 2 — Detailed antenna configuration

FIGURE 3 — Measured side-lobe patterns (peak value)

A: offset Gregorian antenna ($D/\lambda = 66$, 25 GHz, $D = 0.8$ m)
B: offset Cassegrain antenna ($D/\lambda = 750$, 19.5 GHz, $D = 11.5$ m)
C: symmetrical Cassegrain antenna ($D/\lambda = 600$)
As shown in the figure, the high side lobes at about 20° and 150° caused by the spill-over rays around the sub and main reflectors respectively, are greatly reduced by attaching the absorbers. The resultant wide-angle side lobes are as low as —30 to —35 dBi. Almost no effect is anticipated in the on-axis gain due to the microwave absorbers, since these are attached to the area where illumination level is very low.

The antenna noise temperature increase $\Delta T$ due to the microwave absorbers is considered to give its maximum at the zenith. The value $\Delta T$ can be given by:

$$\Delta T = T'_A - T_A = \Sigma_j (\gamma'_A - \gamma_A) T_0$$

where,

- $T'_A$, $T_A$: antenna noise temperature with or without microwave absorbers,
- $\gamma'_A$, $\gamma_A$: antenna beam efficiency with or without microwave absorbers in the $j$-th region,
- $T_0$: temperature of microwave absorbers ($= 290$ K).

The noise temperature increase $\Delta T$ is evaluated to be 4.4 K by using the equation above.

Measurements of antenna noise temperature at 11.7 GHz were carried out under clear sky conditions by use of 3.3 m offset Gregorian antenna with microwave absorbers. Introduction of the microwave absorbers generates an overall noise temperature increase of about 5 K.

5. Conclusion

This Report presents a reference radiation pattern for space research earth stations that can be used when a measured pattern is not available. It has been shown that the offset reflector antenna configuration is very effective for reducing the side-lobe levels, relative to those in the reference pattern.
The side-lobes are further reduced by attaching microwave absorbers around the primary feed system including the sub-reflector, and also around the outer edge of main reflector. The antenna noise temperature increase due to the microwave absorbers was estimated and found to be fairly small.

REFERENCES


REPORT 543-1*

SAFETY ASPECTS OF RADIO-FREQUENCY RADIATION FROM SPACE RESEARCH EARTH STATIONS

Comparison between predicted and measured field strengths at 2 GHz

(Study Programme 15B/2)


1. Introduction

This Report provides a summary of a study in which calculated and measured power flux-densities in the vicinity of a large (64 m) diameter reflector were analyzed and compared. It is an abbreviated version of the previous Report 543 published in Volume II, Geneva, 1982. Reference should be made to that Report for the full details of the studies made, and of the system characteristics. Power flux-densities greater than 10 mW/cm\(^2\) were examined in the greatest detail since they may be considered as being potentially dangerous to human beings exposed to the radiation [USA Standard, 1986]. Intermediate densities, from 1 to 10 mW/cm\(^2\), were covered in lesser detail, since this category is considered safe for occasional exposure. Densities less than 1 mW/cm\(^2\) were examined, although radiation in this category is considered safe for indefinite exposure. The origin of the material discussed here is a report published in the United States of America [Bathker, 1971].

High power radio-frequency radiation constitutes a biological hazard and also a hazard to volatile fuels and electro-explosive devices. This Report is concerned primarily with the levels of radiation which are considered biologically hazardous; applicability to fuels and electro-explosive devices is not discussed. Radio-frequency radiation effects in these areas are discussed elsewhere [Constant and Martin, 1963; IME, 1968, Wood, 1969].

The system discussed is the United States NASA, 64 m diameter, Cassegrain-fed, parabolic reflector antenna at Goldstone, California, operating at 2.12 GHz with 400 kW CW transmitter power input to the antenna. This system is a very carefully optimized transmit/receive arrangement wherein high beam efficiency (percentage of total radiated power delivered to the main beam) and low spillover and scatter (the percentage of the total energy that is wasted in the form of stray radiation) were sought after in design and achieved. This point is important; a poor selection of a feed system could invalidate the results of this study.

* This Report is brought to the attention of Study Group 1 with respect to Question 52/1.
2. Comparison, predicted and measured power densities

A number of radiation surveys have been made in the station area around the 64 m Goldstone reflector. Radiation surveys are typically taken with probes having a rather large (500 cm²) effective area and using a radio frequency thermal detector with a usable sensitivity in the $10^{-2}$ mW class. Such an arrangement responds to the average power flux-density over a few square wavelengths or several spot maxima and minima, if any exist. The minimum detectable average power density is $10^{-5}$ mW/cm², and larger fields are accurately managed by use of attenuators. Experience has shown one characteristic of the stray radiation is strong elliptical polarization, i.e., the polarization tends towards linear for each sample.

Selected results from the various surveys are given in Table I (the entries in Table I indicating the points at which measurements were made; see Fig. 1). The primary purpose of Table I is to show the measured high fields on the 64 m aperture, and in the tubular beam. The moderate fields expected on the ground in front of the reflector at 6° elevation are also shown. The back radiation is seen to be very small.

<table>
<thead>
<tr>
<th>Measurement point</th>
<th>Power flux-density</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured values</td>
<td>Calculated values</td>
<td></td>
</tr>
<tr>
<td>(mW/cm²)</td>
<td>(mW/cm²)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>On 64 m reflector</td>
<td>43-5</td>
<td>29-5</td>
</tr>
<tr>
<td>On 64 m reflector</td>
<td>22-0</td>
<td>19-0</td>
</tr>
<tr>
<td>On tubular beam centre</td>
<td>28-0</td>
<td>30-0</td>
</tr>
<tr>
<td>Below beam, on ground (1)</td>
<td>0-02 to 2-0</td>
<td>4-0</td>
</tr>
<tr>
<td>Reflector edge, on ground (1)</td>
<td>0-32 to 0-8</td>
<td>2-5</td>
</tr>
<tr>
<td>Directly behind reflector</td>
<td>0-11</td>
<td>—</td>
</tr>
<tr>
<td>Directly behind reflector</td>
<td>&lt; 0-02</td>
<td>0-001</td>
</tr>
<tr>
<td>Behind reflector, on ground</td>
<td>0-002</td>
<td>≈ 0-000032</td>
</tr>
<tr>
<td>Back lobe search, on ground (1)</td>
<td>&lt; 0-001</td>
<td>≈ 0-000032</td>
</tr>
<tr>
<td>Under hyperboloid, on ground</td>
<td>0-11</td>
<td>—</td>
</tr>
</tbody>
</table>

(1) At 6° elevation.

FIGURE 1 — 64 m antenna system power flux-density study (see Table I)

Elevation angle: 6.0°
It is considered that the 64 m/400 kW system is very adequately described for power flux-densities greater than 10 mW/cm². Totally independent studies of apertures with tapered illumination show a ratio of power flux-density at the aperture to the density at 2D²/λ of 14.2 dB [Bickmore and Hansen, 1959]. The results obtained here yield 14.3 dB. The calculated tubular beam maximum agrees with the measurement at 700 m to within 0.3 dB. The limitations in handling the multiple and reflected fields near the ground both analytically and during the field surveys should be borne in mind, i.e., the spot maxima and minima phenomenon (standing waves) and the averaging provided by the measuring process are important in interpreting the results*.

The first order tubular beam approach taken above is considered totally valid in the context of this study. A survey party using the hand-held equipment would observe a received power of about 25 W at 7 km while a 2 m diameter dish would receive nearly 1 kW**. Higher power flux-densities are possible in a mis-focused condition. An approximate density increase of 6 dB is available at 14.5 km although the reflector power flux should always remain focused at infinity when transmitting.

In the intermediate (1 to 10 mW/cm²) zone, which, necessarily, is likely to be more loosely controlled, mention of unlikely, but possible, effects should be made. Resonant or focusing devices, perhaps key-rings, metal eyeglass frames or wrenches are capable of exhibiting a reasonable absorption area at 2 GHz. For example, a half-wave dipole (7.0 cm) in a 1 mW/cm² field will deliver 25 mW to a matched load.

Effects of this kind have been reported, but are considered little more than an improbable irritation. Normal tracking motion of the antenna will impose a time limit on the intermediate zone to some extent. In this intermediate zone, spot power flux-densities have been calculated but the measured average power flux-densities (the average over the aperture of the test horn) appear lower as might be expected. It is considered that the average value is important in terms of personnel exposure, while the spots are important in the event of resonant phenomena, if any. In either case, this zone, on the ground, is considered safe for incidental or occasional exposure, even at 6° elevation angle.

The greatest hazard is the tubular beam itself because acceptable siting of large microwave ground antennas generally places such installations in depressions, the primary restriction is to avoid interception of the tubular beam with the surrounding terrain. Surrounding terrain includes man-made objects such as towers, other antennas, power lines and possibly roofs of buildings near to the antenna. Generally, the NASA 64 m station sites are such that the transmitter will be inoperative at 6° elevation angles, due to the above primary restriction. This further helps to alleviate the power flux-density in the intermediate zone, as may be seen by inspection of Fig. 1.

3. Conclusions

As a result of the adopted standards, the following restrictions on the movement of personnel when operating the described system are required:
- access to the reflection surfaces must be avoided;
- access to the tubular beam must be avoided;
- the time during which access into the zone described as intermediate is allowable must be limited (to 1 hour in 24 hours).

All operating personnel should be made well aware of the tubular beam characteristics (range and power density) and the unlikely, but possible, effects in the zone where time-limited access is applicable.

The following environmental restrictions are also important:
- restrictions are necessary as regards the masking of the site by obstacles;
- restrictions are necessary as regards the height of the station buildings;
- collimation and other towers are potentially dangerous.

More recent information based upon the use of a small aperture polarization-independent probe confirms that, in a complex field, measurements taken with such a probe are generally 6 to 10 dB greater than with a large aperture.

** A 2 m dish, 1.5 km from a 25 m/400 kW system operated at 2.39 GHz, has been inadvertently swept, during normal tracking, by the tubular beam. The power flux-density and range of the tubular beam in this case is 186 mW/cm² and 2.7 km, respectively. Further, the 2 dB increase at half range as predicted by the second order tubular beam theory was evident here; the dish collected approximately 5 kW with resultant loss of feed and cabling due to thermal damage.
REFERENCES

BATHKER, D. A. [1971] Predicted and measurement power density description of a large ground microwave system. JPL Technical Memo 33-433.


REPORT 682-1*

PROBABILITY OF HAZARDS TO PERSONNEL WITHIN AIRCRAFT DUE TO RADIATION FROM DEEP-SPACE EARTH STATIONS

(Study Programme 15B/2)

(1978-1986)

1. Introduction

This Report is an abbreviated edition of that published in Volume II, Geneva, 1982. Reference should be made to Annex I to that Report for the main analysis. The subject matter relates to Question 15/2 and to Study Programme 15B/2; historically, it also refers to § 1 and 2 of Question 52/1 (former Question 21/4) and § 8.2 of Report 385. An analysis has been made of the potential hazard to which personnel in aircraft (especially light aircraft) may be exposed when flying in the vicinity of an earth station of the deep-space space research service. This situation is independent of the type of aircraft fuselage construction material used.

2. General

A deep-space earth station utilizes very high gain parabolic antennas in conjunction with high power transmitters and sensitive receivers. The primary function of such a facility is communications with deep-space space stations. The possibility exists that overflights by aircraft may occur in the vicinity of a transmitting earth station.

The possibility of a hazardous situation being created by high powered antennae beams to aircraft is dependent on several factors, such as:

− the types of aircraft flying in the area surrounding the space station,
− the effectiveness of the safeguards and controls imposed by regulatory agencies over the routes traversed by aircraft flying near a potentially hazardous area,
− the probability of an aircraft actually traversing the high power density region of the transmitting station.

3. Probability of a hazardous situation occurring

In the following discussion it is assumed that the regions surrounding a deep-space earth station such as Goldstone Lake, California, are restricted zones in which the flight paths of military and large civilian aircraft are controlled by the administrations in co-ordination with the deep-space operations, so that the major remaining radiation hazard potential problem, arises due to small non-instrumented aircraft deliberately or accidentally traversing the restricted or controlled region.

* The attention of Study Group 1 is drawn to this Report.
The fortuitous circumstances under which an aircraft might encounter a high-power beam emitted from a deep-space facility may be calculated from the following conditional probabilities:

- The probability of an aircraft wandering into a restricted zone inadvertently. (This probability that a general aviation aircraft will enter into a restricted zone contiguous to a deep-space complex is a function of the number of aircraft flights in proximity to such a zone).

- The probability that an aircraft, moving at random, once having entered the restricted area, will enter the antenna butterfly*. (This in its simplest form is the ratio of the area of the butterfly to the area of the available flying space within the restricted zone.)

- The probability that once an aircraft is in the butterfly region, it will intercept the beam of the antenna. (This probability may be determined by assuming that the butterfly region at a given altitude is divided into a number of area segments, each being the same size as the hazardous region of the beam at the given altitude. Since only one of the regions is, in fact, the hazardous region in each case, the probability that the aircraft will intercept that one region is roughly a function of both the size of the hazardous region and the aircraft’s longest path length through the butterfly.)

The overall probability of a small aircraft entering the transmitting antenna beam of the deep-space earth station is the product of the conditional probabilities described above. Since these probabilities are, in general, altitude-dependent, the expected altitude distribution of the general aviation aircraft should be applied as a weighting function to determine the overall probability of an aircraft entering the hazardous region of a deep-space space research station.

4. Conclusions

The principal conclusion, drawn from the numerical values derived for one specific example based upon air traffic taking off or landing in the general area of Southern California, United States of America (see Annex I to Report 682, Geneva, 1982), is that the probability of a light plane accidentally traversing the high power density region of a transmitting deep-space earth station is about one flight in a million.

* The butterfly outline pattern results from the intersection of the minimum antenna elevation (10°) contour and two constant declination contours (± 30°) projected on to the surface of the altitude sphere from the location of the earth station antenna.
1. Introduction

Limits for spurious emissions from transmitters of the space services operating on frequencies above 960 MHz do not currently exist. As the space services continue to expand, the potential for harmful interference due to such emissions may grow to intolerable levels unless definite limits are established. Spurious emission limits are especially important for spaceborne emitters, because transmitter adjustment or modification is normally impossible after launch. If a space station is found to cause unforeseen interference after launch due to spurious emissions, curtailment or modification of operations may be necessary, possibly at great expense.

Setting limits to spurious emissions for all space services is a complex problem, owing to the multiplicity of possible emission frequencies and the number and variety of possible victims of the emissions. No comprehensive analysis has yet been made, but particular systems and services have been examined. Report 713 derives examples, for illustration only, of spurious e.i.r.p. spectral densities for fixed-satellite service earth and space stations, based on permissible interference levels for fixed, radioastronomy, space research, and fixed-satellite service stations and using several assumptions for the sake of simplicity. Report 844 analyzes the possible interference due to harmonics between deep-space research stations and stations of the fixed- and broadcasting-satellite services. Report 697 looks at potential interference to the radioastronomy service caused by spurious emissions of all other services.

This Report describes the general characteristics of spurious emissions from the types of transmitters and modulation methods commonly used in the space services. Techniques for controlling the levels of spurious emissions are reviewed. Finally, based on these findings, the kinds of levels that could be considered in establishing limits for spurious emissions are discussed, with the unique characteristics of the space services in mind.

2. Sources and nature of spurious emissions

2.1 Spurious sources

Spurious emissions are generated primarily through the action of non-linearities in the elements of the transmitter chain such as up-converter mixers, power amplifiers, and surfaces of the antenna structure. The spurious emission components include:

- mixing products, occurring at linear combinations of the frequencies used in the up-conversion process;
- harmonics, occurring at integral multiples of the carrier frequencies of the intentional emissions;
- intermodulation products (IMPs), occurring at linear combinations of the carrier frequencies of the intentional emissions; and
- local oscillator leakage through the transmitter.

Another component of spurious emissions is parasitic oscillation, occurring mainly in power-amplifying tubes. Parasitic oscillations are not harmonically related to the desired emissions.

Causes of spurious emissions for the space services operating above 960 MHz are substantially the same as those present in the lower frequency bands, with one exception. Transmitter intermodulation is a phenomenon that is well known in MF, HF, VHF, and lower UHF bands when multiple transmitters feed the same antenna or multiple antennas are in close proximity. It is due to emissions from one transmitter entering the output circuit of
another transmitter and mixing with the intended output signal(s). This is not a significant problem in transmitters operating at frequencies above 1 GHz because their transmitter output circuits generally contain isolators which prevent power entering the antenna from reaching the output circuit of the transmitter and generating IMPs.

2.2 Nature of harmonics and intermodulation products

The transformation of an input voltage \( v_i(t) \) by a memory-less non-linear device, generates an output voltage \( v_o(t) \) which may be described as follows:

\[
v_o(t) = \sum_{m=1}^{m} a_m \cdot v_i^m(t)
\]

The coefficients \( a_m \) characterize the non-linearity of the device. For example, in mixers, \( a_2 \) dominates. In linear amplifiers, \( a_m = 0 \) for \( m > 1 \), but in most physically realizable amplifiers, the \( a_m \) for odd \( m \) have appreciable values. Coefficients with even \( m \) are present in devices with an asymmetrical response, i.e. \( v_o(v_i) \neq -v_o(-v_i) \). The output voltage of such non-linear devices will contain harmonics and intermodulation products. The spectra and magnitudes of these are determined by the input signal and the coefficients \( a_m \).

The effect of non-linearity on a single, constant amplitude, phase-modulated input signal is the production of harmonics which are located at integer multiples of the carrier frequency. The harmonic signals have the form:

\[
A_n \cos[n\omega_0 t + n\theta(t)]
\]

where:
- \( A_n \): amplitude coefficient;
- \( n \): order of harmonic;
- \( \omega_0 \): fundamental carrier frequency;
- \( \theta(t) \): phase modulation of the fundamental.

When the phase modulation is an analogue waveform, the harmonic of order \( n \) will have the same modulating waveform, but with its deviation increased by a factor \( n \). The spectrum of the \( n^{th} \) harmonic of a wideband FM or PM signal, therefore, will have approximately \( n \) times the bandwidth of the fundamental signal's spectrum.

The phase modulation of an unfiltered digital waveform of order \( m \) is given by:

\[
\theta(t) = 2\pi i/m \quad kT < t < (k + 1)T
\]

where \( i = 0, 1, \ldots \) or \( m - 1 \), \( t \) is time, and \( T \) is the symbol period. The harmonic signals will mostly have spectra that are similar to that of the fundamental, with identical bandwidth. The exceptions are harmonics with order equal to an integral multiple of \( m \). These harmonics have very narrow spectra.

Signals consisting of multiple independent spectral components, when passed through a non-linear device, acquire intermodulation products (IMPs) as well as harmonics. For \( N \) narrowband signals, having carrier frequencies \( f_i (i = 1, 2, \ldots N) \), the intermodulation products appear at frequencies:

\[
k_1 f_1 + k_2 f_2 + \ldots + k_N f_N
\]

where each \( k_i \) is a positive or negative integer, or zero. The order of an IMP is given by:

\[
n = \sum_i |k_i|
\]
Note that harmonics are included in the above expression. If the frequencies \( f_i \) are relatively close to one another, the IMPs are grouped about the original signals and their harmonics. For example, with two signals at frequencies \( f_1 \) and \( f_2 \), some of the IMPs occur at these frequencies:

2nd order:
- \( f_1 + f_2 \)
- \( 2f_1 \)
- \( 2f_2 \)

3rd order:
- \( 2f_1 - f_2 \)
- \( 2f_2 - f_1 \)
- \( 2f_1 + f_2 \)
- \( 2f_2 + f_1 \)
- \( 3f_1 \)
- \( 3f_2 \)

The fundamental group of IMPs are those with associated frequency coefficients satisfying:

\[
\sum_i k_i = 1
\]

These IMPs are most troublesome because they are difficult to filter and produce self-interference. While much of the IMP power would often fall within the assigned band, substantial parts of it would also lie on either side of the assigned band and may interfere with adjacent band services depending on the frequency difference(s) \( f_2 - f_1 \). The extent of the spreading of IMP power beyond the band edges depends on the order of the product, \( n \). IMPs of order \( n \) fall within a band \( n \) times the bandwidth occupied by the transmitted carriers. This spreading is illustrated in Fig. 1.

**FIGURE 1 – Spectral extent of intermodulation products**

- \( \Delta f \): bandwidth occupied by fundamentals
- A: band occupied by fifth order IMPs
- B: band occupied by third order IMPs
- C: band occupied by carriers (assigned band)
The spectrum of an IMP is a scaled version of the convolution of the spectra of the signals that contribute to it. The scaling factor is a function of the coefficients describing the non-linearity. With input $e_i(t)$ consisting of $N$ narrow-band bandpass signals:

$$e_i(t) = \text{Re} \left\{ \sum_{p=1}^{N} A_p \exp \left[ j2\pi f_p t + j\phi_p(t) \right] \right\}$$

the output of a non-linear device has the spectrum [Fuenzalida et al., 1973]:

$$S_o(f) = \sum_{K} M_K \Omega \left( K, f \right) - \sum_{p=1}^{N} k_p f_p$$

where:

- $K = (k_1, k_2, \ldots k_N)$
- $\Omega(K, f) = S(k_1 \phi_1)^* S(k_2 \phi_2)^* \cdots S(k_N \phi_N)^*$
- $S(k_p \phi_p)$: low-pass equivalent power spectrum, normalized to unit power, of a carrier phase modulated by $k_p \phi_p(t)$
- $M_K$: magnitude of spectral component, depending on non-linearity.

Because of the convolution process, the spectrum of an IMP has a bandwidth equal to the sum of the bandwidths of the contributing signals. The self-interference effects of fundamental zone IMPs have been mitigated in some multi-carrier systems by judicious assignment of carrier frequencies. Carriers are assigned frequencies so that IMPs fall primarily in unoccupied slots or out of the assigned band. This practice has the potential for increasing the probability of generating significant spurious emissions via IMPs, while decreasing self-interference.

2.3 Interference effects of spurious emissions

As shown in the previous section, an IMP or harmonic signal produced from phase-modulated carriers is itself a phase-modulated carrier which generally has a greater deviation than any of the carriers. A notable exception to this general situation is the case of the second harmonic of a 2-PSK modulated carrier, and IMPs involving it. The harmonic in that case has a narrow spectrum, and the IMP is likewise narrower. (This applies as well to the fourth harmonic of 2-PSK and 4-PSK, and other higher-order situations.)

IMPs, harmonics, and other spurious emissions of angle-modulated carriers, because they are not substantially different from the signals that produced them, should have an interference effect very similar to that of the fundamental undistorted carriers. This means that the analysis techniques developed to estimate interference effects apply to interfering spurious emissions with validity equal to that when applied to intentional emissions. Further, limits on levels of intentional emissions devised to protect services from intolerable interference can be applied to spurious emissions as well. In cases where an IMP is produced by multiple types of carriers (e.g., FM-FDM and digital 4-PSK), the interfering effects might best be allowed for by assuming that the IMPs were of the carrier type that caused the greater degree of disruption.

3. Spurious emission control techniques

3.1 Power amplifier harmonics and IMPs

Two general methods are available for controlling the level of spurious emissions generated by power amplifiers as described below.

3.1.1 Improvement of linearity

The levels of harmonics and intermodulation products, relative to the desired signal, are reduced by operating the amplifier at a reduced output level. When the output is significantly below the saturation (or significant compression) level, the portion of the amplifier's input-output characteristic that is used is nearly linear. As power is reduced from such a level, the rate of change of the power of an $n$th order harmonic or IMP approaches $n$ times the rate of change of the fundamental power, measured logarithmically [Westcott, 1967]. For example, third order IMPs are reduced by up to 3 dB for each 1 dB reduction in input (or output) power. This rate-order equality is approached only when output back-off is more than about 7 dB.
Various linearizing techniques have been applied to reduce IMPs and thus allow use of more of the power available from high-power amplifiers. These consist of predistorting the input to the power amplifier, or of adding oppositely-phased distortion products at the output. Annex II to Report 708 describes the performance of predistortion linearizers for travelling wave tube amplifiers.

3.1.2 Filtering

Harmonics from power amplifiers are normally suppressed by means of filters placed in the output transmission line. Characteristics of some typical harmonic filters for earth-station transmitters are given in Table I [Varian Associates, 1976].

<table>
<thead>
<tr>
<th>Passband (GHz)</th>
<th>Rated power (kW)</th>
<th>Insertion loss (dB)</th>
<th>2nd</th>
<th>3rd</th>
<th>4th</th>
<th>5th</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.925-6.425</td>
<td>8</td>
<td>0.25</td>
<td>50</td>
<td>50</td>
<td>40</td>
<td>25</td>
</tr>
<tr>
<td>5.925-6.425</td>
<td>10</td>
<td>0.25</td>
<td>30</td>
<td>25</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>7.9 - 8.4</td>
<td>5</td>
<td>0.30</td>
<td>50</td>
<td>40</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>7.9 - 8.4</td>
<td>10</td>
<td>0.20</td>
<td>35</td>
<td>20</td>
<td>20</td>
<td>NS</td>
</tr>
<tr>
<td>14.0 - 14.5</td>
<td>2.5</td>
<td>0.25</td>
<td>20</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
</tbody>
</table>

NS: not specified

In order to attain a specific uniform level of harmonic emission suppression, the required harmonic filter rejection becomes less for each successive harmonic order. This is consistent with the characteristics of high power amplifying tubes, which typically have about 10 dB less harmonic output power for each successive order. The first filter described in Table I, placed at the output of a travelling wave tube, would ensure that all harmonics would be at least 60 dB below the fundamental. Harmonic output of a klystron is typically 15 to 20 dB less than that of a TWT, and would require less harmonic filtering to meet the same specification.

Bandpass filters may be used to attenuate out-of-band and spurious emissions in the vicinity of the passband. Table II gives characteristics of typical bandpass filters [Varian Associates, 1976]. The effectiveness of such filters in controlling emissions falling outside the band is limited by the rate of increase of attenuation with frequency from the band edge. Note that the frequency interval between the band edge and the point where full attenuation is achieved varies from 30% to 100% of the bandwidth for the filters listed. This interval can be made less, but at the expense of more passband loss and phase variation. Because of the finite slope of the filter response, IMPs falling immediately outside the band may be insufficiently rejected and could cause interference in the adjacent band. When transmitting multiple carriers extending up to the band edge, one would expect the out-of-band IMP power density to be high in the vicinity of the band edge.

3.2 Other spurious emission sources

Passive intermodulation products and harmonics are generated by layers of oxide and other surface corrosion products that are exposed to the high RF fields in the vicinity of a transmitting antenna. Metal-to-metal contacts are common IMP sources, especially when between dissimilar metals and when exposed to the atmosphere. Careful design, construction, and maintenance in transmit antennas will reduce the possibility of passive spurious generation of IMPs. Attention must also be paid to metal structures in the antenna's vicinity, which can likewise produce passive spurious emissions.
TABLE II — Examples of bandpass filter characteristics

<table>
<thead>
<tr>
<th>Passband (GHz)</th>
<th>Rated power (kW)</th>
<th>Insertion loss (dB)</th>
<th>Stopband (GHz)</th>
<th>Rejection (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.7-2.9</td>
<td>10</td>
<td>0.25</td>
<td>d.c.- 2.59</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2.59- 2.64</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3.04- 3.84</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3.15- 3.70</td>
<td>50</td>
</tr>
<tr>
<td>5.925-6.425</td>
<td>3</td>
<td>0.25</td>
<td>d.c.- 5.5</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>6.9 - 7.2</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>7.2 - 8.2</td>
<td>60</td>
</tr>
<tr>
<td>7.9-8.4</td>
<td>12</td>
<td>0.5</td>
<td>d.c.- 7.75</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>8.6 -10.0</td>
<td>80</td>
</tr>
</tbody>
</table>

Local oscillator mixing products, or even leakage of the local oscillator signal itself, at frequencies located in the power amplifier passband, are transmitted as spurious emissions. This can be minimized in the design process. Effective filtering of unwanted products at their sources and judicious selection of local oscillator frequencies are necessary.

Parasitic oscillations are abnormal and call for maintenance action. They may be eliminated by adjustment of operating voltages of active elements of the transmitter chain, or by reducing RF leakage at connectors, but replacement of the offending component is usually necessary.

4. Considerations for setting emission limits

4.1 Form of the spurious emission limits

Three general forms of space service spurious emission limits would be useful:
- a required level of spurious emission suppression relative to the power of the fundamental (or carrier) emission;
- a maximum permissible level of spurious emission power expressed as a spectral power density, a radiated spectral power flux-density, or a received spectral power flux-density;
- a receiving power.

The suppression type of limit would perhaps be a convenience to system designers since the specifications for many components are given in the same form (e.g. attenuation of filters). However, conformance with interference criteria can be assured only where limits on the spurious emissions power levels at the victim receiver are applied. The following equation relates these two types of limits:

\[ S(f) = P_i + G_t(f) + G_r(f) - L(f) - I(f) \]

where:
- \( S(f) \): required suppression level (dB) of the spurious emission at the frequency \( f \);
- \( P_i \): interfering carrier power spectral density level (dB(W/B)), where \( B \) is the reference bandwidth established by the interference criteria;
- \( G_t(f), G_r(f) \): transmitter and receiver antenna gains (dBi) at the frequency \( f \) in the appropriate direction;
- \( L(f) \): basic transmission loss (dB) exceeded for all but \( p \% \) of the time at the frequency \( f \), where \( p \) is established by the interference criteria;
- \( I(f) \): permissible level of interference (dB(W/B)), to be exceeded in the reference bandwidth \( B \) for no more than \( p \% \) of the time.
It can be seen from the above equation that many differing suppression levels could be obtained for a given source of interference as the various spurious emissions are considered. Many assumptions must be made with regard to the antenna gains and the basic transmission losses in order to determine the required suppressions in a general analysis.

Table III lists some of the protection criteria that have been developed for many of the services in Study Group 2. The Recommendations should be consulted for further details. In all cases, the total interference power within the indicated reference bandwidth is considered, which necessarily includes the contributions from all sources of out-of-band and spurious emissions. The maximum permissible level of interference from spurious emissions must be less than the thresholds indicated in Table III; however, further analysis is needed to determine appropriate limits.

<table>
<thead>
<tr>
<th>Victim service</th>
<th>Reference</th>
<th>Station location</th>
<th>Frequency range (')</th>
<th>Type of criteria</th>
<th>Threshold</th>
<th>Maximum exceedance probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Space operations</td>
<td>Recommendation 363</td>
<td>Earth</td>
<td>1-8 GHz</td>
<td>Power</td>
<td>-184 dB(W/kHz)</td>
<td>1%/day</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Spacecraft</td>
<td>Any</td>
<td>S/I</td>
<td>20 dB(1 kHz)</td>
<td>1%/day</td>
</tr>
<tr>
<td>Space research (near-Earth, unmanned)</td>
<td>Recommendation 609</td>
<td>Earth</td>
<td>1-20 GHz</td>
<td>Power</td>
<td>-216 dB(W/Hz)</td>
<td>0.1% of time</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Low orbit) Spacecraft</td>
<td>0.1-30 GHz</td>
<td>Power</td>
<td>-177 dB(W/kHz)</td>
<td>0.1% of time</td>
</tr>
<tr>
<td>Space research (near-Earth, manned)</td>
<td>Recommendation 578</td>
<td>Earth</td>
<td>1-20 GHz</td>
<td>Power</td>
<td>-216 dB(W/Hz)</td>
<td>0.001% of time</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Low orbit) Spacecraft</td>
<td>0.1-30 GHz</td>
<td>Power</td>
<td>-177 dB(W/kHz)</td>
<td>0.1% of time</td>
</tr>
<tr>
<td>Deep-space research</td>
<td>Recommendation 514</td>
<td>Earth</td>
<td>near 8 and 13 GHz</td>
<td>Power</td>
<td>-220 dB(W/Hz)</td>
<td>0.001% of time</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Spacecraft</td>
<td>near 7 GHz</td>
<td>Power</td>
<td>-189 dB(W/20 Hz)</td>
<td>0.001% of time</td>
</tr>
<tr>
<td>Earth exploration satellite (telecommunications links)</td>
<td>Recommendation 514</td>
<td>Earth</td>
<td>1-10 GHz</td>
<td>Power</td>
<td>-154 dB(W/MHz)</td>
<td>1% of time</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Near-Earth) Spacecraft</td>
<td>0.3-10 GHz</td>
<td>Power</td>
<td>-161 dB(W/kHz)</td>
<td>0.1% of time</td>
</tr>
<tr>
<td>Earth exploration satellite (passive sensors)</td>
<td>Report 694</td>
<td>Spacecraft</td>
<td></td>
<td></td>
<td>(See Table I, Report 694)</td>
<td></td>
</tr>
<tr>
<td>Radioastronomy</td>
<td>Recommendations 314 and 611</td>
<td>Earth</td>
<td></td>
<td></td>
<td>(See Tables I and II as well as § 4, Report 224)</td>
<td></td>
</tr>
</tbody>
</table>

(') The referenced Recommendation should be consulted for criteria pertaining to other frequency ranges.
4.2 Discussion of relevant material

Report 844 presents information concerning potential interference to earth and space station receivers used for deep-space research, as a result of harmonic emissions of other services in harmonically related bands. The Report also considers potential interference to other services, as may be caused by harmonic emissions of earth and space station transmitters used for deep-space research. The analysis presented in Report 844 is based, in part, on protection criteria for deep-space research, as given in Recommendation 578 and Appendix 28 to the Radio Regulations. It is concluded in Report 844 that significant interference to the various systems included in the analysis would be avoided if the power spectral density of harmonic emissions was suppressed at least 50 dB below the fundamental power spectral density.

For the radioastronomy service, the harmful interference levels given in Tables I and II of Report 224 apply to any man-made signals falling within a radioastronomy band, whether they are intentional or unwanted emissions. Report 697 lists those services most likely to generate IMPs or harmonics that could interfere with radioastronomical observations. It is noted that the second harmonic of broadcasting satellites operating in the 11.7 to 12.5 GHz band would exceed the harmful levels to radioastronomy unless suppressed by 126 dB, assuming that the astronomy antenna were directed at the satellite, or by 56 dB, assuming 0 dB gain for the astronomy antenna. Geostationary meteorological satellites that use the 460 to 470 MHz band to interrogate data collection platforms may interfere with radioastronomy with their third harmonic. Suppression by 94 dB would be required to meet the harmful interference levels, again assuming that the astronomy antenna is directed at the satellite. There is one situation where the harmful interference levels in Report 224 are not adequate. Report 224 suggests that radioastronomy antennas should be able to observe to within 5° of the geostationary-satellite orbit without experiencing harmful interference. The harmful levels applicable in this situation are approximately 15 dB below the values given in Tables I and II of Report 224.

On the practical experience side, it should be noted that the United States of America's domestic FSS space and earth stations in all FSS bands have been operating for many years with spurious emission limits of 50 dB suppression relative to the fundamental without any reports of significant spurious emission interference to other services.

5. Conclusions

The nature of IMP, harmonic, and other spurious emissions, their effects on the performance of possible victims of interference, methods of controlling them, and where in the spectrum they are likely to occur with respect to allocations of other services, are important factors relative to the establishment of spurious emission limits. Assessment of these factors, combined with judicious selection of a "tolerable" level of spurious-generated interference, should make it possible to establish meaningful emission limits.

The nature of harmonics and IMPs, for phase-modulated carriers, is very similar to the carriers that produce them. In general, they appear to be phase-modulated carriers with increased deviations. They may therefore be considered to be intentional emissions in estimating their bandwidths or error rate effects. One exception to this would be certain harmonics of PSK emissions. IMPs occur in groups about the intentional emission spectrum and each harmonic of it.

Spurious emissions from power amplifiers, probably the most common source, are controllable by output power back-off and by filtering. Harmonic levels at least 60 dB below the fundamental are readily attainable with available harmonic filters. Bandpass filters are effective for IMP reduction when the IMPs are sufficiently removed from the band edge. IMPs close to the band edge cannot normally be effectively filtered because of practical limitations on filter cut-off performance.

Further study of the maximum permissible levels of interference from spurious emissions is needed to provide a basis for space service spurious emissions limits. These can then be applied in analyses to determine what levels of spurious emission suppression may be needed and, consequently, the system design and operational measures that would prevent harmful interference from spurious emissions.
1. **Introduction**

The possibility of harmful interference resulting from unwanted emissions to and from stations in other services is of increasing concern to deep-space research. This concern is prompted by the expected increase in utilization of the geostationary-satellite orbit in frequency bands adjacent to and harmonically related to the operational frequencies used for deep-space telecommunications.

This Report presents the results of an analysis of potential mutual interference caused by unwanted emissions from deep-space earth stations, and from some other services. Earth station characteristics used in the analysis are those of the United States Deep-Space Network (DSN). The study also includes an assessment of potential interference to a future geostationary relay station for communication with a station in deep space.

2. **Interference analysis**

Frequency bands that are harmonically related to allocations for deep-space research are shown in Table I. The harmonically related bands are direct multiples and sub-multiples of the deep-space bands. Some services which transmit or receive in all or part of these bands are listed. Of those listed, some are analysed in this Report, as indicated by the reference to a section number.

Of the many potential interference situations resulting from the relationships shown in Table I, certain typical cases have been examined and analysed parametrically in this Report.

The e.i.r.p of unwanted emissions from stations is not generally available for use in analysis of potential interference. It is therefore necessary to treat these levels parametrically, and to calculate the e.i.r.p that would produce the maximum acceptable interference. The difference between this e.i.r.p of harmonic emission and the e.i.r.p of the transmission at the fundamental frequency is the amount of filtering or other suppression of harmonic emission that is needed to avoid violating the protection criteria of the service in the harmonic band.

Pointing statistics for a given DSN earth station have been obtained from a computer study of the trajectories of 40 realized and potential deep-space missions. Figure 1 presents the pointing angle toward the geostationary arc as a function of time for one DSN earth station. It should be noted that some deep-space missions do not require antenna pointing to within 5 to 10° of the geostationary arc for many months or even years of mission duration.

* This Report should be brought to the attention of Study Groups 1, 4, 8, 10 and 11.
TABLE I - Harmonic relationships between deep-space allocations and selected services in other bands

<table>
<thead>
<tr>
<th>Deep-space earth station transmit bands</th>
<th>Harmonic bands</th>
<th>2nd</th>
<th>3rd</th>
<th>4th</th>
<th>5th</th>
</tr>
</thead>
<tbody>
<tr>
<td>2110-2120 MHz</td>
<td></td>
<td>4220-4240 MHz</td>
<td>6330-6360 MHz (Earth-to-space) (See § 3.2)</td>
<td>8440-8480 MHz</td>
<td>10.55-10.6 GHz</td>
</tr>
<tr>
<td>16.6-17.1 GHz</td>
<td></td>
<td>33.2-34.2 GHz Fixed Satellite (Earth-to-space)</td>
<td>49.8-51.3 GHz Fixed Satellite (Earth-to-space)</td>
<td>66.4-68.4 GHz</td>
<td>83.0-85.5 GHz Fixed Satellite (space-Earth) Broadcasting-Satellite</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Deep-space earth station receive bands</th>
<th>Sub-harmonic bands</th>
<th>1/2</th>
<th>1/3</th>
<th>1/4</th>
<th>1/5</th>
</tr>
</thead>
<tbody>
<tr>
<td>2290-2300 MHz</td>
<td></td>
<td>1145-1150 MHz</td>
<td>763-767 MHz</td>
<td>573-575 MHz</td>
<td>458-460 MHz</td>
</tr>
<tr>
<td>8400-8450 MHz</td>
<td></td>
<td>4200-4225 MHz Aeronautical Radionavigation (See § 3.4)</td>
<td>2800-2817 MHz Aeronautical Radionavigation</td>
<td>2100-2113 MHz</td>
<td>1680-1690 MHz</td>
</tr>
<tr>
<td>12.75-13.25 GHz</td>
<td></td>
<td>6375-6625 MHz Fixed-satellite (Earth-to-space) (See § 3.5.1)</td>
<td>4250-4417 MHz</td>
<td>3188-3313 MHz</td>
<td>2550-2650 MHz All Regions: Broadcasting-satellite Region 2: Fixed-satellite (space-to-Earth) (See § 3.5.2)</td>
</tr>
<tr>
<td>31.8-32.3 GHz</td>
<td></td>
<td>15.9-16.15 GHz</td>
<td>10.6-10.77 GHz Fixed-satellite (space-Earth) (See § 3.3)</td>
<td>7.95-8.075 GHz Fixed-satellite (Earth-space) Region 2: Earth-exploration satellite (space-Earth)</td>
<td>6.36-6.46 GHz Fixed-satellite (Earth-space)</td>
</tr>
</tbody>
</table>
3. **Harmonic interference**

3.1 **Interference to a deep-space earth station from a fixed-satellite earth station**

The second harmonic of an earth station in the fixed-satellite service transmitting in the frequency range 6.375 to 6.625 GHz has the potential for interference to a deep-space earth station receiving at 12.75 to 13.25 GHz.

The coordination distance between a transmitting earth station in the fixed-satellite service and a receiving deep-space earth station was computed for two modes of propagation according to the procedure described in Report 724-2.

Those modes are:
- clear air propagation (Mode 1, Zone A2);
- rain scatter (Mode 2, Zone E).
The following assumptions were made for both modes of propagation:

- permissible level of interference to a deep-space earth station is -220 dB(W/Hz);
- elevation angle of transmitting and receiving antennas is taken to be 5° above the horizon.

Assumed fixed-satellite earth station e.i.r.p.'s at 5° off-main beam axis are (see Report 453):
Case 1: 21.0 dB(W/4 kHz) for satellite network with a large earth-station antenna
Case 2: 14.5 dB(W/4 kHz) for FM-TV or single-channel-per-carrier global systems
Case 3: 8.5 dB(W/4 kHz) for FDM-FM systems

Assuming the requirement to protect deep-space earth station receivers, Figures 2 and 3 show the maximum acceptable e.i.r.p. of second harmonic emission as a function of coordination distance. Also shown is the corresponding required suppression of second harmonic emission of a fixed-satellite earth station with respect to the e.i.r.p. of the emission at the fundamental frequency in the fixed-satellite allocation.

![Diagram](image)

**FIGURE 2 – Maximum allowable e.i.r.p. and minimum suppression of 2nd harmonic emission vs. coordination distance**

Propagation mode 1. Radio climatic zone A2

Transmitter: Fixed-satellite earth station in the 6375 - 6625 MHz band.


A: Case 1  B: Case 2  C: Case 3

Use left hand scale for curves A, B, and C.

Use right hand scale for curve D.
3.2 Interference to a satellite of the fixed-satellite service from a deep-space earth station

Potential interference exists to a satellite of the fixed-satellite service receiving in the 6 330 to 6 360 MHz range from the third harmonic of a deep-space earth station transmitting in the 2 110 to 2 120 MHz band.
The assumed deep-space earth-station transmitting characteristics are:

- Frequency 2.1 GHz
- RF power 50 dBW
- Antenna gain 62 dBi
- RF bandwidth 0.3 MHz (telecommand)

It is also assumed that the deep-space earth station is transmitting 100% of the time.

Typical receiver noise temperature and antenna gain of a fixed satellite are 3000 K and 23.0 dBi, respectively (Report 207 (Geneva, 1982)). The interference criterion is taken to be 4% (Appendix 29 to the Radio Regulations) of the noise power of the satellite receiver. It should be noted that this 4% criterion is used only as an indicator, to determine those situations in which a more detailed analysis should be performed.

When tracking a spacecraft in deep-space the antenna beam of the deep-space earth station may pass through the geostationary position of a fixed satellite. Depending upon the level of second harmonic emission, the level of interference could exceed a protection criterion for the fixed satellite. For example, Figure 4 shows the time during which the earth station may cause a 4% increase in the fixed-satellite noise power as a function of e.i.r.p. To limit the duration of interference to 5 sec, the second harmonic emission must be suppressed by 94 dB with respect to the fundamental emission.

**FIGURE 4** - e.i.r.p. of 3rd harmonic emission vs. duration of interference

Transmitter: Deep-space earth station in the 2110 - 2120 MHz band

Receiver: Satellite in the fixed-satellite service in the 6330 - 6360 MHz band
3.3 Interference to a deep-space earth station from a satellite in the fixed-satellite service.

The third harmonic of a satellite station in the fixed-satellite service in the frequency range 10.7 - 10.77 GHz has the potential for interference to a deep-space earth station receiving in the 31.8 - 32.3 GHz band. When tracking a spacecraft in deep-space the antenna beam of the deep-space earth station may pass through the geostationary position of the satellite. The amount and duration of interference received by the deep-space earth station depends upon the e.i.r.p. of the harmonic emission. Figure 5 shows the time during which the protection criterion of the deep-space station is violated, as a function of the e.i.r.p of the third harmonic.

To limit the duration of interference to five seconds, the third harmonic emission must be suppressed by at least 39 dB with respect to the fundamental emission of a satellite transmitter with the following characteristics:

- Antenna gain: 36 dBi main beam in direction of earth station
- RF power: 10 dBW
- RF bandwidth: 72 MHz

If the main beam of the deep-space earth station passes through the orbit position of the FSS satellite on a particular day, the main beam will also pass close to that position for the preceding and following several days or, in some cases, weeks. This is because the position of a deep-space probe changes slowly as seen from the Earth. In order to eliminate this recurring interference it is necessary to suppress the harmonic emission by at least 54 dB.

![Figure 5 - e.i.r.p. of 3rd harmonic emission vs. duration of interference](image)

Transmitter: Satellite in the fixed-satellite service in the 10.6 - 10.77 GHz band.

Receiver: Deep-space earth station in the 31.8 - 32.3 GHz band.
3.4 Interference to a deep-space earth station from an aeronautical radionavigation station

The second harmonic of an aeronautical radionavigation station in the 4200 - 4225 MHz frequency range has the potential for interference to a deep-space earth station receiving in the 8400 - 8450 MHz band. Because of the mobility of airborne transmitters, and their unpredictable location with respect to the main beam of a deep-space earth station, it is necessary to consider the degree of interference via the main beam of the earth station.

For the case of an airborne radio altimeter whose antenna main beam is pointed vertically downward, Figure 6 shows the relationship between the second harmonic e.i.r.p. of the aeronautical station and the protection criterion of the deep-space earth station. For the 100 km and 391 km separation distances, the altimeter antenna gain is assumed to be 0 dBi; for the case where the aircraft flies directly over the earth station at 9 km distance, the altimeter antenna gain is assumed to have a main beam value of 13 dBi. The 391 km separation distance applies is the maximum distance at which there is a line-of-sight path to an aircraft at maximum altitude. The interference shown in the figure is the amount by which the protection criterion is violated.

To insure that the interference does not exceed the protection criterion, the second harmonic emission must be suppressed by an amount that is proportional to the distance between the aircraft station and the earth station. For a distance of 100 km, the minimum needed suppression is 75.1 dB below the fundamental emission of an airborne radiolocation transmitter with the following characteristics:

- Antenna gain: 13 dBi
- RF power: 20 dBW peak pulse, 0.001 duty cycle
- RF bandwidth: 8 MHz
- Spectral peaking factor: 10 dB

For a distance of 391 km, the suppression must be at least 63.3 dB; for 9 km distance, main beam coupling, 109 dB.
FIGURE 6 – e.i.r.p. of 2nd harmonic emission vs. harmful interference

Transmitter: Airborne aeronautical radionavigation station in the 4200 - 4225 MHz band

Receiver: Deep-space earth station in the 8400 - 8450 MHz band

A: 100 km distance
B: 391 km distance
C: 9 km distance
3.5 Interference to a geostationary deep-space relay satellite, from a satellite in the fixed-satellite service

A geostationary satellite may be used in the future to relay signals from deep-space research spacecraft to Earth. The analysis given below considers the potential for interference to a relay satellite from harmonic emissions of a fixed-satellite earth station, and from a satellite in the fixed satellite service. In particular, the effect of angular separation between the two satellites is given.

3.5.1 Interference to a deep-space relay satellite from fixed-satellite earth-station transmissions

The second harmonic of an earth station in the fixed-satellite service transmitting in the frequency range 6.375 to 6.625 GHz has the potential for interference to a deep-space relay satellite receiving from deep space at 12.75 to 13.25 GHz.

For this analysis it is assumed that the deep-space relay satellite has a 45 m receiving antenna and a gain of 0 dBi toward the transmitting FSS earth station. Additionally the same values of harmful interference (-220 dB(W/Hz)) and FSS earth station transmitting characteristics, as assumed in § 3.1, are used. For various levels of second harmonic emissions, the required geocentric angular separation of the receiving fixed satellite and the deep-space relay satellite have been calculated. Even on a worst-case basis of 0 dB suppression (a second harmonic level equal to the fundamental frequency emission) the required spacing is small, as demonstrated below:

| FSS earth station transmit power spectral density | -36 dB(W/Hz) |
| Free space loss | -207 dB |
| Received power spectral density | -243 dB(W/Hz) |

Using -220 dB(W/Hz) as the interference criterion would mean that the gain of the FSS earth station toward the deep-space relay satellite could be as high as 23 dB. This translates via the reference antenna pattern of $32 - 25 \log t_p$ to a spacing on the order of $2.3^\circ$.

At higher levels of harmonic suppression, the required separation is correspondingly less.

3.5.2 Interference to a deep-space relay satellite from FSS satellite transmissions

The fifth harmonic of a broadcasting or fixed satellite transmitting in the 2 550 to 2 650 MHz frequency range has the potential for interference to a deep-space relay satellite receiving from deep space in the 12.75 to 13.25 GHz band.

In this analysis it is assumed that:

- the gain of the fixed satellite antenna toward the deep-space relay satellite is 0 dBi;
- the gain of the fixed satellite antenna toward the Earth is 20 dBi;
- the maximum value of pfd allowed on the Earth’s surface is -137 dB(W/($m^2 \cdot 4$ kHz));
- the deep-space relay satellite interference criterion is -220 dB(W/Hz).
Figure 7 presents the angle by which the deep-space relay satellite main beam must point away from a fixed or broadcasting satellite as a function of the geocentric angular spacing between the two. These curves are shown parametrically for various levels of fifth harmonic suppression.

The probability that the main antenna beam of a deep-space relay satellite will point within a particular angle with respect to a given FSS satellite depends on the orbit characteristics of each deep-space probe and the corresponding requirement for tracking by the relay satellite. Figure 7 shows that, for a given angular separation of the satellites, the minimum angle within which interference can occur is strongly dependent upon the degree of harmonic suppression.

![Diagram](image)

**Minimum angle between main beam of relay satellite and the direction to Fixed-Service satellite (deg)**

FIGURE 7 – Geocentric angular separation between satellites vs. minimum angle between main beam of relay satellite and the direction from relay satellite to Fixed-Service satellite

Transmitter: Satellite in the fixed-Satellite service in the 2550 - 2650 MHz band. e.i.r.p. towards deep-space relay satellite: -31 dB(W/Hz)
Suppression of 5th harmonic:
A: 20 dB
B: 30 dB
C: 40 dB
D: 50 dB

4. **Adjacent band considerations**

In addition to the potential for interference from unwanted emissions in harmonically related bands, there is the possibility of interference from unwanted emissions of services in adjacent bands. Specific analysis of this possibility has not yet been accomplished with respect to the services considered in this Report.

5. **Conclusions**

Interference to a receiver may be caused by a transmitter in the shared band, or by harmonic emissions from a transmitter whose fundamental emission is in another band. For a given level of interference to the receiver, the degradation or interruption of service is, generally speaking, the same in either case. The analysis described in this report derives the maximum allowable e.i.r.p. of a potentially interfering harmonic emission. For a given transmitter, a corresponding required suppression of harmonic radiation may be found.

Table II summarizes the analysis. The listed values of required harmonic suppression are applicable to the indicated distance or time parameters. Other values of time or distance would require correspondingly different suppression. Equipment designers must provide for the needed suppression if interference is to be reduced to a level that is not harmful.

Suppression of harmonic emissions may be accomplished by the combined effects of modulation technique, transmitter output filtering, and the frequency selective characteristics of transmission lines and antennas.

**TABLE II - Partial summary of results**

<table>
<thead>
<tr>
<th>Transmitter</th>
<th>Receiver</th>
<th>Harmonic Suppression$^1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>FSS earth station</td>
<td>Deep-space earth station</td>
<td>4 to 17 dB$^2$ ($§$ 3.1, Fig. 2: 200 km)</td>
</tr>
<tr>
<td>FSS earth station</td>
<td>Deep-space earth station</td>
<td>79 to 92 dB$^2$ ($§$ 3.1, Fig. 3: 200 km)</td>
</tr>
<tr>
<td>Deep-space earth station</td>
<td>FSS satellite</td>
<td>94 dB ($§$ 3.2, Fig. 4: 5 sec)</td>
</tr>
<tr>
<td>FSS satellite</td>
<td>Deep-space earth station</td>
<td>39 dB ($§$ 3.3, Fig. 5: 5 sec)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>54 dB ($§$ 3.3, Fig. 5: 0 sec)</td>
</tr>
<tr>
<td>Aeronautical radionavigation station</td>
<td>Deep-space earth station</td>
<td>63 dB ($§$ 3.4, Fig. 6: 0 dB, 391 km)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>75 dB ($§$ 3.4, Fig. 6: 0 dB, 100 km)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>109 dB ($§$ 3.4, Fig. 6: 0 dB, 9 km)</td>
</tr>
<tr>
<td>FSS satellite</td>
<td>Deep-space relay satellite</td>
<td>50 dB ($§$ 3.5.2, Fig 7)</td>
</tr>
</tbody>
</table>

$^1$ The listed value of harmonic suppression is the minimum amount that would satisfy the protection criterion that is applicable to the particular case.

$^2$ Depending on Case A, B, or C, $§$ 3.1.
REPORT 981-1*

SHARING CONSIDERATIONS NEAR 2 GHz BETWEEN SYSTEMS IN THE EARTH EXPLORATION SATELLITE, SPACE RESEARCH, AND SPACE OPERATION SERVICES AND TERRESTRIAL LINE-OF-SIGHT RADIO-RELAY SYSTEMS

(Question 1/2 and Study Programme 1D/2)

1. Introduction

This Report gives a partial response to studies called for in Study Programme 1D/2. It contains an analysis, agreed for application between services within one administration, to determine pfd limits necessary to protect line-of-sight (LOS) fixed service systems operating near 2 GHz from harmful interference from satellites. Satellites in both geostationary and low orbit are considered. The analysis is also applicable to satellites in highly-elliptical orbits, since as far as the pfd analysis is concerned, the portion of the orbit of interest (near perigee) for these satellites is similar to that for low orbit satellites. Sharing with other services, such as mobile, is not addressed. Systems in the fixed service using troposcatter transmission are protected by the provisions of No. 2560 of the Radio Regulations. The suitability of the interference limit of \(-168\) dBW in any 4 kHz band specified by these provisions has not been reviewed in this Report.

Annex 1 presents a more general analysis of sharing near 2 GHz between terrestrial stations and earth and space stations operating in the space operation service. This analysis focuses on space operation systems involving satellites in low Earth orbit, direct Earth-space transmissions, and transmission of only space operation signals (i.e., transmissions without accompanying space research or earth exploration-satellite service data).

2. Analysis

2.1 General considerations

Both geostationary and low orbit satellites operate near 2 GHz. While signal levels from geostationary satellites into terrestrial receivers can be relatively constant, the potential interference from satellites in other orbits generally varies in intensity and is not continuous.

* This Report should be brought to the attention of Study Groups 1, 4, 8 and 9. It contains text from Report 396-5 which is hereby cancelled.
The results of an analysis which gives the long-term percentage of visibility that a low orbit satellite has in different segments of its orbit are given in Report 684. Additional analyses, discussed here, have led to the development of two different sets of pfd levels to protect fixed-service systems; one for geostationary satellites and one for low orbit satellites [Farrar, 1984; Locke and Rinker, 1978]. The criteria for allowable interference levels in radio-relay circuits from satellites used in these analyses are given in Recommendation 357.

2.2 Interference criteria

Recommendation 393 lists the total allowable noise levels from all sources including satellites that can be used as a guide in the design of a radio-relay circuit. Recommendation 357 gives the maximum allowable values of interference which may be contributed by satellites and earth stations. These interference levels, illustrated in Fig. 1, are for any channel in a 2500 km hypothetical reference circuit, and apply to frequency-division-multiplex, analogue, angle-modulated radio-relay systems that share spectrum with systems in the fixed-satellite service. The circled points shown in Fig. 1 represent the interference levels stated in the Recommendations and the curve connecting these points is one possible interpolation suggested by Recommendation 357. The data in Fig. 1 represent a small fraction of the total noise power levels given in Recommendation 393. The curve shown in Fig. 1 provides the technical basis for this analysis.

2.3 Characteristics of space system and radio-relay circuits in the 2 GHz band

2.3.1 Space systems

Some space research and Earth exploration satellites transmit at about 2100 MHz in the space-to-space direction. Space-to-space transmissions as used from low orbit satellites to data relay satellites are intermittent as a consequence of intermittent visibility and also because of operational considerations. The latter factor was not taken into account in this analysis.
Space research and Earth exploration satellites also operate near 2250 MHz, transmitting in the directions space-to-Earth and space-to-space. The space-to-Earth transmissions can be from the geostationary-satellite orbit (GSO) or from low orbits. Generally, the non-GSO satellites have circular orbits, with altitudes less than 1500 km, or highly elliptical orbits, often with perigees as low as 300 km. Note that in all of the non-GSO cases, transmissions are generally not continuous and that frequencies used usually differ from satellite to satellite.

The nature of the space services and the characteristics of the systems required to implement these services affect the e.i.r.p. needed in the 2 GHz band. Unlike systems in the fixed-satellite service, a majority of 2 GHz satellite transmitters have narrow-band emissions whose widths range from 100 kHz to 5 MHz. The spectral power densities of satellite transmitters in the 2 GHz band are generally not uniform because of their transmission requirements. The narrow-band peaks are the most important in the evaluation of pfd level, because a major portion of the satellite transmitter power is contained in these peaks.

Unlike the fixed-satellite service, space services in the 2 GHz band serve a number of different purposes and their satellites use various different orbits. As a result, transmission paths to a given earth station may sometimes coincide. This is the main reason for satellites in the 2 GHz band generally being assigned different frequencies, and the reason that there are practical limits on the number of satellites that can operate co-channel in the band.

2.3.2 Radio-relay circuits

Technical characteristics representative of radio-relay circuits near the 2 GHz band as given in Report 387, are listed in Table I. That Report contains the analysis which led to the current pfd limits, based on satellites in the GSO.

<table>
<thead>
<tr>
<th>TABLE I — Representative parameters for radio-relay circuits near 2 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of system</td>
</tr>
<tr>
<td>----------------</td>
</tr>
<tr>
<td>Hop length (km)</td>
</tr>
<tr>
<td>Antenna mainbeam gain (dBi)</td>
</tr>
<tr>
<td>Feeder loss (dB)</td>
</tr>
<tr>
<td>Receiver noise temperature (K.)</td>
</tr>
<tr>
<td>Channel free-space thermal noise (pW0p)</td>
</tr>
</tbody>
</table>

For the present analysis, the radio-relay receiver noise temperature was permitted to vary from 300 to 1200 K to ensure that currently known systems were taken into account. The channel thermal noise in Table I depends on the number of hops, receiver noise temperature, and the number of hops fading simultaneously. Calculated results [Panter, 1972] show that the thermal noise in a channel may be based on four different CCIR noise criteria, varying from 7.9 to 62 pW (unweighted). The most stringent requirements are short-term noise specifications set by Recommendation 393. The diversity used in all of the line-of-sight long-haul systems allows the systems to meet the recommended noise criteria. Limiting the interference noise levels in a receiver to a low level is especially important for receivers with higher sensitivities. For this analysis, the channel thermal noise of receivers was assumed to vary from 10 to 25 pW. As a practical matter, 25 pW generally corresponds to receiver noise temperature of 750 K.

The frequency channel arrangement in Recommendation 283 indicates that in the design of radio-relay circuits, adjacent hops should be separated in frequency. This requirement helps mitigate intra-system self-interference. In practice, two, four, and six frequency plans are common. This arrangement tends to reduce the number of possible entry points for interference from a space system into radio-relay circuits.
Two analytical models were used for this analysis. They are modified versions of earlier models. One model, discussed in Report 387, and referred to as the geostationary model, is valid for sharing between fixed-satellite service systems and systems in the fixed service using line-of-sight techniques. The other model, referred to as the non-geostationary model [Locke and Rinker, 1978], is based on the visibility statistics analysis given in Report 684 (Geneva, 1982). This model provides an algorithm for the analysis of sharing between low orbit satellites and fixed-service systems. Both of these models were modified to reflect the differences between satellite systems near 2 GHz and fixed-satellite systems in the 6/4 GHz bands.

### 2.4.1 Geostationary model

The assumptions used in the development of the original model included 3° satellite spacing in the geostationary-satellite orbit and an FDM-FM analogue line-of-sight radio-relay circuit of 50 hops, with a total length of 2500 km. Interference from each visible satellite was assumed to enter each receiver in the radio-relay circuit. The input interference-to-noise ratio, for each 4 kHz bandwidth at the input to a channel, was assumed to be equal to the interference-to-noise ratio at the output of the channel. (The relationship between input and output ratios is termed the receiver transfer function.) These assumptions, while correct for sharing analyses between fixed-satellite systems and radio-relay circuits, are inappropriate for sharing analyses between space systems and radio-relay circuits in the 2 GHz band.

For the modified geostationary model, the satellite angular spacing in the geostationary-satellite orbit was allowed to vary from 10° to 20°. In addition, the fact that satellite emission spectra of space systems in the 2 GHz band are not uniform and are generally narrow-band, requires modification of the receiver transfer function to provide a more appropriate relationship for the analysis in this Report. The derivation and subsequent application of this function are given in [Farrar, 1984].

### 2.4.2 Non-geostationary model

The non-geostationary model uses most of the system characteristics used by the geostationary model, except the satellites are not fixed with respect to radio-relay stations. A low orbit satellite has the following characteristics when observed from a given point on the Earth:

- it is not visible most of the time;
- it is in motion, relative to the ground; and
- in general, when visible, it does not follow the same path, relative to the observer.

This relative motion causes the received emissions from spacecraft to vary widely, both in magnitude and angle-of-arrival. This variation is taken into account by the non-geostationary model.

The interference power received by radio-relay circuits from transmitting non-geostationary satellites, over a long period, can be described as a time-dependent function. The evaluation of this function for any given location, defined by a finite region in an orbit, was done in two steps. The first step was to evaluate the percentage of time that a satellite remains in that region, and the second step was to calculate the interference received by radio-relay circuits in that region. The non-geostationary model procedure for evaluating the interference power is similar to that used in the geostationary model algorithm.

The percentage of visibility time from any point on the Earth for an arbitrarily large number of orbital tracks of a given satellite may be calculated using equation (1) derived in Report 684 (Geneva, 1982).

\[
T = \frac{\Delta \lambda}{2 \pi^2} \left[ \arcsin \left( \frac{\sin(L_1)}{\sin i} \right) - \arcsin \left( \frac{\sin(L_2)}{\sin i} \right) \right] \times 100
\]

where:

- \( T \): percentage of visibility time,
- \( \Delta \lambda \): longitudinal segment on the orbital shell between the latitudinal limits of \( L_1 \) and \( L_2 \) (rad),
- \( L_1, L_2 \): upper and lower latitudes of the visibility region (degrees),
- \( i \): inclination angle of the satellite orbit (degrees).
This equation relates the long-term visibility of a satellite transmitting from a region of its orbit to the inclination angle and latitudinal and longitudinal bounds of the region.

Briefly, the non-geostationary model algorithm uses equation (1) to calculate the percentage of time that every region of the orbital sphere is visible to a radio-relay system. The interference power received by radio-relay circuits as a function of time is then calculated for each region. A plot of the interference received by a radio-relay circuit, as a function of the percentage of time, is the desired output from the model.

3. Results

The model parameters for line-of-sight radio-relay systems used in both the geostationary and non-geostationary models, with a minor change, are listed in Table I. The hop length of 60 km was changed to 50 km to be consistent with the hypothetical reference circuit presented in Recommendation 393 which was used in this analysis.

The overall receiver noise temperature used in the analysis was 750 K, which corresponds to a noise figure of 5.5 dB. This is practical and accommodates future growth in the design of radio-relay receivers in the 2 GHz band. Receivers with noise figures as high as 12 dB are presently in use.

The value of the thermal noise power allowed in a receiver, calculated on the basis of noise criteria discussed in Recommendation 393, varies from 8 to 25 pW0p. Higher allowable values of free-space thermal noise power (see Report 387) result in lower (more negative) permissible pfd limits according to the geostationary and non-geostationary models used in this Report. In the calculations of pfd limits in Report 387, the mean thermal noise power was assumed to be 25 pW0p. The interference analysis in this Report was performed using the pfd levels given in Report 387.

3.1 Sharing between geostationary satellites and fixed-service systems

A review of available satellite data bases indicates that a 10° to 20° separation is currently a reasonable assumption for the 2 GHz band because of the limited number of satellites required to provide service and also due to sharing considerations within the space service.

The maximum pfd levels which do not exceed the criteria given in Recommendation 357 were calculated for 10°, 15° and 20° angular separation and are listed in Table II. These new values will prohibit interference levels from exceeding the criteria given in Recommendation 357. The results in Table II, corresponding to a 15° satellite spacing and double frequency plan for a radio-relay circuit are considered to be reasonable for sharing purposes. Using a 15° separation implies that the emissions from approximately 13 satellites could continuously enter the receivers in a hypothetical reference circuit. This conservative view is necessary to provide freedom for the technological development of future fixed systems. The calculated maximum pfd levels corresponding to 15° satellite spacing and double frequency plan are 10 dB higher than the current pfd limits in No. 2557 of the Radio Regulations.

3.2 Sharing between non-geostationary satellites and fixed-service systems

The orbital parameters for space stations in non-geostationary orbits were derived based on the discussions given in § 2 and the characteristics of space services authorized in the 2 GHz band. Representative characteristics for non-geostationary satellites are listed in Table III.

The parameters listed in Tables I and III were used as inputs to the non-geostationary model. The results plotted by the program are shown in Fig. 2. Curve B is identical to the data shown in Fig. 1 and curve A represents the total interference to a hypothetical reference circuit from eight satellites inserted in orbits ranging from 300 to 1200 km altitude. This curve applies for the case of a radio-relay circuit having a free-space thermal noise level of 25 pW0p and was calculated based on all satellites operating at the maximum allowed pfd levels. Note that curve A is below the curve B criteria by approximately 15 dB for 0.05% of the time. For all other percentages of time, the differences between the two curves are greater than 15 dB. The results show that the pfd levels could be increased by 15 dB without exceeding the interference criteria.
### TABLE II — pfd levels from geostationary satellites which permit sharing with line-of-sight radio-relay systems *

<table>
<thead>
<tr>
<th>Radio-relay circuit</th>
<th>pfd levels (dB(W/(m² • 4 kHz)))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Latitude (degrees)</td>
</tr>
<tr>
<td>Single 20</td>
<td>-147.7</td>
</tr>
<tr>
<td>Single 30</td>
<td>-147.0</td>
</tr>
<tr>
<td>Single 40</td>
<td>-147.2</td>
</tr>
<tr>
<td>Single 50</td>
<td>-149.0</td>
</tr>
<tr>
<td>Double 20</td>
<td>-143.6</td>
</tr>
<tr>
<td>Double 30</td>
<td>-144.0</td>
</tr>
<tr>
<td>Double 40</td>
<td>-143.8</td>
</tr>
<tr>
<td>Double 50</td>
<td>-146.0</td>
</tr>
<tr>
<td>Four 20</td>
<td>-141.1</td>
</tr>
<tr>
<td>Four 30</td>
<td>-140.9</td>
</tr>
<tr>
<td>Four 40</td>
<td>-140.9</td>
</tr>
<tr>
<td>Four 50</td>
<td>-142.2</td>
</tr>
</tbody>
</table>

* For angles of arrival between 0° and 5°.

### TABLE III — Representative characteristics of non-geostationary satellites

<table>
<thead>
<tr>
<th>Satellite orbit altitude (km)</th>
<th>300-1200</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of satellites visible to receivers (')</td>
<td>8</td>
</tr>
<tr>
<td>Satellite inclination angle (degrees)</td>
<td>10-99</td>
</tr>
</tbody>
</table>

(') The assumption of eight satellites implies that there are eight satellite emitters whose emissions are simultaneously received by a radio-relay circuit. In addition, all the satellite orbits are assumed to be statistically independent. These assumptions may seem to be too conservative in favour of the radio-relay circuits. However, it is important to avoid using orbital parameters that are marginal and hence might inhibit the potential growth of radio-relay circuits. It should be pointed out that a relatively large increase in the number of visible satellites results in only a small increase (approximately logarithmic) in total pfd levels.
4. Conclusions

The analyses in this Report, based on Recommendations 357 and 393, indicate that, near 2 GHz, pfd levels from space stations both in geostationary and low orbit could be increased compared to present limits without exceeding the interference criteria of line-of-sight radio-relay circuits. These results are due to the characteristics of space stations and radio relays, satellite orbit spacing, the number of satellites, and radio-relay frequency plans in the 2 GHz band. Additional studies may be required to determine the applicability of these results to sharing with other radio-relay systems in use and being developed at the present time as well as with other services.

REFERENCES

FARRAR, A. [1984] Assessment of satellite power flux-density limits in the 2025-2300 MHz frequency range. Part II, NTIA Report 84-152. US Department of Commerce, National Telecommunications and Information Administration, Washington, DC.


ANNEX I
POSSIBILITIES OF FREQUENCY SHARING BETWEEN THE SPACE OPERATION SERVICE
AND THE FIXED SERVICE (LINE-OF-SIGHT RADIO-RELAY SYSTEMS)
IN THE NEIGHBOURHOOD OF 2 GHz

1. Introduction

The characteristics of systems in the fixed service and the space operation service in the neighbourhood of 2 GHz are reviewed. There follows a study of interference between terrestrial stations and a satellite, and then between a terrestrial station and an earth station.

The following calculation method relating to the study of interference between a terrestrial station and an earth station does not replace the method given in Appendix 28 to the Radio Regulations. It is not intended to be used in evaluating coordination distances. It allows the a priori evaluation of an order of magnitude for acceptable separation distances between an earth station and a terrestrial station, on the basis of a number of parameters. For this purpose, the calculation of the attenuation over the interference path is based not on the worst case but on an average case, with reference exclusively to diffraction caused by an obstacle situated between the two stations. The separation distance thus calculated gives a realistic idea of practical sharing possibilities between the space service and the terrestrial service.

Only one type of space operation system is considered in detail. The system assumed for analysis involves satellites in low Earth orbit, direct Earth-space transmissions (i.e., data relay satellites are not used), transmission of only space operation signals, and other characteristics described below.

2. Technical characteristics

2.1 Characteristics of the space systems in question

2.1.1 Orbits

A large number of space, scientific or applications missions use earth satellites:
- either in orbits close to the Earth (these are often circular at altitudes between 300 and 1200 km);
- or in the geostationary-satellite orbit;
- or in highly eccentric orbits (with apogees up to 200 000 km).

In addition, geostationary satellites are placed in position after having been placed in eccentric orbits (apogee altitude: 36 000 km).

2.1.2 Frequencies

Space operation systems may use up links carrying telecommand and tracking signals in the 2025-2110 MHz band and down links carrying telemetering and tracking signals in the 2200-2290 MHz band. The powers emitted by the satellite or earth stations should be within the regulatory limits.

2.1.3 Bandwidths

The following bandwidths are used:
- earth station: 250 kHz for transmitting and receiving;
- space station: 500 kHz for receiving, on the assumption that there is no automatic frequency control device to compensate the Doppler effect and oscillator drift, and 250 kHz for transmitting.
2.1.4 *Antennas*

A standard type of earth station antenna is used, with a diameter of 9 m. It is assumed that the antenna's radiation diagram is in conformity with that given in Report 391 (see Fig. 3).

2.1.5 *Operational limits*

The use of the earth station, both for transmitting and for receiving, is limited to elevation angles more than 5° above the local horizontal plane. This limit is, however, increased to 10° in the case of telecommand links for highly eccentric satellites in the neighbourhood of the apogee and in the case of geostationary satellites.

The technical characteristics of space links adopted in this study are given in Table IV.
<table>
<thead>
<tr>
<th></th>
<th>Low-altitude circular-orbit satellites</th>
<th>Geostationary satellites</th>
<th>Highly eccentric elliptical orbit satellites</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>300 km</td>
<td>800 km</td>
<td>1200 km</td>
</tr>
<tr>
<td>Earth station</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>At an elevation angle of 5°</td>
<td>-163 dB</td>
<td>-168 dB</td>
<td>-170 dB</td>
</tr>
<tr>
<td>At the zenith</td>
<td>-149 dB</td>
<td>-157 dB</td>
<td>-161 dB</td>
</tr>
<tr>
<td>G&lt;sub&gt;max&lt;/sub&gt;</td>
<td>43 dB</td>
<td>43 dB</td>
<td>43 dB</td>
</tr>
<tr>
<td>Polarization</td>
<td>circular</td>
<td>circular</td>
<td>circular</td>
</tr>
<tr>
<td>TCTP</td>
<td>500 W</td>
<td>500 W</td>
<td>500 W</td>
</tr>
<tr>
<td>T&lt;sub&gt;r&lt;/sub&gt;</td>
<td>300 K</td>
<td>300 K</td>
<td>300 K</td>
</tr>
<tr>
<td>F&lt;sub&gt;r&lt;/sub&gt;</td>
<td>-126 dBm</td>
<td>-126 dBm</td>
<td>-126 dBm</td>
</tr>
<tr>
<td>E.i.r.p.</td>
<td>52 dB (W/4 kHz)</td>
<td>52 dB (W/4 kHz)</td>
<td>52 dB (W/4 kHz)</td>
</tr>
<tr>
<td>B&lt;sub&gt;r&lt;/sub&gt; = B&lt;sub&gt;r&lt;/sub&gt;</td>
<td>250 kHz</td>
<td>250 kHz</td>
<td>250 kHz</td>
</tr>
<tr>
<td>Space station</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>G</td>
<td>-5 dB</td>
<td>0 dB</td>
<td>0 dB</td>
</tr>
<tr>
<td>Polarization</td>
<td>circular</td>
<td>circular</td>
<td>circular</td>
</tr>
<tr>
<td>TMTP</td>
<td>0.3 W</td>
<td>1 W</td>
<td>1 W</td>
</tr>
<tr>
<td>T&lt;sub&gt;r&lt;/sub&gt;</td>
<td>800 K</td>
<td>800 K</td>
<td>800 K</td>
</tr>
<tr>
<td>Y</td>
<td>20 dB</td>
<td>20 dB</td>
<td>20 dB</td>
</tr>
<tr>
<td>Pfd 5°</td>
<td>-163 dB(W/(m&lt;sup&gt;2&lt;/sup&gt;, 4 kHz))</td>
<td>-158 dB(W/(m&lt;sup&gt;2&lt;/sup&gt;, 4 kHz))</td>
<td>-160.5 dB(W/(m&lt;sup&gt;2&lt;/sup&gt;, 4 kHz))</td>
</tr>
<tr>
<td>Pfd zenith</td>
<td>-149 dB(W/(m&lt;sup&gt;2&lt;/sup&gt;, 4 kHz))</td>
<td>-147 dB(W/(m&lt;sup&gt;2&lt;/sup&gt;, 4 kHz))</td>
<td>-150.5 dB(W/(m&lt;sup&gt;2&lt;/sup&gt;, 4 kHz))</td>
</tr>
<tr>
<td>B&lt;sub&gt;r&lt;/sub&gt;</td>
<td>250 kHz</td>
<td>250 kHz</td>
<td>250 kHz</td>
</tr>
<tr>
<td>B&lt;sub&gt;r&lt;/sub&gt;</td>
<td>500 kHz</td>
<td>500 kHz</td>
<td>500 kHz</td>
</tr>
</tbody>
</table>

**G<sub>max</sub>:** axial gain  
**TCTP:** telecommand transmitting power  
**B<sub>r</sub>:** receiver bandwidth  
**TMTP:** telemetering transmitting power  
**B<sub>t</sub>:** transmitting bandwidth  
**Y:** protection ratio  
**Pfd:** permissible interference power  
**T<sub>r</sub>:** equivalent noise temperature
2.2 Characteristics of terrestrial systems

To take account of the great variety of systems in use or planned in the near future, two representative examples have been adopted, called "type 1 stations" and "type 2 stations" (see Table V).

For both type 1 and type 2 stations, antennas have been adopted with diameters of about 3 m but with different configurations, with radiation diagrams in conformity with Report 391 (see Fig. 4).

<table>
<thead>
<tr>
<th>TABLE V — Characteristics of radio-relay systems</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type 1 station</strong></td>
</tr>
<tr>
<td>Frequency band</td>
</tr>
<tr>
<td>Axial gain</td>
</tr>
<tr>
<td>Polarization</td>
</tr>
<tr>
<td>Transmitted power</td>
</tr>
<tr>
<td>Reference bandwidth</td>
</tr>
<tr>
<td>Permissible interference power</td>
</tr>
<tr>
<td>Modulation</td>
</tr>
</tbody>
</table>

3. Study of interference

Four cases of interference may be encountered:

- satellite receives interference from the terrestrial station and vice versa;
- earth station receives interference from the terrestrial station and vice versa (Fig. 5).

Generally speaking, a link without interference satisfies the relation:

\[
P_i = \left[ P_e + G_e + 10 \log \frac{\Delta F_r}{\Delta F_e} - 20 \log \frac{4\pi d}{\lambda} + G_r - D_p - A_b - D_f - A_{sb}(\theta) \right] \geq 0
\] (2)

where:

- \( P_i \): permissible interference level (dBm),
- \( P_e \): transmitted power (dBm),
- \( G_e \): transmitting antenna gain in the direction in question (dBi),
- \( \Delta F_r/\Delta F_e \): receiving/transmitting bandwidth ratio. If it is above 1, the value of 1 is to be used,
- \( G_r \): receiving antenna gain in the direction in question (dBi),
- \( D_p \): polarization losses (dB),
- \( A_b \): receiver connection losses (3 dB),
- \( D_f \): frequency decoupling (see below),
- \( A_{sb}(\theta) \): losses due to relief (see below).

- **Frequency decoupling**: \( D_f \)

Contingent attenuation (dB) due to the difference between the space link frequency and the nearest frequencies of those planned in the arrangement of fixed service radio channels.

- **Losses due to relief (site shielding)**: \( A_{sb}(\theta) \)

An attenuation factor (dB) due to the horizon angle of deviation (\( \theta \)) in accordance with Report 724 (Geneva, 1982):

\[
A_{sb}(\theta) = 20 \log (1 + 4.5 f^{1/2} \theta) + f^{1/2} \theta \text{ with } f \text{(GHz) and } \theta \text{(degrees)}
\] (3)

This factor only comes into play in the case of interference between the earth station and the terrestrial station.

All calculations are made for \( f = 2200 \) MHz.
3.1 Satellite receives interference from the terrestrial station and vice versa

- By way of example, a study was made of the most unfavourable case corresponding to a satellite in circular orbit at an altitude of 300 km.
- In applying the general formula, use is made of the following numerical values:
  \[ D_p = 3 \text{ dB}, \]
  \[ D_f = 0 \text{ dB} \quad \text{(because it will be impossible to guarantee frequency decoupling between a moving satellite and all the terrestrial stations that the satellite may "see" at any time)}, \]
  \[ A_h = 0 \text{ dB}, \]
  \[ A_b = 3 \text{ dB}. \]

3.1.1 Earth-to-space link

First of all, the interference level produced by a single radio-relay transmitter is examined. Two cases are considered:

(a) an average situation in which the satellite is outside the main lobe of the radio-relay antenna at an oblique distance of 600 km. In this case the transmit gain of the radio-relay antenna toward the satellite is 0 dB and the space loss is \(-155 \text{ dB}\).

(b) a particular situation in which the satellite is at the horizon and in the main lobe of the terrestrial station antenna. In this case the transmit gain is the maximum gain and the space loss is \(-165 \text{ dB}\).

For a type 1 terrestrial station the most unfavourable case is carrier interference. Here:

\[ P_e = 20 \text{ dBm} \]
and \( \Delta F_r/\Delta F_e > 1 \), this ratio is therefore replaced by 1.

For a type 2 terrestrial station, the transmitted power is:

\[ P_e = 43 \text{ dBm}. \]

Since various cases are possible for \( \Delta F_e \), consideration is again given to the cases where \( \Delta F_r/\Delta F_e > 1 \), which are the most unfavourable cases; this ratio is therefore once more replaced by 1.

The accumulated effect of a large number of radio-relay transmitters is then added. In order to estimate the total number of radio-relay systems in line-of-sight of the satellite, a density of 5 transmitters per earth surface area \( 10,000 \text{ km}^2 \) is assumed. Six thousand transmitters are found in line-of-sight for an altitude of 300 km.

To estimate the total number of transmitters in situation (b), account is taken of the main-lobe beamwidth, estimated at 3.6\(^\circ\). First of all a calculation is made of the width of the annular strip of land within which the satellite is seen at an angle of elevation of between 0\(^\circ\) and 1.8\(^\circ\). It is deduced that this belt comprises 1200 transmitters. On the assumption that the pointing azimuths of the antennas in the 1200 interfering stations are equally spread out over 360\(^\circ\), 1% of them, i.e. 12 stations, will see the satellite in their 3.6\(^\circ\) wide main lobe.

Finally, the permissible interference level is determined by calculating the power of the received wanted signal at the limit of the earth station's range, that is to say at an angle of elevation of 5\(^\circ\), i.e. at 1500 km; 20 dB, the value \( Y \) in dB adopted for the protection ratio, being subtracted.

\[ P_i = P_r - Y \]
\[ P_i (\text{dBm}) = -20 \text{ dB} + P_e(1500) \text{ dBm} \]

where:

\[ P_r = P_e + G_e - 20 \log \frac{4\pi d}{\lambda} + G_r - A_b \]
\[ P_r (\text{dBm}) = 57 + 43 - 163 - 5 - 3 = -71 \text{ dBm} \]
\[ P_i = -91 \text{ dBm} \]

The results are given in Table VI.

Table VI shows that with type 1 stations interference is less than the permissible level. It would be possible:
- either to tolerate interference from 30 times more stations;
- or reduce the power of the telecommand transmitter.
### TABLE VI - **Satellite receiving interference from the terrestrial stations**

<table>
<thead>
<tr>
<th>Type of interfering terrestrial stations</th>
<th>Position of satellite in relation to interfering station</th>
<th>Power of interference received from a single interfering station (dBm)</th>
<th>Number of stations</th>
<th>Power of interference received from all stations (dBm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type 1 terrestrial station</td>
<td>Average case</td>
<td>-146</td>
<td>6000</td>
<td>-108</td>
</tr>
<tr>
<td></td>
<td>In the main lobe</td>
<td>-121</td>
<td></td>
<td>-110</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-106</td>
</tr>
<tr>
<td>Type 2 terrestrial station</td>
<td>Average case</td>
<td>-123</td>
<td>6000</td>
<td>-85</td>
</tr>
<tr>
<td></td>
<td>In the main lobe</td>
<td>-97</td>
<td></td>
<td>-86</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-82</td>
</tr>
</tbody>
</table>

*Note. — Permissible interference power = -91 dBm.*

With type 2 stations the permissible level is exceeded by 9 dB. Here it would be possible:
- either to tolerate the interference from 8 times fewer stations;
- or multiply the e.i.r.p. of the telecommand transmitter by 8.

These results relate to a spacecraft at an altitude of 300 km. At higher altitudes it can be established that the results would be more favourable.

#### 3.1.2 Space-to-Earth link

The assumed space operation system can comply with the power flux-density limits given in Recommendation 358, i.e. in any 4 kHz band:

- $-154 \text{ dB}(W/m^2)$ for angles of arrival between $0^\circ$ and $5^\circ$ above the horizontal plane;
- $-154 + 0.5(\delta - 5) \text{ dB}(W/m^2)$ for angles of arrival $\delta$ (in degrees) between $5^\circ$ and $25^\circ$ above the horizontal plane;
- $-144 \text{ dB}(W/m^2)$ for angles of arrival between $25^\circ$ and $90^\circ$ above the horizontal plane.

#### 3.2 Earth station receiving interference from the terrestrial station and vice versa

##### 3.2.1 Calculation hypotheses

An attempt has been made to estimate what would be, in practice, the order of magnitude of the separation distances $d$ associated with those cases for which limited sharing is indicated in Tables I and II of Report 396-5 (Dubrovnik, 1986), i.e., distances at which an earth station could operate in relation to an existing radio-relay network after all cases of coordination had been satisfactorily settled. The characteristics adopted for this calculation are given in Figures 6 to 9. So as to allow for practical orders of magnitude, account was taken for calculation purposes of the following favourable factors:

- the earth station is assumed to be placed in a hollow: the elevation angle $\epsilon$ of the physical horizon — varying between $0.5^\circ$ and $4^\circ$ — has been taken as a secondary variable. The earth station is assumed not to operate at angles of elevation below $5^\circ$;
- in the case of non-geostationary satellites, 10 dB may be deducted in order to take into account the variety of the angular positions occupied by the satellites in the line of sight from the earth station (Report 382);
- in the case of geostationary satellites, the earth station is assumed to be pointed at a fixed elevation angle;
- it is also always assumed that the direction of the radio-relay system does not coincide with the straight line joining the terrestrial station to the earth station. As a principal variable, an offset angle $\Theta$ has been assumed between these two directions, varying between $5^\circ$ and a value corresponding to a limit gain of $-10 \text{ dBi}$ (see Fig. 5) (Report 391);
- we have allowed for an additional attenuation of $D_y$ by assuming interleaved frequency assignments for the two services: since it involves bandwidths which are usually less than 1 MHz, the space operation service may choose frequency assignments halfway between two adjacent channels in the plan for the radio-relay systems.
According to the values obtained for the variable $d$, and according to the density of the existing or planned radio-relay network, this method gives an a priori idea of the chances of all the cases of coordination being successfully settled. This means that the concept of separation distance, as calculated above, provides an a priori estimate of the possibility of frequency-sharing between terrestrial and earth stations.

In cases where coordination seems a priori difficult, it may be useful to consider other favourable factors which have not been taken into account in the analysis described above:

- the position envisaged for an earth station is not usually critical and may be moved several hundred kilometres to facilitate coordination;
- if difficult cases of coordination remain in one or two particular azimuths measured from the earth station, it might be possible in these azimuths to raise the normal lower limit of operation of the earth station above a 5° elevation angle;
- the reduction of 10 dB indicated in the second point above is to take account of an angular statistical factor. But earth stations of the space operation service usually do not work on a permanent basis; in particular, the telecommand of a low orbit satellite (altitude less than a few thousand kilometres) lasts about 1 min, four times a day. In this case, account may be taken of a time statistical factor.

3.2.2 Example of calculation

On the basis of the points made above, the separation distances $d$ have been determined in the form of charts as a function of the two variables $\theta$ and $\epsilon$.

Four cases, shown in Figs. 6 and 9, have been taken as examples.

Details of the calculations for Figs. 6 and 8 are given below:

(a) Interference caused to an earth station by a type 1 terrestrial station (Fig. 6):

From general formula (2), we derive the relationship:

$$G_r(\theta) \leq P_t - P_e - G_r - 10 \log \frac{\Delta F_r}{\Delta F_e} + 20 \log \frac{4\pi d}{\lambda} + D_p + A_b + A_h + D_f$$

This gives:

$P_t = 20$ dBm

$P_e = -126$ dBm

$D_p = 0$ dB

$A_b = 3$ dB

$D_f = 22$ dB

$G_r(\theta)$: to take account of the diversity in the angular positions occupied by the earth station tracking a satellite above an angle of elevation of 5°, we take the value at $5 - \epsilon$ from Fig. 3, less 10 dB.

$10 \log \frac{\Delta F_r}{\Delta F_e} = 0$

Thus

$$G_r(\theta) \leq -121 - (G_r - 10) + A_b(\epsilon) + 20 \log \frac{4\pi d}{\lambda}$$

Table VII

<table>
<thead>
<tr>
<th>Point</th>
<th>$\epsilon$</th>
<th>$A_b(1^\circ)$</th>
<th>$G_r(5-\epsilon)$</th>
<th>$20 \log \frac{4\pi d}{\lambda}$</th>
<th>$G_r(\theta) \leq$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d = 20$ km</td>
<td>$1^\circ$</td>
<td>19.1 dB</td>
<td>18.7 dB</td>
<td>126 dB</td>
<td>+ 15.4 dB</td>
</tr>
<tr>
<td>$d = 50$ km</td>
<td>$1^\circ$</td>
<td>19.1 dB</td>
<td>18.7 dB</td>
<td>134 dB</td>
<td>+ 23.4 dB</td>
</tr>
</tbody>
</table>
(b) Interference caused to a type 1 terrestrial station by an earth station (Fig. 8).

From the general formula, we derive the relationship:

\[ G_r(\theta) \leq P_i - P_e - G_e - 10 \log \frac{\Delta F_r}{\Delta F_e} + 20 \log \left( \frac{4\pi d}{\lambda} \right) + D_p + A_s + A_d + D_f \]  

\[ (7) \]

This gives:

- \( P_e = 57 \text{ dBm} \)
- \( P_i = -97 \text{ dBm} \)
- \( 10 \log \frac{\Delta F_r}{\Delta F_e} = 0 \)
- \( L_p = 3 \text{ dB} \)
- \( A_s = 3 \text{ dB} \)
- \( D_f = 12.5 \text{ dB} \)
- \( Ge: \) it is assumed that the earth station is fixed at an angle of elevation of 10°. Therefore we take \( G_e \) at \((10 - \varepsilon)\) read on Fig. 3.

Thus

\[ G_r(\theta) \leq -135.5 - G_e + 20 \log \left( \frac{4\pi d}{\lambda} \right) + A_d(\varepsilon) \]  

\[ (8) \]

**TABLE VIII**

<table>
<thead>
<tr>
<th>Point ( \oplus )</th>
<th>( \varepsilon )</th>
<th>( A_s ) (2°)</th>
<th>( G_e ) (10°-e)</th>
<th>( 20 \log \frac{4\pi d}{\lambda} )</th>
<th>( G_r(\theta) \leq )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( d = 20 \text{ km} )</td>
<td>2°</td>
<td>25.7 dB</td>
<td>11.2 dB</td>
<td>126 dB</td>
<td>+5.0 dB</td>
</tr>
<tr>
<td>( \Phi )</td>
<td>2°</td>
<td>25.7 dB</td>
<td>11.2 dB</td>
<td>134 dB</td>
<td>+13.0 dB</td>
</tr>
</tbody>
</table>

4. **Conclusion**

4.1 It will be remembered that the protection of terrestrial stations against interference from space stations is assured by compliance with the power flux-density limit laid down in Recommendation 358. The study also shows that the interference caused to space stations by terrestrial stations can be kept below the permissible level if, in the case of radio-relay systems with high e.i.r.p., the e.i.r.p. of the telecommand earth stations is increased (see § 3.1.1).

4.2 Before undertaking the coordination procedure described in Appendix 28 of the Radio Regulations, it is often necessary to make a rapid analysis of the practical conditions for the siting of the earth station in an existing radio-relay network. This analysis can be carried out by the graphical method referred to in § 3.2 by which the best sites for the earth station in relation to those of the radio-relay system terrestrial stations can be provisionally determined.
FIGURE 3 — Radiation diagram of the earth station antenna

\[ G(\phi) = 52 - 10 \log \frac{D}{\lambda} - 25 \log \phi \]

outside the main lobe, i.e. beyond the -3 dB points

Other characteristics:
- parabolic antenna of 9 m diameter
- carrier frequency: 2200 MHz
- -3 dB beamwidth = 1°

FIGURE 4 — Radiation diagram of the terrestrial station antenna

\[ G(\phi) = 52 - 10 \log \frac{D}{\lambda} - 25 \log \phi \]

outside main lobe i.e. beyond the -3 dB points

Other characteristics:
- parabolic antenna of 3 m diameter
- carrier frequency: 2200 MHz
- -3 dB beamwidth: 3.2°
FIGURE 5 — Position of the terrestrial stations in relation to the earth station for the study of interference

\[ \text{distance OA} \]
\[ \text{geographical protection angle} \]
\[ \text{earth station} \]
\[ \text{line-of-sight radio-relay link} \]
\[ \text{offset angle} \]
FIGURE 6 — Earth station receiving interference from a type 1 terrestrial station

- $d$: distance separating the earth station from the terrestrial station
- $G_t(\theta)$: antenna gain of the terrestrial station in the direction of the earth station
- $\theta$: offset angle between the direction of the radio-relay link and the straight line joining the terrestrial station to the earth station
- $\varepsilon$: elevation angle of the physical horizon of the earth station in the direction of the terrestrial station

The earth station is assumed to receive the emission from a non-geostationary satellite and to operate at an elevation angle of over 5°.

- $A$: area of improbable interference
- $B$: area of probable interference
- $D_f$: 22 dB corresponding to the use of an interleaved frequency in the plan for the type 1 radio-relay system
FIGURE 7 — Earth station receiving interference from a type 2 terrestrial station

\( d \): distance separating the earth station from the terrestrial station

\( G_r(\theta) \): antenna gain of the terrestrial station in the direction of the earth station

\( \theta \): offset angle between the direction of the radio-relay link and the straight line joining the terrestrial station to the earth station

\( \epsilon \): elevation angle of the physical horizon of the earth station in the direction of the terrestrial station

The earth station is assumed to receive the emission from a non-geostationary satellite and to operate at an elevation angle of over 5°.

A: area of improbable interference

B: area of probable interference

This diagram has been obtained in the special case of a frequency decoupling of \( D_f = 22 \) dB.
FIGURE 8 — Type 1 terrestrial station receiving interference from an earth station

- $d$: distance separating the earth station from the terrestrial station
- $G_r(\theta)$: antenna gain of the terrestrial station in the direction of the earth station
- $\theta$: offset angle between the direction of the radio-relay link and the straight line joining the terrestrial station to the earth station
- $\epsilon$: elevation angle of the physical horizon of the earth station in the direction of the terrestrial station

The earth station antenna is assumed to be transmitting at an elevation angle of $10^\circ$ in the direction of a geostationary satellite and the transmission power is taken at 500 W.

- $A$: area of improbable interference
- $B$: area of probable interference
- $D_f$: $12.5\, \text{dB}$ corresponding to the use of an offset frequency in the plan for the type 1 radio-relay system
FIGURE 9 — *Type 2 terrestrial station receiving interference from an earth station*

\( d \): distance separating the earth station from the terrestrial station  
\( G_r(\theta) \): antenna gain of the terrestrial station in the direction of the earth station  
\( \theta \): offset angle between the direction of the radio-relay link and the straight line joining the terrestrial station to the earth station  
\( e \): elevation angle of the physical horizon of the earth station in the direction of the terrestrial station

The earth station is assumed to be transmitting at an elevation angle of 10° in the direction of a geostationary satellite and the transmission power is taken at 500 W.

A: area of improbable interference  
B: area of probable interference

This figure has been obtained in the special case of a frequency decoupling of \( D_f = 12.5 \) dB.
1. Introduction

This Report is a review of the technology for the transfer of energy through free-space by a highly collimated microwave beam. The collection and conversion of the incoming radio energy to conventional electrical energy comprises a unique technology which differs from the traditional methods of receiving and processing radio energy in communications services. The efficient transfer of energy using an electromagnetic beam could permit coupling of terrestrial power transmission systems to power sources and sinks located in the atmosphere, in space, or on the Earth's surface. The concept of remote energy generation by high power arrays of solar cells on geostationary satellites has been of particular interest.

Energy transfer by radio waves was first pioneered by Tesla [O'Neill, 1944; Hunt and Draper, 1964] at the turn of the century. Tesla became interested in the general concept of resonance and sought to apply this to the transmission of electrical energy from one point to another without wires. He built a large "Tesla coil" with which he hoped to produce oscillations of electrical energy around the surface of the Earth and to set up standing waves into which he could immerse his receiving antennas at the optimum point. His ideas were decades ahead of the technology that would enable their realization [Susskind, 1968]. The event which advanced technical capabilities and precipitated interest in the use of microwaves for power transmission was the development of super-power generation at microwave frequencies in the early 1960s [Skowron et al., 1964; Luebke and Caryotakis, 1966]. This programme resulted in high-efficiency tubes with high power handling capability (several hundreds of kilowatts).

The first demonstration of the efficient transmission of significant amounts of power by microwaves took place in May, 1963 [Brown, 1964]. The technology has since been greatly advanced [Brown, 1969a; Robinson, 1970; Brown and Dickinson, 1975].

Of the various criteria that could be used to evaluate the progress of microwave energy, transfer efficiency is the most important. By this standard, the efficiency of the overall system has moved from 15% in 1963 to 54% in 1975 [Brown and Dickinson, 1975]. Further development of energy conversion components in the system might increase the efficiency to 70%. Additional criteria for the evaluation of the technology, particularly as it relates to system applications, include power handling capability, reliability, ability to dissipate waste heat, and cost. Other, more important criteria, are the external effects, such as radio frequency interference from spurious frequencies and particularly, the impact upon the environment. A discussion of some of these aspects, in addition to efficiency, follows.

2. The technology of free-space microwave energy transmission

A microwave energy transmission system may be divided into three principal elements which link at their physical interfaces. These elements involve separate technologies which combine to determine the overall efficiency and power handling capability of the system. The elements are:

- element (1): conversion of d.c. electrical energy to microwave energy,
- element (2): transmission of the microwave energy,
- element (3): collection and rectification of the microwave energy.

2.1 The conversion of d.c. electrical energy into microwave energy

In the conversion of d.c. energy into microwave energy, the efficiency should be as high as possible to minimize the size of the prime source and the difficulty in dissipating heat due to convertor inefficiency. There are several methods of conversion but only one of them has demonstrated the order of efficiency desirable for a power transmission system. This device is the re-entrant beam, crossed-field device [Brown, 1970]. In its oscillator form, it is called the "magnetron" while in its amplifier form it is called the "amplitron". Both of these forms have resulted in tube designs with efficiencies of 80 to 90%.
2.2 *The microwave beam link*

All elements of transmission from the output of the generator to the aperture area at the receiving point are considered in the discussion of the microwave beam link. It was theoretically shown [Goubau and Schwering, 1961], and later confirmed [Li, 1965] that energy can be transmitted with efficiencies approaching 100% from a properly illuminated and contoured transmitting aperture to a receiving aperture. This relationship [Goubau, 1970] is shown in Fig. 1. The efficiency factor $\tau$ is:

$$\tau = \frac{\sqrt{A_r A_t}}{\lambda D}$$

where:

- $A_r$ and $A_t$: the receiving and transmitting aperture areas respectively,
- $\lambda$: the wavelength of the radiation,
- $D$: the distance between the transmitting and receiving apertures.

The relationship shown in Fig. 1 assumes a tapered illumination of the transmitting aperture and further assumes that the radius of curvature of the phase front at launch is equal to the distance $D$.

That the transmission efficiency can approach 100% has been demonstrated experimentally [Degenford et al., 1964]. Experimental demonstrations may be scaled to small dimensions providing the aperture diameters and the separation of the apertures correspond to several wavelengths.

2.3 *Efficient microwave beam launching*

To launch a microwave beam efficiently the amplitude and phase of the microwave energy must be properly distributed over the face of the transmitting aperture. There are a number of ways of illuminating the transmitting aperture, e.g. by a phased array with corporate feed from a single microwave source, by an active phased array in which the radiating elements are individually driven, by an illuminating horn and lens, or by a traditional illuminating horn and reflector.

Due to the large amount of power involved, the active phased array stands out as superior. This is most applicable to very large arrays, particularly those located in space and working as a retro-directive array to control the phase coherence at the aperture.

2.4 *Collection and reconversion of microwave energy into d.c. energy*

In order to complete the microwave energy transmission system, it is necessary to absorb the microwave energy by a receiving antenna, and to convert it back into d.c. energy. The conventional way of doing this would be to use a large ellipsoidal reflector to reflect the intercepted microwave energy into a small horn which may be terminated in a waveguide or coaxial line. The microwave energy would then be converted back into d.c. energy. However, this procedure involves a number of problems which a new type of structure known as the "rectenna" eliminates [Brown, 1969b]. (The term "rectenna" is a combination of the words "rectifier" and "antenna").

In the rectenna structure, the rectifying elements are uniformly distributed throughout the receiving aperture, so that the microwave energy which is intercepted in a local region of the receiving aperture is immediately converted back into d.c. energy. The rectenna efficiency consists essentially of two parts — the microwave collection efficiency and the rectification efficiency. By careful matching of the rectenna input impedance to that of free space, the collection efficiency can approach 100%. The rectification efficiency depends upon the efficiency of the rectifying diodes themselves and the ability to design a rectifying circuit which effectively restricts re-radiation of harmonics by converting them into useful energy.

3. *Applications for free-space power transmission by microwave beam*

3.1 *General applications*

Properties of microwave energy transmission include:

- no mass either in the form of wire conductors or ferrying vehicles is required between the source of energy and the point of consumption;
- the direction of energy transfer can be rapidly changed by repointing the transmitting antenna;
- there is no loss of energy in the transfer of energy through the vacuum of space. Furthermore, over a relatively broad frequency range there is little loss of energy in the transfer of energy from space to the Earth's surface;
- the mass of the transducers at the transmitting and receiving points can be small.
FIGURE 1 – RF power beam transmission efficiency

\[ \tau = \frac{\sqrt{A_t A_r}}{\lambda D} \]

- **A**: circular aperture
- **B**: quadratic apertures
- **C**: optimum aperture taper
- **\(P_0\)**: power flux-density at the centre of the aperture
- **\(P\)**: power flux-density at the edge of the aperture
- **\(R\)**: radius of the aperture
- **\(\rho\)**: radius to a point on the aperture
- **\(\eta\)**: efficiency

It is unlikely that microwave systems will find wide application for energy transfer in terrestrial systems. However, there could be useful applications for the transmission of power to remote locations or between two points separated by a very hazardous environment, or where it is desired to eliminate a mechanical connection for any reason. In the area of space applications, the transfer of energy between two satellites, up to a distance of a few kilometres, has been studied by NASA [Robinson, 1970]. Here the potential specific application is to use a central source in a space base complex to service the energy needs of several satellites, by simply repointing the transmitting antenna, thereby freeing the satellites from the need of a separate power supply.
3.2 Energy from solar satellites

A system for bringing energy down to Earth from a geostationary-satellite by converting solar energy to electrical energy has been studied. Such a system would provide energy from an inexhaustible source external to the Earth [Glaser, 1968; J. Microwave Power, 1970].

The solar energy falling on the Earth is so diffuse and variable that it is difficult to use. However, a geostationary solar array can be uniformly illuminated 99 per cent of the time, and cancelling of acceleration forces and the absence of atmosphere and wind make it possible to build an extremely lightweight structure, free of many of the corrosive, fouling, and deteriorating mechanisms encountered on Earth. It was therefore proposed [Glaser, 1968] that advantage be taken of such an array in space to achieve a new kind of energy source. This suggestion has led to a baseline design for the Satellite Solar Power Station (SSPS). In this, large solar photo-voltaic cell arrays would convert the Sun's radiant energy to d.c. energy, which would then be transferred to a large active phased array mounted by means of rotary joints to the solar arrays. The active phased arrays would convert the d.c. energy to microwave energy at a preferred wavelength suitable for penetration of the Earth's atmosphere and focus that energy into a narrow beam pointed towards a designated receiving area on the Earth's surface.

The microwave beam in space would be well collimated to arrive at the Earth's atmosphere with the same energy concentration as at launch. The microwave energy reaching the receiving area on Earth would be efficiently converted back to d.c. energy by the rectenna.

4. Conceptual satellite solar power station (SSPS)

A conceptual design of an SSPS [Reference System Report, 1978] has a transmitted power level of 6500 MW. In this design, the transmitting antenna array is 1 km in diameter. The antenna dimensions are derived from the relationship between efficiency and physical parameters given in Fig. 1 for a frequency of 2450 MHz which would penetrate the Earth's atmosphere with low attenuation. The projected overall efficiency of the microwave energy transmission system, including the conversion efficiencies at both ends, is 68%.

A 1 km diameter circular phased array antenna would use an estimated τ of 1.62 (see Fig. 1). The power taper would be 10 dB from the centre to the edge of the aperture and the power of the radiating elements would decrease in steps of approximately 1 dB in 10 nearly equal area concentric rings around the centre of the transmitting array. The half-power beamwidth is 0.008° and the side lobes decrease asymptotically to a level of −49 dB relative to the main beam.

The beam is centred on a beacon transmitter at the middle of the collecting area on Earth. The power flux-density at the centre of the collecting area is 20 mW/cm². A rectenna array 5 km in diameter would encompass all power flux-densities greater than about 0.5 mW/cm². A guard area extending out to a 10 km radius would encompass power flux-densities in excess of about 50 μW/cm². The concentration of the antenna beam would provide protection to radiocommunication services because the side-lobe levels outside the collecting area, and adjacent guard areas on Earth, would be attenuated by 49 dB using the transmitting antenna described previously.

Filtering the out-of-band transmissions can reduce the "spillover" into adjacent frequency bands. The design characteristics of a representative transmitter system output spectrum are illustrated in Fig. 2 where it is assumed that the transmitter power spectrum is spread evenly over the band 2450 ± 10 MHz. At the edge of the 5 km diameter collecting area the power flux-density is −30 dB(W/(m² · 4 kHz)), outside the surrounding guard area it is −50 dB(W/(m² · 4 kHz)). The ITU limits space station emissions in the adjacent frequency bands to a power flux-density of −154 dB(W/(m² · 4 kHz)) (for low elevation angles, see No. 2557 of the Radio Regulations). Hence, the transmitter filters must provide 104 dB attenuation in the 40 MHz between the transmitter spectrum and the edge of the industrial, scientific and medical (ISM) band. The conceptual design for the SSPS envisages a 5-cavity klystron which provides 120 dB attenuation at the band edge (see Fig. 2). The margin of 16 dB appears to provide sufficient protection for the radiocommunication services in adjacent bands. This conceptual design resulted from experiments using magnetrons and klystrons with bandwidths which are of an order of magnitude narrower than that considered in Fig. 2.

Among the current unknowns in the conceptual design, are the power flux-density levels of the harmonic transmissions, the level of the scattered and reflected radiations from the rectennas and the beam pointing capability of the satellite antenna. Should these radiations prove to be harmful, possible solutions are to increase the filtering on the space transmitter, or to designate frequency bands which are harmonic multiples of the 2450 MHz carrier for ISM and energy transmission purposes.
5. Additional considerations

The use of beams of microwave radiation for transmission of energy in free space would entail the radiation of very large quantities of radio energy. This presents problems in ensuring that the microwave radiation is within acceptable levels outside the designated collecting area, and that the spectrum "spillover" into adjacent bands does not result in harmful interference to other radiocommunication services. An additional problem would be that of considering whether passenger carrying aircraft can safely transit a 5 km diameter power beam, and, if not, the setting up of procedures to protect against such transits. Good engineering practices can greatly reduce
the unwanted radiations in space and frequency, but the levels cannot be reduced to zero. If the transmitted power is high, even a high degree of suppression may not eliminate harmful interference to other services. Even though some of the other services may be operating systems capable of tolerating high levels of interference, such services might be subjected to levels of interference which are harmful to their operations. It should be noted that interference to a safety service such as radionavigation could cause serious consequences even if such interference is momentary.

The Radioastronomy Service, in particular, is vulnerable to low-level interfering signals, because of the use of highly sensitive receivers and long integration times. Similar considerations apply to deep-space research stations. The characteristics of radio telescopes and radioastronomy receivers can be described accurately, and the levels of potentially harmful interference can be specified. These requirements have been carefully reviewed and are given in Report 224. The harmful interference levels vary with frequency and are generally many decibels (typically 50 to 90 dB) below the harmful interference levels generally agreed upon for other services.

A review of possible interference to radioastronomy and radar astronomy from solar power satellites [Thompson, 1981] (Report 853) has shown that several mechanisms need to be considered. The power signal in the system proposed is at a frequency near to radioastronomy bands and there are harmonics which are close to others. The strong fields produced at the Earth could overload the input stages of radioastronomy receivers close to the rectenna site or at more distant sites where the interference pattern of the power transmitting antenna can have large peaks. Other interference, more widespread in frequency and in geographical coverage, could result from transmitter-generated noise, thermal noise from the satellite arrays, and perhaps from the reflection of terrestrial signals by those arrays. Interference from the receiving rectennas could occur if sites are not chosen with care in relation to radioastronomy observatories.

All these mechanisms need further study if implementation of solar power satellites proceeds, because there would be zones centred on the geostationary satellite orbit in which radioastronomy observations would be precluded, or at least seriously degraded. The effects of thermal radiation alone could be sufficient to degrade observations over a substantial part of the sky.

In view of the more stringent requirements of the radioastronomy service, the designers of energy transmission systems using radio techniques should refer to the harmful interference levels of Report 224 when assessing the impact of such energy transmission systems on other services.

It is noted that other effects including biological hazards and effects on the ionosphere are not considered.

REFERENCES


HUNT, I. and DRAPER, W. [1964] Lightning in his hand, the life story of Nikola Tesla. Sage, Denver, Colorado, USA.


O’NEILL, J. J. [1944] *Prodigal genius — the life of Nikola Tesla*. Ives Washburn, New York, USA.


BIBLIOGRAPHY


1. Introduction

Continued growth in electro-optical technology — especially lasers — has extended the spectral operating regions for telecommunication systems into the infra-red (IR) and visible portions of the spectrum. This Report examines laser operating principles and selected telecommunication applications of lasers in the infra-red and visible spectra. Additional relevant information is given in Report 666 of Volume I.

In light of these developments, the CCIR has examined the need for technical standards (Report 681-2, Dubrovnik, 1986). It was concluded that international technical standards are not needed for use of the infra-red and visible portions of the spectrum (see also Report 667 of Volume I).

2. Definition

The word "LASER" is an acronym formed from Light Amplification by Stimulated Emission of Radiation. Lasers are optical masers (Microwave Amplification by Stimulated Emission of Radiation) and all such devices constitute a practical application of Planck's Law, i.e.

\[ E = h \cdot v \]  

where:
- \( E \) is the energy emitted, joules
- \( h \) is a constant \((6.625 \times 10^{-34} \text{ joule-second})\)
- \( v \) is the frequency of the energy radiated, Hz

3. Constituents of lasers

All lasers employ the elements illustrated in Figure 1 in their operation. An active medium is stimulated by energy from an external source, raising an electron in an atom, in an ion or in a molecule to a higher energy level. After a time interval, the excited electron spontaneously falls to the original, or ground energy level, emitting the radiant energy predicted by Planck's formula as the transition occurs. If the stimulus is sufficiently intense, more electrons will move to the excited state than those remaining in the base state and a population inversion is then said to exist.

* This Report should be brought to the attention of Study Group 1.
In this condition, a signal applied to the active medium, such as spontaneous radiation (quantum noise), is amplified, since more signal energy is released in triggering downward transitions (with a resultant, in-phase release of radiant energy) than is absorbed in triggering upward transitions.

The system can be turned into an oscillator by providing positive feedback — as with the mirrors in Fig. 1. If the two facing mirrors form a resonant cavity, amplified radiation is reflected back into the active medium in phase with the amplified signal, stimulating further, in-phase amplification on each pass. Provision of a means of extracting a portion of these intra-cavity oscillations at one or both ends of the cavity can then produce a tightly collimated beam of energy which may be essentially monochromatic and highly coherent.

The active medium may be a gas, a liquid, a solid solution of ions in a crystalline or amorphous matrix or a crystalline semiconductor solid, while the external stimulus (or pump) may be a light source, an electric current, an electron beam, etc. The most common crystalline lasers, gas lasers and liquid lasers (see Table I) are optically pumped, while most semiconductor lasers are electrically pumped.

### Table I — Examples of the most common types of laser

<table>
<thead>
<tr>
<th>Type</th>
<th>Materials</th>
<th>Active species</th>
<th>Main Wavelengths (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid-ionic</td>
<td>Neodymium (Nd) dopant in Yttrium Aluminum Garnet</td>
<td>Nd ions</td>
<td>1.06</td>
</tr>
<tr>
<td></td>
<td>Ruby</td>
<td>Chromium ions</td>
<td>0.69</td>
</tr>
<tr>
<td>Gaseous</td>
<td>Helium-Neon mixture</td>
<td>Neon atoms</td>
<td>0.63</td>
</tr>
<tr>
<td></td>
<td>Argon</td>
<td>Argon ions</td>
<td>0.4545 to 0.5287</td>
</tr>
<tr>
<td></td>
<td>CO₂</td>
<td>CO₂ molecules</td>
<td>10.6</td>
</tr>
<tr>
<td></td>
<td>N₂</td>
<td>N₂ ions</td>
<td>0.337</td>
</tr>
<tr>
<td>Liquid</td>
<td>Rhodamine GG dye</td>
<td>Dye molecules</td>
<td>0.53 to 0.66 (tunable)</td>
</tr>
<tr>
<td>Semiconductor</td>
<td>GaAs Al</td>
<td>Electron-hole pairs</td>
<td>0.78 to 0.90</td>
</tr>
<tr>
<td>Semiconductor</td>
<td>GaAsInP</td>
<td>Electron-hole pairs</td>
<td>1.1 to 1.6</td>
</tr>
</tbody>
</table>
4. Operating modes

Most laser materials can be used to produce emitters which can deliver a continuous wave output or a pulsed output, although not usually both from the same design. Both modes find practical use in operating systems depending on the application.

Directly pulsed lasers, i.e. those in which the pulsed output is attained by directly applying a pulsed excitation, can yield pulse widths as short as 100 μs. Pulses as short as 1 to 10 ns are possible from Q-switched lasers. In Q-switching, the Q of the cavity is spoiled as the excitation builds up. At a critical moment, feedback is restored allowing a very large pulse to build up and be coupled out very quickly. The feedback path can be switched by a rotating mirror or by a Pockels cell (or other electro-optical switch). A Pockels cell is an optical device made of a crystalline material which has the property, under the influence of an applied electric field, of rotating the direction of polarization of incident light which does not coincide with one of the main axes of the crystal. When used in combination with a plane polarizer, a Pockels cell is capable of very high speed switching of an optical path. The output of a Q-switched laser employing a Pockels cell as the Q-switch, is a plane polarized light beam. Q-switched lasers can produce very high peak energy levels in very short duration pulses. Even shorter pulses than for Q-switched systems can be produced through other techniques; such as cavity dumping and mode locking.

5. Laser applications

Numerous uses have been conceived for lasers and many have been successfully demonstrated. Table II lists some of the applications of lasers in communications, night vision, space remote sensing and other areas. All of these systems have been developed to some extent and found to be workable. Several of the more promising concepts for space research are described in the following sections.

**TABLE II — Possible laser applications**

<table>
<thead>
<tr>
<th>Space radiocommunications</th>
<th>Terrestrial radiocommunications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Satellite-to-satellite</td>
<td>Atmospheric point-to-point</td>
</tr>
<tr>
<td>Satellite-to-Earth</td>
<td>Underwater point-to-point</td>
</tr>
<tr>
<td>Earth-to-satellite</td>
<td>Intra-system — fibre optics</td>
</tr>
<tr>
<td>Intra spacecraft — fibre optics</td>
<td></td>
</tr>
<tr>
<td>Space remote sensing</td>
<td>Geology and mineral resources</td>
</tr>
<tr>
<td></td>
<td>Geography and cartography</td>
</tr>
<tr>
<td></td>
<td>Oceanography</td>
</tr>
<tr>
<td></td>
<td>Environmental quality</td>
</tr>
<tr>
<td></td>
<td>Agriculture and forestry</td>
</tr>
<tr>
<td></td>
<td>Hydrology and mineral resources</td>
</tr>
<tr>
<td>Guidence</td>
<td>Construction and surveying</td>
</tr>
<tr>
<td>Electro-optical image correlator guidance systems</td>
<td>Drilling, cutting, welding</td>
</tr>
<tr>
<td>Infra-red imaging guidance</td>
<td>Navigation</td>
</tr>
<tr>
<td>Television guidance</td>
<td>Measurement systems</td>
</tr>
<tr>
<td>Laser trackers</td>
<td>Printing and graphics</td>
</tr>
<tr>
<td>Night vision</td>
<td>Readers, recorders and displays</td>
</tr>
<tr>
<td>Low light level television illuminators</td>
<td>Medical systems — surgery and instrumentation</td>
</tr>
<tr>
<td>Image intensifier system illuminators</td>
<td>Materials processing</td>
</tr>
<tr>
<td>Night driving</td>
<td>Nuclear fusion</td>
</tr>
<tr>
<td>Surveillance</td>
<td>Isotope separation</td>
</tr>
</tbody>
</table>
6. Communications

Visible and infra-red radiation can be employed in all the space communication links illustrated in Figure 2. Two way, wideband space-to-space links between synchronous relay satellites have been studied by space research engineers. The most promising approaches are first those proposed around 0.8 \( \mu m \) semiconductor lasers (GaAlAs) and then those using neodymium (Nd:YAG) lasers or 1.3 or 1.55 \( \mu m \) semiconductor lasers (GaAsInP). Space-to-space links between low altitude observation satellites and high synchronous relay satellites have also been found feasible, as well as space-to-Earth down links from synchronous relay satellites to earth stations. This latter application is limited by the weather environment near the earth station, due to the relatively high absorption and scattering of electromagnetic energy in this spectral region by atmospheric moisture.

![Diagram of space applications of laser communications](image)

**FIGURE 2 – Space applications of laser communications**

A: Earth  
B: Synchronous relay satellite (SRS)  
C: Low-altitude observation satellite (LAS)  
D: SRS to Earth down-link  
E: SRS-SRS two-way wideband link  
F: LAS-SRS link

Optical links with distant interplanetary exploration probes are also envisaged. The powers required for this type of mission make neodymium lasers the most attractive sources. Space telecommunications using lasers are dealt with in Annex I.

7. Echo ranging

Active echo ranging systems using laser emitters have been developed for terrestrial use and are now being proposed for space research. Figures 3 and 4 illustrate ground based and spaceborne applications for laser ranging. Precision tracking of several reflecting satellites is planned by means of light detection and ranging (LIDAR) sensors. Reflecting satellites may use retroreflectors and specular reflecting surfaces to return pulsed light energy toward its source. Some of the satellites which use this technique for precision tracking measurements are: GEOS-B, GEOS-III, STARLETTE, LAGEOS and TIMATION.
Laser echo ranging techniques, discussed in Annex II, will be used in Space Shuttle experiments or precision tracking of terrestrial corner cube retroreflectors and satellite-borne reflectors such as those on LAGEOS. A cloud climatology experiment is planned for measuring the backscatter of light energy from clouds, tracking cloud distribution geographically and by altitude, etc.

8. Comparisons

Lasers offer several potential advantages for space-to-space communications when compared with conventional microwave systems. The tightly collimated beams of lasers result in very high directivity gains with consequent high effective radiated power levels. Furthermore, the absence of side and back lobes together with highly collimated beams results in low interference susceptibilities. On the other hand, the tracking servo systems must be much more precise in order to establish and maintain such links. Acquisition procedures may require the use of other, less precise sensors to assist in aligning a transmitter beam toward the receiving station. Also, if the receiving aperture possesses a high gain, receiving aperture alignment may require great precision.

Since angular resolution is proportional to $\lambda/d$, any given resolution requirement can be fulfilled with smaller apertures as wavelength decreases. As a result, high resolution apertures are much smaller at visible and near visible wavelengths than for microwaves. Also, the higher operating frequency of the laser makes wider transmission bandwidths theoretically possible. Bandwidths are currently limited by the electronic modulation and demodulation circuits. The systems under development use amplitude modulation. Other types of modulation (frequency, phase, etc.) are foreseen in the longer term. Also, extremely short pulse widths available from Q-switched, cavity dumped, or mode-locked lasers offer range resolutions unequalled by microwave radars.
9. Conclusions

Optical communication systems employing lasers as radiation sources are now being developed. These systems have the potential for broadband, interference-free links between points in space and between Earth and space. Links between Earth and space are limited by the effects of the atmosphere on electromagnetic radiation in the visible and near-visible spectrum. Links between points in space are not affected by the atmosphere. Interference susceptibility can be drastically reduced or eliminated through the use of tightly collimated beams and narrow receiver fields-of-view. The use of such beams can also yield high e.i.r.p., even with low power transmitters, due to increased gain directivity. However, tightly collimated beams require precision pointing and tracking loops, and special acquisition equipment for establishing communication links. Consequently, the potential advantages to optical communication systems appear to be high data rates, broad bandwidths, small size and lightweight, rather than low cost and simplicity. Nevertheless, once experiments have been successfully completed, optical links could become widespread and offer an alternative to microwave, reducing the constraints imposed on the spacecraft.

Electro-optical echo ranging systems are being developed for a wide variety of applications. These systems are capable of high precision, interference free measurements of slant distance between the sensor and selected targets. Most laser rangefinders are likely to be characterized by tightly collimated, highly directive transmitter beams. Very narrow beamwidths are well suited for high resolution tracking and poorly suited for “search” operations. Consequently, laser rangefinders will probably be used in conjunction with other, less precise sensors which are well suited for the high volume search operations required in target acquisition. Background noise from natural and artificial sources will necessitate careful optical design.
ANNEX I
APPLICATIONS OF LASERS TO TELECOMMUNICATIONS

1. Introduction

An application of lasers to telecommunications is discussed in this Annex. Figure 5 is a functional block diagram of a typical unidirectional, optical communication system. The transmitter, consisting of a radiation source, transmission optics, a modulator and pointing-tracking servo equipment, is shown on the left. A receiver, consisting of collection optics, a detector, a preamplifier/amplifier, a demodulator, output electronics and pointing-tracking servo equipment, is shown on the right. A bidirectional relay link is similar, requiring a transmitter and a receiver at each end of the link to enable two-way communication. Each of these subsystems and components will be discussed in turn.

![Functional block diagram of a typical optical communication system](image)

**FIGURE 5** – Functional block diagram of a typical optical communication system

- A: Transmitter
- B: Receiver
- C: Modulated light beam
- D: Radiation source (laser)
- E: Modulator
- F: Transmitter optics
- G: Receiver optics
- H: Detector
- I: Preamplifier/amplifier
- J: Demodulator
- K: Output electronics
- L: Pointing-tracking servo loops

2. Transmitters

The laser transmitter emissions can either be directly modulated or may be externally modulated by an optical component. This component must be capable of modifying the amplitude, phase, polarization or other properties of the optical signal. The transmitter optics are analogous to a directive RF transmitter antenna. Furthermore, pointing-tracking servo equipment operating on the antenna is used to direct the emitted radiation beam toward the receiver in optical transmitters as well as in RF systems. A primary energy source and equipment are required to stimulate a specific laser and the efficiency of such power conversions are typically less than 10%. For semiconductor lasers, however, conversion efficiency may be as much as 30 to 40%, or even higher according to the internal structure of the component.

3. Lasers

There are many design factors, between which trade-offs occur, and which are important in selecting a laser for communications service.
Those lasers which at present appear to have the highest potential for space communication applications are solid lasers, i.e. semiconductor GaAsAl or possibly GaAsInP lasers and Nd:YAG lasers and frequency doubled Nd:YAG lasers (gas lasers pose serious space rating problems). The Nd:YAG and doubled Nd:YAG lasers are best suited for pulsed transmissions and are usually externally modulated (especially at high data rates) because of the long fluorescent lifetime (230 μs). Nd:YAG lasers can be operated at high output power levels (up to 1000 W), while the output power of doubled Nd:YAG lasers is much lower owing to limited power dissipation by the doubler crystal (LiNbO₃ or Ba₂NaNb₅O₁₅ - localized hot spots at impurities can result in fractures). GaAsAl lasers are the most powerful semiconductor lasers, sustaining up to 100 mW of continuous power with single structures or a few watts with arrays. However, multimode structures produce a bilobe far-field pattern which is not suited to the application concerned and requires a beam shaping system. At present, GaAsInP lasers have maximum powers of a few dozen milliwatts (laboratory prototypes). These lasers may be found in fairly broad spectral windows (120 nm for GaAsAl and 500 nm for GaAsInP), as the wavelength can be adjusted within a relatively narrow window (a few nanometres) by altering the exact composition of the ternary and quaternary mixtures. Finally, this type of laser can be modulated directly with a high level of efficiency.

4. Modulators

Modulators for directly modulated lasers consist of the electronics required to drive the laser oscillator. Direct modulation is normally used only with semi-conductor lasers, such as GaAs, GaAsInP and with HeNe lasers.

External modulators are components inserted in the transmitter optical path which have the capability of rapidly varying some property of the light beam output in accordance with the modulating information. An example is the use of a Pockels cell and linear polarizers to produce amplitude or phase modulation. The Pockels cell contains a crystal which rapidly rotates its plane of polarization under the influence of a varying electric field. The Pockels cell contains a crystal which rotates the direction of polarization of incident light. For amplitude modulation the laser output beam is pre-polarized by a linear polarizer, modulated by the Pockels cell and then passed through a polarization analyser before being propagated through space as an amplitude modulated light beam. In phase modulation, the beam is pre-polarized, modulated by the Pockels cell and then propagated at a constant light amplitude with varying polarization plane. The analyzer is incorporated in the receiver optical path in this latter case.

Another type of modulator is the acousto-optical system, which makes use of photoelastic variations in a crystal resulting from the propagation of acoustic waves. This effect has been observed in GaAs, LiNbO₃ and As₂Se₃. Magneto-optical systems have also been devised using magnetic iron garnet (YIG), which exhibit polarization plane rotation or optical absorption under the influence of a magnetic field.

5. Transmitter optics

The transmitter optics form the aperture through which the modulated beam is propagated toward the receiver. Transmitter optics consist of a collimating telescope, optical path stabilization, beam steering, and any other components or accessories used in transmitting the beam. For example, telecommunication beamwidths may be so narrow (for example, a few microradians) that special provisions must be made to align the transmitter and receiver apertures. Wide angle beacons and beacon trackers at each end are one way of establishing such a link.

6. Transmission medium

For the space-to-space link, propagation is made through free space. For Earth-to-space and space-to-Earth links, however, a part of the propagation path must be made through the atmosphere. In the visible and near visible portion of the spectrum, atmospheric effects are even more important than they are in the RF spectrum. Those effects which must be considered include: absorption, Rayleigh scattering, Mie scattering, refraction, diffraction, turbulence and turbidity. The combined effects are non-linear and difficult to predict for
wide transmission bandwidths. Figure 1 of Report 681-2 (Dubrovnik, 1986) shows the levels of molecular absorption due to the atmosphere, and Report 883 provides further details on atmospheric attenuation.

Atmospheric effects can totally prevent the establishment of optical communication links in certain geographic areas and may severely limit the maximum range in others. The probability of establishing a space-to-Earth or Earth-to-space communication link can be increased significantly by providing several widely separated points for earth stations. However, the expense and complexity of the system is increased considerably by this practice.

Space-to-space links do not experience the complications resulting from atmospherics. Background noise, however, is as important to system performance in this case, as it is in Earth-to-space and space-to-Earth links. Visible and near visible emissions from the Sun and stars, from artificial light sources and from reflections by the Earth, the Moon and planets are all detectable by the optical receiver and must be considered in system design. Trade-offs between field of view, focal length, and aperture size are optimized for particular applications. Special protective circuits using sun sensors to prevent direct viewing of the Sun are also used to solve background problems in optical communication systems.

7. Receivers

Considerations for receiver optics and pointing-tracking servos are similar to those for transmitter optics. Pointing error or receiver optics must be a small part of the beamwidth (e.g. of the order of a microradian or less). A stabilized, steerable, directive receiver aperture is formed for collecting energy from the transmitted beam. The collected radiant energy, is then focused on the sensitive surface of a photodetector. The resultant electrical signal is amplified and demodulated to yield the transmitted information as an output.

The receiver is highly dependent on the type of modulation used. At present, the most common formula is direct detection combined with amplitude modulation. Recourse to frequency or phase modulation would call for heterodyne or even homodyne detection. In such a configuration, apart from the detector itself the receiver includes a local oscillator and a system for recombination of the local oscillator and the received signal.

8. Detector

The detector is a transducer which converts modulated radiant energy to an electrical signal. This signal should be easily processed to remove the transmitted information. Typical detectors are photo-multipliers, photo-conductors, photo-emitters, bolometers (for long wavelength emissions, such as CO$_2$ at 10.6 \mu m), etc. A wide range of photo-sensitive semi-conductor materials is now available for detectors, giving a variety of spectral-temporal-spatial response characteristics for the visible and near-IR spectra. Choices are still limited in the far-IR. Detectors may be uncooled or cooled to reduce internal thermal noise. Coolers may be passive or cryogenically operated.

9. Signal processing

The raw detector output must be processed to yield a usable output. Amplification of the detector output produces a signal level capable of driving a demodulator or other processing circuitry. The name demodulator is given to any circuitry required to extract the transmitted information from the detector output and deliver it to the output electronics, display or other processor/user e.g. recorders, video displays, CRT displays, audio systems, loud speakers, RF relay transmitters, etc.
10. Performance

The received power level at an optical receiver is given by:

\[ P_R = P_T g_T g_R \left( \frac{\lambda}{4\pi S} \right)^2 L \]  

\[ L = \text{Loss factor} = \tau_A K \]

\[ P_R = P_T \left( \frac{4\pi A_T}{\lambda^2} \right) \left( \frac{4\pi A_R}{\lambda^2} \right) \left( \frac{\lambda}{4\pi S} \right)^2 \tau_A K \]

\[ P_R = \frac{\pi^2 P_T D_T^2 \pi}{2} \left( \frac{D_R}{2} \right)^2 \tau_A K \]

\[ P_R = \frac{\pi^2 P_T D_T^2 D_R^2 \tau_A K}{16\lambda^2 S^2} \]

The signal-to-noise ratio for direct detection is given by:

\[ \frac{s}{n} = \frac{\frac{S^2}{R_L}}{2 \epsilon B \left[ (\xi P_T + \xi R_L - I_s) \frac{L}{R_L} - I_s \frac{R_L}{B} \right] + 4 k T B} \]  

(3)

The signal-to-noise ratio for heterodyne detection can be simplified as:

\[ \frac{s}{n} = \frac{\frac{2 \epsilon}{B} \left( \frac{L}{R_L} \right)}{\left[ 2 \epsilon \xi P_T \frac{L}{R_L} + 4 k T \right] B} \]  

(3')

in other words the optimal \( s/n \) ratio is obtained when the quantum noise of the local oscillator is preponderant in comparison with thermal noise.

where:

- \( g_T \): transmitter antenna gain
- \( g_R \): receiver antenna gain
- \( P_R \): received power (W)
- \( P_T \): transmitter output power (W)
- \( D_T \): transmitter aperture diameter (m)
- \( D_R \): receiver aperture diameter (m)
- \( S \): distance (m)
- \( \lambda \): wavelength (m)
- \( \tau_A \): atmospheric transmission loss
- \( K \): correction factor, usually less than 1, due to pointing error
- \( R_L \): detector load resistance (Ω)
- \( g \): detector internal gain
- \( p \): detector responsivity (A/W)
- \( e \): charge on an electron (C)
- \( B \): bandwidth (Hz)
- \( p_B \): background illumination power (W)
$I_b$: bulk-generated dark current (A)

$I_s$: surface-generated current (A)

$F$: receiver preamplifier noise factor

$k$: Boltzmann's constant

$T$: detector temperature (K)

$p_L$: local oscillator power

These relationships can be used to evaluate trade-offs between choice of source and detector, transmitter beamwidth, receiver aperture, bandwidth, etc. Parameters of typical systems using Nd:YAG, doubled Nd:YAG and GaAsAl have been determined from equations (2) and (3) (direct modulation and detection) and are tabulated in Table III.

**TABLE III – Typical laser communication system parameters**

<table>
<thead>
<tr>
<th>Laser type</th>
<th>Nd:YAG</th>
<th>Doubled Nd:YAG</th>
<th>GaAs Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wave length (µm)</td>
<td>1.06</td>
<td>0.23</td>
<td>0.85</td>
</tr>
<tr>
<td>Detector type</td>
<td>Photomultiplier</td>
<td>Photomultiplier</td>
<td>Si avalanche ** * * avalanche p-n * * * avalanche</td>
</tr>
<tr>
<td>Photon energy (J)</td>
<td>$1.85 \times 10^{-19}$</td>
<td>$3.7 \times 10^{-19}$</td>
<td>$2.5 \times 10^{-19}$</td>
</tr>
<tr>
<td>Quantum efficiency (%)</td>
<td>0.03</td>
<td>0.30</td>
<td>0.80</td>
</tr>
<tr>
<td>No. photons per bit (for bit error ratio = $10^{-5}$)</td>
<td>400</td>
<td>67</td>
<td>87</td>
</tr>
<tr>
<td>Average received power for 400 Mbits (W)</td>
<td>$3 \times 10^{-4}$</td>
<td>$1 \times 10^{-4}$</td>
<td>$8 \times 10^{-5}$</td>
</tr>
<tr>
<td>Transmitter aperture $D_T$ (m)</td>
<td>0.12</td>
<td>0.12</td>
<td>0.12</td>
</tr>
<tr>
<td>Transmitter beam half-angle (rad)</td>
<td>$5.6 \times 10^{-4}$</td>
<td>$2.8 \times 10^{-4}$</td>
<td>$4.5 \times 10^{-5}$</td>
</tr>
<tr>
<td>Receiver aperture $D_R$ (m)</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
</tr>
<tr>
<td>Range (m)</td>
<td>$4 \times 10^7$</td>
<td>$4 \times 10^7$</td>
<td>$4 \times 10^7$</td>
</tr>
<tr>
<td>System efficiency</td>
<td>20%</td>
<td>20%</td>
<td>20%</td>
</tr>
<tr>
<td>Transmitted power (W)</td>
<td>0.12</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Modulation</td>
<td>External</td>
<td>External</td>
<td>Direct</td>
</tr>
</tbody>
</table>
1. Introduction

Echo-ranging with light waves is sometimes referred to as Light Detection and Ranging (LIDAR). This Annex examines the operating principles and the technology of LIDAR systems. Furthermore, it explores the performance trade-offs, advantages and disadvantages of this type of range measurement equipment, especially for employment in space research.

2. Block diagram

Figure 6 is a functional block diagram of a typical LIDAR system using infra-red or visible emissions for active echo-ranging. A laser oscillator emits coherent electromagnetic energy which is focused into a collimated beam by an optical lens system and directed toward a target. Energy is reflected by the target, a portion of this energy returning to its source. Energy reflected toward the source is collected by a receiver optical aperture and focused on a detector. The transmitter and receiver may share the same optical “antenna” aperture, or they may employ separate lenses for transmission and reception. The detector output is amplified and compared with the transmitted laser output to measure the time interval or the phase difference between the transmitted signal and the echo. A pulsed radiant output is employed for systems which measure timing interval and a CW output may be employed in phase delay systems. The measured time interval or phase delay between emitted and returning radiation is a function of the slant distance between the target and the LIDAR sensor. Range information thus measured is displayed and/or recorded for use by the sensor operation.

3. Transmitter

The major components of the transmitter are the laser and the modulator. They are discussed in § 3 and 4 of Annex I. Ruby lasers also appear to have potential for LIDAR application.
4. Receiver

The receiver portion of a LIDAR system includes the optical aperture, a detector, signal processing such as amplification and thresholding, a comparator such as an interval timer or a phase comparator, and a display. When the aperture is shared by the transmitter and the receiver, an optical duplexer (e.g., a beamsplitter) must be provided to isolate the two as necessary during the transmit and receive portions of the operating cycle. Furthermore, beam steering capability and tracking servos must be available for target acquisition and tracking. LIDAR beamwidths are often so narrow that they are impractical for "Search" applications. Narrow beam sensors are therefore normally used in conjunction with another more coarse sensor such as radar. The purpose of the transmitter optics is to collimate and direct the output beam. The purpose of the receiver aperture is to collect light energy reflected by the target.

The returning light echo contains spatial information from which a target image can be retrieved. In imaging LIDAR systems the receiver optics are an imaging, objective lens assembly appropriate to the task. Image derotation equipment and image stabilization equipment must often also be provided within the optical-path of which the objective lens is a part. A wide variety of optical and electronic devices can be used to stabilize the optical path. Two or more image stabilization techniques are sometimes used in combination to fulfill a particularly demanding requirement.

The basic types of detectors are discussed in § 8 of Annex I. For imaging echo-ranging sensors, the detector may be a low level television tube such as a Secondary Emission Control (SEC) vidicon, silicon vidicon, etc., or a gated image intensifier. To measure range, an imaging sensor must be capable of being gated "off" and "on". The time interval between a pulsed emission and the opening of the receiver gate is then varied until the target image appears to be "front lighted". This time interval is measured and converted to slant distance for display with the image.

Signal processing is performed as appropriate to the design. For example, a spot detector may employ separate baseband amplifiers with a built-in adjustable threshold to detect an echo pulse. The interval timer may be a frequency counter and precise frequency source, started by the outgoing pulse and stopped by the echo pulse. An imaging detector may employ video amplifiers and/or internal amplification gain (e.g., an image intensifier) to boost the signal level in order to drive the display.

5. Transmission medium

The LIDAR could be operated either in free space or within the Earth's atmosphere. The transmission medium discussions of § 6 of Annex I are also applicable to LIDAR.

Background noise is important to system performance in all applications. Infra-red and visible emissions from the Sun and stars, from artificial sources and from reflections by the Earth, the Moon and planets are detectable by the electro-optical receiver and must be considered in system design. Trade-offs between field of view, focal length and aperture size are optimized for specific applications. Special protective devices using Sun sensors, such as automatic irises, automatic light control (ALC), automatic gain control (AGC), etc., are also sometimes used to prevent the effects of direct viewing of the Sun.

6. Performance

The received power level at an optical receiver is given by the following adaptation of the radar equation:

\[ p_r = \frac{\pi p_T \tau_T M \rho \cos \theta D^2 \tau_E \exp(-2\sigma S)}{4 S^2} \]  

and the peak signal-to-r.m.s. noise power ratio is given by:

\[ s_n = \frac{p_r^2}{2eB (\beta p_b + I_0) R_L s^2 + 2 FKTB} \]

where:

- \( p_r \): received peak signal power (W)
- \( p_T \): peak transmitter power (W)
- \( \tau_T \): transmittance of transmitter optics
\( \tau_R \): transmittance of receiver optics
\( \rho \): target reflectance
\( \theta \): angle of beam incidence at target surface
\( S \): distance (m)
\( D_R \): diameter of receiver aperture (m)
\( \sigma \): atmospheric attenuation coefficient (m\(^{-1}\))
\( R \): slant distance (m)
\( \beta \): responsivity of photodetector (A/W)
\( R_L \): detector load resistance (Ω)
\( g \): internal gain of photodetector
\( e \): charge on an electron (1.60 \times 10^{-19} \text{ C})
\( B \): video bandwidth of receiver (Hz) > 0.5/\( t \)
\( t \): pulse width
\( I_d \): detector dark current (A)
\( F \): receiver noise factor
\( k \): Boltzmann's constant (1.38 \times 10^{-23} \text{ J/K})
\( T \): detector temperature (K)
\( p_b \): sunlight power received from target and background (W), and

\[
p_b = \frac{\pi (H_{35} B_s + H_s X) \sigma_R^2 D_R^2 \tau_R}{16} \left\{ \rho \exp(-\sigma S) + \frac{\sigma S}{4\sigma} [1 - \exp(-\sigma S)] \right\}
\]

\( H_{35} \): solar spectral irradiance (W/m\(^2\) Angstrom at operating wavelength \( \lambda \))
\( B_s \): receiver optical filter bandwidth (Angstrom)
\( H_s \): solar irradiance (W/m\(^2\)) over spectral region of detector
\( X \): transmittance of receiver optical filter outside passband
\( \alpha_R \): receiver bandwidth (field of view) (rad)
\( \alpha_T \): transmitter beamwidth
\( \sigma_s \): atmospheric backscatter coefficient (m\(^{-1}\))

The geometry factor, \( M \), is dependent on the relationship between target diameter, and transmitter and receiver beamwidths. There are three distinct cases to be considered and, therefore, three distinct values for the geometry factor. These cases are illustrated in Fig. 7. Briefly summarized they are:

**Case I:** Transmitter beamwidth larger than receiver field of view and target diameter larger than receiver field of view \( M = \frac{\alpha_R^2}{\alpha_T^2} \).

**Case II:** Transmitter beamwidth and receiver field of view larger than target diameter \( M = \frac{D_R^2}{\alpha_T^2} S^2 \).

**Case III:** Receiver field of view equal to or larger than transmitter beamwidth, and transmitter beamwidth and receiver field of view smaller than target diameter \( M = 1 \).

The previous relationships can be used to evaluate performance trade-offs between choice of source and detector, transmitter beamwidth, receiver aperture, bandwidth, etc. Typical performance calculations have been made for four different rangefinders and tabulated in Tables IV and V. Table IV lists parameters held constant for the analysis. Table V summarizes specific system characteristics and the resulting performance. Calculations were made for the following combinations:

- **Ruby laser** S-20 photomultiplier
- **Ruby laser** silicon photodiode
- **Nd:YAG laser** S-1 photomultiplier
- **Nd:YAG laser** silicon photodiode
A: Laser
B: Target
S: Slant distance to target

Case I: \( \alpha_R S < D_T \) and \( \alpha_T > \alpha_R \)
\[ M = \frac{\alpha_R}{\alpha_T} \]

Case II: \( \alpha_R S > D_T \) and \( \alpha_T S > D_T \)
\[ M = \frac{D_T^2}{\alpha_T S^2} \]

Case III: \( \alpha_T S < D_T \) and \( \alpha_R > \alpha_T \)
\[ M = 1 \]

**FIGURE 7 – Relationship between beam size, field of view, target size and geometry factor M**

TABLE IV – Summary of parameters for typical laser rangefinder performance calculations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range ( S )</td>
<td>5 km</td>
</tr>
<tr>
<td>Pulsewidth ( t )</td>
<td>20 ns</td>
</tr>
<tr>
<td>Bandwidth ( B )</td>
<td>25 MHz</td>
</tr>
<tr>
<td>Receiver lens diameter ( D_R )</td>
<td>2.8 in (7.1 cm)</td>
</tr>
<tr>
<td>Geometry factor ( M )</td>
<td>1</td>
</tr>
<tr>
<td>Receiver beamwidth ( \alpha_R )</td>
<td>1 mrad</td>
</tr>
<tr>
<td>Transmitter beamwidth ( \alpha_T )</td>
<td>1 mrad</td>
</tr>
<tr>
<td>Target reflectance ( \rho )</td>
<td>1</td>
</tr>
<tr>
<td>Receiver noise factor ( F )</td>
<td>1.5</td>
</tr>
<tr>
<td>Detector load resistor ( R_L )</td>
<td>1000 ( \Omega )</td>
</tr>
<tr>
<td>Transmittance of receiver optics ( \tau_R )</td>
<td>0.7</td>
</tr>
<tr>
<td>Transmittance of transmitter optics ( \tau_T )</td>
<td>0.7</td>
</tr>
<tr>
<td>Target incidence angle ( \theta )</td>
<td>0°</td>
</tr>
<tr>
<td>Signal-to-noise ratio ( \text{s/n} ) for probability of detection 0.98 and false alarm rate of 1 per 1000 pulses</td>
<td>53</td>
</tr>
</tbody>
</table>
### TABLE V - Typical laser rangefinder performance

<table>
<thead>
<tr>
<th>Laser:</th>
<th>Ruby</th>
<th>Ruby</th>
<th>Nd : YAG</th>
<th>Nd : YAG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength $\lambda$ ($\mu$m)</td>
<td>0.694</td>
<td>0.694</td>
<td>1.06</td>
<td>1.06</td>
</tr>
<tr>
<td>Detector</td>
<td>PM(S-20)</td>
<td>Si photodiode</td>
<td>PM(S-1)</td>
<td>Si photodiode</td>
</tr>
<tr>
<td>Attenuation coefficient $\sigma$ (km$^{-1}$)</td>
<td>0.139</td>
<td>0.139</td>
<td>0.114</td>
<td>0.114</td>
</tr>
<tr>
<td>Atmospheric transmittance $\tau_A$</td>
<td>0.499</td>
<td>0.499</td>
<td>0.565</td>
<td>0.565</td>
</tr>
<tr>
<td>Solar spectral irradiance $H_{AS}$ (W/m$^2$ A)</td>
<td>0.12</td>
<td>0.12</td>
<td>0.06</td>
<td>0.06</td>
</tr>
<tr>
<td>Filter leakage transmittance $X$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Backscatter coefficient $\sigma_S$ (km$^{-1}$)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Background power $P_b$ (W)</td>
<td>$1.66 \times 10^{-10}$</td>
<td>$1.66 \times 10^{-10}$</td>
<td>$4.6 \times 10^{-11}$</td>
<td>$4.6 \times 10^{-11}$</td>
</tr>
<tr>
<td>Optical filter bandpass $\theta_o$ (A)</td>
<td>40</td>
<td>40</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Detector gain $g$</td>
<td>$5 \times 10^4$</td>
<td>1</td>
<td>$1.5 \times 10^4$</td>
<td>1</td>
</tr>
<tr>
<td>Cathode dark current $I_d$ (pA)</td>
<td>0.030</td>
<td>$10^4$</td>
<td>12.9</td>
<td>$10^4$</td>
</tr>
<tr>
<td>Detector responsivity $s$ (A/W)</td>
<td>0.028</td>
<td>0.517</td>
<td>$3.5 \times 10^{-4}$</td>
<td>0.152</td>
</tr>
<tr>
<td>Peak received signal power $P_s$ (W)</td>
<td>$1.23 \times 10^{-9}$</td>
<td>$2.5 \times 10^{-7}$</td>
<td>$1.64 \times 10^{-7}$</td>
<td>$8.48 \times 10^{-7}$</td>
</tr>
<tr>
<td>Single pulse range accuracy $sR$ (m)</td>
<td>0.82</td>
<td>0.82</td>
<td>0.82</td>
<td>0.82</td>
</tr>
</tbody>
</table>

$sR = \frac{C}{2B \sqrt{3/n}}$ (single pulse)
REPORT 222-5

EFFECTS OF ARTIFICIAL PLASMAS
ON COMMUNICATIONS WITH SPACECRAFT

(Question 3/2)


1. Introduction

Some communication problems arise from the presence of a plasma, e.g. ionized air, in the vicinity of a spacecraft and its antenna. Natural plasmas are present in the ionospheres of Earth and other planets, but also as "solar wind" in interplanetary space, especially in the neighbourhood of the Sun. Artificial plasmas are produced mainly by two mechanisms:

- as "ionized gases" generated by spacecraft propulsion and control systems, and
- as "plasma sheath" forming around a spacecraft entering a planetary atmosphere.

Two main effects of plasmas must be considered, namely:

- that on antenna performance, and
- that on propagation of radio waves.

This Report gives a summary of the effects of artificial plasmas on communications with spacecraft. More detailed analyses are presented in Report 222 (Geneva, 1974 and 1982).

2. Summary of atmospheric entry plasma effects

Atmospheric entry plasma effects on communications will vary greatly with the mission, which determines the vehicle trajectory and configuration. Selection of signal frequency, antenna location, and antenna type can be used to circumvent or minimize the re-entry signal loss in many cases. Criteria which influence this selection include the plasma thickness, collision frequency, ablation material, and the nature of the non-equilibrium phenomena (i.e. producing or recombining type plasma). Also practical considerations such as power requirements, signal modulation techniques, tracking station capabilities, and relative location with respect to the spacecraft (look angle) enter into the selection.

Some experimental results indicate that the critical frequency of the plasma sheath is often as high as 1 to 10 GHz and may sometimes be even higher. It is concluded that frequencies of 10 GHz or higher are technically required for certain re-entry communications, especially for re-entry from lunar or planetary missions.

At these frequencies, absorption in the planetary atmospheres can be very important. For the atmosphere of the Earth, Report 719 gives some relevant data. It also shows that there are several "windows" above 60 GHz where the absorption in atmospheric gases may be acceptably low. The data however, indicate that attenuation in tropospheric precipitation could be prohibitively high. Frequencies near 90 GHz and perhaps those near 140 GHz might be preferable in this respect.

Other experimental programmes have demonstrated an increased understanding of the re-entry plasma sheath. Data from in-flight measurements at orbital re-entry velocities using diagnostic antennas and rakes of immersed electrostatic probes are in excellent agreement with theory, except at the extremities of the plasma attenuation period [Akey and Cross, 1970; Grantham, 1970; NASA, 1971]. The electrostatic probe measurements agree not only in peak plasma density, but also in the plasma profile.

Moreover, the effects of the plasma sheath have been reduced by modifying the plasma itself; for example, by aerodynamic shaping (sharp nose or spike configurations) to reduce the plasma thickness; by the injection of liquid materials into the flow field that have restored radio-frequency signals otherwise blacked out by the plasma during the re-entry attenuation period [Akey and Cross, 1970]; and by the choice of ablation materials which can significantly affect plasma density [Grantham, 1970]. Also, by sufficiently applying a strong magnetic field the configuration could be influenced and/or a propagation window could be produced, by the so-called "whistler mode" (see Report 262). Possibly, combinations of these techniques may be used to reduce the plasma sheath effects.

* This Report should be brought to the attention of Study Group 6.
3. Summary of rocket exhaust plasma effects

Exhaust plasma is always produced in the flames of rocket motors, but may also appear in other propulsion systems, for example, electric propulsion. In its origin and as a result of different boundary conditions such a plasma is different from a typical re-entry plasma.

To describe an exhaust plasma, the factors associated with the flame must be known, such as fuel and oxidant composition, mixture ratio, alkali metal impurities, nozzle characteristics, thermo-chemical kinetics, dynamics of the expanding gases, etc. With these factors and knowledge of ambient atmospheric conditions the exhaust plume structure may be deduced [Jensen and Wilson, 1975]. Changes in gas flow due to induced turbulence are now understood and can be included in calculations of exhaust structure. Problems introduced by the use of multiple jets are outstanding and still require further study.

Practical and theoretical investigations have been conducted and have led to methods for predicting the effects of exhaust gases. Because the plasma configuration is not one of a sheath surrounding the vehicle it presents problems different from those of re-entry. Plasma densities differ and the antenna is unlikely to be immersed in the plasma; consequently alternative propagation paths may be found (other than through the most highly ionized regions) [ELDO, 1966]. Plasma effects include absorption, refraction, diffraction, amplitude and phase modulation. Total signal loss can be a combination of these effects. Absorption depends upon electron concentration and collision frequency [Williams, 1965], the approximate distribution of which can be deduced from a knowledge of the motor design. Significant diffraction may occur in an exhaust where the absorption is high [Dang, 1974]. Spurious modulation will be encountered due to forward scattering into the antenna from the turbulent jet stream. Doppler displaced frequencies given by varying eddy velocities within the exhaust, produce plume related spectra. Comparison between experimentally derived and computed spectra is good. [Williams, 1966; Williams et al., 1971]. Radar echoing (back scatter) has been treated in a similar manner. The propagation path relative to the exhaust is another important factor; refraction effects on the ray path may not always be negligible [Kopp, 1966; Golden et al., 1968].

As an example, for a large chemical rocket firing into a vacuum, the exhaust in the immediate vicinity of the nozzle exit is a high-pressure plasma having an electron collision frequency of about 10^11/s and an electron density of 10^16 to 10^17 per m^3. It is therefore a region of high damping with marked resonances (critical frequencies). Subsequent expansion of the gases results in a transition from this collision dominated region to effectively collision free conditions. Radio blackout due to critical frequency effects alone, is possible only in those regions of the plume where the collision frequency is less than 10^8/s. Due to the expansion of the efflux, this order of collision frequency is necessarily associated with a low electron density (10^13 per m^3); this means that there is a high probability that radio frequencies down to 100 MHz, or even below, will penetrate the entire flame. Nevertheless, the overall absorption measured can be large (10 to 30 dB), due entirely to the long path lengths through the flame, encountered in certain directions. Experimental confirmation for predictions has been sought by measurements on the ground and during actual rocket launches [McD. Cummings and Wilson, 1967; Wilson, 1967].

Other work has been directed towards improvement of the prediction techniques, particularly the fluid dynamics, the representation of turbulent fluctuations and in the treatment of chemical processes within the exhaust. Fluid dynamic calculations have been improved by the inclusion of shock structure and a better description of the effects of forward flight on the plume, including treatment of base recirculation. Methods are now available for determination of those turbulent quantities i.e. turbulent length scale and turbulent intensity, needed to describe electromagnetic scattering by exhaust gases. The effect of finite rate chemical reactions are included during the calculation of plume structure, this being particularly important for the calculation of electron density since this is strongly influenced by chemical reaction at low and intermediate altitudes. [Jensen and Pergament, 1971]. The major interest has been in the field of tactical rockets; nevertheless, these studies are complementary to the problems of space vehicle exhausts and can be directly related to situations encountered in space flight.

REFERENCES


BIBLIOGRAPHY


REPORT 1119*

METHOD OF CALCULATING ATTENUATION, NOISE TEMPERATURE, AND TELECOMMUNICATION LINK PERFORMANCE FOR THE SELECTION OF PREFERRED FREQUENCY BANDS

(Question 22/2)

1. Introduction

The selection of radio frequency bands that are preferred for a particular radio service is based partly on analysis of link performance as a function of frequency. The link performance varies because of the frequency dependent characteristics of propagation and equipment. This report presents a method of calculating telecommunication link performance as affected by attenuation and noise temperature for an assumed set of equipment characteristics. The purpose of the report is to show how propagation information from CCIR Study Group 5 may be utilized by Study Group 2 for analysis of telecommunication links between Earth and space.

Report 683-2 (Geneva, 1986), Frequency Bands in the 1 to 20 GHz Range that are Preferred for Deep Space Research, is an example of the use of link performance curves for the selection of preferred frequency bands. In this context, preferred frequency bands are those which give the best link performance as expressed in terms of a signal to noise ratio.

The selection of preferred bands may also be partly determined by other factors such as the operational characteristics and requirements of the particular service. These other factors are not considered in this report.

2. References

The method and calculations to be described are based on information in the following references:


Report 563-3, Radiometric data

Report 564-3, Propagation data required for space telecommunication systems

Report 719-2, Attenuation by atmospheric gases

* This Report should be brought to the attention of Study Group 5.
Report 720-2, Radio emission from natural sources above about 50 MHz

Report 721-2, Attenuation by hydrometeors, in particular precipitation, and other atmospheric particles

(2) Bell Telephone Labs. Inc. [1971].

NOTE: Some of the reports cited above may have been subsequently changed. Be sure to use the latest available propagation data when making the calculations described in this report.

The preferred frequency curves in Report 683-2 are based on calculations performed in accordance with data found in Reports and Recommendations of the CCIR, 1978, Volume V, Propagation in Non-ionized Media, Kyoto, 1978. Those reports have been extensively revised.

3. Calculation procedures

A step by step discussion of calculations needed for the selection of preferred frequency bands is given in Annex 1. For convenience in presenting the method, and for conceptual clarity, the calculations are grouped into five sections:

- Calculations of attenuation and noise temperature for clear air (no rain or clouds)
- Calculation of the effects of rain on attenuation and noise temperature
- Calculations of attenuation and noise temperature for clear air plus rain
- Calculation of link performance for clear air (no rain or clouds)
- Calculation of link performance for clear air plus rain

NOTE: For a space - Earth propagation path through a rainy atmosphere, the attenuation is equal to the attenuation caused by the clear atmosphere along the path, plus the additional attenuation caused by the rainfall along the path. The attenuation caused by the atmosphere alone, and the attenuation caused by the rainfall alone are separately calculated. See 2., Report 564-2.

The sky noise temperature attributed to the rainy atmosphere is calculated with respect to the total attenuation, and is not equal to the sum of the noise temperatures that could be calculated for each of the two components of the total attenuation.

Annex 1 contains tables that illustrate each step in each of the five cases listed above.
4. Discussion of propagation data

The propagation data needed for calculation of link performance is found in five separate Study Group 5 reports. Much of the data in these reports is based on measurements made at various times and places throughout the world. This empirical data is often expressed in terms of tables and charts, or in the form of a mathematical expression derived by a curve fitting technique.

It is important that analysis based on this data be clearly referenced to a particular revision of the report being used. This is necessary because some of the data may change with succeeding revisions of the report. For example, the curves shown in Report 683-2 of 1986 are based on data found in the 1978 issue of Vol. 5.

It is also important to recognize that some of the equations that describe frequency dependent parameters are useful only within specified frequency ranges. These frequency limitations are usually mentioned in connection with the equations listed in Annex I, but the reader is cautioned to refer to the corresponding report from which each equation is taken.

The information presented in the Study Group 5 reports is generally clear with regard to the data and how it is to be used. A possible exception to this is the calculation of the attenuation caused by the gaseous constituents of the atmosphere. The constituents are oxygen and water vapor. The attenuation caused by each of these is given by the product of a specific attenuation per unit length and a corresponding path length. The path length is expressed as an equivalent height. Expressions for computing specific attenuation and equivalent height are given in Report 719. The basic form of these expressions assumes that the earth station is at sea level.

Corrections to the specific attenuation and equivalent height values are needed to account for the elevation of the earth station above sea level. For water vapor, a correction is applied to its equivalent height. (As a practical matter, for the case of a path between a satellite and an earth station the correction is negligible.) In addition, the height dependence of the specific attenuation due to water vapor is accounted for by using the water vapour density at the station elevation, rather than sea level.

For oxygen, a correction is applied only to the equivalent height. This correction is sufficient because of an implicit assumption concerning the exponential height dependence of the specific attenuation.

5. Types of analysis for frequency selection

The analysis described in the Annex is for a space to Earth link involving ideal equipment and therefore limited only by natural phenomena. More generally, for links between a spacecraft and the Earth, four types of analysis may be identified:

1. Space to Earth, as limited only by natural phenomena
2. Space to Earth, including the effects of equipment
3. Earth to space, as limited only by natural phenomena
4. Earth to space, including the effects of equipment
For the space to Earth link, the receiving system noise temperature must include the effect of cosmic and galactic backgrounds as well as the atmosphere.

For the Earth to space link, contributions to the noise temperature of the spacecraft receiving system also include the cosmic and galactic backgrounds, but the contribution from atmosphere of the Earth may be relatively small. For deep space probes the Earth occupies such a small portion of the receiving antenna pattern that the noise temperature contribution of the atmosphere is negligible. The attenuation of the atmosphere must nevertheless be included in the link analysis since it directly affects the received signal power.

It is useful to consider links using two types of antennas. The first link assumes fixed diameter transmitting and receiving antennas. In this case the gain of both antennas varies with frequency. The second type of link assumes the use of one fixed diameter antenna and one fixed beamwidth antenna. In this case the gain of the fixed beamwidth antenna is nearly independent of frequency. An example of this case is the use of an omnidirectional antenna on a space station in order to allow communication during course correction maneuvers or loss of attitude control.

The shape of link performance curves depends on the antenna types assumed.

6. Selection of preferred frequency bands.

The calculations described in Annex 1 are used to create two sets of link performance curves. In the first set, the equipment is assumed to be perfect. The antennas are assumed to be ideal with gain that varies as the square of the frequency, or with a beamwidth (gain) that is constant with respect to frequency. The transmitter power is assumed constant with respect to frequency and the noise temperature of the receiving system equipment is neglected. The purpose of these assumptions is to allow selection of preferred frequency bands as limited only by natural phenomena.

The second set of curves includes the frequency dependent variations of a particular set of equipment parameters. Some parameters of the earth station antenna also depend upon elevation angle, and these variations are included. Factors considered include antenna gain variation as a function of elevation angle; the noise temperature contribution of the warm Earth as coupled via the feed support structure and illumination spillover; and receiver equipment noise temperature. The purpose of including these factors is to allow selection of preferred frequency bands for a link that includes the characteristics of practical equipment.

By considering the performance of currently realizable links as well as ideal links, it is possible to identify preferred frequency bands for the present time and also for the future when equipment is further improved.

Examples of the two kinds of curves may be found in Report 683-2. An additional example of the performance achievable with ideal equipment is given in Figure 1. The Figure shows curves for a space to Earth path, calculated according to the method given in Annex 1. Perfect equipment is assumed, including fixed diameter antennas for transmitting and receiving. If it is desired
to select frequency bands in the 1 to 20 GHz range that yield performance within approximately 1 dB of the maximum available, the curves and supporting data result in the following for the case of 30 deg elevation angle:

<table>
<thead>
<tr>
<th>PROPAGATION CONDITION</th>
<th>PREFERRED FREQUENCY BAND</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clear air (no rain or clouds)</td>
<td>12.5 - 19.2 GHz</td>
</tr>
<tr>
<td>Clear air plus 0.1% rain</td>
<td>4100 - 9400 MHz</td>
</tr>
</tbody>
</table>

NOTE: These results differ from those presented in Report 683-2, and reflect the effect of more recent propagation data, and a change from the rain rate exceeded 0.001% of the time to the rain rate exceeded 0.1% of the time.

REFERENCES


ANNEX 1

CALCULATION PROCEDURE

1. Introduction

The calculation of space to Earth link performance under conditions of clear air and clear air plus rain is described. Tables I - V list the several parameters included in the calculation. The tables are:

I. Attenuation and noise temperature as a function of frequency, elevation angle and water vapor density for clear air propagation.

II. Attenuation and noise temperature due to rainfall alone, as a function of frequency, elevation angle, and rain rate

III. Attenuation and noise temperature for a propagation path including clear air plus rain, using data from Table 2.

IV. Link performance for an assumed set of transmitter, antenna, and distance parameters, and considering the attenuation and noise temperature data from Table 1.

V. Link performance for an assumed set of transmitter, antenna, and distance parameters, considering the attenuation and noise temperature data from Table 3.

The Tables show the various parameters and values for a few frequencies. In determining preferred frequency bands, a much larger set of frequencies is used. The Tables were prepared by using a commercially available spread sheet program running on a personal computer.

NOTE: Values given in the Tables are the result of analytic calculations. It should not be inferred that listing of these values to a precision of several decimal places is an indication of the accuracy or precision of the underlying propagation data or associated analytic expressions. Prediction of actual link performance to the indicated precision is not generally possible.
For each line in each table there is a description of the parameter or calculation and, usually, a particular report and section is referenced. Each CCIR report reference implies the 1986 version plus subsequent modifications approved by Study Group 5.

2. Calculations for clear air (no rain or clouds)

Table I presents calculated values of attenuation caused by the atmosphere, and of noise temperature caused by the combined effects of the cosmic background noise, galactic background noise, and the noise temperature related to attenuation by the atmosphere. The calculations shown in Table I are for conditions of clear air (no rain or clouds). Referring to the line numbers shown at the left side of the Table, the calculations are made as follows:

Line 7. Vapor density, gm/m³, is the water vapor density in the atmosphere that is assumed for the particular calculation.

Line 8. Station elevation, km, is the elevation of the earth station above sea level. The example given in Table I is 0.81 km for the deep space earth station at Madrid, Spain.

Line 10. Frequency, GHz, is the radio frequency for the particular calculation.

Line 12. \( H_o' \), km, is the equivalent oxygen height at the earth station elevation. \( H_o' \) is derived from a correction to the value of \( H_o \), the equivalent oxygen height at sea level, and for frequencies < 57 GHz is given by

\[
H_o\left( e^{- \frac{\text{station elevation}}{H_o}} \right) \text{ km}
\]

where \( H_o = 6 \text{ km at sea level} \)

See § 3.2, Report 719-2.

Line 13. \( \gamma \) (\( \text{dB/km} \)), is the specific attenuation at ground level due to oxygen at a temperature of 15 deg C, and for frequencies < 50 GHz is given by

\[
(7.19 \cdot 10^{-3}) + \frac{6.09}{f^2 + 0.227} + \frac{4.81}{(f-57)^2 + 1.5} \cdot 10^{-3} \text{ dB/km}
\]


Line 14. \( H_w' \), km, is the equivalent water vapor height at the earth station elevation. \( H_w' \) is derived from a correction to the value of \( H_w \), the
equivalent water vapor height at sea level. The nature of the correction is such that for a path between an earth station and a satellite, \( H_w' = H_w \). For frequencies < 350 GHz, \( H_w \) is given by

\[
2.2 + \frac{3}{(f-22.3)^2 + 3} + \frac{1}{(f-183.3)^2 + 1} + \frac{1}{(f-323.8)^2 + 1} \text{ km}
\]

Note: For frequencies less than 57 GHz, only the first two terms of the expression are needed.

See § 3.2, Report 719-2.

Line 15. 
W_{\gamma}, \text{ dB/km}, is the specific attenuation at ground level due to water vapor at a temperature of 15 deg C, \( \rho < 12 \text{ gm/m}^3 \), and frequencies < 350 GHz and is given by

\[
3 + \frac{9}{(f-22.3)^2 + 7.3} + \frac{4.3}{(f-183.3)^2 + 6} + \frac{10}{(f-323.8)^2 + 10}
\]

\[
\left( \frac{0.067 + 3}{(f-22.3)^2 + 7.3} + \frac{9}{(f-183.3)^2 + 6} + \frac{4.3}{(f-323.8)^2 + 10} \right) \text{ dB/km}
\]

where \( \rho \) is the water vapor density at the station elevation.

Note: For frequencies less than 57 GHz, only the first two terms of the expression between brackets are needed.


Line 17. 
Galactic temp @ 408 MHz, \( K \), is the galactic temperature for a particular region of the sky and is used to calculate the galactic noise temperature for other frequencies for the same region of the sky. For Table I, a value of 30 K was arbitrarily selected.


Line 18. 
Galactic temp, \( K \), is the temperature calculated for a particular frequency, and is given by

\[
\left( \text{ Galactic temp @ 408 MHz } \right) \left( \frac{\text{ Frequency}}{0.408} \right)^{-2.75} \text{ K}
\]


Line 19. 
Cosmic noise, \( W/Hz \), is the power spectral density of the cosmic background noise and is given by

\[
\frac{hf}{e^{(hf/kT)} - 1} \text{ W/Hz}
\]
where \( h = 6.626 \times 10^{-24} \) joule second (Planck’s constant)
\( f = \) frequency, Hz
\( k = 1.3806 \times 10^{-23} \) joule/K. (Boltzman’s constant)
\( T = \) noise temperature, taken as 2.7 K


Line 20. Cosmic temp, \( K \), is the cosmic background noise temperature, and is given by
\[
\text{(Cosmic noise) / } k = K
\]
where \( k \) is Boltzman’s constant, \( 1.3806 \times 10^{-23} \) joule/K

Line 21. Cosmic+galactic, \( K \), is the sum of the cosmic and galactic noise temperatures at a particular frequency, and is given by
\[
\text{(Cosmic temp) + (Galactic temp) } = K
\]

Line 22. Zenith attn, dB, is the one-way attenuation through the atmosphere in the zenith direction, and is given by
\[
(\text{HO} \cdot \text{Ogamma}) + (\text{HW} \cdot \text{Wgamma}) \text{ dB}
\]

See § 3.2.1, Report 719-2.

Line 23. Zenith atmos noise, \( K \), is the noise temperature caused by the atmosphere in the zenith direction and is given by
\[
280 \left(1 - 10^{(-A(dB)/10)}\right) \text{ K}
\]
where 280 is the mean radiating temperature of the atmosphere and \( A \) (dB) is the one-way attenuation through the atmosphere in the zenith direction.

See § 2, Eq. (8), Report 720-2.

Line 24. Zenith Cosmic+galactic, \( K \), is the sum of the cosmic and galactic noise temperature, as reduced by the zenith attenuation, and is given by
\[
\frac{(\text{cosmic+galactic})}{e^{(A(dB)/4.34)}} = K
\]

See § 2, Eq. (8), Report 720-2.

Line 25. Zenith total noise, \( K \), is the sum of the zenith atmospheric noise temperature, and the zenith cosmic+galactic noise temperature, and is given by
zenith atmos noise + zenith cosmic+galactic  K

Line 29. Elev angle, deg, is the elevation angle of the earth station antenna for the particular calculation.

Line 30. Elev attn, dB, is the one-way attenuation through the atmosphere at the particular elevation angle, and for elevation angles greater than 10 deg is given by

\[ \text{zenith attenuation / sin (elevation angle)} \quad \text{dB} \]

See § 3.2.1, Report 719-2.

Line 31. Elev atmos noise, K, is the noise temperature caused by the atmosphere in the direction of the elevation angle, and is given by

\[ 280 \left(1 - 10^{-\frac{B(\text{dB})}{10}}\right) \quad \text{K} \]

where 280 is the mean radiating temperature of the atmosphere and B (dB) is the one-way attenuation through the atmosphere in the direction of the elevation angle.

Line 32. Elev cosmic+galactic, K, is the sum of the cosmic and galactic noise temperatures, as reduced by the attenuation at the particular elevation angle, and is given by

\[ \frac{(\text{cosmic+galactic})}{e^{\left(\frac{B(\text{dB})}{4.34}\right)}} \quad \text{K} \]

where B is the one-way attenuation through the atmosphere in the direction of the elevation angle.

Line 33. Elev total noise, K, is the sum of the atmospheric noise and the cosmic+galactic noise at the particular elevation angle, and is given by

\[ \text{elev atmos noise + elev cosmic+galactic} \quad \text{K} \]

Line 34. Elev noise, dBW/Hz, is the noise power spectral density corresponding to the elev total noise, and is given by

\[ -228.6 + 10 \log (\text{elev total noise}) \quad \text{dBW/Hz} \]

where -228.6 is the logarithmic expression of Boltzman's constant, 1.3806 \times 10^{-23} \text{ joule/K}.

Lines 37 - 42 and 45 - 50 are similar to lines 29 - 34 except for the effects of different elevation angles.
3. Calculation of the effects of rain

Table II presents data showing attenuation and noise temperature resulting from the effects of rain (hydrometeors) alone, not including effects of the gaseous atmosphere. Referring to the line numbers given at the left side of the Table, the calculations are made as follows:

Line 7. Station latitude, deg., is the latitude of the earth station. The example given in Table II is 40 deg for the deep space earth station at Madrid, Spain.

Line 8. Station elevation, km, is the elevation of the earth station above sea level: 0.81 km for Madrid, Spain.

Line 9. Rain rate, mm/hr., is the rain rate exceeded 0.01% of the year, and for this example is 32 mm/hr for Madrid, Spain (rain climate H).

See § 2.2.1.1, step 5, Report 564-3, and Fig. 12 and Table I, Report 563-3.

Line 10. Rain height, km. Given by

4.0 km for lat < 36 deg

4.0 - 0.075 (lat - 36) for lat => 36 deg

where lat is the latitude of the earth station.

See § 2.2.1.1, step 1, Report 564-3, and § 4.4.3, Report 563-3.

Line 12. Frequency, GHz.

Line 14. Coeff kH is a coefficient used for estimating specific attenuation due to rain.

See § 2.5 and Table I, Report 721-2.

For values of kH not given directly in the Table, the formula for interpolation is

\[
\log kH = \frac{\log kH_2 - \log kH_1}{\log f_2 - \log f_1} (\log f - \log f_1) + \log kH_1
\]

where the numbers 2 and 1 refer to the higher and lower tabulated values between which the unknown value lies.

Line 15. Coeff kA is a coefficient used for estimating specific attenuation due to rain.

See § 2.5 and Table I, Report 721-2.
For values of kA not given directly in the Table, the formula for interpolation is

\[
\frac{a_{H2} - a_{H1}}{\log f_2 - \log f_1} = (\log f - \log f_1) + a_{H1}
\]

where the numbers 2 and 1 refer to the higher and lower tabulated values between which the unknown value lies.

Line 16. \(r_{\Gamma}\) is the specific attenuation due to rain and is given by

\[
kH \cdot (\text{Rain rate}^{(kA)}) \text{ dB/km}
\]

See § 2.5, Report 721-2. See also § 2.2.1.1, step 6, Report 564-3.


Line 20. Slant path, km, is the length of the slant path through the rain from the earth station to the rain height, and is given by

\[
((\text{Rain height} - \text{station elevation}) / \sin (\text{elevation angle})) \text{ km}
\]

See § 2.2.1.1, step 2, Report 564-3.

Line 21. Horiz proj, km, is the horizontal projection of the slant path, and is given by

\[
\text{slant path} \cdot \cos (\text{elevation angle}) \text{ km}
\]

See § 2.2.1.1, step 3, Report 564-3.

Line 22. Reduction, 0.01%, is the reduction factor for 0.01% of the time, and is given by

\[
1 + (0.045 \cdot (\text{horizontal projection}))
\]

See § 2.2.1.1, step 4, Report 564-3.

Line 24. Atten .01%, is the rain attenuation exceeded 0.01% of the year, and is given by

\[
(r_{\Gamma}) \cdot (\text{slant path}) \cdot (\text{reduction 0.01%}) \text{ dB}
\]

See § 2.2.1.1, step 7, Report 564-3.

Line 25. Atten 0.1%, is the rain attenuation exceeded 0.1% of the year, and is given by

\[
0.38 \cdot (\text{atten 0.01%}) \text{ dB}
\]
Note: The selection of a particular percentage of time is based on operational considerations. 0.1% is appropriate for some space research missions and was chosen for this example in order to illustrate the method of calculation.

See § 2.2.1.1, step 8, Report 564-3.

Lines 28 - 34 and 37 - 43 are similar to lines 19 - 25 except for the effects of different elevation angles.

4. **Calculations for clear air plus rain**

Table III presents calculated values of attenuation caused by the clear atmosphere plus rain, and of noise temperature caused by the effects of the cosmic background noise, galactic background noise, and the noise temperature related to attenuation by the combination of clear air and rain. Referring to the line numbers at the left side of the Table, the calculations are made as follows:

Lines 1 through 30 are as explained for Table I.

Line 31. Elev rain attn, dB, is the attenuation due to rain along a path at the specified elevation angle. The value given is the attenuation that is exceeded 0.1% of the time at Madrid and is obtained from Table II.

Line 32. Elev total attn, dB, is the sum of the attenuation due to the atmosphere and the attenuation due to rain.

Line 33. Elev atmos + rain noise, K, is the noise temperature due to the elevation total attenuation, and is given by

\[ 280 \left(1 - 10^{-B/10}\right) \text{K} \]

where 280 is the mean radiating temperature of the atmosphere and B (dB) is the one-way attenuation along the path.

Line 34. Elev cosmic+galactic, K, is the sum of the cosmic noise temperature and the galactic noise temperature, as reduced by the attenuation along the path at the particular elevation angle. See Line 19, Table I.

Line 35. Elev total noise, K, is the sum of the atmospheric and rain noise and the cosmic+galactic noise for the particular elevation angle.

Line 36. Elev noise power, dBW/Hz, is the noise power spectral density corresponding to the elev total noise, and is given by

\[ -228.6 + 10 \log (\text{elev total noise (K)}) \text{ dBW/Hz} \]
where $-228.6$ is the logarithmic expression of Boltzman's constant, 
$1.3806 \times 10^{(-23)}$ joule/K

Lines 39 - 46 and 49 - 56 are similar to lines 29 - 36 except for the effects of different elevation angles.

5. **Link performance for clear air**

Table IV presents link performance calculated for an assumed set of equipment and distance parameters, using the attenuation and noise temperature values for propagation under conditions of clear air.

**Line 9.** Frequency, GHz, is the radio frequency for which the calculation is made.

**Line 11.** Spacecraft power, $P_o$, dBW, is the assumed spacecraft transponder power, in this case 25 W, given by

$$P_o = 10 \log 25$$

**Line 12.** Gain, 3.7m diam., dBi, is the assumed gain of the spacecraft transmitting antenna, in this case a 3.7m diameter parabola with assumed 100% efficiency, and is given by

$$20.40 + 20 \log (\text{Diameter (m)}) + 20 \log (\text{Frequency (GHz)}) \text{ dBi}$$

**Line 13.** Free space loss, dB, is the attenuation for a free space path, in this case for a path length of $8x10^6$ km, and is given by

$$230.51 + 20 \log (\text{Frequency (GHz)}) \text{ dB}.$$  

**Line 14.** Gain, 70m diam., dBi, is the gain of the earth station receiving antenna, in this case a 70m diameter parabola with assumed 100% efficiency, and is given by

$$20.40 + 20 \log (\text{Diameter (m)}) + 20 \log (\text{Frequency (GHz)}) \text{ dBi}.$$  

**Line 16.** Elev angle, $15$, is the elevation angle of the earth station receiving antenna and propagation path through the atmosphere, in this case 15 deg.

**Line 17.** Atmos attn, dB, is the attenuation due to the atmosphere at the specified elevation angle and is taken from Table I.

**Line 18.** Received power, dBW, is the power received at the terminals of the earth station antenna and is given by

$$(\text{Line 11} + \text{Line 12} - \text{Line 13} + \text{Line 14} - \text{Line 17})$$

**Line 19.** Noise power, dB(W/Hz), is the received noise power spectral density and is taken from Table I. For the example presented by Table IV,
the noise temperature contribution of the earth station receiving system has been assumed to be zero.

Line 20. $\frac{P_r}{N_0}$, dB(W/(W/Hz)), (often expressed as dB Hz), is the ratio of received power to noise power spectral density and is given by (Line 18 - Line 19). The variation of $\frac{P_r}{N_0}$ with frequency provides the basis for selection of preferred frequency bands in terms of link performance. Frequencies with highest $\frac{P_r}{N_0}$ provide the best performance for a given set of assumed conditions and equipment characteristics.

Lines 22 - 26 and 28 - 32 are similar to lines 16 - 20 except for different values of elevation angle.

6. Link performance for clear air plus rain.

The calculation of link performance for clear air plus rain is shown in Table V. Tables IV and V are similar except that the values of attenuation and noise temperature are taken from Table III.
TABLE I - Data for selection of prefered frequencies.

Attenuation and noise temperature, clear air, no rain.

31 March 1987. Filename: CLRPATH

<table>
<thead>
<tr>
<th>Frequency, GHz</th>
<th>Vapor density, gm/m^3</th>
<th>Station elevation, km</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7.5</td>
<td>0.81</td>
</tr>
<tr>
<td>1.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ho'</th>
<th>5.242</th>
<th>5.242</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ogamma</td>
<td>0.005</td>
<td>0.006</td>
</tr>
<tr>
<td>Hw</td>
<td>2.207</td>
<td>2.207</td>
</tr>
<tr>
<td>Wgamma</td>
<td>0.000</td>
<td>0.000</td>
</tr>
</tbody>
</table>

| Galactic temp @ 408 MHz | 2.549 | 0.836 | 0.379 | 0.205 |
| Cosmic noise, W/Hz      | 3.66E-23 | 3.66E-23 | 3.66E-23 | 3.66E-23 |
| Cosmic temp, K          | 2.676 | 2.664 | 2.652 | 2.640 |
| Cosmic+galactic, K      | 5.225 | 3.500 | 3.031 | 2.846 |

| Zenith attn, dB         | 0.03 | 0.03 | 0.03 | 0.03 |
| Zenith atmos noise, K    | 1.68 | 1.89 | 1.98 | 2.05 |
| Zenith cosmic+galactic, K| 5.19 | 3.48 | 3.01 | 2.82 |
| Zenith total noise, K    | 6.88 | 5.36 | 4.99 | 4.87 |

| Elev angle, deg         | 15.00 |       |       |       |
| Elev atmos attn, dB     | 0.10  | 0.11  | 0.12  | 0.12  |
| Elev atmos noise, K      | 6.45  | 7.22  | 7.59  | 7.83  |
| Elev cosmic+galactic, K  | 5.11  | 3.41  | 2.95  | 2.77  |
| Elev total noise, K      | 11.55 | 10.63 | 10.54 | 10.59 |

| Elev noise power, dBW/Hz | -217.97 | -218.33 | -218.37 | -218.35 |

| Elev angle, deg         | 30.00  |       |       |       |
| Elev atmos attn, dB     | 0.05  | 0.06  | 0.06  | 0.06  |
| Elev atmos noise, K      | 3.36  | 3.76  | 3.95  | 4.08  |
| Elev cosmic+galactic, K  | 5.16  | 3.45  | 2.99  | 2.80  |
| Elev total noise, K      | 8.52  | 7.22  | 6.94  | 6.88  |

| Elev noise power, dBW/Hz | -219.30 | -220.02 | -220.18 | -220.22 |

| Elev angle, deg         | 75.00  |       |       |       |
| Elev atmos attn, dB     | 0.03  | 0.03  | 0.03  | 0.03  |
| Elev atmos noise, K      | 1.74  | 1.95  | 2.05  | 2.12  |
| Elev cosmic+galactic, K  | 5.19  | 3.48  | 3.01  | 2.82  |
| Elev total noise, K      | 6.94  | 5.43  | 5.06  | 4.94  |

<p>| Elev noise power, dBW/Hz | -220.19 | -221.25 | -221.56 | -221.66 |</p>
<table>
<thead>
<tr>
<th>Station latitude, deg</th>
<th>40</th>
<th>1.5</th>
<th>2</th>
<th>2.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Station elevation, km</td>
<td>0.81</td>
<td>8.68E-05</td>
<td>1.54E-04</td>
<td>2.45E-04</td>
</tr>
<tr>
<td>Rain rate, mm/hr, 0.01%</td>
<td>32</td>
<td>0.912</td>
<td>0.942</td>
<td>0.963</td>
</tr>
<tr>
<td>Rain height, km</td>
<td>3.7</td>
<td>3.87E-05</td>
<td>9.13E-04</td>
<td>8.22E-03</td>
</tr>
<tr>
<td>Frequency, GHz</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Coeff kH</td>
<td>3.87E-05</td>
<td>8.68E-05</td>
<td>1.54E-04</td>
<td>2.45E-04</td>
</tr>
<tr>
<td>Coeff aH</td>
<td>0.912</td>
<td>0.942</td>
<td>0.963</td>
<td>1.014</td>
</tr>
<tr>
<td>rGamma</td>
<td>9.13E-04</td>
<td>2.27E-03</td>
<td>4.33E-03</td>
<td>8.22E-03</td>
</tr>
<tr>
<td>Elevation angle, deg</td>
<td>15</td>
<td>10.79</td>
<td>5.78</td>
<td>2.99</td>
</tr>
<tr>
<td>Slant path, km</td>
<td>11.17</td>
<td>9.01</td>
<td>5.01</td>
<td>2.99</td>
</tr>
<tr>
<td>Horiz proj, km</td>
<td>0.67</td>
<td>0.82</td>
<td>0.97</td>
<td>0.77</td>
</tr>
<tr>
<td>Reduction 0.01%</td>
<td>0.007</td>
<td>0.017</td>
<td>0.033</td>
<td>0.062</td>
</tr>
<tr>
<td>Attenu .01%, dB</td>
<td>0.003</td>
<td>0.007</td>
<td>0.013</td>
<td>0.024</td>
</tr>
<tr>
<td>Attenu 0.1%, dB</td>
<td>0.004</td>
<td>0.011</td>
<td>0.020</td>
<td>0.039</td>
</tr>
<tr>
<td>Elevation angle, deg</td>
<td>30</td>
<td>10.79</td>
<td>5.78</td>
<td>2.99</td>
</tr>
<tr>
<td>Slant path, km</td>
<td>11.17</td>
<td>9.01</td>
<td>5.01</td>
<td>2.99</td>
</tr>
<tr>
<td>Horiz proj, km</td>
<td>0.67</td>
<td>0.82</td>
<td>0.97</td>
<td>0.77</td>
</tr>
<tr>
<td>Reduction 0.01%</td>
<td>0.007</td>
<td>0.017</td>
<td>0.033</td>
<td>0.062</td>
</tr>
<tr>
<td>Attenu .01%, dB</td>
<td>0.003</td>
<td>0.007</td>
<td>0.013</td>
<td>0.024</td>
</tr>
<tr>
<td>Attenu 0.1%, dB</td>
<td>0.001</td>
<td>0.003</td>
<td>0.005</td>
<td>0.009</td>
</tr>
</tbody>
</table>
TABLE III - Data for selection of preferred frequencies.

Attenuation and noise temperature, clear air plus rain.

30 March 1987. Filename: RAINPATH

<table>
<thead>
<tr>
<th></th>
<th>30 March 1987. Filename: RAINPATH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vapour density, g/m³</td>
<td>7.50</td>
</tr>
<tr>
<td>Station elevation, km</td>
<td>0.81</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Frequency, GHz</th>
<th>1.0</th>
<th>1.5</th>
<th>2</th>
<th>2.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₀'</td>
<td>5.242</td>
<td>5.242</td>
<td>5.242</td>
<td>5.242</td>
</tr>
<tr>
<td>Ω₀₂</td>
<td>0.005</td>
<td>0.006</td>
<td>0.006</td>
<td>0.006</td>
</tr>
<tr>
<td>H</td>
<td>2.207</td>
<td>2.207</td>
<td>2.207</td>
<td>2.208</td>
</tr>
<tr>
<td>Ω₀₃</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>Galactic temp @ 408 MHz</td>
<td>30</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Galactic temp, K</td>
<td>2.549</td>
<td>0.836</td>
<td>0.379</td>
<td>0.205</td>
</tr>
<tr>
<td>Cosmic noise, W/Hz</td>
<td>3.69E-23</td>
<td>3.68E-23</td>
<td>3.66E-23</td>
<td>3.65E-23</td>
</tr>
<tr>
<td>Cosmic temp, K</td>
<td>2.676</td>
<td>2.664</td>
<td>2.652</td>
<td>2.640</td>
</tr>
<tr>
<td>Cosmic+galactic, K</td>
<td>5.225</td>
<td>3.500</td>
<td>3.031</td>
<td>2.846</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Zenith attn, dB</th>
<th>0.03</th>
<th>0.03</th>
<th>0.03</th>
<th>0.03</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zenith atmos noise, K</td>
<td>1.68</td>
<td>1.89</td>
<td>1.98</td>
<td>2.05</td>
</tr>
<tr>
<td>Zenith cosmic+galactic, K</td>
<td>5.19</td>
<td>3.48</td>
<td>3.01</td>
<td>2.82</td>
</tr>
<tr>
<td>Zenith total noise, K</td>
<td>6.88</td>
<td>5.36</td>
<td>4.99</td>
<td>4.87</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Elev angle, deg</th>
<th>15.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elev atmos attn, dB</td>
<td>0.10</td>
</tr>
<tr>
<td>Elev rain attn, dB</td>
<td>0.00</td>
</tr>
<tr>
<td>Elev total attn, dB</td>
<td>0.10</td>
</tr>
<tr>
<td>Elev atm + rain noise, K</td>
<td>6.62</td>
</tr>
<tr>
<td>Elev cosmic+galactic, K</td>
<td>5.10</td>
</tr>
<tr>
<td>Elev total noise, K</td>
<td>11.72</td>
</tr>
<tr>
<td>Elev noise power, dBA/Hz</td>
<td>-217.91</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Elev angle, deg</th>
<th>30.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elev atmos attn, dB</td>
<td>0.05</td>
</tr>
<tr>
<td>Elev rain attn, dB</td>
<td>0.00</td>
</tr>
<tr>
<td>Elev total attn, dB</td>
<td>0.05</td>
</tr>
<tr>
<td>Elev atm + rain noise, K</td>
<td>3.46</td>
</tr>
<tr>
<td>Elev cosmic+galactic, K</td>
<td>5.16</td>
</tr>
<tr>
<td>Elev total noise, K</td>
<td>8.62</td>
</tr>
<tr>
<td>Elev noise power, dBA/Hz</td>
<td>-219.24</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Elev angle, deg</th>
<th>75.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elev atmos attn, dB</td>
<td>0.03</td>
</tr>
<tr>
<td>Elev rain attn, dB</td>
<td>0.00</td>
</tr>
<tr>
<td>Elev total attn, dB</td>
<td>0.03</td>
</tr>
<tr>
<td>Elev atm + rain noise, K</td>
<td>1.81</td>
</tr>
<tr>
<td>Elev cosmic+galactic, K</td>
<td>5.19</td>
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<tr>
<td>Elev total noise, K</td>
<td>7.00</td>
</tr>
<tr>
<td>Elev noise power, dBA/Hz</td>
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### TABLE IV - Data for selection of preferred frequencies.

Ideal link performance, space to Earth, clear air, no rain.

30 March 1987. Filename: CLNKSEFD

<table>
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<td>60.82</td>
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<tr>
<td>---------------</td>
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<td>58.13</td>
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<td>57.15</td>
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</tbody>
</table>
FIGURE 1 — Space-to-Earth link performance, $P_r/N_0$
Fixed diameter space station and earth station antennas
- clear atmosphere, 7.5 gm/m$^3$ water vapor
- atmosphere plus rain, 10 mm/hr
$\Delta$: elevation angle (deg) of earth station antenna

REFERENCES

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SECTION 2C: SPACE OPERATIONS

REPORT 845-1

SPACE OPERATION SYSTEMS

Frequencies, bandwidths and protection criteria
(Question 18/2)

(1982-1986)

1. Introduction

The World Administrative Radio Conference, Geneva, 1979, defined the space operation service as follows:

"A radiocommunication service concerned exclusively with the operation of spacecraft, in particular space tracking, space telemetry and space telecommand.

These functions will normally be provided within the service in which the space station is operating."

To understand the meaning of the second sentence in the definition, it should be borne in mind that the original idea was to carry out space operation functions solely in the bands allocated to missions. Experience showed, however, that space operation could be facilitated in some cases by the specific allocation of bands to this service. In particular, this makes it possible to use a small number of stations for the space operation of satellites with missions pertaining to different services, such as the space research, meteorological-satellite, Earth exploration-satellite, fixed- and mobile-satellite and broadcasting-satellite services.

Furthermore, the frequency bands technically suitable for space operation do not always coincide with the bands which are suitable to missions, and there may be different protection criteria for space operation and mission telecommunication receivers.

This Report covers successively the functions to be carried out, the preferred frequency bands, the bandwidths, the protection criteria and various operational aspects of space operation systems.

All aspects are dealt with in such a way that the conclusions are applicable both for cases where space operation functions are performed in a frequency band related to a satellite's mission, and for cases where they are carried out in a frequency band allocated to the space operation service.

Links in space operating systems may be established either directly between spacecraft and earth stations or through data relay satellites. Only direct links are considered here. For links via data relay satellites, see Report 848.

2. Space operation functions

The main functions of space operations are:

- maintenance telemetry,
- telecommand,
- tracking,
- RF sensing for attitude control.

2.1 Maintenance telemetry

To ensure the maintenance of a spacecraft, a large number of measured data, most of them with a low data rate, have to be transmitted to the Earth. They include:

- temperature measurements, either for monitoring and regulation or for correction of on-board instrument readings in the light of their temperature;
- magnetic field measurements, to provide particulars of the instantaneous attitude of the spacecraft or its rotation speed;
- measurements of moving units: separation indicators, safety stops for deployed components;
- inertial measurements (rate gyros, accelerometers), useful for satellite attitude and station keeping;
- optical measurements, to ascertain the attitude of the spacecraft in relation to the Earth, the Sun and stars;
- measurements of pressure in tanks and electrochemical batteries;
- current and voltage measurements;
- reports on the condition of a component or the reception or execution of a command.
All these measurements may be used to monitor the condition of spacecraft and their payloads which depends on the external environment and on configuration orders addressed to the spacecraft by telecommand or provided by an on-board sequencer according to a predetermined programme.

These data are useful for ensuring proper operational conditions, optimizing the spacecraft and payload mission facilities and analyzing unforeseen situations. They also serve to broaden knowledge of the behaviour of materials in orbit and to improve the development of new systems.

Telemetering data from the on-board memory may be transmitted in real time or stored and subsequently transmitted.

An example of maintenance telemetry is given in Annex I.

2.2 Telecommand

Most spacecraft should be able to receive orders by telecommand. No. 2612 of the Radio Regulations makes this mandatory in the case of the active satellites defined in No. 172.

2.2.1 In the case of short-mission spacecraft, such as launchers, most of the orders can be recorded before the flight and distributed as necessary by an on-board sequencer.

Nevertheless, space telecommand is generally used for safety purposes (e.g. stopping the propulsion of a launcher deviating from its assigned trajectory or destroying it if required).

Certain telecommand functions can also be carried out by a radar transponder operating in the radiolocation service.

2.2.2 In most other cases, telecommand is needed to modify the operation of the spacecraft and its payload:
- according to successive utilization phases during the mission,
- according to different flight phases (orbit insertion, eclipse periods, etc.), or
- as a result of abnormal events, such as operational anomalies.

The orders transmitted to the spacecraft when it is in line of sight of an earth station may be either carried out immediately or stored in a memory from which they are extracted later for execution at a time also stored in the memory.

Delayed-action telecommand is particularly important for complex spacecraft missions requiring an on-board computer. In such cases, a megabit of information may have to be transmitted in a few minutes. Satisfactory reception of telecommand signals is generally acknowledged by telemetry.

An example of telecommand is given in Annex I.

2.3 Tracking

Space tracking, i.e., the determination of the orbit, velocity or instantaneous position of an object in space by means of the propagation properties of radio waves (see Nos. 130 and 10 of the Radio Regulations), has to be carried out during every space mission to meet one or more of the following requirements.

2.3.1 Spacecraft orbit control system

Broadly speaking, this is one of the methods for controlling the orbit of a spacecraft by means of telecommand facilities and on-board propulsion systems. In practice, orbit control may be used for:
- placing in parking or transfer orbit;
- modification of orbits: e.g., for changing from a transfer orbit to the geostationary-satellite orbit;
- fine orbit correction: e.g., for geostationary satellite station-keeping and for rendezvous manoeuvres;
- returning a recoverable spacecraft to Earth.

2.3.2 Surveillance, safety, recovery

The surveillance and safety functions cover anti-collision measures for spacecraft in neighbouring orbits and prediction of the impact or landing site of re-entering launcher stages or spacecraft.
2.3.3 Orbital accuracy

Evaluation of the accuracy of launches or other orbital manoeuvres.

2.3.4 Attribution of location data to mission measurements and observations

Measurements must be related to the position where the spacecraft is situated at the moment when the measurements are taken. This is particularly important when the spacecraft is carrying out scientific measurements of its environment, such as measurements of the magnetic field, particle density, etc. It is also essential in Earth observation missions, independently of the facilities offered during these missions by identification of control points on the transmitted pictures.

2.3.5 Publication of ephemeris tables

Forecasts of visibility and the pointing angle towards the spacecraft are essential for the organization of the work of earth stations and for the pointing of such directional instruments as high-gain antennas, telescopes, etc.

2.3.6 Remarks

Tracking functions which are the main objectives of space missions, such as space geodesy and satellite radionavigation, have been deliberately omitted from the above list.

Certain space tracking functions, particularly some of those cited under § 2.3.1, 2.3.2 and 2.3.3, may be carried out under the radiolocation service, with or without the use of a spacecraft radar transponder.

A brief description of tracking systems is given in § 3.4 of Report 548 (Geneva, 1982).

An example of a range and range rate system is given in Annex I to this Report.

2.4 RF sensing for attitude control

Report 546 on spacecraft attitude control contains a paragraph (§ 4.4) dealing with attitude sensing in relation to the Earth by means of antennas and circuits aboard the spacecraft receiving signals from a ground based beacon. This method may also be used for pointing of spacecraft antennas, for instance on board broadcasting satellites.

3. Preferred frequency bands

From the technical point of view, the space operation functions described in the preceding paragraph may be carried out in the frequency range between approximately 100 MHz and 30 GHz.

In the special case of communications effected during the re-entry of a spacecraft into the Earth's atmosphere, frequencies of 10 GHz or higher must be chosen (see Report 222). In other cases, the technical choice of frequencies mainly depends on the factors described below.

3.1 Lower limits

The lower limit of frequencies for space operations is bound up with the effect of ionospheric propagation on the accuracy of tracking measurements.

3.1.1 Ionospheric effects on tracking accuracy

Report 263 describes all the ionospheric effects on Earth-space propagation. A summary pertinent to the subject of this Report is given below.

A typical error in ranging carried out by group delay measurement is 400 m for a vertical path at 100 MHz. For very low elevation angles, the value should be multiplied by about 3. Real values, however, can vary considerably and may be up to 10 times smaller or greater. In practice, it is impossible to correct these errors by using models, owing to the great time and space variability of the ionosphere. To reduce ionospheric errors, the frequencies used must be sufficiently high, since the error follows a $1/f^2$ law. (A frequency pair may also be used (see Report 988).) At 1 GHz, for example, the typical error for a vertical path is 4 m and for very low elevations, 12 m.
The remarks made with regard to group delay distance measurements also apply to phase delay measurements, except that the error has the opposite sign (apparent shortening instead of lengthening).

Error in the pointing direction of an autotrack antenna at 30° elevation has a typical value of 0.5 milliradian at 100 MHz and exceeds 2.5 milliradians in less than 10% of cases. These values also follow a $1/f^2$ law and should be divided by 100 for a frequency of 1 GHz.

Range rate and interferometric measurements are affected by the ionosphere in a similar way as range and angle measurements. They are further affected by the microstructure of the ionosphere, i.e., the differential effect of the ionosphere on the two paths measured for difference. Nevertheless, these subsidiary effects are generally less serious than the main ones, and like the latter they decrease with increasing frequency.

3.1.2 Necessary tracking accuracy. Effect on choice of frequencies

The required accuracy of tracking measurements depends on a satellite's mission, and also on the number of earth stations involved in tracking and on their geographical location on the Earth's surface and in relation to the satellite orbit.

For many application missions, the satellites have to be maintained in a specific orbit. The two most usual cases are station-keeping with a geostationary satellite and keeping an Earth exploration satellite in heliosynchronous orbit. In both these cases, the required accuracy is about 50 m, on the assumption that a small number of stations is appropriately distributed.

Since the overall accuracy of the measuring system depends not only on the ionosphere but also on other factors, particularly on the quality of the measuring instrument, the share due to the ionosphere should be less than 50 m. In the light of the foregoing, this condition begins to be fulfilled from the moment that the frequency exceeds 1 GHz.

In conclusion, it may be assumed that from the point of view of tracking accuracy most application missions require frequencies above 1 GHz. This conclusion also applies to certain scientific missions, although some scientific missions (for astronomy, for example) and some types of application missions can be effected with lower accuracy and therefore at frequencies below 1 GHz.

3.2 Upper limit

Although the frequency range to be used for space operations is approximately 100 MHz to 30 GHz, the upper part of this range is generally less favourable when a link has to be established or maintained in all operating phases of a space system. A frequent requirement, in fact, is the possibility of establishing at any moment, or permanently maintaining, telemetry or telecommand links, i.e. independent of the spacecraft attitude. For this reason, a great number of satellites rely on quasi-omnidirectional antenna coverage for space operations.

For large satellites with complex structures such antennas are frequently difficult to implement at frequencies above 8 GHz. At higher frequencies, spacecraft antenna coverage will not be any more quasi-omnidirectional, but be restricted to certain aspect angles. This can result in a loss of RF contact with the satellite for unfavourable aspect angles.

Furthermore, at frequencies above 15 GHz additional propagation conditions in the atmosphere may lead to a deterioration of the link, unless either the transmitted power or the $G/T$ of the receiving station is considerably increased.

In these circumstances, the antenna gain to be taken into account in drawing up the link budget is not that of the main lobe minus 3 dB, as is usual for mission telecommunications, but is the gain guaranteed in the troughs within the minimum required coverage. The gain in the trough depends not only on antenna design, but also on antenna layout and the dimensions and shape of the spacecraft structure and its appendages such as booms, solar panels, other antennas, etc.

The masking effect produced by the body of the spacecraft may be reduced by placing the antenna at the end of a suitably long boom. There could also be an automatic system aboard the spacecraft to guarantee the link performance with the earth station in the event of loss of nominal attitude. This link may be intermittent.

The range of 100 MHz to 30 GHz should be divided into 3 sub-ranges:

- **below 1 GHz**

  The body of the satellite affects the radiation pattern, which may be an advantage for small satellites (less than 1 m) and a disadvantage for larger ones.
1 to 8 GHz
The radiation is mainly defined by the characteristics and arrangement of the antennas.

8 to 30 GHz
Obtaining the required radiation entails stricter constraints on the design and manufacture of the spacecraft antennas.

It appears that the highest frequency used so far for links which are independent of the attitude of the spacecraft is 6425 MHz, but current projects provide for the use of frequencies as high as 14 GHz.

3.3 Other factors to be taken into account in choosing frequencies

To facilitate decoupling of Earth-to-space and space-to-Earth links while using the same antenna in both directions, the ratio between the frequencies of the two links should be between 1.06 and 1.1.

To optimize spectrum utilization, it would be desirable for all space systems operating in these bands to adopt the same ratio. However, this approach may not always be possible, in particular at earth station sites located within areas covered by dense terrestrial networks, operating in the same frequency band. In the bands 2025 to 2120 and 2200 to 2300 MHz, various space systems already in operation use coherent transponders with a frequency ratio of 240/221 between the down link/up link permitting range rate measurements.

3.4 Summary of preferred frequency bands
To sum up, the preferred frequencies for space operations lie approximately between 1 and 8 GHz.

Lower frequencies may be used, particularly for small spacecraft carrying out missions which do not call for high-precision tracking.

Higher frequencies may be preferred for space operation functions of spacecraft using these frequencies as well for mission links with the Earth.

4. Necessary bandwidth

From the point of view of bandwidth requirements, a distinction should be made between launchers and other spacecraft.

In the case of launchers, the bandwidth of the space-to-Earth link is related to the transmission of many rapidly changing parameters, mainly vibrations and pressures.

In the other cases, the bandwidth of the space-to-Earth link is generally determined, not by telemetry, but by ranging signals. An example is given in Annex I.

With regard to the Earth-to-space link, the necessary bandwidth is also generally determined by the transmission of ranging signals.

In conclusion, the necessary bandwidths are generally determined by the transmission of ranging signals and are of the order of 200 kHz to 1 MHz for classical modulation methods. New modulation techniques such as spread spectrum will require bandwidths in excess of 1 MHz while allowing a multiple reuse of the same band. Lower values may suffice if tracking is effected by interferometry or by range rate measurement (Doppler effect measured on the carrier).

5. Protection criteria

5.1 Protection level of earth station receivers

Attempts are generally made to reduce the necessary power of on-board transmitters to a minimum, and earth station receivers therefore have to operate at maximum sensitivity.

Above 1 GHz, it is considered that the total noise temperature of earth stations is 100 K or more which at the receiver input is equivalent to a noise power spectral density of \( kT = -208.6 \text{ dB(W/Hz)} \).

It is considered that in most cases additional protection of about 5 dB is required against all types of interference.

The total interference power spectral density must therefore not exceed \(-214 \text{ dB(W/Hz)}\) at the receiver input.

Below 1 GHz, owing to the increase in galactic noise temperature, the permissible interference level may be raised by 20 dB per decreasing frequency decade.
5.2 Protection ratio of space station receivers

The power of earth station transmitters can generally be increased within the limits imposed by the Radio Regulations and on-board receivers therefore do not always operate at maximum sensitivity. In particular, for communication with low-altitude satellites operating close to sources of interference from terrestrial services, the transmitted power of earth stations can be kept as high as for geostationary satellites for example, in order to keep an adequate signal-to-interference ratio.

The protection of space station receivers is therefore more conveniently expressed by protection ratios than by protection levels.

A signal-to-total interference protection ratio of 20 dB is sufficient in most cases.

5.3 Reference bandwidth

The reference bandwidth in which the protection level or ratio must be specified depends on the characteristics of the receivers used and their susceptibility to continuous wave, amplitude modulated or low-index modulation phase-modulated interferences. Phase-locked receivers are often used; in such cases the reaction of the receiver to a narrowband interfering source is characterized by the equivalent noise bandwidth of the loop. This bandwidth is normally fixed at a value between a few hundred hertz and a few kilohertz. A value of 1 kHz may therefore be adopted for the reference bandwidth.

5.4 Reference percentage of time

Generally the percentage of time during which space operation links can tolerate an interference level above the protection level may be fixed at 1% each day. This value is based on the assumption that the spacecraft is equipped with memory and automatic devices to ensure its safety during interruptions of telecommunications. This condition was not always fulfilled in the past, but it is considered reasonable to require it to be met by future systems.

However interference lasting for as long as 15 consecutive minutes is intolerable during certain foreseeable critical stages, such as launch phases, critical spacecraft manoeuvres, or for such short-lived spacecraft as rocket probes. It would be unreasonable to lay down protection criteria on the basis of such exceptional situations, and it would be preferable to invite concerned administrations to carry out special analyses of the interference likely to be caused and to take counter-measures which should be temporary and limited to specific regions.

5.5 Conclusions on protection criteria

For earth stations carrying out space operation functions, above 1 GHz, the total interference power at the receiver input in any 1 kHz band should not exceed −184 dBW for more than 1% of the time each day; below 1 GHz, this value may be increased by 20 dB per decreasing frequency decade.

For space stations carrying out space operation functions, the ratio of signal power to total interference power in any 1 kHz band should not fall below 20 dB for a period exceeding 1% of the time each day.

6. Frequency sharing possibilities

Sharing within the space operation service near 2 GHz: see Annex II.

Sharing with other services: see Reports 396, 678 and 846.

7. Operational aspects

A comparison is given below of the advantages and disadvantages of the use for space operation functions of mission frequency bands and frequency bands allocated to the space operation service or a combination of the two.

7.1 Use of mission telecommunication bands for space operation

7.1.1 Advantages

Since most spacecraft are equipped with transmitters and receivers for telecommunications directly concerned with their mission, it is generally preferable to use the same equipments for maintenance telemetry, telecommand and tracking, in order to reduce the cost of on-board and earth station equipment and to economize the spectrum.
7.1.2 Disadvantages

Experience shows that this mode of operation is not always the best:

— when frequencies above 7 GHz are used for mission telecommunications, it is often difficult to ensure on board the spacecraft the necessary radiation pattern to guarantee maintenance of links during launching and during nominal attitude loss phases;
— in certain frequency bands allocated to mission telecommunications, the allotment plans do not provide specifically for the transmission of space operation data;
— economy of on-board equipment is less than it appears at first sight in those cases where it becomes necessary to install a wide-coverage antenna system for space operation functions in addition to the directional radiation antennas usually used for mission telecommunications;
— economy of earth station equipment is also not necessarily guaranteed, since space operation functions may necessitate a geographical location of stations different from that required for mission functions.

7.2 Use of specific space operation service bands

7.2.1 Advantages

In view of all the expenditure on board and on the ground, it may be cheaper to have a single network of earth stations for space operation. These would operate with satellites carrying out missions for several services to which different frequency bands are allocated. The common network would use frequencies allocated specifically to the space operation service.

7.2.2 Disadvantages

The advantage of a multi-purpose earth station network using frequencies allocated exclusively to the space operation service and working with several spacecraft is limited if some of the spacecraft require the permanent operation of telemetry links, which would make it necessary to increase the number of earth stations. This would reduce, particularly for geostationary satellites, the efficient use of frequencies and increase the interference potential.

7.3 Combined use of mission and specific frequency bands

In conclusion, the best solution, especially for mission telecommunications using frequencies above 8 GHz, may be to equip spacecraft with two maintenance telemetry, telecommand and tracking systems, one operating in the band allocated to the mission and the other in the frequency band which is most suitable for space operations, i.e., the band 1-8 GHz. The first system would be used preferably in the routine phases and could be brought into operation by mission telecommunication earth stations or by a specialized earth station; the second system would be used during the launch phase and during other critical phases, without unduly overloading the multi-purpose earth station network. The additional cost of the on-board equipment is less than might appear at first sight, because the telemetry encoder and the telecommand decoder would not have to be duplicated and because the on-board antennas would have to be duplicated in any case to ensure the necessary coverage during critical phases. The additional cost of ground equipment would be shared between the user systems. To offset these additional investments, this solution would ensure the greatest operational reliability and flexibility at all phases of the mission without entailing any appreciable increase in operational costs. An example is given in Annex II, § 2.5.

ANNEX I
EXAMPLE OF SPACE OPERATION SYSTEMS
TELECOM 1 System

1. General information

The satellite system comprises an active satellite system TELECOM 1A and a back-up satellite TELECOM 1B, both in geostationary orbit. It can provide services for metropolitan France and adjacent parts of Europe as well as for the French Overseas Departments from the Caribbean to the Indian Ocean.

For its missions, the system uses the frequency bands 14/12 GHz and 6/4 GHz. Telecommand and telemetry signals can be transmitted in the 6/4 GHz band or in the 2 GHz band allocated to the space operation service under Nos. 747 and 750 of the Radio Regulations.
2. Choice of frequency band for use in space operation

2.1 Principles

The telemetry, telecommand and ranging sub-system operates in the 2 GHz band during orbit acquisition operations and at 6/4 GHz during the operational phase. The 2 GHz link may also be used to back up the 6/4 GHz link for short periods during the operational phase.

2.2 Launching and positioning phases

In the launching phase, the sub-system operates in the 2 GHz band. After entry into the drift orbit and after the attitude control sub-system has stabilized the spacecraft in the direction of Earth, the 6/4 GHz receivers and transmitters can be switched on by the 2 GHz telecommand system.

2.3 Operational phase

During the operational phase, telecommand reception is automatically assured provided a telecommand signal at 6 GHz is present and there is an adequate signal-to-noise ratio on the sub-carrier. In the absence of the 6 GHz signal, telecommand signals can be received in the 2 GHz band.

During the operational phase, the telemetry sub-system can transmit simultaneously and continuously on two carriers, one in the 2 GHz band and the other in the 4 GHz band. Either transmission can be cut off by telecommand. The nominal operating mode is in the mission band (4 GHz).

3. Characteristics of space operation links

The main link characteristics are given in Tables I and II.

TABLE I — Main characteristics of space operation up links

<table>
<thead>
<tr>
<th></th>
<th>2 GHz band</th>
<th>6 GHz band</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum earth station e.i.r.p. (dBW)</td>
<td>71</td>
<td>70</td>
</tr>
<tr>
<td>Receive gain of space-station antenna for Earth coverage with oriented satellite (dBi)</td>
<td>0</td>
<td>16.7</td>
</tr>
<tr>
<td>Equivalent receiving space station noise temperature (K)</td>
<td>1100</td>
<td>1700</td>
</tr>
</tbody>
</table>

**Telecommand signal**

<table>
<thead>
<tr>
<th></th>
<th>2 GHz band</th>
<th>6 GHz band</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulation</td>
<td>PCM(NRZ-L)-PSK-PM</td>
<td>PCM(NRZ-L)-PSK-FM-PM</td>
</tr>
<tr>
<td>Rate (bit/s)</td>
<td>1000</td>
<td>1000</td>
</tr>
<tr>
<td>Sinusoidal PSK sub-carrier frequency (kHz)</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>FM sub-carrier frequency (kHz)</td>
<td>-</td>
<td>70</td>
</tr>
<tr>
<td>Frequency deviation (kHz)</td>
<td>-</td>
<td>±12 peak-to-peak</td>
</tr>
</tbody>
</table>

**Sinusoidal ranging signals**

<table>
<thead>
<tr>
<th></th>
<th>2 GHz band</th>
<th>6 GHz band</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulation</td>
<td>PM</td>
<td>PM</td>
</tr>
<tr>
<td>Major tone frequency (fine measurement) (kHz)</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Minor tone frequencies (ambiguity resolution) (kHz)</td>
<td>Between 15 and 20</td>
<td>Between 15 and 20</td>
</tr>
</tbody>
</table>
### TABLE II — Main characteristics of space operation down links

<table>
<thead>
<tr>
<th></th>
<th>2 GHz band</th>
<th>4 GHz band</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum space station e.i.r.p. (dBW)</td>
<td>3</td>
<td>11</td>
</tr>
<tr>
<td>Receive gain of earth-station antenna (dBi)</td>
<td>45</td>
<td>46</td>
</tr>
<tr>
<td>Equivalent receiving earth station noise temperature (K)</td>
<td>160</td>
<td>200</td>
</tr>
</tbody>
</table>

**Telemetry signal**

<table>
<thead>
<tr>
<th></th>
<th>2 GHz band</th>
<th>4 GHz band</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulation</td>
<td>PCM(bi-phase-L)-PSK-PM</td>
<td>PCM(bi-phase-L)-PSK-PM</td>
</tr>
<tr>
<td>Rate (bit/s)</td>
<td>160</td>
<td>160</td>
</tr>
<tr>
<td>Sinusoidal sub-carrier frequency (kHz)</td>
<td>40.96</td>
<td>40.96</td>
</tr>
</tbody>
</table>

**Sinusoidal ranging signals**

<table>
<thead>
<tr>
<th></th>
<th>2 GHz band</th>
<th>4 GHz band</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulation</td>
<td>PM</td>
<td>PM</td>
</tr>
<tr>
<td>Major tone frequency (fine measurement) (kHz)</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Minor tone frequencies (ambiguity resolution) (kHz)</td>
<td>Between 15 and 20</td>
<td>Between 15 and 20</td>
</tr>
</tbody>
</table>

### ANNEX II

INTRA-SERVICE SHARING CONSIDERATIONS FOR THE UHF BAND
(2025 TO 2110 MHz AND 2200 TO 2290 MHz) ALLOCATED TO THE SPACE OPERATION SERVICE

1. **Introduction**

The European Space Agency (ESA) which is responsible for the development and operation of a great variety of spacecraft is constantly faced with the requirement of optimizing its use of the 2 GHz frequency bands allocated to the space operation service. With a view to arriving at this goal, several methods of increasing the capacity of the 2 GHz bands have been studied and the results are given below.

2. **Possibilities for sharing**

Since the earth station antennas used for space operations functions are typically 10 m and upwards in diameter, spatial separation offers a first means of discrimination between users sharing the band. A second possibility is the assignment of different frequencies to different users. The third means of sharing is to use distinctive address and synchronization words in the data itself. In this may be included the use of different data rates, sub-carriers, formats, etc. Frequency re-use by polarization discrimination tends to be ruled out by the poor polarization characteristics of the broad beam antennas which are typically used on the spacecraft.

Each of these methods of sharing will be examined in some detail.

2.1 **Spatial separation**

ESA uses two classes of earth station equipment for supporting spacecraft in the 2 GHz band allocated to the space operation service. The basic network, designed primarily for geostationary transfer orbit, is equipped with 10 m dish antennas with an e.i.r.p. of 65 to 75 dBW and a $G/T$ of 22 dB(K$^{-1}$). Several 15 m antennas with an e.i.r.p. of 68 dBW to 78 dBW and a $G/T$ of 27.5 dB(K$^{-1}$) are also available. Spacecraft antennas are generally of the quasi-omnidirectional radiator type.
Down links are almost always modulated but up links are unmodulated during a short period (of the order of a few seconds) preceding each signal transmission for on-board transponder acquisition. Thus to afford 20 dB protection to a modulated up link from an unmodulated up link, operating at the same frequency, around 30 dB of power difference is required. If the interfering station is already 10 dB more powerful than the other station one can see that at least 40 dB attenuation in the side lobes of the ground station antenna is required to ensure freedom from interference.

The 10 m antennas reach a side-lobe level of —40 dB at about 16° from boresite, while the 15 m ones reach —40 dB at 9°. Consequently, the feasibility of many spacecraft sharing the same frequency is limited. It must also be kept in mind that during their positioning phase on the geostationary-satellite orbit (GSO), satellites will move along rather large arcs of the orbit and may pass other satellites using the same frequency. Frequency re-use by orbital separation on the GSO can only be used as a means for increasing the capacity of the 2 GHz band, if the angular distance between the satellites operating at the same frequency is sufficient.

The 10 m antennas reach a side-lobe level of —40 dB at about 16° from boresite, while the 15 m ones reach —40 dB at 9°. Consequently, the feasibility of many spacecraft sharing the same frequency is limited. It must also be kept in mind that during their positioning phase on the geostationary-satellite orbit (GSO), satellites will move along rather large arcs of the orbit and may pass other satellites using the same frequency. Frequency re-use by orbital separation on the GSO can only be used as a means for increasing the capacity of the 2 GHz band, if the angular distance between the satellites operating at the same frequency is sufficient.

Frequency re-use by spatial separation can be practical in many cases with little or no inconvenience caused, between satellites on the GSO and non-geostationary satellites, as well as between several non-geostationary satellites. Certain precautions have to be taken before proceeding to an assignment of identical frequencies to two satellites on different orbits: a "protection cone" around each satellite has to be defined, its "vertex" angle being as a first approximation that of the orbital separation calculated above for two geostationary satellites. (The size of the "protection cone" is very strongly influenced by the side-lobe pattern of the earth station antennas.)

Subsequently the times of "angular coincidence" referred to a particular earth station have to be studied, i.e. those orbital constellations when the "protection cones" of the two spacecraft fully or partially overlap; however, interference periods will generally be very short (a few minutes) for satellites on orbits below 2000 km. For highly eccentric orbits these periods may become quite long depending on the orbital parameters, thus possibly precluding a sharing of the same frequency with a geostationary satellite.

2.2 Frequency separation

The viability of a scheme based on minimum frequency separation depends on two factors: a good characterization of the spectra involved and a knowledge of the frequency discrimination of the receiving systems. ESA's approach to the former is to define a standard mask, with a rather rapid fall off in frequency, around each radiated signal and to ensure minimum spectrum occupancy by the use of suitably shaped video waveforms. For the functions of telecommand and ranging it is possible to define values of the occupied bandwidth which will be met by most missions (66 kHz for telecommand and 360 kHz for ranging). For down-link telemetry it is only possible to define a typical occupied bandwidth for those cases where a low bit rate housekeeping telemetry is used. However, also in the case of the down link the ranging signals determine the occupied bandwidth.

Thus in general, one is left with ranging as the most demanding function taking an occupied bandwidth of 360 kHz (—15 dB points contain 99% of the power, which defines the occupied bandwidth in accordance with No. 147 of the Radio Regulations).

From the arguments enumerated above, about 30 dB protection is required which means that the channel bandwidth should be taken as around 400 kHz. For those spacecraft subject to the Doppler effect, the up link operates at the assigned frequency but the down link, in the coherent ranging mode, shows a frequency shift of twice the spacecraft Doppler. Thus an extra 150 kHz should be added to the channel bandwidth to ensure protection. This additional bandwidth is also adequate to take care of on-board oscillator instability when in the non-coherent mode.

Both on board the satellite and on the ground, the receiving systems use relatively wideband IF circuits before recovering the residual carrier in narrow-band phase lock loops. These have typical bandwidths (2B_L) in the range 100 Hz to 1 kHz. Pre-detection filters in front of the loops have typically 20 times greater bandwidths. The bandwidth of the receiving system is sufficiently small that it has no impact on channel spacing requirements.

Thus one can conclude that a channel spacing of about 550 kHz should ensure sufficient protection from interference.
2.3 Separation by data addresses and types

Each of ESA's spacecraft has its own signature of bit rates, sub-carriers, format structure, application of coding, etc., and each is equipped with unique address words which form a part of the format. It is thus almost impossible for the receiving systems to accept data coming from an interfering link and interpret it as valid data. On the other hand, for two spacecraft placed close together in orbit and using the same radio frequency, each set of data would appear as 100% interference to the other; with the presently used modulation standards there would be no way of recovering the wanted data with any degree of accuracy. What can be done is to time-share the link. Such a scheme is very suitable for the up link of telecommands. Generally very few telecommands are sent per day and with the hardware available on board the spacecraft for storing and expanding commands, it is possible to group commands together so that an up link need be established only from time to time e.g. when ranging is required. So far one does not have similar possibilities on the down link, since there is still a marked preference for a complete real time record of the spacecraft telemetry.

It is very common, in particular for non-geostationary satellites, to use parts of frequencies with a fixed ratio for up and down links in the 2 GHz band because this is compatible with coherent ranging systems. (In many agencies the frequency ratio used is 221/240.) Since the up-link and down-link frequency bands have approximately the same width, there is little point in time-sharing an up-link frequency if the down link is permanently on.

2.4 Polarization separation

In the 2 GHz space operations band ESA makes major use of two different antenna systems on board the spacecraft in order to achieve the wide beam coverages required. The first is a system which switches between two quadrifilar helix elements, each of which covers a hemisphere and is circularly polarized with a polarization gain discrimination of better than 6 dB.

The second is a dual mode cardioid antenna covering a half angle of up to 140°. This antenna is circularly polarized on axis but the predominant polarization broadside-on is linear. These antennas represent the result of considerable work on the optimization of coverage for the preferred sense of circular polarization while avoiding illumination of the spacecraft body (which causes undesirable ripples and nulls in the gain pattern). The scope for improvement of the cross-polar performance is limited. There is virtually no possibility to reach cross-polar levels of around — 20 dB as would be required for frequency re-use.

2.5 Operational intra-service frequency sharing

Recent studies by Japan have shown the technical feasibility of frequency sharing to permit re-use of the available spectrum in the space operation and mission frequency bands. A specific problem is the simultaneous control of a geostationary satellite already in position and a satellite which is being placed into position, and which use similar tracking, telemetry and telecommand (TTC) systems.

Interference may occur between space operation up links of a geostationary satellite and a satellite being positioned. Interference may also occur on the respective down links, although the down-link telemetry of the geostationary satellite in the space operation band can be turned off, at least for a short period of time, since it is also transmitted in the mission band. Consequently, no harmful interference is foreseen for down links.

However, for up links, severe interference conflicts may arise. In many cases, to reduce weight, the telecommand decoders are shared between receivers working in the mission band and those working in the space operation band, as described in § 7.3 of this Report. In this case, an automatic search switch connects the shared telecommand decoders to the receivers alternately.

The satellite undergoing positioning manoeuvres usually operates in the space operation band and if necessary, the receivers working in the mission band can be cut off by command, but it is usually preferred to keep the receivers working in the space operation band alive in order to keep the command channels always available.

A geostationary satellite is usually controlled by the mission earth station in the mission operation band, but, if the telecommand decoder of the geostationary satellite is locked on to an undesired space operation up link, the decoder cannot receive commands sent in the mission band.

As simultaneous operation of both the geostationary satellite and the satellite being positioned is very important, time sharing cannot be used.
To solve this problem, an “up-link hold” method is proposed in which the mission telecommunications earth station should continuously transmit its telecommand signal in order to keep the telecommand decoder working in the mission band, thus permitting simultaneous and independent control of the satellites. Note that this approach may require cooperation between operating authorities.

3. Future developments

Conscientious frequency assignment will undoubtedly remain the cornerstone of intraservice sharing for many years to come. Spatial separation of spacecraft using common frequencies can be expected to become more usual particularly in the case of, for example, a series of global earth monitoring spacecraft spaced around the equator in geostationary-satellite orbit (e.g. GOES, GMS, Meteosat) or a series of low orbit earth resources spacecraft in orbits which do not lead to one earth station viewing two spacecraft simultaneously.

As shown above, intraservice sharing possibilities will be greatly increased if standardized transmission link parameters are used for similar missions, resulting in a certain degree of standardization in system performance. These parameters would typically include, both on spacecraft and in earth stations, $G/T$ and e.i.r.p. It is essential to limit not only the e.i.r.p. but also the occupied bandwidth to values which are realistically required for a particular mission (e.g. for geostationary satellites: earth station e.i.r.p. of the order of 65 dBW).

Spread spectrum techniques, although leading to more complex space and Earth segment equipments, are certain to play a prominent part in future plans for sharing. By spreading the energy of the transmissions uniformly and by incorporating ranging into the spreading code, it will be possible to pack more spacecraft into a given bandwidth since guard bands and allowances for Doppler and oscillator instability will become negligible. Tracking and data relay satellites (TDRS) and global positioning systems (GPS) are typical forerunners of this trend. However, it must be remembered that such schemes will work optimally only when there is a large degree of uniformity between all the different spacecraft and earth station systems operating within the spread spectrum band.

REPORT 678

TECHNICAL FEASIBILITY OF FREQUENCY SHARING BETWEEN THE SPACE OPERATION SERVICE AND THE SPACE RESEARCH SERVICE IN THE 1 TO 10 GHz BAND

(Question 1/2)

1. Introduction

The Space Operation Service, within which the vital satellite functions — maintenance, telemetry, telecommand and tracking — can be performed, will assume growing importance as satellite systems in many services move to frequency bands beyond 15 GHz and as increasing use is made of high-gain spot-beam antennas for the illumination of rather limited service areas. Thus, satellite systems using the geostationary orbit will run into more and more difficulties, particularly during the injection and transfer orbit phase, when relying on the service frequency bands for their maintenance telemetry, telecommand and tracking transmissions. The antenna systems, which frequently have only high-gain spot-beams will, in many cases, not be adequate to provide the required coverage. One way to overcome this problem would be to use additional satellite equipment, operating at lower frequencies, and having the required antenna characteristics and link performance. This equipment would logically operate in the bands of the Space Operation Service.

The purpose of this Report is to demonstrate the technical feasibility of frequency sharing between the Space Operation and Space Research Service. If frequency sharing is proved to be feasible, it should be possible to make certain bands already allocated to the Space Research Service available also to the Space Operation Service. In this way the utilization of the spectrum can be made more efficient without adversely affecting the interests of the Space Research Service.

Finally, the sharing of the same frequency bands by the Space Operation Service and Space Research Service, together in some cases, with the joint use of the same earth station sites, would considerably ease the task of coordination with other frequency users (mostly terrestrial) sharing the same band: once the earth station site has been coordinated in a particular frequency band for the Space Research Service, it would be automatically coordinated for the Space Operation Service.
2. Sharing analysis

The sharing analysis is limited to the 1 to 10 GHz band; below 1 GHz the feasibility of sharing between the Space Research Service and Space Operation Service is well established and certain bands are allocated simultaneously to the two Services; above 10 GHz, problems similar to those outlined in the Introduction will occur, hampering the reliable performance of maintenance, telemetry, telecommand and tracking. Quasi-omnidirectional or hemispherical coverage antennae with an acceptable gain make considerable technological demands at frequencies above 10 GHz. At the same time, propagation conditions — particularly in areas of low geographical latitude — require considerable additional safety margins for a reliable link performance.

### TABLE I — Typical system parameters (at 2 GHz)

<table>
<thead>
<tr>
<th>Mode</th>
<th>System parameters</th>
<th>Space research</th>
<th>Space operation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Near-Earth</td>
<td>Deep-space (up to</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>geostationary altitude)</td>
</tr>
<tr>
<td>Reception at earth station</td>
<td>Telemetry bandwidth</td>
<td>10 kHz - 30 MHz</td>
<td>1 Hz - 4 MHz</td>
</tr>
<tr>
<td></td>
<td>Tracking bandwidth</td>
<td>400 kHz - 1 MHz</td>
<td>1 Hz - 4 MHz</td>
</tr>
<tr>
<td></td>
<td>G/T earth station</td>
<td>20-35 dB(K⁻¹)</td>
<td>37-60 dB(K⁻¹)</td>
</tr>
<tr>
<td>Transmission from earth station</td>
<td>Telecommand bandwidth</td>
<td>100 kHz - 1 MHz</td>
<td>1 Hz - 3 MHz</td>
</tr>
<tr>
<td></td>
<td>Tracking bandwidth</td>
<td>400 kHz - 1 MHz</td>
<td>1 Hz - 3 MHz</td>
</tr>
<tr>
<td></td>
<td>e.i.r.p. earth station</td>
<td>60 - 90 dBW</td>
<td>75 - 116 dBW</td>
</tr>
</tbody>
</table>

2.1 1 to 6 GHz band

The analysis of this band will be based on typical equipment (existing or planned) in the 2 GHz band. Table I provides a comparison of the system parameters of the Space Research Service (for near-Earth satellites and deep-space probes) and of the Space Operation Service.

The system parameters of satellites in the Space Research Service (near-Earth) and the Space Operation Service are very similar, the Space Operation Service usually occupying the lower part of the performance range. The latter fact substantiates the statement made in the Introduction concerning the coordination with other services (terrestrial) sharing the band. Finally, the standards used for maintenance, telemetry, telecommand and tracking, are identical or very similar. The Space Research Service (near-Earth) and the Space Operation Service are thus mutually compatible and can consequently share the same bands.

As for the frequency sharing between the Space Research Service (deep-space) and the Space Operation Service, the results of Report 685 are directly applicable, i.e. sharing is not feasible in this case.

Interference situations between satellites operating in the Space Research Service (near-Earth) and the Space Operation Service occur relatively rarely and are generally of short duration. This is explained, in particular, by the fact that the majority of research satellites use low orbital altitudes (up to 2000 km). Typical interference durations of less than 1 minute would be encountered between a low-orbiting satellite and a satellite at geostationary altitude for a pass through the centre of the antenna beam with both satellites operating at the same frequency. Consequently, interference periods can be kept to well below 0.1% of the time, which is acceptable for both Services. Interference situations can be further reduced by conscientious frequency assignments based on frequency coordination between spacecraft operators, where possible even ahead of the advance publication (see No. 1042 of the Radio Regulations).
2.2 6 to 10 GHz band

The sharing situation in the 6 to 10 GHz range is virtually the same as in the 1 to 6 GHz range: system parameters of the Space Research Service (near-Earth) and the Space Operation Service are very similar (see Table II) and standards used for maintenance, telemetry, telecommand and tracking are identical or very similar, which renders the Services mutually compatible. Sharing should thus be feasible between the Space Research Service (near-Earth) and the Space Operation Service; it is not feasible in the case of the Space Research Service (deep-space).

From a technological point of view, sharing in the 6 to 10 GHz band is far less attractive than in the 1 to 6 GHz band, the main reasons being that towards the upper end of the 6 to 10 GHz range antenna technology for quasi-isotropic or hemispheric coverage becomes more difficult, while at the same time propagation conditions are inferior to those in the 1 to 6 GHz band — particularly the lower part thereof.

<table>
<thead>
<tr>
<th>Mode</th>
<th>System parameters</th>
<th>Space research</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Near-Earth</td>
</tr>
<tr>
<td>Reception at earth station</td>
<td>Telemetry bandwidth</td>
<td>100 kHz – 30 MHz</td>
</tr>
<tr>
<td></td>
<td>Tracking bandwidth</td>
<td>100 kHz – 2 MHz</td>
</tr>
<tr>
<td></td>
<td>G/T earth station</td>
<td>25 – 45 dB(K⁻¹)</td>
</tr>
<tr>
<td>Transmission from earth station</td>
<td>Telecommand bandwidth</td>
<td>100 kHz</td>
</tr>
<tr>
<td></td>
<td>Tracking bandwidth</td>
<td>100 kHz – 2 MHz</td>
</tr>
<tr>
<td></td>
<td>e.i.r.p. earth station</td>
<td>70 – 90 dBW</td>
</tr>
</tbody>
</table>

3. Conclusions

Sharing between the Space Research Service (near-Earth) and the Space Operation Service should be feasible in the 1 to 10 GHz band. For technological and propagation reasons the lower part of the band is more attractive than the upper part. Sharing between the Space Research Service (deep-space) and the Space Operation Service is not feasible.

Interference situations within the shared bands can be kept at an insignificant level provided that frequency assignments are made conscientiously within the framework of Article 11 of the Radio Regulations.
CHARACTERISTICS OF DATA RELAY SATELLITE SYSTEMS

1. System concepts of data relay satellites

A data relay satellite is a satellite used to relay data between space stations and earth stations.

The purpose of this report is to present a general description of telecommunication links between earth stations and low orbit space stations which use one or more geostationary satellites as intermediate relays. Reference to Reports 846 and 847 should be made for more detailed information relating to sharing and compatibility with other services and to sharing within the space research service.

Annex I contains the description of a data relay satellite system developed by the United States and which is now in operation. Annexes II and III contain descriptions of data relay satellite systems being proposed for future use.

Before the advent of data relay satellite systems, the United States, Europe and other countries could only use widespread networks of earth stations to receive telemetry from spacecraft-borne instrumentation. These data, once received by an earth station, are routed by various means to central data processing sites. In addition to receiving the scientific data from spacecraft, the Earth-based network must transmit commands to the spacecraft and annotate the received data with auxiliary information such as the spacecraft to earth station range and rates of change of range and time of arrival of the data.

The principal purposes of a data relay satellite system are to improve the efficiency and reduce the cost of returning spacecraft-gathered scientific data to Earth and to improve the reliability and continuity of communications with manned space stations and other low orbit spacecraft. An operational system might comprise two geostationary satellites, separated by up to about 130 degrees of longitude in conjunction with a single earth station, or by up to about 180 degrees of longitude when implemented using two separate earth stations. A data relay satellite system can thus not only replace a network of some 10 to 20 earth stations but can also provide increased capability for obtaining data from and supporting communications with low orbit spacecraft.
A data relay satellite must be capable of supporting at least four distinct links:

- an Earth-to-space link in the forward direction, from the earth station to the data relay satellite (sometimes known as the up-link);
- a space-to-space link in the forward direction, from the data relay satellite to the low orbit spacecraft (sometimes known as the forward link);
- a space-to-space link in the return direction, from the low orbit spacecraft to the data relay satellite (sometimes known as the return link); and
- a space-to-Earth link in the return direction, from the data relay satellite to the earth station (sometimes known as the down-link).

For these four links, four separate frequency bands are required, with a guard band between the signals transmitted from and those received by the data relay satellite. Because of the diverse requirements of the low-orbit spacecraft, especially in terms of the transmission bandwidth required and the pointing accuracy of the antenna on the low orbit spacecraft which can be achieved, some data relay spacecraft may support space-to-space links in two or more pairs of frequency bands.

2. Telecommunication requirements for near-Earth spacecraft using data relay satellite systems

The new generation of low-orbit spacecraft will include permanently-manned, intermittently-manned and unmanned space stations. These spacecraft will carry very large payloads comprising multiple experiments and operational instruments for earth observation, space science, astronomy, life sciences, material processing and other applications. They will also carry increasingly sophisticated instrumentation for spacecraft attitude and orbit control and for management of spacecraft power, thermal and life support systems. Many experiments will require regular video monitoring, and the use of robot control of materials in space will require real-time video links. Astronauts on board the spacecraft require real-time two-way voice links and video links both from space-to-ground and ground-to-space. Space-to-ground links are required to allow ground support personnel to monitor on-board operations, as well as for public information purposes. Ground-to-space links are required to allow ground personnel to demonstrate the operation of equipment to the astronauts, and for television. Complex data transmission networks are being developed to handle these multiple interleaved communications requirements.

Data relay satellites may be required to provide many different types of links for these spacecraft, used for one or more of the following purposes:

- To forward commands, for which a high-quality digital link is required. Data rates are likely to be low, from a few tens of kbit/s to a few hundreds of kbit/s, depending on the complexity of the spacecraft.
To forward data, software control programmes, timing and other signals to control systems associated with the spacecraft or with the experiments or other payloads carried on board the spacecraft, for which a high-quality link is required. (This quality can be attained by use of forward error-correction techniques as well as by use of error-detection associated with "selective request for repeat" (ARQ) techniques.) Data rates may need to be higher, up to a few Mbit/s, to accommodate the many different data streams.

To return telemetry data from the spacecraft. In normal operation, several hundred kbit/s may be required. An emergency mode, providing only a few kbit/s may also be required.

To return experimental data from the spacecraft. This may range from a few kbit/s to several hundreds of Mbit/s depending on the spacecraft payload. Example payloads include high-resolution radar and visual imaging sensors each of which may have an output data rate exceeding 100 Mbit/s.

To measure the location of the spacecraft by means of two-way ranging signals. Such signals generally occupy only narrow bandwidths but may require a separate carrier or sub-carrier.

To communicate with the crew on manned space vehicles by two-way voice.

To provide video links to or from the spacecraft.

The total communications requirements of a spacecraft using a data relay satellite system are likely to include direct space-to-ground links as well as space-to-space links between space stations in close proximity to each other, which are not discussed here. The requirements for the communications links through the data relay satellite are likely to vary depending on the mission phase and the spacecraft operational status. At any time, one of the following types of link is likely to be required:

- A two-way link at very low data rate (a few kbit/s) with an omnidirectional antenna on the low orbit spacecraft. Such links are used during spacecraft launch or re-entry when a high-gain antenna cannot be deployed, or during loss of control of spacecraft attitude. Low data rate links are also used for on orbit tracking, telemetry and command functions.

- A one-way or two-way link at low data rate (typically up to a few tens of kbit/s) using a number of low-gain fixed antennas on the low orbit spacecraft, any one of which can be selected for use when the data relay satellite is in the appropriate sector of view, using open loop pointing only.
Links at low data rate (typically up to a few kbit/s forward and a few Mbit/s return) with steerable antennas on the low orbit spacecraft, having relatively low gain, which can be steered towards the data relay satellite by open loop pointing, only.

Forward and associated return links at medium data rates (up to tens of MBPS), with high gain steerable antennas on the low orbit spacecraft which require active closed loop steering to direct them towards the data relay satellite.

Forward links at medium data rates, associated with return links at high data rates (up to hundreds of MBPS), with high gain steerable antennas on the low orbit spacecraft which require active closed loop steering to direct them towards the data relay satellite.

3. Preferred frequency bands

Choice of the frequencies to be used for space-to-space links may be guided by two major considerations. In some cases, it may be desirable to use the same frequencies as for direct links, so that the low orbit spacecraft can use the same terminal for both direct links to Earth and links via the relay satellite. This is valid in particular for tracking, telemetry, maintenance and telecommand links. In other instances, one may wish to take advantage of the absence of any atmosphere between the low orbit spacecraft and the relay satellite to use higher, less congested frequencies, thereby opening up the possibility of larger bandwidths and very high antenna gains. This might be appropriate, for example, for mission data transmissions. Also the attenuation of higher frequencies by the Earth's atmosphere will help reduce the mutual interference potential between terrestrial systems and space-to-space links.

For provision of links to spacecraft equipped with omnidirectional or low-gain antennas steered only by open loop pointing, frequencies in band 9 are technically preferred.

For provision of links at medium data rates (up to tens of Mbit/s) where higher gain antennas are required, frequencies in band 10 are technically preferred.
For links at high data rates, considerable bandwidth is required, and individual spacecraft may require links with data rates aggregating up to hundreds of Mbit/s in the return direction (return link and down-link) and up to tens of Mbit/s in the forward direction (up-link and forward link). A single data relay satellite will be required to handle signals from several low orbit spacecraft simultaneously, so may eventually need to handle up to 1 Gbit/s at a time in the return direction and 100 Mbit/s in the forward direction. The modulation techniques must be designed to operate in a severe environment where mass and power, both on the low orbit spacecraft and on the data relay satellite, are severely limited. Suitable techniques, such as phase modulation in conjunction with half-rate forward error-correction coding, require bandwidths to data rate ratios of approximately 1.6 Hz per bit/s. Thus total bandwidths of up to 1.6 GHz in the return direction and 200 MHz in the forward direction are required. On this basis, frequencies in bands 10 or 11 are technically preferred.

Information on preferred frequencies for space-to-space links may also be found:

- in Report 982 concerning earth exploration satellites;
- in Report 984 concerning spacecraft for near-Earth space research;
- in Report 849 concerning spacecraft for deep-space research.

Use of optical laser systems is also being studied and experimental optical inter-orbit link systems are being developed. Additional information concerning these types of system can be found in Report 680.

4. Conclusions

Data relay satellite systems are able to replace complex, world-wide networks of earth stations and to improve the availability and continuity of communications between the Earth and low orbit spacecraft. New manned and unmanned spacecraft will be designed to use data relay satellite systems to provide their communication requirements.
ANNEX I

THE UNITED STATES TRACKING AND DATA RELAY SATELLITE (TDRS) SYSTEM

1. TDRS low and medium data-rate communications

The data rates produced by the majority of scientific spacecraft are modest, generally ranging from about 1 to 250 kbit/s. The TDRS system will be capable of relaying data from up to 20 low-orbit spacecraft simultaneously to the TDRS ground station. The TDRS sub-system which performs this function, operates on frequency of 2287.5 MHz. The capability of receiving up to 20 co-frequency data streams, each originating from a separate spacecraft, is obtained through the use of code division multiplexing techniques, and the use of a multi-beam phased array antenna on board the TDRS. At the low-orbit spacecraft, the scientific data along with pseudo noise (PN) code are modulated onto the transmitted carrier frequency. This signal is received by a 30 element array antenna on board a TDRS satellite. The information received by each of the 30 antenna elements is isolated, using frequency division multiplex techniques, translated to 13.5 GHz, and retransmitted to the TDRS earth station. After reception at the earth station, the data streams from all 30 antenna elements are demultiplexed, each data stream delayed slightly in phase, and then recombined. Delaying the phase of the signal received by each element of TDRS antenna array creates a synthetic phased array beam. The phase delay introduced into each of the 30 received data streams from the desired satellite is adjusted to maximize the signal based upon the predicted satellite position which, in effect, "aims" this synthesized beam at the low-orbit spacecraft. As the low-orbit spacecraft moves in orbit, the phase delays introduced into the 30 antenna element signals are changed to keep the synthesized beam "tracking" the spacecraft.

After the synthesized beam has been formed, the enhanced signal is processed to remove the PN code modulation. This processing further enhances the data signal while simultaneously suppressing interference and signal components from the other 19 scientific satellites being received on the same centre frequency.

As implemented, the limitation on the total number of scientific spacecraft which may simultaneously use this TDRS “multiple access” (MA) system is based upon the number of MA processing computers available at the TDRS ground station. In the US system, 20 such computers will be employed, thereby limiting the number of multiple access user satellites to 20, regardless of the actual number of TDRS satellites in orbit.

In addition to receiving data from low-orbit spacecraft, the multiple access system is capable of relaying commands from the TDRS earth stations to the low-orbit spacecraft. Seventeen of the 30 elements in the phased array antenna contain programmable phase shifters. These elements, under control of the TDRS earth station, can be used to form a single phased array transmit beam which can be directed at a scientific spacecraft. The multiple access command information is transmitted from the earth station to a TDRS satellite on 14.8 GHz, where it is frequency-shifted to 2106.4 MHz, and retransmitted to the low-orbit spacecraft. In order to ensure that only one of the low-orbit spacecraft responds to the multiple access commands, the command information is modulated on a PN data stream. The transponders in the low-orbit spacecraft will only respond to a single unique PN code. The use of the PN modulation also spreads the command signal energy over a 6.2 MHz bandwidth. This spectrum spreading technique reduces the power flux-density at the surface of the Earth, while simultaneously allowing the low-orbit satellite to receive command information with a usable signal strength.

Each TDRS phased array antenna is capable of forming only one transmit beam at a time, therefore the number of multiple access command links corresponds to the number of operational TDRS satellites.

2. TDRS high data-rate communications

In order to provide for the relay of high data rate telemetry to and from the scientific spacecraft, each TDRS satellite is equipped with two 4.9 m steerable parabolic reflector antennas. Each of these antennas will be used to track a low-orbit satellite and relay communications between the low-orbit satellite and the TDRS earth station. The antennas are equipped with dual feeds capable of operating in either band 9 or band 10. An additional 2 m antenna, operating only in band 10, relays data to and from the TDRS satellite and the TDRS earth station. For high data rate applications the TDRS satellites operate as simple frequency translating repeaters. The band designation, “band 10 or band 9” refers to the frequency band in which the TDRS to low-orbit spacecraft communications takes place.
2.1 Band 9 high data-rate communication

The TDRS band 9 high data rate communication system (also termed the "S-band" single access or SSA system) will transmit from the geostationary TDRS satellite to the low-orbit spacecraft in the 2025-2110 MHz frequency band. This system has a usable bandwidth of 20 MHz; however, for most applications the relayed signal will be a 6.2 MHz PN coded PSK signal. The maximum usable data rate using the PN coded signal is 1 Mbit/s. The 20 MHz TDRS system bandwidth will allow for high data rate communication using non-PN coded PSK modulation should this capability be required.

The TDRS satellites receive the data, which is to be relayed to the low-orbit spacecraft, from the TDRS earth station at 14.68 and 14.72 GHz.

The low-orbit spacecraft-to-TDRS communications will take place in the 2200-2290 MHz frequency band. The low-orbit spacecraft will transmit on a 10 MHz wide channel within this frequency range, and will usually use PN coded 6.2 MHz bandwidths. The maximum information data rate with PN coding is about 1 Mbit/s although up to 5 Mbit/s can be relayed by the TDRS system if non-PN coded transmissions are used.

Within the TDRS satellite the two band 9 high data rate channels are up-converted to band 10 for transmission to the TDRS earth station. These space-to-Earth links are implemented at 13.768 and 13.698 GHz respectively.

2.2 Band 10 high data-rate communication

The band 10 high data rate communications system (also termed "K-band single access or KSA system") transmits from the TDRS to the low-orbit spacecraft on 13.775 GHz.

While the system is capable of relaying up to 25 Mbit/s of FSK modulated data, the usual transmitted signal will consist of up to 1 Mbit/s of information on a 6.2 MHz PN modulated data stream. The actual maximum information data rate will depend upon the gain and receiver noise temperature of the low-orbit spacecraft. The corresponding Earth-to-TDRS links, for this service, will be implemented at 14.625 and 15.2 GHz.

A single channel is available for receiving high data rate transmissions from low-orbit spacecraft. This channel has a bandwidth of 225 MHz, and is received at the TDRS satellite on a centre frequency of 15.0 GHz. When two low-orbit spacecraft are simultaneously transmitting to the TDRS on this frequency band, one of the transmissions will use left-hand circular polarization and the other right-hand circular polarization. The resulting polarization discrimination, in conjunction with the TDRS antenna discrimination, is sufficient to separate the two signals. The two signals are relayed to the TDRS earth station on 13.53 and 13.93 GHz respectively.

3. Ranging operations in the TDRS system

Information concerning the orbital parameters of scientific spacecraft is of extreme importance to the completion of the spacecraft mission. For this reason two types of ranging operations will take place with the TDRS system. The first type of operation yields information on the overall communication path length between the TDRS earth station and the low-orbit spacecraft. However, since this operation is relayed through the TDRS geostationary satellite, any change in the position of the TDRS satellite itself will affect the measured distance to the low-orbit spacecraft during ranging operations. The second ranging operation (termed bilateration ranging) is designed to supply precise information on location of the TDRS satellites so that movement of the TDRS satellite can be taken into account when determining the position of the low-orbit spacecraft.

Both types of ranging operations are carried out in a similar fashion, and are based upon determining the time a signal takes to go from the TDRS earth station, through the TDRS satellite, to a low-orbit spacecraft transponder and then return to the earth station. The range from the TDRS earth station through the TDRS satellite to the low-orbit spacecraft transponder is of the order of 70 000 km. A signal transmitted by the earth station, transponded and then received by the earth station will take about half a second to make the round trip. By precisely measuring the signal round trip time and accounting for the equipment time delay and other known factors, the range to the low-orbit spacecraft transponder can be determined to an accuracy of several tens of metres. As mentioned above, this ranging system can be used two ways:

- if the transponder is placed at a known position on the surface of the Earth, then the location of the TDRS can be determined (actually several measurements using different locations on the surface of the Earth are required to yield an accurate location of the TDRS satellite);
- if the transponder is on board a low-orbit spacecraft, and if several measurements of range and range rate are made, the orbital motions of the scientific spacecraft can be accurately determined.
This ranging system is implemented in the TDRS system, by modulating a long sequence PN ranging code in quadrature with the standard information bearing PN signal. This ranging code can be used in conjunction with either the low data rate or high data rate system.

The bilateration system, used to determine the position of the TDRS satellite, will operate using the low-data rate band 9 system. The bilateration earth terminals will receive on 2106.4 MHz and transmit on 2287.5 MHz, using a 6.2 MHz and a 5 MHz bandwidth respectively. These terminals will use 23 dB gain antennas and have an e.i.r.p. of 35 dBW.

4. Time transfer

Once the range to a particular TDRS user transponder has been determined, as discussed in § 3, the time a signal takes to go from the TDRS earth station to the transponder is known. With this information it is possible to transmit precise time information for use at the transponder. By using this technique, both scientific spacecraft and selected Earth-based facilities may be supplied with very accurate time information. The details of the actual technique used to transfer time information via the TDRS system have been defined and the system will use the standard low-data rate TDRS link. The time transfer system is compatible with the bilateration earth terminals and the low-orbit spacecraft low-data rate transponders.

5. Simulation and spacecraft testing

Before a spacecraft is launched, all of its operating systems must be fully tested. In order to test the communication systems of spacecraft prior to launch, spacecraft simulation stations located at the launch sites will be connected to a simulator terminal, via a hard-wired connection, and the entire spacecraft, TDRS satellite and TDRS earth station system will be tested.

Two other simulation-terminals will be used to test portions of communications systems. These terminals are located at the US Goddard Space Flight Center and at the TDRS earth station.

6. TDRS command and control links

The TDRS system uses two independent command and telemetry systems, an operational system operating in band 10, and an emergency back-up system which operates in band 9. The operational command and telemetry system utilizes the 18 m antenna at the TDRS ground station and operates with 80.3 dBW of e.i.r.p. The TDRS telemetry is transmitted to the TDRS earth station at 13.731 GHz, and the commands are transmitted from the earth station at 14.786 GHz.

The emergency command and telemetry system is designed to operate automatically if a TDRS satellite loses attitude control. The telemetry system, transmitting via an omnidirectional antenna on the TDRS, operates on 2210 MHz. The corresponding emergency command system operates on 2036 MHz.

In addition, a highly stable 15.15 GHz “pilot tone” is transmitted from the TDRS ground station to the TDRS satellites. This tone is used on board the satellite as a frequency reference to ensure that the various frequency translation operations are carried out in a precise manner.

7. Summary of TDRS system parameters

Table I gives the technical parameters of a DRS system developed in the United States of America. This Table is extracted from Report 537 (Kyoto, 1978).
### TABLE I
**TDRS system technical parameters**

<table>
<thead>
<tr>
<th></th>
<th>Earth station to relay</th>
<th>Relay to user spacecraft</th>
<th>User spacecraft to relay</th>
<th>Relay to earth station</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Frequency band</strong></td>
<td>Band 10</td>
<td>Band 9</td>
<td>Band 10</td>
<td>Band 10</td>
</tr>
<tr>
<td></td>
<td><strong>Radio-frequency</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>bandwidth (MHz)</td>
<td>330</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td><strong>Data rate (Mbit/s)</strong></td>
<td>(1)</td>
<td>0-1</td>
<td>1</td>
</tr>
<tr>
<td><strong>Earth station</strong></td>
<td>e.i.r.p. (dB(W/Hz))</td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Relay satellite</strong></td>
<td>Receive antenna gain (dB)</td>
<td>50</td>
<td>36</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>Receive system noise temperature (K)</td>
<td>2300</td>
<td>720</td>
<td>2300</td>
</tr>
<tr>
<td></td>
<td>e.i.r.p. (dB(W/Hz))</td>
<td>-28</td>
<td>-26</td>
<td>-26</td>
</tr>
<tr>
<td><strong>User</strong></td>
<td>receive system noise temperature (K)</td>
<td>800</td>
<td>-51 (2)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>e.i.r.p. (dB(W/Hz))</td>
<td>2050</td>
<td>-49 (3)</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Earth station</strong></td>
<td>receive system noise temperature (K)</td>
<td>10 - 28</td>
<td></td>
</tr>
<tr>
<td></td>
<td>e.i.r.p. (dB(W/Hz))</td>
<td></td>
<td></td>
<td>420</td>
</tr>
</tbody>
</table>

(1) Composite of all signals sent to user spacecraft.
(2) Composite of all signals received from user spacecraft.
(3) Actual value dependent upon user satellite altitude.

### BIBLIOGRAPHY


REDISCH, W. N. [1975] ATS-6 description. IEEE Electronics and Aerospace Systems Convention (EASCON '75), Convention Record 1S3-C.


ANNEX II

THE EUROPEAN DATA RELAY SATELLITE (EDRS) SYSTEM

1. Introduction

System design studies are currently underway in Europe to define a European data relay satellite system (EDRS) which will provide an operational data relay satellite service to support the communication requirements of the European Polar Platform (PPP) satellites, the European man-tended free flier (MTFF) (elements of the COLUMBUS Programme) and the European space plane, HERMES, as well as providing a capability to support other European or non-European user spacecraft.

2. System configuration

Two geostationary relay satellites are planned, one at 44 degrees West longitude and one at 59 degrees East longitude.

Each relay satellite will be able to serve a number of user spacecraft by means of independent, fully steerable inter-orbit link (IOL) antennas. Design options under study incorporate from two to four antennas, with reflectors of 2.5 to 3.0 metres diameter, each able to support one user, using a "single-access" technique. Each antenna will be equipped with either one feed system, capable of operating in band 10, or two feed systems configured so that the antenna is capable of operating either in band 9 or in band 10.

Each relay satellite will serve earth stations across the entire visible area of the Earth by means of two feeder-link antennas, operating in the bands 27.5 - 30.0 GHz in the forward (Earth-to-space) direction and 17.7 - 20.2 GHz in the return (space-to-Earth) direction. The primary feeder-link antenna will provide extended coverage of most of Western Europe. The second feeder-link antenna will be fully steerable so as to be able to serve an earth station at any location on the Earth's surface visible from the DRS satellite.

The EDRS system differs from other data relay satellite systems in its decentralized communications configuration which separates the relay satellite control functions from the data relay functions and allows different earth stations in different locations to be used to communicate with each of the user spacecraft in low orbit. Plans are to provide protection against forward feeder-link interference by installing frequency converters in the relay satellite forward-link repeaters (tunable by means of telecommand signals), and to design earth stations and user spacecraft to operate each on one assigned frequency.

3. EDRS low and medium data-rate communications

The EDRS is planned to provide low and medium data-rate communications using frequencies in band 9 from 2 025 MHz - 2 110 MHz in the forward direction and from 2 200 MHz - 2 290 MHz in the return direction.
When operating in band 9, an IOL antenna will be connected to a tunable frequency-translating repeater and will point towards and track the user spacecraft by open loop pointing. This technique employs a sequence of telecommands derived from a knowledge of its orbital parameters.

The forward link is designed to handle data rates from 100 bit/s up to 1 Mbit/s and the return link data rates from 100 bit/s up to 5 Mbit/s, using phase modulation either directly or in conjunction with a pseudo-noise (PN) code, nominally at 3 Mchip/s in order to reduce the power flux-density of the signal.

4. **EDRS high data-rate communications**

The EDRS is planned to provide high data-rate communications using frequencies in band 10 in the forward direction from 23.15 GHz - 23.55 GHz and in the return direction from 25.25 GHz - 27.50 GHz.

When operating in band 10, an IOL antenna will initially point towards the user spacecraft by open loop pointing and will then track it by means of closed loop antenna steering.

The forward link is designed to handle data rates from 1 kbit/s up to 25 Mbit/s, using phase modulation, and the return link is designed to handle data rates from 1 kbit/s up to 600 Mbit/s, using one or more channels each with a data rate up to 150 Mbit/s and using phase modulation. On the return link half-rate convolutional coding, which will be decoded at the earth terminal by a soft-decision Viterbi decoder, will reduce the required signal power densities by a useful amount, and also render the system less susceptible to interference.

5. **EDRS high data-rate communications (Optical)**

The European Space Agency is developing an experimental optical intersatellite communications system which may be flown on EDRS to provide a pre-operational data relay service. The tentative specifications for this service are similar to those of the high data-rate service using band 10.

6. **EDRS technical parameters**

Table II below gives the provisional technical parameters of the data relay system presently under study in Europe.
# TABLE II

**EDRS technical parameters**

<table>
<thead>
<tr>
<th></th>
<th>Forward direction</th>
<th>Return direction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Earth station to relay</td>
<td>Relay satellite to user spacecraft</td>
</tr>
<tr>
<td><strong>Frequencies (4)</strong></td>
<td>27.5 GHz to 30.0 GHz</td>
<td>2025 MHz to 2110 MHz</td>
</tr>
<tr>
<td><strong>Data rate per channel</strong></td>
<td>up to 1 Mbit/s</td>
<td>up to 25 Mbit/s</td>
</tr>
<tr>
<td><strong>Channels per user spacecraft</strong></td>
<td>1 (3)</td>
<td>1 (3)</td>
</tr>
<tr>
<td><strong>Earth station e.i.r.p. (dB(W/Hz))</strong></td>
<td>28</td>
<td></td>
</tr>
<tr>
<td><strong>Receive system noise temperature (K)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Relay satellite receive antenna gain (dB)</strong></td>
<td>38</td>
<td>34</td>
</tr>
<tr>
<td><strong>Receive system noise temperature (K)</strong></td>
<td>1600</td>
<td>760</td>
</tr>
<tr>
<td><strong>e.i.r.p. spectral density (dB(W/Hz))</strong></td>
<td>-23</td>
<td>-9</td>
</tr>
<tr>
<td><strong>User spacecraft receive antenna gain (dB)</strong></td>
<td>25</td>
<td>46</td>
</tr>
<tr>
<td><strong>Receive system noise temperature (K)</strong></td>
<td>760</td>
<td>1450</td>
</tr>
<tr>
<td><strong>e.i.r.p. spectral density (dB(W/Hz))</strong></td>
<td>-29</td>
<td>-23</td>
</tr>
</tbody>
</table>
Notes to Table II, Annex II

(1) Composite of all signals sent to user spacecraft.

(2) Composite of all signals received from user spacecraft.

(3) Some user spacecraft are planned for space-to-space links in band 10 for normal operations and in band 9 for emergency and back-up operations.

(4) An additional pre-operational space-to-space link using optical transmission is also under study.

BIBLIOGRAPHY

DICKINSON, A., DINWIDDY, S.E. and SANDBERG, J. [August 1987] - The European data relay system as part of the in-orbit infrastructure ESA bulletin, No. 51, 47-52.
ANNEX III

AN ADVANCED DATA RELAY SATELLITE SYSTEM OF THE UNITED STATES

1. Introduction

Studies are currently underway in the United States to define a follow-on data relay satellite system to replace the current TDRS system. The new system will be an advanced data relay satellite system which, in addition to maintaining the capabilities of the current TDRS system for service continuity, will also provide increased capacity and new services to user satellites. The new system will replace the TDRS system in a gradual transition and, when fully deployed, will meet communication and tracking requirements in the 1995-2010 time frame.

2. System capacity

The advanced data relay satellite concept is currently expected to be capable of supporting national and international space station programmes, several polar orbiting satellites and 10 to 25 other scientific satellites. It is currently expected that the aggregate data requirements associated with Space Station Freedom operations will result in average data rates occasionally exceeding 500 Mbit/s. Other high rate communications needs; such as those associated with microgravity experiments, solar flare experiments and life sciences observations, may drive overall data rate requirements into the gigabit per second range by the year 2000.

3. Frequency plan

Current data rate requirements indicate the need for two 650 Mbit/s channels and two 300 Mbit/s channels per data relay satellite. Because of the bandwidth requirements associated with these data needs it is expected that links between the earth station and each relay satellite (feeder links) will, eventually, be accommodated in fixed-satellite service allocations near 20 GHz and 30 GHz.

Current space research service allocations at 2 GHz and 14 GHz are inadequate to support the maximum bandwidth requirements of space-to-space links. Therefore, it is anticipated that these links will be accommodated in allocations above 20 GHz.

In consideration of these data needs, study is being focused on advanced data relay satellite operations to be conducted in frequency bands as shown in Table III.
### TABLE III

**BANDWIDTH/DATA RATE REQUIREMENTS BASELINE FOR ADVANCED DATA RELAY SATELLITE**

<table>
<thead>
<tr>
<th>DIRECTION</th>
<th># OF LINKS</th>
<th>DATA RATE</th>
<th>FREQUENCY BAND (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relay Satellite to User</td>
<td>2</td>
<td>100 Mbit/s</td>
<td>Above 20 GHz¹</td>
</tr>
<tr>
<td>(Forward Link)</td>
<td>4</td>
<td>50 Mbit/s</td>
<td>Near 15 GHz</td>
</tr>
<tr>
<td>User to Relay Satellite</td>
<td>2</td>
<td>300 Kbit/s</td>
<td>Near 2 GHz</td>
</tr>
<tr>
<td>(Return Link)</td>
<td>2</td>
<td>10 Kbit/s</td>
<td>Near 2 GHz</td>
</tr>
<tr>
<td>User to Earth</td>
<td>2</td>
<td>650 Mbit/s</td>
<td>Above 20 GHz¹</td>
</tr>
<tr>
<td>to Relay Satellite</td>
<td>4</td>
<td>300 Mbit/s</td>
<td>Near 15 GHz</td>
</tr>
<tr>
<td>Earth to Relay Satellite</td>
<td>2</td>
<td>To Be Determined</td>
<td>Near 15 GHz</td>
</tr>
<tr>
<td>(Up-link)</td>
<td></td>
<td></td>
<td>Near 30 GHz</td>
</tr>
<tr>
<td>Relay Satellite to Earth</td>
<td>1</td>
<td>To Be Determined</td>
<td>Near 15 GHz</td>
</tr>
<tr>
<td>(Downlink)</td>
<td></td>
<td></td>
<td>Near 20 GHz</td>
</tr>
</tbody>
</table>

Notes: ¹ Including bands near 60 GHz.
REPORT 982

DATA RELAY SATELLITES FOR THE EARTH EXPLORATION SATELLITE SERVICE

(Question 11/2)

(1986)

1. Introduction

Future operational Earth exploration satellites (EES) will require data handling systems capable of supporting the combined data rates of multiple high resolution imaging sensors. The attendant data rates from these low-orbit EES satellites will be as high as 600 Mbit/s and will require large bandwidths which are only available at frequencies above 10 GHz. However, pfd and technology constraints above 10 GHz severely limit the usefulness of direct transmission from an EES to an earth station. Due to these constraints and the requirements for world-wide coverage, a synchronous relay satellite will be necessary. The relay satellite will be designed to relay simultaneously 600 Mbit/s data links from two low orbit EES to a single earth station. Each data link will require an 800 MHz transmission bandwidth, for a total bandwidth requirement with guard bands of 1800 MHz.

This Report describes the preferred frequency bands and sharing aspects of a relay satellite capable of simultaneously supporting two future wideband EES satellites and also discusses the technical characteristics of one possible implementation of an operational EES relay satellite.

The telecommunication system required to transfer these large quantities of data can be implemented by the use of two wideband data links and a narrowband command link as shown in Fig. 1. The links required are:

- A space-to-Earth link from the relay satellite to an earth station in the vicinity of a large data processing facility. This segment will resemble a fixed-satellite service down link.

- A space-to-space data link from the low-orbit EES to a geostationary relay satellite. This link may be implemented anywhere in the spectrum where sharing problems are not encountered and where near-future technology can provide a workable system. The region of 25 to 30 GHz appears to be a good choice for this link from both a sharing and technology standpoint.

- In addition, a command relay channel though the relay satellite is required to control the EES. If the command links (earth station-relay satellite and relay satellite-EES) are close enough in frequency to the EES wideband data links, the space-space portion can utilize the high gain pointable antennas required on board the EES and relay satellite spacecraft for data transmission.

2. Relay satellite to Earth data link

Due to the similarity of the relay satellite-to-Earth wideband data link to a fixed-satellite service system, this link might be implemented in the 15 to 20 GHz portion of the spectrum where the required bandwidth of 1800 MHz is available. Table I shows a typical link calculation for a relay satellite earth station down link that yields an overall carrier-to-noise plus interference ratio of 13 dB and a bit-error probability of $10^{-6}$. 
FIGURE 1 — Operational EES relay satellite data transfer system

A: Relay satellite to EES telecommand link
B: EES to relay satellite link
C: Earth to relay satellite telecommand link
D: Relay satellite to Earth data link
E: Data relay satellite
F: Earth exploration satellite (EES)
G: Large central data processing facility

TABLE I — Relay satellite to earth station typical link parameters
(near 19 GHz, 800 MHz bandwidth)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>12.3</th>
<th>52.5</th>
<th>64.8</th>
<th>-163.2</th>
<th>-29.0</th>
<th>-1.2</th>
<th>-5.5</th>
<th>-4.0</th>
<th>-1.0</th>
<th>+18.9</th>
<th>-60.0</th>
<th>-180.2</th>
<th>-200.6</th>
<th>20.4</th>
<th>3.0</th>
<th>17.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relay satellite transmit power (dBW)</td>
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<tr>
<td>Relay satellite transmit gain (dBi) (antenna diameter: 3 m)</td>
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<tr>
<td>e.i.r.p. (dBW)</td>
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<tr>
<td>Allowance for spreading loss (40 600 km, 10° elevation) (dB)</td>
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<tr>
<td>Bandwidth conversion (MHz/800 MHz) (dB)</td>
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<tr>
<td>Atmospheric absorption (dB)</td>
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<td>Precipitation attenuation (dB)</td>
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<td>Cloud loss (dB)</td>
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<td>Miscellaneous losses (dB)</td>
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<tr>
<td>Receiver antenna effective area $S$ (12.2 m diameter at 19 GHz) (10 log $S$)</td>
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<tr>
<td>Bandwidth conversion (Hz/MHz) (dB)</td>
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<tr>
<td>Received power spectral density (dB(W/Hz))</td>
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<tr>
<td>Receiver system noise spectral density ($T = 400 K$) (dB(W/Hz))</td>
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<tr>
<td>$C/N$ down path (dB)</td>
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<td>Margin (dB)</td>
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<tr>
<td>Required $C/N$ down path (dB)</td>
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</tr>
</tbody>
</table>
3. **EES to relay satellite data link**

A choice of EES-to-relay satellite up-link parameters will be determined by the available power, the allowable antenna sizes and the pointing capabilities of both the EES and the relay satellite spacecraft.

The relationship between transmitter power, antenna size, and carrier frequency was evaluated to determine the minimum power EES configuration. This analysis assumed a data rate of 600 Mbit/s, a $C/N$ ratio of 14.9 dB and a maximum range from the geostationary orbit to a 5000 km spacecraft of 51 000 km. The following pointing accuracies and minimum beamwidths were assumed:

- EES pointing accuracy = 0.1°
- minimum beamwidth = 0.5°
- relay satellite pointing accuracy = 0.05°
- minimum beamwidth = 0.125°

The analysis determined that an EES having a 100 W transmitter and a 1.5 m antenna would be compatible with the above accuracies if the EES-to-relay satellite link were implemented in the 25 to 29 GHz spectral region. There are several existing frequency bands in this spectral region which are wide enough to support the simultaneous up-link operations from two 600 Mbit/s systems (1800 MHz required bandwidth).

Table II presents the link parameters for an EES-to-relay satellite system operating in the vicinity of 27 GHz. The actual implementation of a system such as this, is dependent upon the technical feasibility of constructing the satellites. The EES must carry a 100 W transponder operating near 27 GHz with a 1.5 m antenna, pointable to 0.1°. The relay satellite will require a 3.0 m antenna, pointable to 0.05°. These characteristics are within the range of technological advances in the foreseeable future.

<table>
<thead>
<tr>
<th>TABLE II — EES-to-relay satellite (space-to-space) link parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>EES transmit power (dBW)</td>
</tr>
<tr>
<td>EES antenna gain (1.5 m at 27 GHz; beamwidth 0.5°) (dBi)</td>
</tr>
<tr>
<td>Line losses (dB)</td>
</tr>
<tr>
<td>EES e.i.r.p. (dBW)</td>
</tr>
<tr>
<td>Free space loss (51 000 km at 27 GHz) (dB)</td>
</tr>
<tr>
<td>Relay satellite antenna gain (3.0 m at 27 GHz; beamwidth 0.26°) (dBi)</td>
</tr>
<tr>
<td>Line losses (dB)</td>
</tr>
<tr>
<td>DRS received power (dBW)</td>
</tr>
<tr>
<td>Bandwidth conversion (800 Mbit/s) (dB)</td>
</tr>
<tr>
<td>Relay satellite received power density (dB(W/Hz))</td>
</tr>
<tr>
<td>Relay satellite receiver noise density ($T = 2500$ K) (dB(W/Hz))</td>
</tr>
<tr>
<td>Received $C/N$ (dB)</td>
</tr>
</tbody>
</table>
4. Command links

The EES system requires two command links — one from the earth station to the relay satellite and one from the relay satellite to the EES. The required command link data rates and beamwidths are considerably less than that for the high data rate links. The command bandwidth will be of the order of 50 MHz. However, if the command link frequency bands are sufficiently close to the data frequencies, a weight and size reduction can be achieved by using the same antennas for both the relay satellite-EES command link and the EES-relay satellite data link. This consideration underlies the choice of 27.5 to 30 GHz for the command channel, provided the wide band data channel is at 25.25 to 27.5 GHz.

The technical characteristics chosen for the command links are shown in Table III.

<table>
<thead>
<tr>
<th>TABLE III — EES command (Earth-to-space and space-to-space) link parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>27.5 to 30.0 GHz Earth relay satellite link</strong></td>
</tr>
<tr>
<td>Earth station transmitter power density (dB(W/Hz))</td>
</tr>
<tr>
<td>Earth station transmitter antenna gain (dBi)</td>
</tr>
<tr>
<td>Earth station transmitter e.i.r.p. density (dB(W/Hz))</td>
</tr>
<tr>
<td>Relay satellite receiver antenna gain (1 m, 28 GHz) (dBi)</td>
</tr>
<tr>
<td>Relay satellite receiver noise temperature (K)</td>
</tr>
<tr>
<td><strong>27.5 to 30.0 GHz relay satellite EES link</strong></td>
</tr>
<tr>
<td>Relay satellite transmitter power density (dB(W/Hz))</td>
</tr>
<tr>
<td>Relay satellite transmitter antenna gain (dBi)</td>
</tr>
<tr>
<td>Relay satellite transmitter e.i.r.p. density (dB(W/Hz))</td>
</tr>
<tr>
<td>EES receiver antenna gain (dBi)</td>
</tr>
<tr>
<td>EES receiver noise temperature (K)</td>
</tr>
</tbody>
</table>

5. Sharing analysis

This section analyses sharing for the preferred frequency bands discussed in previous sections of this Report.

5.1 Relay satellite to Earth data link

There are two principal elements of the sharing analysis:
— ensuring that the relay satellite meets the existing pfd requirements in the band;
— determining the required angular separation between the relay satellite and a “typical” fixed satellite space station to protect the FSS earth station from interference.

Table IV gives the pfd calculation for the relay satellite-to-Earth data link and indicates that the pfd is 13.4 dB below the existing pfd limit for this band.

To determine the angular separations required between the relay satellite and the fixed satellite, a maximum single entry interference-to-carrier ratio of -35 dB is assumed to protect the fixed satellite system and -30 dB to protect the relay satellite system.
For the fixed-satellite systems described in Report 561, Table I, the carrier pfd on the Earth's surface will be of the order of $-125.9$ dB(W/(m$^2$ · MHz)). This value is $3.0$ dB above the relay satellite pfd; however, the interference criteria for the EES relay satellite is $5$ dB less than for the fixed satellite. Consequently, the separation angle required is about the same for the protection of each system. The required separation angle is approximately $2^\circ$, and applies only for co-located earth stations.

**TABLE IV — Calculation of pfd near 20 GHz**

<table>
<thead>
<tr>
<th>Calculation of pfd near 20 GHz</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Relay satellite e.i.r.p. (dBW)</td>
<td>64.8</td>
</tr>
<tr>
<td>Bandwidth conversion (MHz/800 MHz) (dB)</td>
<td>$-29.0$</td>
</tr>
<tr>
<td>Relay satellite transmit power density (dB(W/MHz))</td>
<td>35.8</td>
</tr>
<tr>
<td>Allowance for spreading loss (40 600 km, 10° elevation) (dB)</td>
<td>$-163.2$</td>
</tr>
<tr>
<td>Spectral power flux-density (dB(W/(m$^2$ · MHz)))</td>
<td>$-128.4$</td>
</tr>
<tr>
<td>Allowable pfd limit (Earth's limb) (dB(W/(m$^2$ · MHz)))</td>
<td>$-115.0$</td>
</tr>
<tr>
<td>Margin (dB)</td>
<td>$-13.4$</td>
</tr>
</tbody>
</table>

5.2 **EES to relay satellite data link**

The 25.25 to 27.5 GHz frequency band is allocated to the fixed and mobile services. The closest band, for which a pfd limit has been adopted, is 17.7 to 19.7 GHz band, with a limit of $-115$ dB(W/(m$^2$ · MHz)) at the Earth's limb edge, escalating to $-105$ dB(W/(m$^2$ · MHz)) at the spacecraft nadir.

The EES system transmits to the relay satellite with an e.i.r.p. of 69.5 dBW, comprised of 50.0 dBi antenna gain, a 20.5 dBW transmit power, and a 1 dB line loss. The emission bandwidth will be 800 MHz. The maximum resultant pfd at the Earth's surface would occur should the EES-to-relay satellite line-of-sight graze the Earth's limb. The slant range for a 1000 km altitude orbit to the limb is approximately 3700 km, yielding a maximum pfd of $-97.7$ dB(W/(m$^2$ · MHz)). In order to protect the fixed and mobile services, 17.3 dB of discrimination must be provided by the EES. This discrimination is best accomplished by constraining the EES antenna to point no closer to the Earth's limb than 0.9° (assuming a 50.0 dB antenna gain and a discrimination pattern of $32 - 25 \log \varphi$ (off-axis angle)). This does not impose any operational constraints on an EES system.

In addition to the allocation for the Earth exploration-satellite service (space-to-space) the WARC-79 added up links for the standard frequency and time signal-satellite service in the 25.25 to 27.5 GHz band. Sharing between these two services will be a function of satellite separation angle between the data relay satellite and the standard time and frequency satellite and can be accommodated via coordination according to the Appendix 29 procedure.

The fixed-satellite service has an allocation in a portion of the 25.25 to 27.5 GHz band, specifically 27.0 to 27.5 GHz. Sharing with this service also can be handled according to Appendix 29 procedures.

5.3 **EES earth station — relay satellite link sharing with fixed-satellite service**

The earth station transmission parameters for the relay satellite command link are given in Table III. The transmitted power density is approximately equal to that expected from a fixed service earth station. Assuming that both the relay satellite earth station and the fixed-satellite earth station were in the main beam of a fixed satellite, then a satellite separation of less than $2^\circ$ is required to protect the fixed satellite with a single entry $C/I$ of 35 dB.

Conversely, taking the relay satellite command link interference criteria as a $C/I$ of 30 dB, the satellite separation must also be of the order of $2^\circ$ to protect the relay satellite, again assuming that both earth stations are within the relay satellite main beam. The 3 dB beamwidth of the relay satellite antenna is approximately $0.25^\circ$, implying that both earth stations must be located within about 125 km of each other for this situation to occur.
5.4  **EES earth station — relay satellite link sharing with fixed and mobile systems**

Sharing between the relay satellite earth station and the fixed and mobile services can be implemented via the procedures of Appendix 28 of the Radio Regulations. Since the transmit power density of the relay satellite earth station is the same as the expected transmit power density of the fixed-satellite service, the resulting coordination contours for the EES relay satellite system should be equal to those of the fixed satellite system.

5.5  **Relay satellite-EES link sharing with fixed and mobile services**

There are currently no power flux-density limits in the 28 GHz region for protection of the fixed and mobile services. If it is assumed that the pfd required to protect the fixed and mobile services can be extrapolated from the limits at 18 GHz, a resulting pfd limit of $-111 \text{ dB}(W/(m^2 \cdot \text{MHz}))$ at low elevation angles is obtained. The following calculation (Table V) presents the anticipated pfd produced on the Earth from relay satellite emissions arriving at low elevation angles:

<table>
<thead>
<tr>
<th>Calculation of pfd near 28 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relay satellite transmitter power (dB(W/Hz))</td>
</tr>
<tr>
<td>Relay satellite antenna gain (dBi)</td>
</tr>
<tr>
<td>Feed loss (dB)</td>
</tr>
<tr>
<td>e.i.r.p. (dB(W/Hz))</td>
</tr>
<tr>
<td>Allowance for spreading loss (to Earth’s limb at 41 730 km) (dB)</td>
</tr>
<tr>
<td>Spectral power flux-density (dB(W/(m$^2 \cdot$ Hz)))</td>
</tr>
<tr>
<td>or (dB(W/(m$^2 \cdot$ MHz)))</td>
</tr>
</tbody>
</table>

This level of pfd is 2 dB below that expected to be required for protection of the fixed and mobile services. Consequently, sharing with the fixed and mobile services is considered feasible.

5.6  **Relay satellite-EES link sharing with fixed-satellite service**

The possibility exists that the relay satellite command link transmissions could enter the receiver of a fixed-satellite service space station. This interference mode can occur only when the line connecting the relay satellite and EES spacecraft is near the Earth’s limb and simultaneously near the equator. The magnitude of the power density which will be received by FSS receiver, at any given time, is a function of the instantaneous antenna coupling of the FSS and the relay satellite systems.

Using the relay satellite transmit parameters developed previously, the maximum pfd which can be transmitted across the geostationary-satellite orbit is $-179.6 \text{ dB}(W/(m^2 \cdot \text{Hz}))$.

Assuming a minimum usable fixed-satellite earth-station elevation angle of 20°, a carrier-to-interference criterion of 35 dB and fixed-satellite receiver noise temperature of 2500 K, results in an interference threshold of $-214.6 \text{ dB}(W/Hz)$. Therefore, the relay satellite must provide 25 dB antenna pattern discrimination to protect the fixed satellite.

Using the antenna pattern of Report 810 the required 25 dB discrimination is obtained at 1.44 times the relay satellite antenna 3 dB beamwidth or approximately 0.4° from its main beam.

Therefore, in order to provide protection to the fixed-satellite service the relay satellite should be constrained from transmitting whenever the relay satellite-EES line-of-sight is within 0.4° of the geostationary orbit. This corresponds to locations of the EES satellite within 3° latitude of the equator and near the Earth’s limb as seen from the relay satellite. This would create two small areas of potential interference of short duration. This can be handled via operational procedures for the EES command system.
On the other hand, the possibility exists that the fixed-satellite earth-station transmissions could enter the command and control receiver on the EES low-orbit satellite. Three potential interfering geometries exist and are illustrated in Fig. 2. Calculations for each case are presented in Table VI and are based on the following system parameters:

- **Fixed-satellite earth station**
  - Transmit power density: $-30 \text{ dB}(W/\text{Hz})$
  - Gain: 60 dBi

- **EES low-orbiting satellite**
  - Gain: 50 dBi
  - Receiver noise temperature: 2500 K
  - $C/N$ ratio: 20 dB
  - $C/I$ ratio: 30 dB.

**FIGURE 2** — *Interference possibilities into an Earth exploration satellite from an earth station in the fixed-satellite service*

A : Earth
B : Earth exploration-satellite orbit
C1, C2 and C3 : Earth exploration satellite (cases 1, 2 and 3)
D1, D2 and D3 : data relay satellite
E : earth station of fixed-satellite service
S : space station of fixed-satellite service
$\theta$ : elevation angle
$\psi$ : off beam angle

*Note.* — Orbits are not necessarily co-planar. Geometry is shown in 2 dimensions in order to simplify the diagram.
TABLE VI — Calculation of interference from earth station into EES

<table>
<thead>
<tr>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>FSS ((^1) transmit power (dB (W/Hz))</td>
<td>-30</td>
<td>-30</td>
</tr>
<tr>
<td>Gain towards EES (dBi)</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Path loss (dB)</td>
<td>-180.4</td>
<td>-192</td>
</tr>
<tr>
<td>EES receiver gain towards FSS earth station (dBi)</td>
<td>-10</td>
<td>-10</td>
</tr>
<tr>
<td>Received interference power density (dB(W/Hz))</td>
<td>-160</td>
<td>-172</td>
</tr>
<tr>
<td>Receiver noise power density (dB(W/Hz))</td>
<td>-195</td>
<td>-195</td>
</tr>
<tr>
<td>Minimum required $C/N$ (dB)</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Required $C/I$ (dB)</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Resulting $C/I$ (dB)</td>
<td>-15</td>
<td>-3</td>
</tr>
<tr>
<td>Required isolation (dB)</td>
<td>45</td>
<td>33</td>
</tr>
<tr>
<td>Angle off FSS earth station main beam</td>
<td>± 4.78(^*)</td>
<td>± 1.585(^*)</td>
</tr>
<tr>
<td>Angle off FSS space station main beam</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>FSS elevation angle</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Percentage of time of interference (%)</td>
<td>0.174</td>
<td>0.019</td>
</tr>
</tbody>
</table>

\(^1\) FSS: fixed-satellite service.

For cases 1 and 2, interference exists for a small percentage of time. Such interference can be handled, and avoided by operational procedures of the EES command system.

For case 3, the EES command antenna must avoid pointing within 4° of the Earth's horizon as seen from the satellite. This does not constrain the EES service. When the fixed-satellite elevation angles are less than 20°, the EES command antenna would have to point further off the Earth's horizon. These low elevation angle stations would experience greater coordination difficulty.

6. Conclusions

The preferred frequency bands for a relay satellite supporting future wideband Earth exploration satellites have been described. Technical characteristics of one possible implementation of an operational EES relay satellite have been presented.

The preferred frequency bands and constraints which would permit sharing with other services are presented in Table VII. None of the required constraints would materially affect the operational capabilities of an EES system.
TABLE VII — Preferred frequency bands and constraints for sharing with other services

<table>
<thead>
<tr>
<th>Frequency band (GHz)</th>
<th>EES link</th>
<th>Shared service</th>
<th>Sharing constraint</th>
</tr>
</thead>
<tbody>
<tr>
<td>15 to 20 (data link)</td>
<td>Relay satellite-to-earth station</td>
<td>Fixed/Mobile</td>
<td>Existing pfd limits</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Standard FSS (') spacing</td>
</tr>
<tr>
<td>25 to 29 (data link)</td>
<td>EES-to-relay satellite</td>
<td>Fixed satellite</td>
<td>Pfd limits</td>
</tr>
<tr>
<td>25 to 30 (command link)</td>
<td>Earth station-to relay satellite</td>
<td>Fixed/Mobile</td>
<td>Appendix 29 to the Radio Regulations</td>
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<td>Appendix 28 to the Radio Regulations</td>
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<td></td>
<td>Antipodal transmission constraint (see text)</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>May have to restrict command operations over certain limited areas (see text)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fixed/Mobile</td>
<td>Appropriate pfd limits</td>
</tr>
<tr>
<td></td>
<td>Relay satellite-to-EES</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(') FSS: fixed-satellite service.

REPORT 983

THE MINIMUM LONGITUDE SEPARATION ANGLE NECESSARY TO SHARE FREQUENCIES BETWEEN TWO DATA RELAY SATELLITES

(Question 11/2) (1986)

1. Introduction

Since the rapidly growing space activities require a larger number of data relay satellite (DRS) systems, it seems probable, in the future, that several such systems will be developed separately.

The complexity of a DRS system having multiple space-to-Earth, Earth-to-space and space-to-space links (see Report 848) makes the problem of developing a generalized DRS-to-DRS sharing model difficult. This Report is an initial attempt to quantify the minimum geostationary longitude separation angle necessary for two DRS systems so that they can share the same frequencies.

A DRS system, as discussed in this Report, consists of a DRS placed in geostationary orbit, one or more user satellites and earth stations. Each earth station has access to each user satellite via the DRS.

The link between an earth station and a DRS is not addressed in this Report. Frequency sharing between a DRS system and other space research systems is discussed in Report 846.
The relationship between a DRS and user satellites is similar to a base station and mobile stations. It is essential that parameters which describe the orbits of the user satellites and the probability of interference be taken into consideration in developing a detailed DRS-to-DRS frequency sharing model which would also include all of the factors providing DRS system-to-system isolation. Some of these factors are inter-system frequency discrimination, modulation/code discrimination, polarization discrimination and antenna side-lobe discrimination. This Report examines only the effect of antenna discrimination to derive an approximate expression for the proportion \((P)\) of service area of a DRS system, over which interference from a second DRS system could be greater than a given threshold.

This expression is a function of the longitudinal separation angle between two DRSs, for given values of DRS and user satellite antenna diameters and for a given value of wanted-to-unwanted signal powers \((W/U)\) at the victim receiver.

2. Development of sharing model

Sections 2.1 to 2.3 discuss the assumptions and approximations used in developing the DRS-to-DRS sharing model. Sections 2.4 and 2.5 develop the sharing expression and necessary definitions of terms used in the sharing expression for the forward (i.e. DSR-to-user satellite) and return (user satellite-to-DRS) links, respectively.

2.1 Basic assumptions

The approach used in this Report assumes that the two DRS systems are similar in terms of the DRS antenna diameters, the user satellite antenna diameters and both DRS and user satellite e.i.r.p.s. Additionally it is assumed that the DRS satellites utilize directional antennas. The user satellites may use either directional or omnidirectional antennas. It is further assumed that the user satellite altitudes are much less than that of the geostationary orbit.

2.2 Antenna radiation patterns

Directional antennas are used for data relay satellites and for some user satellites. Considering that the radiation pattern of the main lobe and the first side lobe are more important for orbit utilization, the radiation patterns of DRS system satellite directional antennas are defined as the following:

\[
G_m - G(\varphi) = 2.5 \times 10^{-3} \left( \frac{D}{\lambda} \right)^2 \text{ dB for } 0 < \varphi < \frac{89.4 \lambda}{D}
\]

\[
G_m - G(\varphi) = 20 \text{ dB for } \frac{89.4 \lambda}{D} < \varphi
\]

where:

- \(G_m\): maximum gain in the main lobe (dBi),
- \(\varphi\): the angle between the axis of the main beam and the direction in question,
- \(G(\varphi)\): gain at \(\varphi\) degrees,
- \(D\): diameter of antenna,
- \(\lambda\): wavelength.

The patterns derived from these equations correspond to curves A and B in Fig. 13 of Report 558 (Geneva, 1982). The equations were derived by using the approximation that half of the 3 dB beamwidth of a parabolic antenna can be expressed as \(\lambda/2D\). For the case of an omnidirectional user satellite antenna, the gain is assumed to be 0 dBi.

2.3 Ratio of DRS service area to interference area

As seen from a geostationary DRS, the orbital sphere of a user satellite may appear as a ring (see Fig. 1). The angular width of the highest altitude user satellite is termed, in this Report, the DRS service area, and is assumed to be 2\(\Omega\) degrees wide. The angular area of this service area will be proportional to \((2\Omega)^2\).

Given that a second DRS system is operating co-frequency with the wanted DRS system, whenever the wanted user satellite and unwanted user satellite approach within some angular distance \(\omega\), the \(W/U\) ratio of the wanted system will decrease below some threshold value. If \(N\) user satellites are operating within the unwanted DRS system, there will be \(N\) independent interference regions within the wanted DRS service area. The sum of the angular area of all of these interference regions will be proportional to \(N\omega^2\).
Assuming that both the wanted and unwanted user satellites may be anywhere within the DRS service area with equal probability, the risk of inter-system interference will be proportional to the ratio of angular areas, or

$$ P = \left( \frac{\omega}{\Omega} \right)^2 N $$

(1)

In an actual DRS system, the user satellite will not reside at all points in the service area with equal probability. The relationship between the user satellite position for an actual DRS system and the assumption made in this section should be the subject of further study.

2.4 Forward link

Because both the wanted and unwanted DRS satellites are assumed to have identical e.i.r.p.s, the $W/U$ ratio measured at the wanted user satellite will be:

$$ W/U = \Gamma + \gamma \quad \text{dB} $$

(2)

where:

$\Gamma$: off-axis attenuation of the unwanted DRS satellite in the direction of the wanted user satellite (dB),

$\gamma$: off-axis attenuation of the wanted user satellite in the direction of the unwanted DRS (dB).
The off-axis attenuation, \( \gamma \), is defined by the diameter of the user antenna (\( D_2 \)), frequency and parallax angle \( \alpha \) in Fig. 2a. Even if \( \alpha \) varies according to its orbit, the minimum value of \( \alpha \) is always greater than \( \theta/2 \) as long as the altitude of the user satellite does not exceed that of the geostationary-satellite orbit, where \( \theta \) is the longitude separation angle between both data relay satellites. Therefore, the value of \( \gamma \) corresponding to \( \theta/2 \) is used in this calculation.

The \( W/U \) at each satellite receiver is defined as the following:

\[
W/U = 2.5 \times 10^{-3} \left( \frac{D_1}{\lambda} \right)^2 + 2.5 \times 10^{-3} \left( \frac{D_2}{\lambda} \frac{\theta}{2} \right)^2
\]

(3)

where:

\( D_1 \): diameter of the unwanted data relay satellite antenna,
\( D_2 \): diameter of the wanted user satellite antenna,
\( \lambda \): wavelength.

The value of \( \omega^2 \) corresponding to the necessary \( W/U \) is derived from equation (3).

\[
\omega^2 = \left[ \frac{\lambda^2 [W/U]}{2.5 \times 10^{-3}} - D_2^2 \left( \frac{\theta}{2} \right)^2 \right] \frac{1}{D_2^2}
\]

(4)

where:

\([W/U]\): necessary \( W/U \)

\([W/U] \ll 20 \text{ dB}\)

The approximate proportion \( P \) that \( W/U \) is less than the necessary \( W/U \) is derived from equations (1) and (4).

\[
P = \frac{N\omega^2}{\Omega^2} = \frac{N}{\Omega^2 D_1^2} \left( \frac{\lambda^2 [W/U]}{2.5 \times 10^{-3}} - \frac{D_2^2 \theta^2}{4} \right)
\]

(5)

where:

\( N \): for the forward link case, is equal to the maximum number of unwanted user satellites that can be commanded simultaneously.

### Return link

In the return link case, it is assumed that both the wanted and unwanted user satellites have identical e.i.r.p.s. The inter-system discrimination will then be a function of the wanted DRS satellite antenna and the unwanted user satellite antenna (see Fig. 2b). The equations for the return link analysis have the same form as those for the forward link. The symbols, however, have a different meaning as follows:

\( \Gamma \): off-axis attenuation of the wanted DRS satellite in the direction of the unwanted user satellite;
\( \gamma \): off-axis attenuation of the unwanted user satellite in the direction of the wanted DRS;
\( D_1 \): diameter of the wanted DRS satellite antenna;
\( D_2 \): diameter of the unwanted user satellite antenna;
\( N \): number of unwanted user satellites that may transmit simultaneously.

### 3. Example calculation

With the assumption of identical antennas on both the wanted and unwanted DRS systems, the major difference between the expressions developed for the forward and return links is the value of \( N \). Choosing the parameters shown below as examples, Fig. 3 presents the results of applying equation (5) to both the forward and return links of DRS system.

\( \Omega = 20^\circ \) (8050 km orbital altitude)
\( \lambda = 0.15 \text{ m} \) (2.0 GHz)
\( D_1 = 10 \text{ m} \)
\( D_2 = 1 \text{ m} \)
\([W/U] = 14 \text{ dB}\)
\( N = 3 \) for the forward link
\( N = 20 \) for the return link
FIGURE 2a – Forward link  
FIGURE 2b – Return link

**DRS**\textsubscript{A}: wanted DRS  
**DRS**\textsubscript{B}: unwanted DRS  

FIGURE 3 – The relation between $P$ and $\theta$ for $|W/U| = 14$ dB  

Curves A: return link case; $N = 20$  
B: forward link case; $N = 3$
4. Discussion and conclusions

The DRS and user satellite antenna diameters, $D_1$ and $D_2$ respectively, influence the results of applying equation (5) quite differently. The approximate proportion value calculated is directly proportional to $\frac{1}{D_1^2}$. The effect of increasing or decreasing $D_1$ will be to lower or raise the entire curve given in Fig. 3. The effect of changing the value of $D_2$, on the other hand, will be to change the shape of the curve without changing the $\theta = 0$ value. (Both parameters $D_2$ and $\theta$ have the same effect on the interference.) The value of the curve at $\theta = 0$ is the approximate proportion of interference for DRS systems with omnidirectional user satellite antennas.

The DRS sharing model has shown wanted-to-unwanted signal levels below 14 dB for relatively low percentages of time, less than 1% for forward link and less than 7% for the return link, between two systems operating with a significant number of user satellites in orbits near 8000 km. However, this is a limited model that considers only homogeneous systems operating with the same user altitudes, assuming a constant region of interference and equal probability of a user satellite being anywhere on the orbital sphere. This model, as such, predicts relatively high levels of interference in some cases (i.e. for users in orbits less than about 1000 km). Since, in practice, many widely varying situations may be encountered, a detailed model for DRS systems must take into account several inter-system isolation factors as well as specific orbital dynamics. Some areas that need to be considered are:

- definition of a fixed area about a wanted user satellite within which an unwanted satellite causes interference. The actual area about the wanted user within which an unwanted satellite will cause interference will vary with orbital position and will also vary with each set of orbital parameters considered;
- phasing of satellites in the same orbit;
- Earth blockage effects;
- polarization discrimination;
- coding, modulation and transmissions characteristics.

A more detailed analysis will be required using actual system parameters when determining the minimum longitude separation angle between data relay satellites sharing the same frequency band.

REPORT 846

DATA RELAY SATELLITES*

Sharing with other space research systems near 2 GHz

(Question 11/2)

(1982)

1. Introduction

At present, data telemetered from satellites in the space research service are received directly by earth stations. While it is anticipated that many of these transmissions will, in the future, be routed through a data relay satellite (DRS), some transmissions will still be sent directly to earth stations. Since the satellites using the DRS will share the frequency bands with other space research satellites, the potential for sharing between the two types of service must be investigated. For the purpose of clarity in this Report, satellites directly using earth stations will be referred to as space research satellites and satellites using a DRS will be referred to as DRS user satellites.

For the purpose of this analysis both the space research and DRS user satellites are assumed to be in circular orbits, and the sharing situations involving geostationary satellites and those in highly elliptical orbits and in transfer orbits are not considered.

* This Report is also of importance to space operations.
2. **Forward/up-link interference**

The DRS forward link (DRS to user satellite) will share frequency bands with the up link of other space research satellites. Interference may exist if two or more satellites operate co-channel. Typically, space research satellites near 2 GHz use near omnidirectional antennas having a maximum gain ranging up to approximately 6 dBi. The potential for interference with these receivers is largely a function of the relative pfd's of the desired and interfering signals, and the periods of time in which the interference can be expected to occur.

2.1 **Interference to other space research service satellites**

The maximum power level of the DRS forward link (space-to-space) is restricted due to the limitation in the Radio Regulations concerning the maximum pfd that can be incident at the Earth’s surface. The pfd limit near 2 GHz is $-154 \text{ dB}(W/m^2)$ in a 4 kHz bandwidth for an angle of incidence less than 5° (No. 747 of the Radio Regulations). This effectively places a limit on the maximum e.i.r.p. of the DRS satellite and determines the maximum pfd incident on a low orbit satellite. The highest pfd that a satellite in a 1000 km orbit could experience due to the DRS emissions is $-152 \text{ dB}(W/m^2)$ in a 4 kHz bandwidth, occurring when the low-orbit satellite makes its closest approach to the DRS.

Typical earth stations in the space research service in the United States have an antenna gain of 43 dBi, a minimum antenna elevation of 5° and an e.i.r.p. of 31 dBW in 4 kHz. These earth stations would produce a minimum mainbeam pfd at 1000 km altitude satellite of $-110 \text{ dB}(W/m^2)$. The pfd of this desired signal, when compared to the pfd of the interfering DRS transmission, will result in a carrier-to-interference ratio in the space research satellite receiver of at least 42 dB. This minimum carrier-to-interference ratio would be improved in a non-worst case sharing situation, or if antenna discrimination factors were considered.

2.2 **Interference to DRS user satellites**

The DRS forward link has a bandwidth of 10-20 MHz and a typical data rate of 1000 bit/s. This results in a processing gain of 40 dB or more against an interfering signal. Using the value for the DRS pfd of $-154 \text{ dB}(W/m^2)$ in 4 kHz, the processing gain, and a required signal-to-noise ratio of 16 dB, a value of $-130 \text{ dB}(W/m^2)$ in 4 kHz is obtained as the level of interfering signal power flux-density that may cause interference in the receiver of a DRS user. As shown in the previous section, a space research service earth station would produce pfd levels much higher than $-130 \text{ dB}(W/m^2)$ at a DRS user satellite when the satellite is in the mainbeam of the earth station antenna. This, however, is a relatively rare event, due to the small beamwidth of the 43 dBi earth station antenna and the rapid movement of low-orbit satellites relative to the earth station. The probability of interference occurring can be calculated for the long term.

The power flux-density produced at a DRS user satellite by a transmitting earth station over the long term cannot be adequately described by a single time-independent quantity since a spacecraft in a low altitude earth-orbit “rises” and “sets” on the horizon as seen from a fixed point on the Earth. To a first approximation, the satellite can be envisaged as circulating in a plane which is fixed with respect to inertial space. The rotation of the Earth beneath the spacecraft causes the spacecraft ground track to follow a path which is repeated only after an extended period of time. An individual satellite is visible to a fixed point on the Earth for less than 10% of the time.

The proportion of time that a low-orbit satellite resides in a portion of its orbital sphere may be determined using equations contained in Report 684, “Preliminary Analysis of Low-Orbit Satellite Visibility Statistics”. This Report describes a bounding equation which relates the long-term visibility of a circular-orbit satellite to the orbital inclination and the latitude and longitude bounds of a region on the satellite orbital sphere. The problem of expressing the pfd at a DRS user satellite as a statistical time function can then be reduced to determining the pfd with the satellite positioned in the centre of a small region of its orbital sphere, and then determining the proportion of time that the satellite spends in the region. If this procedure is carried out over the entire region of the orbital sphere visible to the earth station antenna, then all of the necessary information is available to properly determine the statistical satellite pfd function.

Figure 1 represents a statistical function of the pfd produced at a DRS user satellite by emissions from a space research earth station. The curve was generated using the earth station characteristics of § 2.1 and assumed a radiation pattern according to Report 391-3 (Kyoto, 1978) $(D/\lambda = 66)$. The curve shown is the maximum of curves generated considering various latitudes for the earth station and various altitudes and inclinations for the satellite. As shown in Figure 1 the interfering signal pfd will exceed the $-130 \text{ dB}(W/m^2)$ level less than 0.03% of the time.
3. **Down/return link interference**

The DRS return link (space-to-space) (user satellite to DRS) will share frequency bands with the down link of other space research satellites and interference may exist if two or more satellites operate co-channel. The earth station and the DRS each have very high gain antennas, so that the sharing situation is highly dependent on the relative locations and pointing directions of the antennas.

3.1 **Interference caused to space research earth stations**

Transmissions from both space research and DRS user satellites are subject to the Radio Regulations restriction on the maximum pfd incident at the Earth's surface. The pfd produced at the Earth's surface by a DRS user satellite will be no greater than the pfd limit and, because the transmissions are directed towards a geostationary satellite, will generally be considerably lower. Table I provides typical examples for the calculation of interference into a space research earth station from a DRS user satellite. The Table considers two cases, one in which the space research and DRS user satellites are visible to the earth station at a 5° elevation angle, and a second case in which the satellites are visible at higher elevation angles. The earth station antenna radiation pattern was defined in § 2.2. Power flux-density levels in the 1 kHz reference bandwidth were obtained by subtracting 6 dB from the pfd in 4 kHz.
The desired signal pfd levels given in Table I were derived from typical parameters given in Report for earth stations which carry out space operation functions. This analysis shows that there will not be interference when the angle between the space research earth station antenna boresight and the DRS user satellite is greater than 6.3°. Depending upon the design and orientation of the DRS user satellite, this angle could be reduced or eliminated due to factors such as DRS user antenna discrimination and shielding of the antenna by the body of the satellite.

### Table I — Determination of required off-axis angle at earth station

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<thead>
<tr>
<th></th>
<th>Case 1</th>
<th>Case 2</th>
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</thead>
<tbody>
<tr>
<td>Interfering signal (DRS user satellite):</td>
<td></td>
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<tr>
<td>Satellite elevation angle (degrees)</td>
<td>5</td>
<td>&gt; 25</td>
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<td>pfd limit in 4 kHz (dBfW/m²) (No. 747 of the Radio Regulations)</td>
<td>-154</td>
<td>-144</td>
</tr>
<tr>
<td>Resultant pfd level in 1 kHz at earth station (dB(W/m²))</td>
<td>-160</td>
<td>-150</td>
</tr>
<tr>
<td>Desired signal (space research satellite):</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Satellite elevation angle (degrees)</td>
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<td>90</td>
</tr>
<tr>
<td>pfd level in 4 kHz (dB(W/m²))</td>
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<td>-149</td>
</tr>
<tr>
<td>Resultant pfd level in 1 kHz at earth station (dB(W/m²))</td>
<td>-169</td>
<td>-155</td>
</tr>
<tr>
<td>C/I of pfd levels in 1 kHz reference bandwidth at earth station (dB)</td>
<td>-9</td>
<td>-5</td>
</tr>
<tr>
<td>Required protection ratio (C/I in dB)</td>
<td>20</td>
<td>20</td>
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<tr>
<td>Required discrimination in earth station antenna (dB)</td>
<td>29</td>
<td>25</td>
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<tr>
<td>Required off-axis angle at earth station to achieve required antenna discrimination (degrees)</td>
<td>6.3</td>
<td>4.4</td>
</tr>
</tbody>
</table>

#### 3.2 Interference to DRS receivers

The DRS return link is pseudo-random noise coded so as to provide a processing gain against interfering sources of 17 dB or more, depending upon the rate of data being transmitted. This in itself is sufficient to protect the DRS receiver from harmful interference, since the e.i.r.p. of a potentially interfering space research satellite towards the DRS could not be greater than, and in virtually all cases would be less than, the e.i.r.p. of the DRS user's desired signal.

#### 4. Conclusion

The sharing possibilities between space research satellites using a data relay satellite and other space research systems can be summarized as follows:

- data relay satellite transmitters produce a relatively low pfd in the vicinity of low-orbit satellites and, based on an analysis of satellites in a 1000 km orbit, are not expected to cause interference to the reception of the higher-powered signals from space research earth station transmitters;
- space research service earth stations use high gain antennas and, due to the transient passage of low-orbit satellites, operate only for a fraction of the time. The probability that both the space research earth station and the DRS user satellite are operating in the same area at the same time is small. Interference to the DRS satellite receiver could not occur more than 0.03% of the time;
— the analysis showed that there will not be interference when the angle between the space research earth station antenna boresite and the DRS user satellite is greater than 6.3°. Depending upon the relative elevations of the satellites and the design and orientation of the DRS user satellite, this angle may be reduced or eliminated due to factors such as DRS user antenna discrimination and shielding of the antenna by the body of the satellite. However coordination should be performed for the protection of space research earth stations (Nos. 747 and 750 of the Radio Regulations);

— space research satellites have an e.i.r.p. towards the geostationary arc that is less than the e.i.r.p. of a DRS user towards the arc. Since signal processing of the DRS user produces 17 dB or more of gain against interfering signals, the space research satellites will not produce harmful interference to the DRS receiver.

This Report has only considered potential interference to satellites operating in low-altitude circular orbits. Further studies concerning space research geostationary satellites and those in highly elliptical orbits and in transfer orbits should be considered.

REPORT 847-1*

DATA RELAY SATELLITES

Sharing with other services in bands 9 and 10

(Question 11/2)

(1982-1986)

1. Introduction

The purpose of this Report is to summarize the results of several studies of the feasibility of frequency sharing between space research systems, using geostationary data relay satellites and other services. A description of a data relay satellite (DRS) system including technical parameters is contained in Report 848. The feasibility of frequency sharing between DRS systems and other systems within the space research service is discussed in Report 846.

Further details relating to the frequency sharing and compatibility studies summarized in this Report may be obtained by consulting the Reports referenced in each of the following sections. The particular problems related to use of the band allocated to the aeronautical radionavigation service near 13 GHz are discussed in Report 690 (Geneva, 1982) and Recommendation 511 (Geneva, 1982).

2. Terrestrial systems in band 9 (Report 537-1 (Kyoto, 1978))

A general method was developed in Report 537-1 (Kyoto, 1978) to determine TDRS system design parameters of interest whereby frequency sharing in band 9 between space research systems using a DRS and terrestrial systems would be feasible. A series of inequalities was derived which would help determine what sets of design parameters allow frequency sharing with any terrestrial service based upon acceptable interference to the TDRS space links.

A graphic translation of these inequalities using typical system parameters (user orbital altitude = 500 km, and in accordance with Tables II and V of Report 537-1 (Kyoto, 1978)) shows where appropriately designed antenna systems permit frequency sharing. The feasibility of sharing is thus dependent upon appropriate combinations of main beam gain and discrimination of the antennas in question. Using the $32 - 25 \log \phi$ antenna pattern as a first approximation and typical TDRS parameters used in Report 848, an estimate can be obtained in each case indicating when the DRS link in question can expect interference-free operation.

* This Report should be brought to the attention of Study Groups 4, 8, 9, 10 and 11.
3. Fixed and mobile services in band 10 (Report 689 (Kyoto, 1978))

The feasibility of frequency sharing between the fixed and mobile services and the TDRSS is discussed in Report 689 (Kyoto, 1978) and summarized in the following sections.

3.1 Earth station-to-DRS link

The DRS earth station characteristics are comparable with those expected to be utilized by the fixed-satellite service earth stations in the same frequency range. Hence, the potential for interference from the DRS uplink to a fixed and mobile services antenna and the resultant coordination contours should be comparable with those of the fixed-satellite service.

3.2 DRS transmissions

In tracking a near-earth user satellite or in transmitting to the earth station in the downlink, the DRS may illuminate a terrestrial antenna of the fixed and mobile services. It is recommended that the DRS systems in the space research service can operate near 15 GHz within the following pfd restrictions, which have been determined for transmissions from the fixed-satellite service. The recommended limits, now embodied in the Radio Regulations, for the nearest band where limits apply, are:

\[
\begin{align*}
-148 & \text{ dB(W/m}^2\text{)} & & \delta < 5^\circ \\
-148 + (\delta - 5)/2 & \text{ dB(W/m}^2\text{)} & & 5^\circ < \delta < 25^\circ \\
-138 & \text{ dB(W/m}^2\text{)} & & 25^\circ < \delta < 90^\circ \\
\end{align*}
\]

in any 4 kHz band. \(\delta\) is the angle of arrival of the signal, measured in degrees above horizontal. For the proposed operational parameters of the DRS, the maximum power flux-density of the RF wave from DRS transmissions at the surface of the Earth would be \(-152 \text{ dB(W/m}^2\text{)}\) in the worst 4 kHz band. Hence, no potential for harmful interference to the fixed and mobile services is seen in this case.

3.3 User satellite-to-DRS link

Interference to a receiving antenna of the fixed and mobile services is possible when the user satellite is transmitting to the DRS on the return link and the user satellite is on the horizon of the terrestrial station. In order to protect the fixed and mobile services reception, the user satellite must be constrained to operate within the limits of Recommendation 510 by limiting e.i.r.p. and operational pointing directions.

4. Radiolocation service in the band 13.4 to 14.0 GHz (Report 691 (Kyoto, 1978))

The summary that follows of the potential for interference from the TDRSS to the radio-location service is taken from Report 691 (Kyoto, 1978) and other sources as cited therein. No radiolocation systems are currently planned in this band, but future systems could be designed to monitor and control airport surface traffic particularly during periods of low visibility. All results of this section are matched to hypothetical, typical radiolocation system parameters.

4.1 Earth station-to-DRS link

Whenever a radiolocation antenna is above the DRS earth station horizon, interference at the radiolocation receiver during earth station transmissions to the DRS is possible. The maximum allowable interference spectral power density at a typical radiolocation receiver is assumed to be \(-203 \text{ dB(W/Hz)}\); (see § 4 of Report 691 (Kyoto, 1978)). The two TDR satellites are assumed to be separated by 130° and at an angle of elevation of about 17° above earth station horizontal to achieve maximum signal-to-noise ratio. The DRS earth station is considered to be at 35° N latitude with a transmitting power of \(-56 \text{ dB(W/Hz)}\) and an antenna gain of 60 dBi.
With these suppositions, plus data on the propagation mode and the rain-climate zone type (see Reports 563-1, 564-1 and 569-1 (Kyoto, 1978)), a calculation can be carried out to determine the required separation of the DRS earth station and the radiolocation earth station so as not to exceed $-203 \text{ dB(W/Hz)}$ in the radiolocation receiver (see Report 382-3 (Kyoto, 1978)). In this case, distances in the 220 to 250 km range provide separations sufficient for interference-free operation of radiolocation equipment, depending on climate/zone assumptions. In cases where the actual separation distance between DRS earth station and the radiolocation receiver is less than the required separation, coordination procedures could be used to determine locations of DRS earth stations where non-interference operations could occur.

### 4.2 DRS-to-user satellite link

A radiolocation site within the DRS horizon may suffer interference from the DRS main beam only if some part of the area within the DRS antenna beam scans across a radiolocation site along a grazing sightline while tracking the user satellite. According to the criteria for unacceptable interference at a radiolocation receiver (assumed in § 4.1), the DRS may produce unacceptably high levels of interference at the radiolocation antenna. Hence, an analysis is undertaken of the relative frequency of occurrence of such levels of interference in a typical, multi-user environment.

The value obtained is for a radiolocation beam scan rate of 135 rpm and 6 user satellites. In this case, the probability of interference from the DRS at the radiolocation antenna being unacceptably high is $1.13 \times 10^{-5}$. This is not considered a serious impediment to the operation of a radiolocation service receiver.

### 4.3 User satellite-to-DRS link

A main beam-to-main beam interference path between near-Earth research spacecraft of the space research service (using a DRS) and a radiolocation system exists only if the radiolocation equipment is located within a narrow spherical cap centred at the DRS-user spacecraft horizon along a grazing sightline. For the radiolocation systems to experience main lobe interference, it must be located within this cap while all systems are operating. A typical user spacecraft is assumed to have a spectral e.i.r.p. of $-28 \text{ dB(W/Hz)}$ producing an interference power of $-172 \text{ (W/Hz)}$ at the radiolocation receiver. If the radiolocation antenna provides 35 dBi of gain, the receiver will suffer 31 dB of interference power higher than the maximum allowable according to limitations set out in § 4.1.

An analysis on the basis of relative frequency of unacceptable interference to the radiolocation antenna was carried out. User satellite orbital altitudes typically range from 200 km to 1200 km with corresponding main beam-to-main beam coupling times (during a coupled orbit) of 0.46 to 2.2 min. These values lead to a "worst-case" estimate of the probability of occurrence of interference at the radiolocation system of $2.76 \times 10^{-8}$ (this corresponds to the 1200 km orbit). This probability is not considered an obstacle to adequate radiolocation performance.

### 5. Feeder links to broadcasting satellites in the 14.5 to 14.8 GHz band

The fixed-satellite service (FSS) and the space research service both have frequency allocations at 14.5-14.8 GHz. However, for territories outside Europe and for Malta, use of the FSS allocation is restricted to feeder links for the broadcasting-satellite service (BSS). In the space research service, this band is used by some DRS systems for Earth-to-space links. Consequently, potential interference exists between the two systems when the earth station of one service illuminates the receiving satellite of the other service. This analysis considers the mutual interference potential between broadcasting and geostationary data relay satellites.

Using typical DRS and BSS parameters (taken from IFRB publications and the Final Acts of the WARC ORB-85), link calculations were performed in the case of DRS up-link interference to BSS feeder links (see Annex I for details). The interference criterion was specified as a minimum $C/I$ ratio of the BSS satellite of 45 dB. Results indicate that this protection ratio can be met with a BSS and DRS satellite spacing of the order of $2^\circ$ even if the associated earth stations are assumed to be co-located.

A similar analysis was performed in the case of BSS feeder-link interference into DRS up links (see also Annex I). The interference criterion was specified as the ratio of the received interference power to the receiving system noise power. In the case where BSS and DRS satellites are separated by at least $14^\circ$, sharing is feasible.
even if the respective earth stations are co-located. For satellite spacings of less than this amount however, sharing will be feasible provided that the DRS satellite receive antenna has sufficient discrimination towards the BSS feeder-link earth station serving the adjacent BSS satellite. Consequently, care needs to be exercised in the selection of DRS earth-station sites and also in the selection of DRS satellite locations.

6. Fixed-satellite service near 15 GHz (Report 686 (Kyoto, 1978))

The sections which follow summarize the feasibility of co-channel operations between the TDRSS and up links of the fixed-satellite services (FSS) from Report 686 (Kyoto, 1978) and other sources cited below.

6.1 Earth station-to-DRS

It is possible for an FSS up link to receive interference from DRS earth station transmissions toward the DRS which irradiate a geostationary FSS satellite in a geostationary position near the DRS. According to Appendix 29 to the Radio Regulations (1976), there may be unacceptable interference to a satellite up link if there were a 2% increase in the interference-to-noise ratio in that link due to the incoming interference (in the Radio Regulations of 1982 this number has been changed to 4% which would lessen the sharing constraints). This amounts to a \(-17\) dB ratio of incoming interference-to-noise power ratio at the FSS receiver. The following existing or typical parameters are assumed for the two services: a DRS earth station e.i.r.p. density of \(4\) dB(W/Hz), an FSS satellite antenna gain of \(40\) dBi or less depending on off-axis angle (1.5° spot beam), FSS up-link system noise temperature of 1000 K and a total link-to-up-link noise ratio of 5 for the FSS. Under these conditions, an angular separation of 5.7° between the satellites of the two services is required. This requirement can be reduced to 4° by placing the DRS earth station outside the \(-3\) dB contour of the FSS spot beam antenna (approximately 500 to 600 km distance from the FSS earth station). The calculations are based upon antenna radiation reference patterns in Recommendation 465-1 (Kyoto, 1978) for earth stations and Report 558-1 (Kyoto, 1978) for FSS satellite antennas.

6.2 DRS-to-user satellite

In tracking the user spacecraft (worst-case assumption of 0° user satellite inclination), DRS transmissions could interfere with FSS satellites operating on geostationary arc segments of width no greater than 2.3° antipodal to the DRS. Given that potentially unacceptable interference is determined as in § 6.1 and again using the satellite antenna reference radiation pattern of Report 558-1 (Kyoto, 1978), an antenna discrimination of 7.6 dB is required at the FSS spacecraft to avoid a 2% increase in the interference-to-noise power ratio in the FSS up link, which would occur for about 10% of the time. The discrimination figure amounts to a needed 1.3° off-beam angle between the DRS transmission and the FSS antenna axis.

In the hypothetical case studied above, wherein the FSS space stations are located antipodal to the DRS satellite and the FSS earth station is located near the equator and near the limb of the earth as seen from the DRS satellite, some constraints may need to be placed on the DRS-to-user operations.

6.3 User satellite-to-DRS

As in § 6.1, the FSS satellite is most likely to receive interference from a user spacecraft transmission toward the DRS, when the FSS satellite is located in an adjacent orbital position. Again, as in § 6.1, the criteria for interference to a satellite link can be obtained from Appendix 29 of the Radio Regulations. In this case, the mission spacecraft is assumed to possess a main beam gain of 40 dBi and an orbital altitude of 200 km (to determine the worst-case condition). Using the satellite antenna reference radiation pattern of Report 558-1 (Kyoto, 1978), an angular separation of 2.7° between the geostationary satellites of the two services as viewed from the user satellite is necessary to avoid exceeding the Appendix 29 criterion for interference to the FSS up link. Recalling from § 6.1 that a topocentric angular separation of at least 5.7° between the two geostationary satellites is already required because of DRS earth station emissions intercepting the FSS satellite, the separation required by this interference path is already satisfied. Therefore, the interference caused by mission spacecraft in its return link to the DRS to the FSS up link should not endanger FSS up link performance while sharing frequencies with the TDRSS.
ANNEX I

FREQUENCY SHARING BETWEEN FEEDER LINKS FOR THE BROADCASTING-SATELLITE SERVICE (BSS) AND THE SPACE RESEARCH SERVICE AT 14.5-14.8 GHz

1. Introduction

This Annex evaluates the feasibility of Earth-to-space frequency sharing between typical data relay satellite (DRS) systems in the space research service and feeder links to the broadcasting-satellite systems in the 14.5-14.8 GHz band. The BSS feeder-link operations in this band may be planned for Regions 1 and 3 at the WARC ORB(2). In Region 2, BSS feeder links are planned in the 17.3-18.1 GHz band.

2. Interference analysis

2.1 Interference from a DRS earth station to a BSS satellite

The ensuing analysis is based upon typical parameters of BSS and DRS operations. These parameters are:

- **BSS parameters:**
  - Earth-station antenna gain: 57 dB
  - Maximum e.i.r.p.: 82 dBW
  - RF bandwidth: 27 MHz
  - Required \( \frac{C}{I} \) ratio: 45 dB

- **DRS parameters:**
  - Earth-station antenna pattern: \( 32 - 25 \log \theta^* \)
  - Power spectral density: \(-62\, \text{dB(W/Hz)}\)
  - Total power in 27 MHz: 12.3 dBW

The carrier (C) to interference (I) ratio produced at the BSS satellite can be calculated by comparing the e.i.r.p.s of each system towards the BSS satellite in 27 MHz as follows:

\[
\frac{C}{I} = \frac{\text{BSS e.i.r.p.} - \text{DRS e.i.r.p.}}{\text{BSS e.i.r.p.}}
\]

or

\[
\frac{C}{I} = 82 - \left(12.3 + 32 - 25 \log \theta\right)
\]

For a required \( \frac{C}{I} \) of 45 dB, the required satellite spacing is calculated as:

\[
\theta = \log^{-1} \left(\frac{45 - 37.7}{25}\right)
\]

or

\[
\theta = 2^\circ
\]

This calculation assumes co-located earth stations, a worst-case assumption. The value of \(2^\circ\) would be an acceptable angular separation and would indicate feasible operations on this link.

* Where \(\theta\) is the angular separation between DRS and BSS satellites as seen from DRS earth station.
2.2 Interference from BSS feeder-link earth station to DRS satellite

The transmissions of a BSS earth station may also illuminate a receiving antenna of a DRS satellite adjacent to a BSS satellite. Using the parameters described in § 2.1, assuming a DRS satellite receiver noise temperature of 2300 K and a DRS satellite receiver antenna peak gain of 44.5 dBi, the interference to noise ratio produced by a BSS earth station at an adjacent DRS satellite can be calculated as follows:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>BSS transmit antenna pattern</td>
<td>$32 - 25 \log \theta$</td>
</tr>
<tr>
<td>Power delivered to antenna</td>
<td>25 dBW</td>
</tr>
<tr>
<td>Bandwidth conversion</td>
<td>$-74.3 \text{dB(Hz/27 MHz)}$</td>
</tr>
<tr>
<td>Spectral distribution factor*</td>
<td>4 dB</td>
</tr>
<tr>
<td>Free-space loss</td>
<td>$-207.7$ dB</td>
</tr>
<tr>
<td>DRS satellite peak gain</td>
<td>$+44.5$ dBi</td>
</tr>
<tr>
<td>Interference power spectral density (dB(W/Hz))</td>
<td>$-176.5 - 25 \log \theta$</td>
</tr>
</tbody>
</table>

Therefore:

$$I/N = -176.5 - 25 \log \theta - k - T$$ dB

$$I/N = 18.5 - 25 \log \theta$$ dB

where:

$k$: Boltzmann's constant (equivalent to $-228.6 \text{dB(W/(Hz \cdot K)})$),

$T$: DRS satellite receiver noise temperature (equivalent to 33.6 dB(K)).

If an allowable $I/N$ ratio at the DRS is taken as $-10$ dB, then the required spacing $\theta$ between BSS and DRS satellites can be calculated by:

$$-10 = 18.5 - 25 \log \theta$$

$$\theta = \log^{-1} (28.5/25)$$

or:

$$\theta = 13.8^\circ$$

This angular spacing is that which would be required if the BSS and DRS earth stations were co-located. If, however, the earth stations are not co-located and therefore additional discrimination toward the unwanted signal can be realized through DRS satellite antenna off-axis pointing, more acceptable satellite spacings can be achieved as shown in Fig. 1. If care in the selection of DRS earth-station sites is exercised, frequency sharing is feasible.

* Spectral distribution factor is defined as the difference between peak (maximum) and average power spectral density of the signal. While the value of 4 dB is used in this calculation, Fig. 1 presents results also for a value of 7 dB.
Minimum satellite spacing (degrees)

FIGURE 1 - Minimum allowable satellite spacing as a function of DRS antenna discrimination

Curves A: spectral distribution factor = 4 dB
B: spectral distribution factor = 7 dB

BIBLIOGRAPHY


REINHART, E. E. [May, 1974] Orbit spectrum sharing between the fixed-satellite and broadcasting-satellite services with applications to 12 GHz domestic systems. R-1463-NASA, Santa Monica, Rand Corporation, CA, USA.
1. Introduction

This Report presents a summary of the telecommunication requirements for near-Earth space research. Such research uses spacecraft or other objects in near-Earth space for scientific or technological research purposes. The discussions provide a foundation for establishing radio-frequency spectrum requirements for the space research service and for frequency sharing between the space research service and other services which are considered in Reports 984 and 985 respectively.

The following concept of near-Earth space research is based on the definition of near-Earth space as:

**Near-Earth space:**

Space at altitudes above the major portion of the atmosphere of the Earth, but significantly less than the distance to the Moon.

2. General system considerations

2.1 Types of mission

The field of space research using near-Earth satellites includes:

- solar/terrestrial physics (ionospheric, magnetospheric, solar wind studies, geomagnetism, etc.);
- cosmic particles and electromagnetic radiation;
- atmospheric physics;
- astronomy, using observations at various frequencies;
- radio propagation;
- geodesy and geodynamics;
- biology, life sciences;
- Earth exploration and meteorology (experimental phases);
- testing of new technology.

2.2 Mission duration

The duration of an unmanned mission is determined by the mission objective, and may often be limited by the power and total energy available on the spacecraft. For manned missions, an additional limiting factor is the maximum length of time a human being can safely stay in space. Mission durations may last from a few months to several years for unmanned missions, and from several days to several months for manned missions. For certain manned space research experiments, the human factor that limits its duration can be circumvented by a change of spacecraft personnel.

2.3 Orbit types

Near-Earth satellite orbits are classified as either low, geosynchronous or highly elliptical.

2.3.1 Low orbit

A low orbit is defined as one in which the apogee and perigee are significantly nearer the Earth than is the geostationary-satellite orbit. A feature of the orbit is that the percentage of time a spacecraft is visible to its earth station or any other fixed terrestrial station, is low. Report 684 discusses the visibility of low-orbit satellites.
2.3.2 Geosynchronous-satellite orbit

The period of rotation for a satellite in this orbit is about 23 h 56 min. A particular type of geosynchronous-satellite orbit which is of interest for space research telecommunications is the geostationary satellite-orbit. Two important characteristics of this orbit are:

- the position of a geostationary satellite relative to a point on the Earth is fixed. This implies that visibility is continuous between a geostationary satellite and its associated earth station, and all other stations located in the field of the view of the satellite;
- a geostationary satellite can provide significant coverage to a low-orbit satellite. Inter-satellite links can further permit continuous radio contact between a low-orbit satellite and a single main earth station.

2.3.3 Highly elliptical orbits

A characteristic of this type of orbit is that the percentage of time a satellite is visible to its associated earth station can be high. Nearly continuous data transfer to and from the satellite is feasible.

3. Critical communication periods

During each space-research mission, there are certain periods which are critical to the success of the mission. Failure of reliable communications during these critical periods may cause anything from a minor difficulty to the total failure of the mission. Launch, injection and landing (manned) phases are particularly critical periods. For many near-Earth missions which depend on a limited number of tracking facilities, critical periods will generally occur when the spacecraft is within viewing range of the tracking site.

4. Communication requirements

The communication system of any space-research network comprises four basic sub-systems. They are:

- the maintenance telemetry sub-system required for transmitting sensor data regarding the health and condition of the spacecraft or of its human occupants, to Earth;
- the mission telemetry sub-system required for transmitting scientific, engineering, and video data to Earth and for voice communications;
- the command sub-system necessary to provide guidance and control of spacecraft. In the case of a manned spacecraft, the capability of command is not intended to replace control of the spacecraft by its human occupant, but rather to supplement it;
- the tracking sub-system required to provide information regarding the position and velocity of the spacecraft necessary for computing its orbit.

Because of severe limitations on size and weight, many spacecraft combine the tracking, telecommand, telemetering, voice and video systems by integrating the various functions into a single radio system. Such integrated systems consolidate the many various separate transmitters, receivers and antennas by allowing one receiver and one transmitter to perform several functions simultaneously, thus resulting in simplicity, on the spacecraft and on the ground. Additionally, it may provide efficient usage of the spectrum.

Transmission of telecommunication functions may be accomplished by either employing a direct telecommunication link between the spacecraft and earth station, or by an indirect relay satellite link (see Report 537 (Kyoto, 1978)).

For some missions, direct communication links may be adequate to satisfy mission communication requirements. However, for many missions, communication via a geosynchronous relay satellite affords significant benefits to the user community. Some of these benefits, which are a result of the extended coverage provided by relay satellites, are:
- significant increase in real time telemetry;
- reduction or elimination of on-board data storage equipment, e.g. tape recorders;
- real time command control and experiment modification;
- improved scheduling for all uses of the system.
In considering the limitations in the power capabilities of spacecraft, channel coding and modulation techniques reduce the transmitter power while achieving the required bit-error ratio. In certain applications, e.g. relay satellite transmissions, additional burdens such as interference and multipath problems may be placed on the communication system. Since multipath signals are proportional to the transmitted power, the direct signal-to-multipath signal ratio always remains the same, negating an increase in signal power as an option for overcoming the multipath problem. Furthermore, increases in signal power to overcome interference problems are also limited by either spacecraft power capabilities or power flux-density restrictions. For these and other problems associated with relay satellite links, the use of spread spectrum and/or channel coding techniques has been effective.

In the presence of interference, the required energy per information bit may be reduced by increasing the channel bandwidth and either using an appropriate modulation technique (for narrow-band interference) or using channel coding (for wideband interference).

4.1 Maintenance telemetry sub-system

The primary purpose for the maintenance sub-system is to ensure the safety of spacecraft personnel and success of the mission, so the communication link should have a capacity large enough to handle all essential information and in the case of propagation through the atmosphere, there should be a link which is independent of weather. Baseband bit error ratio of 1 in $10^5$ is the usual requirement for this sub-system.

Data rates during launch and orbit adjustment can be as high as 1 kbit/s, and range from a few bits per second to several thousand bits per second for normal real-time telemetry formats. Special read-outs, such as from computers or tape recorders, are generally at higher rates such as a few hundred kilobits per second.

Power output for maintenance telemetry links ranges from a few milliwatts to several watts. Directional antennas are often used for telemetry links, omnidirectional antennas are primarily used for launch and injection phases, spacecraft rendezvous and emergency situations.

4.2 Mission telemetry sub-system

4.2.1 Telemetry rates

The volume of mission telemetry data transmitted depends on the types of mission, sophistication of the spacecraft and the available contact hours between transmitting spacecraft and receiving earth station. Real-time telemetry rates may range from several kilobits per second for low data rate spacecraft, to several hundred megabits per second for more sophisticated spacecraft. For data relay satellites, studies have indicated that future systems will need to process data at a rate of gigabits per second. Telemetry rates for stored or computed data, transmitted in the playback or dump mode, are similar to real-time telemetry rates.

4.2.2 Voice communications

In manned space flight, voice communication with its inherent flexibility in the transmission of information, is an essential factor in guaranteeing successful missions with maximum safety of the astronaut.

Requiring an information bandwidth of the order of 3 kHz, and a post-detection signal-to-noise ratio of 20 dB, frequency modulated analogue systems can provide reliable and intelligible communication between space and earth stations. However, digital voice encoding techniques such as pulse code modulation (PCM) or adaptive delta modulation (ADM) schemes followed by error correction coding can provide a level of performance which is significantly greater than that practically attainable using analogue systems [Schilling et al., 1978].

4.2.3 Television

Requiring an information bandwidth of the order of 4.5 MHz, television signal transmission is generally accomplished by using analogue frequency modulation techniques. Digital systems have not yet been adopted because the required bandwidth is much larger than that required by an analogue system for a desired level of picture quality. However, developments in digital coding techniques have established that significant compression of digital television data can be achieved by using relatively sophisticated source coding algorithms. It is anticipated that video will be transmitted using digital techniques in the near future [Habibi and Batson, 1978].
4.3 Command sub-system

A telecommand sub-system, as with the maintenance telemetry sub-system, is of paramount importance to the safety and success of any mission and as such must be particularly reliable under all adverse transmission conditions, e.g., unfavourable weather and radio interference. The problem of interference to telecommand receivers in spacecraft is especially difficult in that the wanted signal is not always present, and the interfering signal must not trigger the telecommand receiver even in the absence of the wanted signal. Required reliability is therefore quite high, with bit error ratios not exceeding $1 \times 10^{-5}$ for all telecommand links. Additionally, the false command rejection ratio should be at least $1 \times 10^{-8}$.

Providing high reliability of telecommand links necessitates the following:

- a weather independent Earth-to-space link;
- high command e.i.r.p. to compensate for the low gain omni-antennas used by the receiving spacecraft during launch and injection phases and during emergencies;
- command encoding to ensure sufficient false command rejection caused by error bursts, fading or spurious signals.

Typical information rates of a command code, range from as low as a few bits per second to about 2 kbit/s for more complex spacecraft. For manned spacecraft, information rates may be as high as 3 kbit/s. The inclusion of a simple parity bit or the use of the complement of the command words are simple error detection methods. More elaborate multi-error correcting codes are also used.

4.4 Tracking sub-systems

Reliable radio tracking of spacecraft is one of the basic requirements of any space-research mission. In addition to providing information necessary to determine the location in space of the spacecraft at any instant, tracking is also necessary for evaluation of launch performance, for vernier corrections to trajectories, for determining precise timing for critical manoeuvres such as retrorocket firing and for the transfer of data between earth and space stations. During these times, earth and space-station receivers track the carrier signal with the aid of phase-locked loops and directive antennas. Loss of carrier lock by the phase-locked loops during moments of data transfer may seriously degrade the reliability of the communication link (see Reports 544 and 545 (Geneva, 1982) for a discussion of interference into phase-locked loops).

Standard spacecraft tracking techniques generally involve the determination of one or more of the parameters: range, range-rate and angle data.

Range is determined by measuring the round trip time of a radio signal to and from a spacecraft, range-rate is usually determined by measuring the Doppler-shift in the signal, and angle data is obtained by measuring the angle between the observer's reference plane and the line from a reference point in the plane to the spacecraft. The following techniques are used in the space research service for spacecraft tracking:

- interferometer tracking,
- radar tracking,
- coherent and non-coherent range and range-rate tracking,
- bilateral tracking.

5. Summary

The basic telecommunication requirements for the space research service as outlined in this Report, show that telemetry, tracking and telecommand sub-systems will be required by all space research spacecraft and that voice and video communication are essential to manned missions.

As differing research missions have significantly different requirements, the overall data requirement for an individual mission ranges from a few kilobits per second to many hundreds of megabits per second.
1. Introduction

This Report presents some characteristics of deep-space research missions conducted by several administrations, the functional and performance requirements for telecommunications needed to conduct deep-space research with spacecraft, and the technical methods and parameters of systems used in connection with such missions. A much more comprehensive treatment of these and related topics may be found in [Yuen, 1983].

Considerations regarding preferred frequency bands for deep-space research can be found in Reports 683 and 849. Interference, protection criteria and sharing are discussed in Report 685.

2. Telecommunication requirements

Deep-space missions require highly reliable communications over long periods of time and great distances. For example, a spacecraft mission to gather specific information at the planet Neptune takes eight years and requires telecommunication over a distance of $4 \times 10^9$ km. The need for high e.i.r.p. and very sensitive receivers at earth stations is a result of the large communication distances involved in deep-space research.

Continuous usage of deep-space communication bands is a consequence of the several missions now in existence and others being planned. Because many deep-space missions continue for periods of several years, and because there are usually several missions in progress at the same time, there is a corresponding need for communication with several spacecraft at any given time.

In addition, each mission may include more than one spacecraft, so that simultaneous communication with several space stations will be necessary. The US Mars orbiter/lander (Viking) mission was designed for simultaneous operation of two Earth-to-space links and three space-to-Earth links, using a single earth station. Simultaneous co-ordinated communication between a space station and more than one earth station may also be required.

2.1 Telemetering requirements

Telemetering is used to transmit both maintenance and scientific information from deep space.

Maintenance telemetering information about the condition of the spacecraft must be received whenever needed to ensure the safety of the spacecraft and success of the mission. This requires a weather independent telecommunications link of sufficient capacity. The propagation properties of the current 2 GHz allocation meet the requirement. Maintenance telemetering data rates are relatively low. For example, the Galileo spacecraft has data rates of 40 and 1200 bit/s for maintenance telemetering.
Science telemetering involves the sending of data from measurements made by the on-board scientific instruments. The scientific data are of two types: imaging (television-like), and non-imaging (general). For example, the imaging experiment on the US 1975 (the dates quoted in this section are launch dates for the space probes) Mars lander (Viking) consisted of two facsimile cameras; non-imaging science experiments were biological, meteorological, seismological, molecular and mineral analysis. Data rates and acceptable error rates may be quite different for the two types of data. Video data rates up to 134 kbit/s have already been used.

Telemetering link capacity has steadily increased with the development of new equipment and techniques. This increase can be used in two ways:
- to gather larger amounts of scientific data about nearby planets, and
- to permit missions to more distant planets.

For a particular telemetering system, the maximum possible data rate is proportional to the inverse square of the communication distance. The same link capability that provides for a Galileo data rate of 134 kbit/s from the vicinity of the planet Jupiter (9.3 \( \times \) 10\(^5\) km) would also provide for a data rate of 5 Mbit/s from the vicinity of the planet Venus (1.5 \( \times \) 10\(^5\) km). Because higher data rates require wider transmission bandwidths, the ability to effectively utilize the maximum telemetering capability depends in part on the number of simultaneous deep-space missions and the width of allocated bands.

As imaging experiments become more sophisticated, even higher bit rates will be required. This is discussed in § 4.6, including the effect on bandwidth [Davies and Murray, 1971].

An important contribution to telemetering has been the development of coding methods that permit operation with a lower signal to noise ratio [Forney, 1970; Viterbi and Omura, 1979]. The coded signal requires a wider transmission bandwidth. The use of coded telemetering at very high data rates may be limited by allocation width.

2.2 Telecommand requirements

Reliability is the principal requirement of a telecommand link. Commands must be received accurately and when needed. For US deep-space missions the telecommand link is required to have a bit error ratio not greater than 1 \( \times \) 10\(^{-5}\). Commands must be received successfully, without regard to spacecraft orientation, even when the primary high gain antenna may not be pointed to Earth. For such circumstances, reception using a nearly omni-directional spacecraft antenna is required. Very high e.i.r.p. is needed at earth stations because of low spacecraft antenna gain, and to provide high reliability.

With computers on the spacecraft, automatic sequencing and operation of spacecraft systems is largely predetermined and stored on-board for later execution. For some complicated sequences, automatic operation is a requirement. Telecommand capability is required for in-flight alteration of stored instructions, which may be needed to correct for observed variations or malfunctions of spacecraft behaviour. This is particularly true for missions of long duration, and for those circumstances where sequencing is dependent on the results of earlier spacecraft events. For example, the commands for spacecraft trajectory correction are based on tracking measurements and cannot be predetermined.

Command data rates have been as low as one bit per second, with an increase to a few kilobits per second expected in the future.

The telecommand link must be relatively free from weather effects. Reliable telecommand includes the need for weather independent maintenance telemetering to verify that commands are correctly received and loaded into command memory. The 2 GHz allocations provide weather independence.

2.3 Tracking requirements

Tracking provides information used for spacecraft navigation and for radio science studies.
2.3.1 Navigation

The basic tracking measurements for navigation are radio-frequency Doppler shift and the round-trip propagation time of a ranging signal. The measurements must be made with a degree of precision that satisfies navigation requirements [Curkendall and Stephensen, 1970]. Measurement accuracy is affected by variations in velocity of propagation, knowledge of station location, timing precision, and electronic circuit delay in earth and space station equipment. Table I lists accuracy specifications for the Viking Mars orbiter/lander and Voyager Jupiter/Saturn flyby missions. Future requirements for longer or more difficult missions require more accurate navigation and tracking [Melbourne, 1976].

<table>
<thead>
<tr>
<th>Mission (launch date)</th>
<th>Required navigation accuracy (km)</th>
<th>Doppler frequency measurement accuracy (Hz)</th>
<th>Range measurement accuracy (m)</th>
<th>Estimated accuracy of earth station location (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Viking Mars Orbiter/Lander (1975)</td>
<td>300 (at Mars)</td>
<td>± 0.003</td>
<td>± 20</td>
<td>± 20</td>
</tr>
<tr>
<td>Voyager Jupiter/Saturn flyby (1977)</td>
<td>400 (at Jupiter)</td>
<td>± 0.001</td>
<td>± 4</td>
<td>± 2</td>
</tr>
<tr>
<td></td>
<td>1300 (at Saturn)</td>
<td>± 0.001</td>
<td>± 4</td>
<td>± 2</td>
</tr>
<tr>
<td>Galileo Jupiter Orbiter</td>
<td>300 (at Jupiter)</td>
<td>± 0.0005</td>
<td>± 2</td>
<td>± 1</td>
</tr>
</tbody>
</table>

2.3.2 Radio science

Spacecraft telecommunication links can also be important to studies of propagation, relativity, celestial mechanics, and gravity [Anderson, 1973; Hennes and Fulmer, 1972; Michael, 1972; Eshleman et al., 1977]. Amplitude, phase, frequency, polarization and delay measurements provide the needed information. The opportunity to make these measurements depends upon the availability of appropriate allocations. Above 1 GHz transmission delay and Faraday rotation (charged particle and magnetic field effects) decrease rapidly with increasing frequency, and thus are best studied with the lower frequencies. The higher frequencies provide relative freedom from these effects and are more suitable for studies of relativity, gravity and celestial mechanics. For these studies, calibration of charged particle effects at the lower frequencies is also needed.

Range measurements with an absolute accuracy of one or two centimetres are required for this fundamental scientific work. This ranging accuracy depends upon wide band codes and the simultaneous use of multiple frequencies for charged-particle calibration.

2.4 Requirements for manned deep-space missions

Manned missions beyond the moon have not yet been flown. The functional requirements of such a mission will be similar in kind to those for unmanned missions. The presence of human occupants in spacecraft will place additional requirements for reliability on the telemetering, telecommand and tracking functions. Given the necessary level of reliability, the significant difference between manned and unmanned missions will be the use of voice and television links for both Earth-to-space and space-to-Earth communication. From a telecommunication standpoint, the effect of this will be an expansion of transmission bandwidth in order to accommodate the video signals. Given the link performance to accomplish the required data transfer rates, telecommunications for manned and unmanned deep-space research are similar enough in concept that separate discussion is generally not required.
3. Technical characteristics

3.1 Locations and characteristics of deep-space earth stations

Table II gives the locations of earth stations in the deep-space networks of the various administrations.

For the United States, Deep Space Network (DSN), the earth station complexes are located at approximately 120° longitude intervals. At each complex there is one 70 m antenna, one 34 m antenna, one or more 26 m antennas, high power transmitters with extremely precise frequency control, sensitive phase-locked loop receivers, and associated equipment [Reid et al., 1973]. The DSN is interconnected via terrestrial communication lines and communication satellite facilities to a control centre in California, United States.

In Japan, a single 64 m antenna is operated at Nagano.

The earth stations in the deep-space communication network of the USSR are located near the towns of Evpatoriya and Ussuriisk: each station is equipped with parabolic antennas of diameter 70 and 32 m, operating for reception and transmission. An earth station located in the village of Medvezhi Ozera (near Moscow) is equipped with a single 64 m diameter parabolic antenna operating for reception only.

### TABLE II

**Locations of earth stations for deep-space research**

<table>
<thead>
<tr>
<th>Administration</th>
<th>Location</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Height above mean sea level (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>USA</td>
<td>Goldstone, California, USA</td>
<td>35°22'N</td>
<td>115°51'W</td>
<td>1019</td>
</tr>
<tr>
<td></td>
<td>Canberra, Australia</td>
<td>35°28'S</td>
<td>148°59'E</td>
<td>818</td>
</tr>
<tr>
<td></td>
<td>Madrid, Spain</td>
<td>40°26'N</td>
<td>4°17'W</td>
<td>791</td>
</tr>
<tr>
<td>Japan</td>
<td>Usuda, Nagano, Japan</td>
<td>36°08'N</td>
<td>138°22'E</td>
<td>1489</td>
</tr>
<tr>
<td>USSR</td>
<td>Evpatoriya, Ukrainian SSR</td>
<td>45°11'N</td>
<td>33°11'E</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Ussuriisk, USSR</td>
<td>44°01'N</td>
<td>131°45'E</td>
<td>75</td>
</tr>
<tr>
<td></td>
<td>Medvezhi ozera, USSR</td>
<td>55°52'N</td>
<td>37°57'E</td>
<td>152</td>
</tr>
</tbody>
</table>

The major characteristics of these various kinds of earth station are listed in Tables IIIa and IIIb for the United States, Table IIIc for Japan and Tables IIId and IIIe for the USSR.
### TABLE IIIa

**Characteristics of DSN earth stations with 70 m antennas operated by the United States**

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>Antenna gain (dBi)(^{(1)})</th>
<th>Antenna beamwidth (deg)</th>
<th>Transmitter power (dBW)</th>
<th>c.i.r.p. (dBW)</th>
<th>Receiving system noise temperature (K)</th>
<th>Receiving system noise spectral density (dBW/Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1 Earth-to-space</td>
<td>62</td>
<td>0.14</td>
<td>50</td>
<td>112</td>
<td>To be determined</td>
<td>To be determined</td>
</tr>
<tr>
<td>3.3 Space-to-Earth</td>
<td>63</td>
<td>0.13</td>
<td>56(^{(3)})</td>
<td>118</td>
<td>26(^{(1)}) 21(^{(2)})</td>
<td>-214(^{(1)}) -213(^{(2)})</td>
</tr>
<tr>
<td>7.2 Earth-to-space</td>
<td>72</td>
<td>0.04</td>
<td>43</td>
<td>115</td>
<td>To be determined</td>
<td>To be determined</td>
</tr>
<tr>
<td>8.4 Space-to-Earth</td>
<td>74</td>
<td>0.04</td>
<td>---</td>
<td>---</td>
<td>37(^{(1)}) 27(^{(2)})</td>
<td>-213(^{(1)}) -214(^{(2)})</td>
</tr>
<tr>
<td>13.0 Space-to-Earth</td>
<td>77</td>
<td>0.02</td>
<td>---</td>
<td>---</td>
<td>44(^{(1,4)}) 31(^{(2,4)})</td>
<td>-212(^{(1,4)}) -214(^{(2,4)})</td>
</tr>
<tr>
<td>17.0 Earth-to-space</td>
<td>79</td>
<td>0.02</td>
<td>To be determined</td>
<td>To be determined</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>32.0 Space-to-Earth</td>
<td>83</td>
<td>0.01</td>
<td>---</td>
<td>---</td>
<td>83(^{(1,4)}) 61(^{(2,4)})</td>
<td>-209(^{(1,4)}) -211(^{(2,4)})</td>
</tr>
<tr>
<td>34.5 Earth-to-space</td>
<td>83</td>
<td>0.01</td>
<td>To be determined</td>
<td>To be determined</td>
<td>---</td>
<td>---</td>
</tr>
</tbody>
</table>

\(^{(1)}\) Clear weather, 30 deg elevation angle, diplex mode for simultaneous transmission and reception.

\(^{(2)}\) Clear weather, 30 deg elevation angle, receive only.

\(^{(3)}\) 56 dBW transmitter power used only during spacecraft emergencies.

\(^{(4)}\) Estimate.
<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>Antenna gain (dBi)</th>
<th>Antenna beamwidth (deg)</th>
<th>Transmitter power (dBW)</th>
<th>e.i.r.p. (dBW)</th>
<th>Receiving system noise temperature (K)</th>
<th>Receiving system noise spectral density (dB(W/Hz))</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1 Earth-to-space</td>
<td>55</td>
<td>0.30</td>
<td>43</td>
<td>98</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>2.3 Space-to-Earth</td>
<td>56</td>
<td>0.27</td>
<td>---</td>
<td>---</td>
<td>33(^{(1)})</td>
<td>-213(^{(1)})</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>27(^{(2)})</td>
<td>-214(^{(2)})</td>
</tr>
<tr>
<td>7.2 Earth-to-space</td>
<td>66</td>
<td>0.09</td>
<td>43</td>
<td>109</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>8.4 Space-to-Earth</td>
<td>67</td>
<td>0.07</td>
<td>---</td>
<td>---</td>
<td>30(^{(1)})</td>
<td>-214(^{(1)})</td>
</tr>
</tbody>
</table>

(1) Clear weather, 30 deg elevation angle, diplex mode for simultaneous transmission and reception.
(2) Clear weather, 30 deg elevation angle, receive only.
### TABLE IIIc

**Characteristics of Japan's Deep Space Centre with 64 m antenna**

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>Antenna gain (dBi)</th>
<th>Antenna beamwidth (degree)</th>
<th>Transmitter power (dBW)</th>
<th>e.i.r.p (dBW)</th>
<th>Receiving system noise temperature (K)</th>
<th>Receiving system noise spectrum density (dBW/Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>E: Earth</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.1 Earth-to-space</td>
<td>62</td>
<td>0.14</td>
<td>43</td>
<td>105</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2.3 Space-to-Earth</td>
<td>63</td>
<td>0.13</td>
<td>-</td>
<td>-</td>
<td>30</td>
<td>-214</td>
</tr>
<tr>
<td><strong>S: Space</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>see Note 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.2 Earth-to-Space</td>
<td>71</td>
<td>0.042</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>8.5 Space-to-earth</td>
<td>72</td>
<td>0.035</td>
<td>-</td>
<td>-</td>
<td>TBD</td>
<td>TBD</td>
</tr>
</tbody>
</table>

1. Clear weather, 90° elevation angle, diplex mode for simultaneous reception and transmission, and with a gas-Helium-cooled parametric amplifier.

2. The parameters for 7.2 and 8.5 GHz are design values.

3. The antenna is designed to be fed through a beam waveguide system which enables transmitters and low noise amplifiers to be operated from a fixed mounting on the horizontal floor regardless of antenna pointing direction.
### TABLE IIId

**Parameters of 70-metre antenna earth station operated by the USSR**

<table>
<thead>
<tr>
<th>Link</th>
<th>Frequency (GHz)</th>
<th>Antenna gain (dB)</th>
<th>Beamwidth (°)</th>
<th>Tx power (dBW)</th>
<th>e.i.r.p. (dBW)</th>
<th>Rx noise temperature (°K)</th>
<th>Rx spectral noise density dB(W/Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earth-to-space</td>
<td>5.0</td>
<td>69.4</td>
<td>0.056</td>
<td>47</td>
<td>116.4</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Space-to-Earth</td>
<td>5.8</td>
<td>71.0</td>
<td>0.046</td>
<td>-</td>
<td>-</td>
<td>40*</td>
<td>-212.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>57**</td>
<td>-211.0</td>
</tr>
<tr>
<td>Space-to-Earth</td>
<td>8.4</td>
<td>73.9</td>
<td>0.033</td>
<td>-</td>
<td>-</td>
<td>to be determined</td>
<td>to be determined</td>
</tr>
</tbody>
</table>

* for elevation angle greater than 20 degrees  
** for elevation angle less than 20 degrees

1 USSR systems operated on the band 5.000 - 5.025 GHz (E-S) and in the band 5.870 - 5.890 GHz (S-E), on a non-interference basis (RR 342).
### Table IIIe

Parameters of the 32-metre earth station operated by the USSR

<table>
<thead>
<tr>
<th>Link</th>
<th>Frequency (GHz)</th>
<th>Antenna gain (dB)</th>
<th>Beamwidth (°)</th>
<th>Tx power (dBW)</th>
<th>e.i.r.p. (dBW)</th>
<th>Rx noise temperature (°K)</th>
<th>Rx spectral noise density dB(W/Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earth-to-space</td>
<td>5.0</td>
<td>61.4</td>
<td>0.120</td>
<td>49</td>
<td>110.4</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Space-to-Earth</td>
<td>5.8</td>
<td>63.0</td>
<td>0.100</td>
<td>-</td>
<td>-</td>
<td>41*</td>
<td>-212.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>58**</td>
<td>-211.0</td>
</tr>
<tr>
<td>Space-to-Earth</td>
<td>8.4</td>
<td>65.9</td>
<td>0.071</td>
<td>-</td>
<td>-</td>
<td>to be determined</td>
<td>to be determined</td>
</tr>
</tbody>
</table>

* for elevation angle greater than 20 degrees
** for elevation angle less than 20 degrees

The system noise temperatures listed in Table IIIa are for the specified conditions. The noise temperature varies with the operating mode, weather conditions and elevation angle. This variation must be included in performance and interference calculations. The noise contribution of the earth station receiver alone is shown in Fig. 1. The curve is based on current US experience in the 2 and 8 GHz bands and estimates of possible implementation at the higher frequencies.
The receiving performance of deep-space earth stations is usually specified in terms of the ratio of signal energy per bit to noise spectral density required to give a particular bit error ratio. Another way to show the high performance and sensitivity of these stations is to express the ratio of antenna gain to noise temperature. This quotient, commonly referred to as G/T, is approximately 50 dB/K at 2.3 GHz, and 59.5 dB/K at 8.4 GHz. These values may be compared with the lower and typical 41 dB/K of some fixed satellite earth stations.

3.2 Space stations

Spacecraft size and weight is limited by the payload capability of the launch vehicle. The power of the space station transmitter and the size of the antenna are limited in comparison with those parameters at earth stations. The noise temperature of the receiver is higher because a simple uncooled preamplifier is generally used.

The space station has a combined receiver-transmitter, called a transponder, which operates in one of two modes. In the turn-around, (also called two-way) mode, the carrier signal received from an earth station is used to control the oscillator in a phase-locked signal loop. The frequency of this oscillator is then used to control the transmitter frequency of the transponder according to a fixed ratio. In the one-way mode, no signal is received from an earth station, and the transmitter frequency is controlled by a crystal oscillator.

In the two-way mode, the spacecraft transmitted frequency and phase is controlled very precisely because of the extreme accuracy and precision of the signal received from an earth station.

Table IV lists major characteristics of space stations designed for the Galileo mission to Jupiter.

TABLE IV

<p>| Selected characteristics of radio equipment for the Galileo Jupiter Orbiter spacecraft |
|---------------------------------|-------|-------|----------------|--------|--------|</p>
<table>
<thead>
<tr>
<th>Space-to-Earth frequency (MHz)</th>
<th>Antenna size (m)</th>
<th>Antenna gain (dBi)</th>
<th>Antenna beamwidth (degrees)</th>
<th>Transmitter power (dBW)</th>
<th>e.i.r.p. (dBW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2295</td>
<td>3.7</td>
<td>37</td>
<td>2.3</td>
<td>13</td>
<td>50</td>
</tr>
<tr>
<td>8425</td>
<td>3.7</td>
<td>48</td>
<td>0.64</td>
<td>13</td>
<td>61</td>
</tr>
<tr>
<td>Earth-to-space frequency (MHz)</td>
<td>Antenna size (m)</td>
<td>Antenna gain (dBi)</td>
<td>Antenna beamwidth (degrees)</td>
<td>Receiver noise temperature (K)</td>
<td>Receiver noise spectral density (dB(W/Hz))</td>
</tr>
<tr>
<td>---------------------------------</td>
<td>-------</td>
<td>-------</td>
<td>----------------</td>
<td>----------------</td>
<td>----------------</td>
</tr>
<tr>
<td>2115</td>
<td>3.7</td>
<td>36</td>
<td>2.6</td>
<td>1200</td>
<td>-198</td>
</tr>
<tr>
<td>7150</td>
<td>3.7</td>
<td>48</td>
<td>0.64</td>
<td>390</td>
<td>-202</td>
</tr>
</tbody>
</table>

Because of the limited e.i.r.p. of space stations, the earth station must have the most sensitive receiver possible. Receivers with lower sensitivity may be used in space stations as a result of the very high e.i.r.p. of the earth station. Data rate requirements and considerations of size, weight, cost, complexity and reliability determines the receiver noise temperature needed for a particular spacecraft.

The Helios spacecraft of the Federal Republic of Germany had a receiver noise temperature of 600 K at 2.1 GHz. A 7150 MHz receiver being developed for the Galileo mission to Jupiter is expected to have a noise temperature of 390 K. The Japanese Halley's comet explorers Suisei (PLANET-A) and Sakigake (MS-T5) achieved a receiver noise temperature of 238 K at 2.1 GHz excluding feeder loss.
At the present time, the power of the space station transmitter is limited primarily by the electrical power that can be supplied by the spacecraft, and not by transmitter technology.

4. Deep-space telecommunication methods

Telemetering and telecommand functions for deep-space telecommunications are typically accomplished by transmission of phase modulated carriers [Viterbi, 1966; Lindsey, 1972; Lindsey and Simon, 1973]. Doppler tracking is done by phase coherent detection of the carrier. By adding a ranging signal to the modulation, the ranging function is performed [Edelson, 1972; NASA, 1976].

4.1 Carrier tracking and Doppler measurement

As received on Earth, the frequency of a signal transmitted by the spacecraft is modified by the Doppler effect [Curkendall and Stephensen, 1970]. The means to measure the Doppler shift, and hence the velocity of the spacecraft with respect to the earth station, is provided by carrier phase tracking. Earth and space station receivers track the carrier signal with a phase-locked loop. In the two-way transponder mode, the frequency and phase in the space station phase-locked loop are used to develop one or more space-to-Earth frequencies. This provides signals to the earth station that are correlated with the Earth-to-space frequency, enabling precise Doppler measurements to be made.

In the one-way mode, the space-to-Earth frequencies are derived from the oscillator in the transponder, and the Doppler measurement is based on a priori knowledge of the oscillator frequency.

The carrier tracking process also provides the local oscillator signal used to convert the radio frequency to the receiver intermediate frequency.

4.2 Modulation and demodulation

The radio links use phase (angle) modulation of the radio frequency carrier. The base-band digital data signal is used to modulate a subcarrier, which in turn phase modulates the radio frequency carrier. A square wave subcarrier is typically used for telemetering; for telecommand the subcarrier may be sinusoidal. The modulation index is adjusted to provide a desired ratio of residual carrier power to data sideband power. This ratio is selected to provide optimum carrier tracking and data detection in the receiver.

RF carrier and data subcarrier demodulation is accomplished by phase-locked loops. Data detection generally uses correlation and matched filter techniques.

Television and voice links for manned missions may use other modulation and demodulation techniques.

4.3 Coding

In a digital telecommunication link, error probability can be reduced if the information bandwidth is increased. Coding accomplishes this increases by translating data bits into a larger number of code symbols in a particular way. Some examples of coding types are block and convolutional codes [Forney, 1970; Lindsey and Simon, 1973; Viterbi and Omura, 1979]. After transmission, the original data are recovered by a decoding process that is matched to the code type. The performance advantage of coded transmission is related to the wider bandwidth, and can amount to 3.8 dB (convolutional coding as used in the Voyager Jupiter/Saturn mission, with a maximum bit error ratio of $1 \times 10^{-7}$).

4.4 Multiplexing

Science and maintenance telemetering may be combined into a single digital data stream by time division multiplexing; or may be on separate subcarriers that are added to provide a composite modulating signal. A ranging signal may also be added in combination with telemetering or telecommand. The amplitude of the different data signals is adjusted to properly divide the transmitter power between the carrier and information sidebands.
4.5 **Ranging**

Ranging is performed from an earth station using the space station transponder in the two-way mode. Ranging modulation on the Earth-to-space signal is recovered in the transponder and used to modulate the space-to-Earth carrier. At the earth station, comparison of the transmitted and received ranging codes yields a transmission delay measurement proportional to range.

A fundamental limitation to ranging precision is the ability to measure time correlation between the transmitted and received codes. The system currently in use employs a highest code frequency of 0.5 MHz. The code period is 2 µs and resolution to 4 ns is readily achieved, assuming sufficient signal-to-noise ratio. This resolution is equivalent to 120 cm in a two-way path length, or 60 cm in range. This meets the current navigation accuracy requirements of Table II.

For the 1 cm accuracy needed for future radio science experiments (§ 2.3.2), a code frequency of at least 30 MHz is required.

4.6 **Bandwidth**

The total bandwidth suitable for deep-space telecommunications is a function of the required data rates, the number of spacecraft in each mission, the number of missions, and the extent to which frequencies may be shared without mutual interference.

4.6.1 **Link bandwidth**

Earth-to-space and space-to-Earth bandwidths are governed by required telemetering data rates [Davies and Murray, 1971] and ranging precision [Couvillon et al., 1970]. By contrast, the telecommand spectrum width is relatively narrow as a result of the relatively low data rate.

To pass a periodic square modulation waveform with no more than 0.3 dB loss, the bandwidth must include the fifth harmonic of the modulating frequency. For the telemetering signal, the radio frequency bandwidth must be wide enough to pass the fifth harmonic of the sub-carrier frequency plus the fifth harmonic of the clock rate (1/2 the bit rate). With present techniques, the sub-carrier frequency must be high enough to provide 1.5 sub-carrier cycles per data bit. The total bandwidth required is therefore:

\[
BW = 2\left( BR \times 1 \right) + 5 \times \frac{1}{2} BR
\]

or

\[
= 20 BR
\]

where,

- \( BW \): RF bandwidth,
- \( BR \): bit rate.

For example, a 1 Mbit/s uncoded data rate requires a 1.5 MHz subcarrier and 20 MHz RF bandwidth.

Figure 2 shows a curve representative of telemetering spectra.
As telemetering data rates increase, the need for a sub-carrier to keep the data power outside the carrier tracking loop bandwidth becomes less important. This is because the carrier loop bandwidth is a relatively smaller fraction of the data spectrum bandwidth. By the use of appropriate coding, data power near the carrier frequency can be minimized so that sub-carriers are not necessary. Elimination of sub-carrier reduces the total bandwidth requirement to:

\[
BW = 2[5 \times \frac{1}{2} BR] = 5 BR
\]  

Direct modulation of the carrier may be used, requiring less bandwidth.

The current implementation of ranging uses square wave biphase modulation. The bandwidth required for the transmitted ranging signal is determined by the highest code frequency. The spectrum to the fifth harmonic is shown in Fig. 3. A bandwidth equal to six times the code frequency is usually considered acceptable. For some deep-space missions, the maximum bandwidth requirement will be determined by ranging accuracy considerations.
Future requirements for very high telemetering and ranging code rates may result in the need for additional reduction of transmitted spectrum bandwidth in order to accommodate one or more spacecraft within a particular band allocation. This is particularly true for the relatively narrow 2 and 8 GHz allocations. Suitable techniques include quadrature modulation, minimum shift keying utilizing waveforms with reduced harmonic power, and data compression. Some of these techniques impose a penalty in link performance or data quality.

Link bandwidth requirements for deep-space research are based on needed bit rates for the various functions shown in Table V.

The maximum radio frequency bandwidth needed for a particular mission is determined by the total bit rate required to permit simultaneous functions, and by the method of modulation. The ranging function is usually the most significant determinant of the maximum total bit rate. For current implementation, the maximum radio frequency bandwidth for a single unmanned spacecraft is approximately 3 MHz. For the VLBI function (§ 4.8.2), a pair of spectral lines spaced up to 25 MHz from the carrier frequency will be a part of the transmitted signal. Future requirements for the higher rates shown in Table V will result in required transmission bandwidths up to several hundred Megahertz.
### TABLE V — Required bit rates for a deep-space mission

<table>
<thead>
<tr>
<th>Direction and function</th>
<th>Link</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Weather independent</td>
</tr>
<tr>
<td><strong>Earth-to-space</strong></td>
<td></td>
</tr>
<tr>
<td>Telecommand (bit/s)</td>
<td>1–1000</td>
</tr>
<tr>
<td>Computer programming (kbit/s)</td>
<td>1–50</td>
</tr>
<tr>
<td>Voice (kbit/s)</td>
<td>45</td>
</tr>
<tr>
<td>Television (Mbit/s)</td>
<td>1–4</td>
</tr>
<tr>
<td>Ranging (Mbit/s)</td>
<td>1</td>
</tr>
<tr>
<td><strong>Space-to-Earth</strong></td>
<td></td>
</tr>
<tr>
<td>Maintenance telemetering (bit/s)</td>
<td>8–500</td>
</tr>
<tr>
<td>Scientific data (kbit/s)</td>
<td>0.008–115</td>
</tr>
<tr>
<td>Voice (kbit/s)</td>
<td>45</td>
</tr>
<tr>
<td>Television (Mbit/s)</td>
<td>0.2–0.8</td>
</tr>
<tr>
<td>Ranging (Mbit/s)</td>
<td>1</td>
</tr>
</tbody>
</table>

#### 4.6.2 Mission bandwidth

Some deep-space missions use two or more spacecraft. At some times during the mission, the spacecraft may be simultaneously within the beamwidth of the earth station antenna. A mission where the spacecraft are placed in the orbit around a planet is an important example of this condition. Under these circumstances, the simultaneous operation of the telecommunication links results in a requirement for radio frequency bandwidth sufficient to accommodate the several signals without mutual interference.

Typical mission design, along with consideration of simultaneous function requirements and the possibility of more efficient use of the spectrum, result in the conclusion that expected deep-space missions can be conducted within a total bandwidth of approximately 500 MHz.

#### 4.6.3 Multiple mission bandwidth

Several deep-space missions to different parts of the solar system may share the same radio frequencies except during those times when mutual interference results. This interference typically can occur for brief periods when one spacecraft is close to the Earth, resulting in very high signal strength, or when spacecraft from different missions are within the earth station beamwidth. Analysis of current and proposed missions shows that periods of mutual interference are brief enough so that they may be avoided by time-sharing the use of telecommunication links.

The conclusion that 500 MHz bandwidth will accommodate the maximum requirements of future deep-space missions (§ 4.6.2) is also appropriate for a multi-mission environment.
4.6.4 Link reliability and the utilization of allocated bands

The foregoing sub-section set forth the maximum bandwidth required for the conduct of deep-space research. Existing allocations near 2 and 8 GHz cannot accommodate these maximum requirements. These allocations do, however, provide an essential capability for deep-space research.

The 10 MHz wide allocations near 2 GHz provide for links that are relatively immune to adverse effects of rain and cloud. Past and currently-planned spacecraft include the equipment needed to make use of these allocations to ensure at least partial mission success in the event of adverse weather that precludes the use of higher frequency bands.

Current missions rely primarily on the 50 MHz wide allocations near 8 GHz to provide the links for normal mission operations. Where maximum possible data rates are not required for a particular mission, these allocations will continue to provide needed deep-space links.

The 500 MHz allocations near 15 and 32 GHz provide for future high performance links that meet the maximum bandwidth requirements specified in the foregoing sub-sections.

4.7 Antenna gain and pointing

For the parabolic antennas typically used in space research, the maximum gain is limited by size and by the accuracy with which the surface approaches a true parabola [Ruze, 1966]. The latter limitation places a bound on the maximum frequency that may be effectively used with a particular antenna.

One factor in surface accuracy, common to both Earth and space station antennas, is manufacturing precision.

For earth station antennas, surface deformation is caused by wind and thermal effects. As elevation angle is varied, gravity introduces additional distortion of the surface.

For space station antennas, size is limited by space available in the launch vehicle, and by the state of the art in the construction of unfurlable antennas. Thermal effects cause distortion in space station antenna surfaces.

The maximum usable gain of antennas is limited by the ability to point them accurately. The beamwidth must be adequate to allow for the angular uncertainty in pointing. All the factors that cause distortion of the reflector surface also affect pointing accuracy. The accuracy of the spacecraft attitude control system (often governed by the amount of propellant which can be carried) is a factor in space station antenna pointing.

The precision with which the location of the earth and space stations are known with respect to each other affects the minimum usable beamwidth and the maximum usable gain.

Table VI shows typical limits on antenna performance. Figure 4 shows the gain of the 70 m earth station antennas as a function of frequency and elevation angle.

<table>
<thead>
<tr>
<th>Limiting parameter</th>
<th>Space station antennas</th>
<th>Earth station antennas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical minimum value of parameter</td>
<td>Maximum gain</td>
<td>Typical minimum value of parameter</td>
</tr>
<tr>
<td>Accuracy of dish surface</td>
<td>0.024 cm r.m.s. on a 3.7 m diameter reflector</td>
<td>66 dB(1) at 100 GHz</td>
</tr>
<tr>
<td>Pointing accuracy</td>
<td>± 0.15° (3σ)</td>
<td>55 dB(1)</td>
</tr>
</tbody>
</table>

(1) Gain at other frequencies will be lower.
(2) Gain of antenna with half-power beamwidth equal to 2 x pointing accuracy (3σ). Beamwidth of antenna with higher gain will be too narrow with respect to the available pointing accuracy.
4.8 Additional radionavigation techniques

Doppler and ranging measurements provide the basic tracking information needed for navigation. Additional techniques have been developed to enhance navigation accuracy.

4.8.1 Calibration of the velocity of propagation as affected by charged particles

Range and Doppler measurements are influenced by variations in the velocity of radio wave propagation caused by free electrons along the transmission path. The electrons exist in varying densities in space and in planetary atmospheres, and are particularly dense near the Sun. Unless accounted for, these variations in propagation velocity can introduce errors in navigation calculations.

The charged particles cause an increase in phase velocity and a decrease in group velocity. By comparing range change with integrated Doppler over a period of time, the charged particle effect may be determined. The effect on propagation velocity is inversely proportional to the square of the radio frequency. This frequency dependence may be used for additional calibration accuracy. Turnaround ranging and Doppler tracking can be performed with simultaneous space-to-Earth signals in two or more separate bands. The charged particle effects in the separate bands are different in magnitude, and this difference is used to improve the calibration.

The charged particle effect is discussed in Reports 683 and 849.
4.8.2 Very long baseline interferometry (VLBI)

Accuracy of spacecraft navigation depends upon the precise knowledge of earth station location with respect to the navigation co-ordinate system. A 3 metre error in the assumed station location can result in a 700 kilometre error in the calculated position of a spacecraft at Saturn distance. VLBI provides a means of improving the estimate of station location by using a celestial radio source (quasar) as a signal source at an essentially unchanging point on the celestial sphere [Rogers, 1970]. It is possible to record the quasar signals in such a way as to determine with great accuracy, the difference in time of reception at two widely separated stations. Using a number of measurements the station locations can be determined to a relative accuracy of 10 cm. Frequencies near 2 and 8 GHz are used for VLBI at the present time.

The VLBI technique is also used to measure directly the spacecraft declination angle. Two accurately located earth stations separated by a large north/south distance, measure the range to the spacecraft. The declination can then be calculated with great precision.

A third application of the VLBI method can be used to improve the accuracy of measurement of spacecraft angular position [Reid et al., 1973]. Two or more earth stations alternately observe a spacecraft signal and a quasar signal. By knowing time, station location, and the effect of Earth rotation on the received signals, the angular position of the spacecraft can be determined with respect to the celestial references. When fully developed the techniques will provide a significant improvement over the current accuracy of 0.01 arc second. The improved accuracy will permit more precise navigation [Swenson and Mathur, 1968; Melbourne and Curkendall, 1977].

The Phobos missions of the USSR were designed to use this last technique. One of the two spacecraft in each mission is designed to land on the Mars satellite Phobos; the other spacecraft is an orbiter. The angular coordinates of the long-term landers are to be determined by means of VLBI earth stations in the USSR, with the support of other space research and radioastronomy earth stations around the world. The Phobos space station has the following basic characteristics:

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmitter frequency</td>
<td>Near 2 GHz</td>
</tr>
<tr>
<td>Transmitter power</td>
<td>5 W</td>
</tr>
<tr>
<td>Antenna gain</td>
<td>10 dBi</td>
</tr>
<tr>
<td>VLBI Spectral line width</td>
<td>1 Hz</td>
</tr>
<tr>
<td>VLBI Spectral line separation</td>
<td>14 MHz</td>
</tr>
</tbody>
</table>

More detailed information is contained in [CCIR, 1986-90a, b].

5. Performance analysis and design margins

Table VII shows a link budget used for performance analysis. The example given is for high rate telemetering from Jupiter. Similar analysis for telecommand and ranging is done during mission planning. The earth and space station characteristics shown earlier are used as the basis for calculating a performance margin for each telecommunication function.

A most important point in the design of deep-space missions is that the telemetering performance margin is quite small (3.5 dB in the example given). This small margin is a consequence of the need to obtain maximum scientific value from each spacecraft. To design with a 10 dB larger margin of safety would reduce the quantity of telemetered data by a factor of 10. The risk of using a system with small performance margin is its susceptibility to harmful interference, and for bands above 2 GHz, decreased reliability caused by weather effects.
TABLE VII – Performance budget. Spacecraft-to-Earth from Jupiter

Mission: Voyager Jupiter/Saturn 1977
Mode: Telemetering, 115.2 kbit/s, coded, 8.45 GHz carrier

<table>
<thead>
<tr>
<th>Transmitter parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>RF power, (dBW) (21W)</td>
<td>13.2</td>
</tr>
<tr>
<td>Circuit loss, (dB)</td>
<td>-0.2</td>
</tr>
<tr>
<td>Antenna gain, (dB) (3.7m)</td>
<td>48.1</td>
</tr>
<tr>
<td>Pointing loss, (dB)</td>
<td>-0.2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Path parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Free space loss between isotropic antennas, (dB)</td>
<td>-290.4</td>
</tr>
<tr>
<td>8.45 GHz, 9.3 x 10^6 km</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Receiver parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Antenna gain, (dB) (64m, 30° elevation angle)</td>
<td>72.0</td>
</tr>
<tr>
<td>Pointing loss, (dB)</td>
<td>-0.3</td>
</tr>
<tr>
<td>Weather attenuation, (dB)</td>
<td>-0.1</td>
</tr>
<tr>
<td>System noise spectral density, (dBW/Hz) (22.6K)</td>
<td>-215.1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total power summary</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Link loss, (dB)</td>
<td>-171.1</td>
</tr>
<tr>
<td>Received power, P(T), (dBW)</td>
<td>-157.9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Carrier tracking performance (two-way)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier power/total power, (dB)</td>
<td>-15.4</td>
</tr>
<tr>
<td>Received carrier power, (dBW)</td>
<td>-173.3</td>
</tr>
<tr>
<td>Carrier threshold noise bandwidth, (B = 10 Hz) (10 log B)</td>
<td>10.0</td>
</tr>
<tr>
<td>Noise power, (dBW)</td>
<td>-205.1</td>
</tr>
<tr>
<td>Threshold signal/noise, (dB)</td>
<td>20</td>
</tr>
<tr>
<td>Threshold carrier power, (dBW)</td>
<td>-185.1</td>
</tr>
<tr>
<td>Performance margin, (dB)</td>
<td>11.8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Data detection performance</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Data power/total power, (dB)</td>
<td>-0.3</td>
</tr>
<tr>
<td>Data reception and detection losses, (dB)</td>
<td>-0.5</td>
</tr>
<tr>
<td>Received data power, (dBW)</td>
<td>-158.7</td>
</tr>
<tr>
<td>Noise bandwidth, dB (effective noise bandwidth for matched filter detection of 115.2 kbit/s data)</td>
<td>50.6</td>
</tr>
<tr>
<td>Noise power, (dBW)</td>
<td>-164.5</td>
</tr>
<tr>
<td>Threshold signal/noise (0.005 bit error rate) (dB)</td>
<td>2.3</td>
</tr>
<tr>
<td>Threshold data power, (dBW)</td>
<td>-162.2</td>
</tr>
<tr>
<td>Performance margin, (dB)</td>
<td>3.5</td>
</tr>
</tbody>
</table>

REFERENCES


CCIR Documents

[1986-90]: a. 2/16 (USSR); b. 2/144 (USSR).

**BIBLIOGRAPHY**


1. Introduction

This Report provides the basis for the selection of frequencies for near-Earth space research. Preferred frequencies for use by the space research service for near-Earth missions are presented based upon propagation and technical considerations. The Annex to this Report mentions and discusses propagation factors which affect the transmission of a radio wave and considers other technical aspects relating specifically to the space research service. Preferred frequency bands for passive near-Earth space research are discussed in Report 693.

2. Frequency range

Frequencies for consideration in this analysis range from 100 MHz to 350 GHz. The lower limit is determined by those frequencies at which waves penetrate the ionosphere without important modifications. Although this lower limit is about 30 MHz, factors such as ionospheric disturbances, geographical locations, galactic and man-made noise, mitigate against the use of these low frequencies and place a practical lower limit of about 100 MHz for space research applications (see Report 263). The upper limit of 350 GHz is chosen, as this is above the highest frequency (275 GHz) currently allocated by the ITU.

2.1 Frequency range division

Due to atmospheric and precipitation effects, it is convenient to divide the frequency spectrum under consideration into two ranges: 100 MHz-22 GHz, and 22 GHz-350 GHz. Division was chosen at 22 GHz because this frequency is near the first absorption peak of water vapour, and also because it is at the region above which the attenuation due to rain is so high, that, even during periods of low rain rate, trans-atmospheric propagation is not practicable at the low elevation angles employed by the space research service. Precipitation effects in the frequency of range 22-350 GHz are therefore not to be considered as a determininant for preferred frequencies in this Report.
3. Link performance

In the calculation of link performance, use was made of the information and formulae pertaining to atmospheric and precipitation effects given in Reports 563, 564, 670, 719, 720 and 721 (Geneva, 1982). Figures 1 and 2 show total attenuation and sky-noise temperature for an antenna elevation of 5°. A 5° elevation angle has been assumed in this analysis as it is considered to be about the minimum angle that will be required for establishing telecommunications between a space research spacecraft and an earth station. Further, since an earth station will spend considerably more time in communication with a spacecraft at the lower elevation angles than at the higher elevation angles, the 5° earth-station antenna elevation essentially depicts a "worst-case" situation.

![Diagram of total attenuation due to molecular effects and molecular/precipitation effects]

**FIGURE 1 - Total attenuation due to molecular effects and molecular/precipitation effects**

Curves:

- A: rain rate = 20 mm/h, \( \rho = 7.5 \text{ g/m}^3 \), temperature = 20 °C
- B: rain rate = 50 mm/h
- C: rain rate = 100 mm/h
- D: rain rate = 140 mm/h

Legend:

- S1: clear sky at 5° elevation
- S2: clear sky at 20° elevation
Assumed system and receiver noise temperatures for space and earth stations are shown in Figs. 3 and 4 respectively. The noise temperatures are depicted as a step function because of the assumption that the receiver noise temperature will not change significantly over its frequency of operation, but rather remain fairly constant over the operating frequency ranges for which it is designed.

Using the above data and the formulae from § 4.1 of Annex I, normalized link performance values were computed for bidirectional propagation through the atmosphere and for the two cases of antenna restrictions (see Annex I, § 4). These normalized link performance values are plotted in Figs. 5 to 8 for the frequency range 0.1-22 GHz, and in Figs. 9 to 12 for the frequency range 22-350 GHz.

4. Discussion

Bandwidths required for near-Earth space research depend on the sophistication and objectives of space missions. The range of typical link bandwidths to meet the diverse requirements of the space research services is discussed in Annex I.

The important features of the link performance curves are the locations of the maxima and the effect of the weather on the optimum frequency range. The optimum frequency range was determined by noting those frequencies on either side of a curve maximum, which correspond to a link performance value of approximately 1 dB below that of the maximum. A decrease of the order of 1 dB below a curve maximum was considered sufficient to represent a relatively flat portion of the curve about its maximum.
In each of the Figs. 5 to 8, a set of parametric curves is shown for precipitation conditions with rain rates of 20, 50, 100 and 140 mm/h and for clear-sky conditions. From these figures, it can be seen that rain has a pronounced effect on the optimum range of frequencies, shortening and shifting the optimum range to lower frequencies for higher rain rates. For countries located in regions of high rain rate (see Report 563 (Geneva, 1982)), the choice of suitable frequencies is critical if they are to maintain a high quality of performance despite adverse weather conditions.

For the frequency range 22-350 GHz, Figs. 9 to 12 show a series of normalized link performance curves for clear-sky conditions only. Figure 1 shows the difference in attenuation for elevation angles of 5° and 20°.

FIGURE 3 – Assumed satellite system noise temperature

FIGURE 4 – Assumed earth-station receiver noise temperature

Note. – The values in Figs. 3 and 4 are derived from a number of technical references. They are typical of existing equipments in bands below about 20 GHz and represent anticipated developments in bands above 20 GHz.
FIGURE 5 – Normalized Earth-to-space link performance. 
Space station antenna diameter fixed

Curves A: rain rate = 20 mm/h  
B: rain rate = 50 mm/h  
C: rain rate = 100 mm/h  
D: rain rate = 140 mm/h  
S: clear sky

FIGURE 6 – Normalized Earth-to-space link performance. 
Space station antenna beamwidth fixed

Curves A: rain rate = 20 mm/h  
B: rain rate = 50 mm/h  
C: rain rate = 100 mm/h  
D: rain rate = 140 mm/h  
S: clear sky
FIGURE 7 – Normalized space-to-Earth link performance.
Space station antenna diameter fixed

Curves A: rain rate = 20 mm/h
B: rain rate = 50 mm/h
C: rain rate = 100 mm/h
D: rain rate = 140 mm/h
S: clear sky

FIGURE 8 – Normalized space-to-Earth link performance.
Space station antenna beamwidth fixed

Curves A: rain rate = 20 mm/h
B: rain rate = 50 mm/h
C: rain rate = 100 mm/h
D: rain rate = 140 mm/h
S: clear sky
5. Conclusions

In this Report, preferred frequencies for near-Earth space research have been presented based upon propagation (Table I) and technical considerations and the link performance analyses contained in Annex I.

<table>
<thead>
<tr>
<th>Direction</th>
<th>Earth-station antenna</th>
<th>Space-station antenna</th>
<th>Frequency bands (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Clear sky RR = 20 mm/h</td>
</tr>
<tr>
<td>Earth-to-space (E-S)</td>
<td>Fixed diameter</td>
<td>Fixed diameter</td>
<td>14-20</td>
</tr>
<tr>
<td></td>
<td>Fixed diameter</td>
<td>Fixed beamwidth</td>
<td>0.1-10</td>
</tr>
<tr>
<td>Space-to-Earth (S-E)</td>
<td>Fixed diameter</td>
<td>Fixed diameter</td>
<td>12-20</td>
</tr>
<tr>
<td></td>
<td>Fixed diameter</td>
<td>Fixed beamwidth</td>
<td>0.3-10</td>
</tr>
<tr>
<td>Space-to-space (S-S)</td>
<td>Directive antennas on both relay and space stations</td>
<td></td>
<td>54-70</td>
</tr>
</tbody>
</table>

RR: rain rate

Space-to-space links are best located in the frequency ranges of high atmospheric attenuation as this virtually eliminates any problem of interference to and from terrestrial sources. These ranges, located in the troughs between successive maxima shown in Figs. 9 to 12, correspond to the region around the oxygen and water vapour absorption peaks.

Above about 150 GHz, trans-atmospheric communications are subject to a high level of signal attenuation when the elevation angle is low. However, the range of frequencies above 150 GHz may be considered for links through the atmosphere, where the elevation angle of operation is not low.

The list of frequency bands given in Table II is intended to identify those frequency ranges which are preferred from a technical standpoint. The inclusion of a band in the table is not intended to indicate that there will be sufficient available link margin or bandwidth. Also, exclusion of other frequencies from the table does not necessarily preclude operations in these bands where frequency sharing considerations and state of the art equipment limitations dictate their use.

The list of typical individual link bandwidths given in Table III is intended to reflect link bandwidths which can be supported with current technology. The inclusion of a link bandwidth in the table is not intended to indicate the frequency band in which the individual link may be required to operate nor to limit the numbers of such links that may be required to support any particular spacecraft or mission systems.
FIGURE 9 - Normalized Earth-to-space link performance. 
Space station antenna diameter fixed

FIGURE 10 - Normalized Earth-to-space link performance. 
Space station antenna beamwidth fixed
FIGURE 11 – Normalized space-to-Earth link performance. Space station antenna diameter fixed

FIGURE 12 – Normalized space-to-Earth link performance. Space station antenna beamwidth fixed
### TABLE II — Preferred frequency bands and their uses

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>Direction</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3-2.5</td>
<td>S-E</td>
<td>An all-weather link, optimum also when communications must be established regardless of spacecraft orientation</td>
</tr>
<tr>
<td>0.1-3.0</td>
<td>E-S</td>
<td></td>
</tr>
<tr>
<td>0.3-10</td>
<td>S-E</td>
<td>A clear-weather link, optimum when a broad or fixed beamwidth antenna is required on the spacecraft</td>
</tr>
<tr>
<td>0.1-10</td>
<td>E-S</td>
<td></td>
</tr>
<tr>
<td>2-4</td>
<td>S-E</td>
<td>An all-weather link for use with directive antennas</td>
</tr>
<tr>
<td>2-5</td>
<td>E-S</td>
<td></td>
</tr>
<tr>
<td>2-3</td>
<td>S-S</td>
<td>Bands necessary to provide space-to-space communications with existing and proven space equipment and technology. Also necessary to provide continuity of service until other bands show practical and technical usability</td>
</tr>
<tr>
<td>13.5-23</td>
<td>S-S</td>
<td></td>
</tr>
<tr>
<td>12-20</td>
<td>S-E</td>
<td>A clear-weather link, optimum for a high or medium gain antenna on the spacecraft</td>
</tr>
<tr>
<td>14-20</td>
<td>E-S</td>
<td></td>
</tr>
<tr>
<td>28-35</td>
<td>E-S</td>
<td></td>
</tr>
<tr>
<td>27-32</td>
<td>S-E</td>
<td></td>
</tr>
<tr>
<td>85-100</td>
<td>E-S and S-E</td>
<td></td>
</tr>
<tr>
<td>127-137</td>
<td>E-S and S-E</td>
<td></td>
</tr>
<tr>
<td>54-70</td>
<td>S-S</td>
<td>Bands affording maximum clear-sky interference protection to space-to-space links from terrestrial applications, optimum for high to medium gain spacecraft antennas</td>
</tr>
<tr>
<td>117-120</td>
<td>S-S</td>
<td></td>
</tr>
<tr>
<td>178-188</td>
<td>S-S</td>
<td></td>
</tr>
<tr>
<td>318-328</td>
<td>S-S</td>
<td></td>
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</tbody>
</table>

### TABLE III — Typical individual link bandwidths and their uses

<table>
<thead>
<tr>
<th>Use</th>
<th>Direction</th>
<th>Typical bandwidth</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Telecommand</td>
<td>E-S</td>
<td>10-500 kHz</td>
<td></td>
</tr>
<tr>
<td>Maintenance telemetry</td>
<td>S-E</td>
<td>5-500 kHz</td>
<td></td>
</tr>
<tr>
<td>Telemetry</td>
<td>S-E (direct)</td>
<td>100 kHz-100 MHz</td>
<td>Direct satellite to Earth</td>
</tr>
<tr>
<td>Telemetry</td>
<td>S-E (relay)</td>
<td>225-650 MHz</td>
<td>Relay satellite to earth station, data from one or more user satellites</td>
</tr>
<tr>
<td>Telemetry</td>
<td>S-S</td>
<td>5-225 MHz</td>
<td>User satellite to relay satellite</td>
</tr>
<tr>
<td>Telemetry</td>
<td>S-S</td>
<td>&gt; 1 GHz</td>
<td>Relay satellite to relay satellite</td>
</tr>
<tr>
<td>Tracking</td>
<td>S-E</td>
<td>500 Hz-500 kHz</td>
<td>Interferometry</td>
</tr>
<tr>
<td>Tracking</td>
<td>E-S</td>
<td>1-3 MHz</td>
<td>Range and range rate systems</td>
</tr>
<tr>
<td>Tracking</td>
<td>E-S</td>
<td>1-10 MHz</td>
<td>Radar</td>
</tr>
<tr>
<td>Tracking</td>
<td>E-S</td>
<td>5-6 MHz</td>
<td>Bilateral ranging</td>
</tr>
</tbody>
</table>
ANNEX I

ANALYSIS OF FREQUENCY SELECTION FOR THE
NEAR-EARTH SPACE RESEARCH SERVICE

1. Introduction

In this Annex, an analysis is provided that serves as the basis for the selection of radio frequencies for the near-Earth space research service.

By considering the frequency dependent elements of a basic link equation, the received signal power to noise density ratio \((P_r/N_0)\) is established as an index of link performance and used in the determination of preferred frequencies.

2. Propagation considerations

2.1 Ionospheric effects

Ionospheric effects arise due to the interaction of the transmitted radio wave, the Earth's free electron density, which varies as a function of geomagnetic latitude, diurnal cycle, yearly and solar cycle, etc., and the Earth's magnetic field. Ionospheric effects above 10 GHz are generally small and not considered significant (see Report 263).

2.2 Tropospheric effects

In the absence of precipitation, tropospheric effects are unlikely to produce serious fading in space telecommunications systems at frequencies below about 10 GHz and at elevation angles above 10° (see Reports 718 and 881 (Geneva, 1982)). However, the magnitude of tropospheric amplitude scintillations can occasionally be serious at low elevation angles and at frequencies above about 10 GHz (see Report 564 (Geneva, 1982)). Signal attenuation due to absorption by molecular oxygen and water vapour and due to absorption and scattering by rain can severely affect link performance and therefore the selection of frequencies. Detailed discussion of these factors can be found in Reports 719 and 721 (Geneva, 1982) respectively.

3. Technical and operational considerations

Technical considerations may be divided into two categories, namely mission requirements and hardware or equipment factors.

3.1 Mission frequency support requirements

3.1.1 Telecommand and maintenance telemetering

The basic requirement of any mission is its safety and success. In order that this requirement be met, the telecommand and maintenance telemetry link must function with the spacecraft in any orientation. As this can only be achieved through the use of a broad-beam, omni-type antenna aboard the spacecraft, the use of such an antenna must be considered when selecting frequencies.

Telecommand bandwidths of 10-50 kHz are adequate for most missions, although more sophisticated spacecraft may require link bandwidths of the order of 500 kHz or more. Maintenance telemetry link bandwidths range from several kilohertz to several hundred kilohertz.

3.1.2 Mission telemetry

For many missions, telemetry data are gathered and stored for play-back to Earth. For some of these missions, there may only be a single opportunity for the spacecraft to transmit the recorded data; these missions must therefore be capable of operating under all weather conditions. For missions which do not need to operate under such constraints, a frequency may be selected where data rate can be maximized for clear-sky conditions.

Link bandwidths depend on the complexity and sophistication of the spacecraft. For direct spacecraft-to-Earth station links, bandwidths of 100 kHz to 100 MHz can be expected. Bandwidths for relay satellite space-to-Earth links presently range from 225 to 650 MHz; however, this is expected to increase to above 1 GHz to meet future requirements.

Space-to-space link bandwidths presently range from about 5 to 225 MHz for direct user satellite to relay satellite communications. Inter-relay satellite bandwidths will be considerably wider, possibly greater than 1 GHz.
3.1.3 Tracking

Near-Earth space research involves various methods for determining spacecraft orbital information. For interferometer tracking, consideration of factors such as a good omnidirectional antenna on a spacecraft, transmitter efficiency, and earth-station antenna beamwidth, usually favours a frequency below 1 GHz. More elaborate moving antenna interferometers have been built for frequencies greater than 5 GHz, but atmospheric attenuation and noise usually limit their performance at frequencies greater than 6 GHz. Typical bandwidths range from several hundred hertz to several kilohertz.

Range and range-rate systems which must operate with the minimum of disturbances from ionospheric and trans-atmospheric effects are in the 1-8 GHz range for precision tracking systems. The main factor which dictates the maximum bandwidth needed per one-way channel is the range resolution required. Range resolutions of the order of metres can be obtained by using appropriate modulation with bandwidths of about 1-3 MHz.

Radar tracking is also employed although atmospheric attenuation usually limits the use of frequencies above about 6 GHz for tracking by primary radar systems. For many of these systems, a bandwidth in the range of 1-10 MHz is usually sufficient.

Bilateration ranging is designed to supply precise information on the location of a relay satellite so that its movement can be taken into account when determining the orbital parameters of user spacecraft via the relay satellite. Typical links must be weather independent, and have bandwidths of about 5 to 6 MHz.

3.2 Equipment factors

Equipment factors which have an effect on link performance and whose characteristics depend on frequency to some extent are transmitter power, antenna gain (for a fixed-size antenna) and the receiver noise temperature. Of these three, the antenna gain is a function of the square of the frequency, whereas the transmit power and receiver noise are indirectly coupled to the frequency of operation. Their performance is therefore considered uniform over a wide frequency range.

The existence of proven space equipment and systems must also be considered in the selection of frequency bands to provide operational consistency.

Because of practical limits of diplexers, Earth-to-space and space-to-Earth pairs of frequencies should be separated by at least 7% to allow simultaneous transmit/receive operations using a single antenna.

4. Link performance

In this Report, the impact of propagation effects on the signal strength and system noise in a basic link equation has been considered, and an index of link performance, determined as the ratio of received signal power to noise spectral-density \( (P_r/N_0) \), has been established as the criterion for frequency selection.

The link analyses presented in § 4.1.1 are based upon a fixed diameter earth-station antenna, and cover both a fixed diameter and a fixed beamwidth space-station antenna. The fixed-diameter space station antenna is included to account for situations where a large antenna is employed on the spacecraft, and there are no pointing limitations. The fixed beamwidth case is included to account for situations where antenna pointing accuracy determines the minimum beamwidth, or where an antenna must provide wide coverage to permit communication without regard to spacecraft orientation as in the case of an emergency telemetry or command link.

In the analyses, the effects of precipitation are considered only for frequencies below about 22 GHz. The effects of precipitation above 22 GHz are not considered because even low rain rates can seriously degrade communications on trans-atmospheric links. Therefore only clear weather usage is assumed above 22 GHz.
Maximum data rate capability is obtained by using the frequency bands where \( P_r/N_0 \) is a maximum for the weather conditions and space-station antenna limitations considered. These bands are shown in Table I and are obtained from the normalized \( P_r/N_0 \) curves given in this Report. The general width of the bands was determined by noting the frequencies corresponding to the levels approximately 1 dB below the peaks of the curves. In order to provide a concise presentation of preferred frequency bands, the contents of Table I have been summarized and presented in Table II. A high rain rate was assumed when determining the width of all-weather frequency bands in Table II in order that the results be applicable world-wide. Bands outside this range may be suitable for areas of lower rain rates.

4.1 Calculation of link performance as a function of frequency

4.1.1 Basic link performance equations

The index of link performance, received power-to-noise spectral density ratio, is given by the basic link equation:

\[
\frac{P_r}{N_0} = 10 \log \left( \frac{P_t G_t G_r}{L_s L_a L_r T} \right) \text{ dB}
\]

where:
- \( P_r \): received power (W),
- \( N_0 \): noise spectral density (W/Hz),
- \( P_t \): transmitted power (W),
- \( G_t \): transmitting antenna gain,
- \( L_s \): free-space loss,
- \( L_a \): transmission loss due to attenuation in the clear atmosphere,
- \( L_r \): transmission loss due to rain attenuation,
- \( G_r \): receiving antenna gain (dBi),
- \( k \): Boltzmann's constant (J/K),
- \( T \): total system noise temperature (K).

Assuming no waveguide loss \( T \) is given by:

\[
T = T_r + T_s + T_g
\]

where:
- \( T_r \): receiver noise temperature (K),
- \( T_s \): sky contribution (due to atmospheric and precipitation effects) to antenna noise temperature (K),
- \( T_g \): ground contribution to antenna noise temperature (K).

By isolating the frequency-dependent terms in equation (1), the equation may, for a fixed distance between space and earth station, be written as follows:

**Case 1:** Earth and space-station antenna diameters are fixed:

\[
\frac{P_r}{N_0} = C + 10 \log \left( \frac{1}{\lambda^2 L_a L_r T} \right) \text{ dB}
\]

**Case 2:** Earth-station antenna diameter is fixed, space-station antenna beamwidth is fixed:

\[
\frac{P_r}{N_0} = C_1 + 10 \log \left( \frac{1}{L_a L_r T} \right) \text{ dB}
\]

where:
- \( C \) and \( C_1 \) are constant in equations (2) and (3) respectively and expressed in dB and the terms in the brackets are the frequency-dependent terms. Any change in the value of the constant will merely raise or lower the \( P_r/N_0 \) curves, the overall shape of the curves will remain unchanged.
REPORT 683-3*

FREQUENCY BANDS IN THE 1 TO 40 GHz RANGE THAT ARE PREFERRED FOR DEEP-SPACE RESEARCH

(Question 22/2, Study Programme 22A/2)


1. Introduction

Mission requirements, equipment factors and link performance define the frequency bands preferred for deep-space research using manned and unmanned spacecraft. This Report presents the analysis and considerations that lead to the selection of preferred frequency bands. Report 536 contains a discussion of the telecommunications requirements for deep-space research; some of these requirements influence the choice of preferred frequency bands.

The objective of identifying preferred frequency bands is to provide the basis for allocations from which the designer can select operating frequencies best suited to mission requirements.

2. Criteria for selection of preferred frequency bands

For each telecommunication function, i.e., maintenance and science telemetering, telecommand, tracking and radio science, there is a frequency band, or set of frequency bands, which will provide best performance. Best performance may be expressed in terms of lowest error rate, highest measurement accuracy, maximum data rate, best link reliability, or some combination of these parameters. The best performance that is obtainable at a particular time with a particular system depends upon propagation conditions.

A convenient index of best performance is the ratio of received signal power-to-noise power spectral density ratio, $P_r/N_0$. The frequency band which provides the highest value of $P_r/N_0$ for a particular system and propagation conditions is defined as a preferred frequency band.

The potential for interference was not considered in the selection of preferred frequency bands.

3. Link performance analysis

Annex I presents an analysis of the variation in $P_r/N_0$ as a function of frequency. From the resulting curves, one may identify frequency ranges that provide optimum performance for the assumed conditions.

* This Report is brought to the attention of Study Groups 5 and 6 for their comment on how the analysis might be affected by recent changes in propagation data.
3.1 Equipment considerations

Earth stations for deep space research typically employ large steerable parabolic antennas. These are very expensive and infrequently constructed. A mission designer is generally not free to consider a range of earth station antenna diameters when selecting frequencies. For this reason, the analysis in Annex 1 considers the earth station antenna to have a fixed diameter. The gain and beamwidth of this antenna are a function of frequency.

For space stations, the designer may consider a variety of antenna types and sizes. Annex I accounts for this freedom by considering two cases: a parabolic reflector antenna with a fixed diameter and whose gain is a function of frequency, and an antenna whose beamwidth (gain) does not vary with frequency. The fixed diameter case arises when the antenna pointing accuracy does not limit the minimum beamwidth. For this case, the antenna diameter may be chosen to be as large as practicable with regard to considerations other than frequency. The selected diameter may be used when analyzing link performance as a function of frequency.

The fixed beamwidth case arises when antenna pointing accuracy determines the minimum beamwidth, or when the antenna must give very wide coverage to permit communication without regard to space station attitude. An omnidirectional antenna is an example of the fixed beamwidth case.

3.2 Propagation considerations

Analysis of link performance requires assumptions about propagation conditions. A critical assumption is the rain rate and resulting attenuation. For low noise receiving systems typical of deep space research, particularly the earth station receivers, even a small increase in attenuation caused by rain results in a significant reduction in $P_r/N_0$. This is because the increase in sky noise is several times as large as the receiver noise temperature, and therefore dominates the overall system noise temperature.

The analysis in Annex I assumes a rain rate of 10 mm/hr (the amount exceeded 0.1 % of the time at an earth station near Madrid, Spain, which is in rain climate H, Report 563).

Although this rate results in only 1 dB of attenuation compared to the clear air case at 8.4 GHz, 30 deg elevation angle, it causes a 5.8 dB degradation in the space to Earth $P_r/N_0$. As a result of the sensitivity of system performance ($P_r/N_0$) to small changes in attenuation along the propagation path, the performance curves in Annex I are strongly influenced by the assumed rain rate.

3.3 Results of performance analysis

Table I shows optimum frequency ranges, for an elevation angle of 30 deg, selected on the basis of the analysis in Annex I. The criterion for selecting a frequency range was performance within approximately 1 dB of the maximum available.

The uplink functions mentioned in Table I include telecommand and the Earth-to-space portion of Doppler measurement and turnaround ranging. The downlink functions include telemetering, the space-to-Earth portion of Doppler measurement and turnaround ranging, and signals for very long baseline interferometry (VLBI).
### TABLE I - Optimum frequency ranges and their application

<table>
<thead>
<tr>
<th>FREQUENCY RANGE (GHz)</th>
<th>APPLICATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 to 2</td>
<td>Earth-to-space links using the spacecraft wide beam low-gain antenna during clear or rainy weather. Used for uplink functions.</td>
</tr>
<tr>
<td>1 to 4</td>
<td>Space-to-Earth links using the spacecraft wide beam low-gain antenna during rainy weather. Used for downlink functions.</td>
</tr>
<tr>
<td>1 to 8</td>
<td>Space-to-Earth links using the spacecraft wide beam low-gain antenna during clear weather. Used for downlink functions.</td>
</tr>
<tr>
<td>4 to 10</td>
<td>Space-to-Earth links using the spacecraft high-gain antenna during rainy weather. Used for downlink functions.</td>
</tr>
<tr>
<td>7.5 to 18</td>
<td>Earth-to-space links using the spacecraft high-gain antenna during rainy weather. Used for uplink functions.</td>
</tr>
<tr>
<td>12 to 35.5</td>
<td>Earth-to-space link using the spacecraft high-gain antenna during clear weather. Used for uplink functions.</td>
</tr>
<tr>
<td>26.5 to 39.5</td>
<td>Space-to-Earth links using the spacecraft high-gain antenna during clear weather. Used for downlink functions.</td>
</tr>
</tbody>
</table>

(1) Based on analysis that includes the effect of equipment characteristics.

4. **Selection of preferred frequency bands**

Preferred frequency bands may be chosen from the optimum ranges listed in Table I. Several additional considerations influence the selection.

4.1 **Diplexer characteristics**

Because of practical limits of diplexers, simultaneous transmission and reception with a single antenna requires that the uplink and downlink frequencies be separated by at least 7%. Pairs of bands chosen from the ranges listed Table I must therefore also be separated by the same amount.
4.2 **Link and allocation bandwidth**

Associated with the identification of preferred frequency bands is the determination of needed bandwidth. The bandwidth required for a particular telecommunication link, and the estimated number of separate links, provide an indication of needed allocation width. Report 536 discusses bandwidth requirements.

4.3 **Simultaneous use of several bands**

Precise knowledge of the velocity of propagation is required to satisfy the requirements of radio science and spacecraft navigation. To determine the velocity of propagation it is necessary to account for the group delay caused by charged particles along the transmission path. The group delay measurement applies only to the particular spacecraft at a particular time.

If group delay caused by charged particles along the propagation path is not accounted for, there will be an error in range measurement, as discussed in Annex I.

The needed precision of group delay measurement may require the simultaneous use of links in two separate bands, preferably differing in frequency by at least a factor of four. The group delay between the two downlinks is different and this difference can be used to compute a suitable correction for the delay in each link. As an example of the use of separate bands, an uplink near 2 GHz may be used to provide a phase reference for simultaneous downlinks near 2 and 8 GHz. A downlink operating at a frequency above 20 GHz is relatively free of charged particle effects, and can provide a particularly valuable reference for calibration of a link operating at a lower frequency.

4.4 **Rain rate assumptions**

If a different rain rate had been assumed for the analysis given in Annex I, the resulting ranges of optimum performance shown in Table I would also be different. The selection of preferred frequency bands would be correspondingly affected.

5. **Current allocations as compared to preferred frequency ranges**

Table II lists current band allocations for deep space research, and the corresponding ranges of preferred frequencies as determined by the analysis in Annex I. In most cases, the range of preferred frequencies depends on the assumed weather condition; the condition is indicated in the Table.
# TABLE II - Current allocations and preferred frequency ranges.

<table>
<thead>
<tr>
<th>CURRENT ALLOCATIONS(^{(1)}) (GHz)</th>
<th>LINK DIRECTION</th>
<th>RANGE OF PREFERRED FREQUENCIES(^{(3)}) (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.110 - 2.120</td>
<td>Earth-to-space</td>
<td>1 to 2</td>
</tr>
<tr>
<td>2.290 - 2.300</td>
<td>Space-to-Earth</td>
<td>1 to 4, rain</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 to 8, clear</td>
</tr>
<tr>
<td>7.145 - 7.190(^{(2)})</td>
<td>Earth-to-space</td>
<td>7.5 to 18, rain</td>
</tr>
<tr>
<td></td>
<td></td>
<td>12 to 35.5, clear</td>
</tr>
<tr>
<td>8.400 - 8.450</td>
<td>Space-to-Earth</td>
<td>4 to 10, rain</td>
</tr>
<tr>
<td>12.75 - 13.25(^{(2)})</td>
<td>Space-to-Earth</td>
<td>4 to 10, rain</td>
</tr>
<tr>
<td></td>
<td></td>
<td>26.5 to 39.5, clear</td>
</tr>
<tr>
<td>16.6 - 17.1</td>
<td>Earth-to-space</td>
<td>7.5 to 18, rain</td>
</tr>
<tr>
<td></td>
<td></td>
<td>12 to 35.5, clear</td>
</tr>
<tr>
<td>31.8 - 32.3</td>
<td>Space-to-Earth</td>
<td>26.5 to 39.5, clear</td>
</tr>
<tr>
<td>34.2 - 34.7</td>
<td>Earth-to-space</td>
<td>12 to 35.5, clear</td>
</tr>
</tbody>
</table>

\(^{(1)}\) See the Radio Regulations for more detailed information concerning allocation status and region or country of applicability.

\(^{(2)}\) This allocation is not in the preferred frequency range.

\(^{(3)}\) Based on analysis that includes the effect of equipment characteristics.

5.1 The 2110 to 2120 MHz and 2290 to 2300 MHz allocated bands

These bands meet the requirement for weather-independent links using either high or low gain spacecraft antenna. The 10 MHz allocation width imposes a limit on telemetering data rate and ranging precision, especially when communicating with two or more spacecraft within the earth station antenna beam.

5.2 The 7145 to 7190 MHz and 8400 to 8450 MHz allocated bands

As compared to the 2 GHz bands, these bands provide increased link performance using the spacecraft high gain antenna. The 7145 to 7190 MHz allocation is not optimum for the weather conditions assumed in Annex I, but provides acceptable performance. The 50 MHz allocation width allows telemetering and ranging that is adequate for several types of deep space missions. These bands in combination with the 2 GHz allocations provide for multi-frequency charged particle calibration.

The 7 and 8 GHz band pair provide the principal telecommunication links used for current deep space research.
5.3 The 12.75 to 13.25 GHz, 16.6 to 17.1 GHz, 31.8 to 32.3 GHz, and 34.2 to 34.7 GHz allocated bands

The 13 and 17 GHz band pair provides the opportunity for improved performance, as compared to the lower frequency bands. The 13 GHz band is not optimum for the clear weather case.

The 32 and 34 GHz band pair provides the opportunity for still higher performance. Equipment which will make use of this opportunity is under development in some administrations. Use of these bands for deep space research is the next logical step in planetary exploration.

All four bands are 500 MHz wide, permitting advanced radio science experiments that require ranging to centimeter accuracy; allowing the use of widely separated signals needed for very long baseline interferometry; and providing the bandwidth for very high rate coded telemetering.

These bands will also provide reduced propagation group delay for improved navigation and scientific experiments. In addition, reduced scintillation will permit communication and measurements for ray paths passing closer to the sun than those that can be utilized at lower frequencies. In combination with links in the lower frequency bands, they will enable very accurate calibration of charged particle effects.

6. Conclusion

This report has presented the information needed for the selection of preferred frequency bands for deep space research, based on an assumed set of equipment and weather conditions. Current band allocations generally fall within the frequency ranges that provide optimum performance for these conditions.
ANNEX I

FREQUENCY SELECTION CONSIDERATIONS FOR DEEP-SPACE RESEARCH

1. Introduction

The identification of frequency bands that would provide the best performance for deep space links depends on analysis of frequency dependent propagation parameters and equipment characteristics. This annex presents a discussion of these parameters and characteristics, and includes curves of relative link performance as a function of frequency, weather conditions, and the elevation angle of the earth station antenna.

2. Calculation of link performance as a function of frequency

One index of link performance is the ratio of received signal power-to-noise spectral power density:

\[
\left( \frac{P_r}{N_0} \right) = P_t + G_t - L_p - L_a - L_{Ra} + G_r - 10 \log(kT_t) \quad (\text{dB}(W/(W/Hz)))
\]

where

- \( P_r \): received power (dBW)
- \( N_0 \): noise spectral density (dB(W/Hz))
- \( P_t \): transmitter power (dBW)
- \( G_t \): transmitting antenna gain (dBi)
- \( L_p \): free space basic transmission loss (dB)
- \( L_a \): excess transmission loss through the atmosphere including water vapour (dB)
- \( L_{Ra} \): excess transmission loss through rain (dB)
- \( G_r \): receiving antenna gain (dBi)
- \( k \): \(1.38 \times 10^{-23}\) (Joule/K)
- \( T_t \): total noise temperature at the receiver input terminals (K)

and

\[ T_t = T_a + T_{Ra} + T_g + T_f \] (K)
where,

\[ T_{a+Ra} : \text{noise temperature corresponding to the sum of } L_a \text{ and } L_{Ra} \] (K)

\[ T_g : \text{cosmic and galactic background noise temperature, as reduced by attenuations } L_a \text{ and } L_{Ra} \] (K)

\[ T_r : \text{noise temperature of receiver} \] (K)

For an Earth-to-deep space link, the noise power contribution of earth atmosphere and rain may be neglected and for this case:

\[ T_t = T_g + T_r \]

The optimum frequency for a link may be determined by calculating the index of performance as a function of frequency.

3. Propagation considerations

Report 1119 describes a method of calculating the value of each factor that contributes to the index of performance, \( P_r/N_0 \). Some propagation characteristics that influence the choice of frequencies for particular space research missions are discussed in the following paragraphs.

3.1 Attenuation by atmospheric gases and precipitation

Figure la presents curves of attenuation between space and Earth as a function of frequency and elevation angle of the earth station antenna. This figure is based on the method of calculation given in Report 1119. The curves labeled "clear weather" were calculated for one-way attenuation through a moderately humid atmosphere (7.5 g/m^3 at the surface). The curves for rain are for a rate (10 mm/h) exceeded 0.1% of an average year at, for example, an earth station near Madrid, Spain (in rain climate H, Report 563), and include attenuation due to the gaseous constituents of the atmosphere.

3.2 Sky noise temperature

Figure lb presents curves of total sky-noise temperature for the conditions listed above for Figure la, plus the contributions of galactic and cosmic background noise, calculated according to the method of Report 1119.
FIGURE 1 - Attenuation (dB) and sky noise temperature (K), space-to-earth path

- clear atmosphere only, 7.5 gm/m³ water vapor
- atmosphere plus rain, 10 mm/hr

Parameter Δ: elevation angle (deg) of earth station antenna
3.3 Tropospheric scintillation and refraction

Reports 564, 718 and 881 (Geneva, 1982) indicate that the effects of tropospheric scintillation and refraction may be negligible for deep space links, if transmission frequencies are below 20 GHz and antenna elevation angles are greater than 3 deg. These effects have not been included in the selection of preferred frequency bands.

3.4 Ionospheric scintillation

Electron-density irregularities in the ionosphere create refractive inhomogeneities which result in signal amplitude and phase variations. Fading of 3 to 4 dB at frequencies in the 4 to 8 GHz range has been observed. Scintillation effects in the ionosphere are discussed in Report 263. This factor has not been included in the selection of preferred frequency bands.

3.5 Range measurement error caused by charged particles

In passing through an ionized medium the phase velocity of a radio signal is increased and the group velocity is decreased. The effect is proportional to the integrated electron density along the path, and inversely proportional to the square of the frequency.

The process of measuring the distance to a spacecraft by radio techniques is called ranging. Ranging is typically accomplished by measuring the time required for a radio signal to travel from an earth station to the spacecraft and be returned to Earth. The time includes the group delay caused by charged particles along the path. Unless the group delay is accounted for, the range measurement will be in error.

A principal source of group delay is the ionosphere of the Earth. Propagation through the ionosphere is discussed in Report 263. An estimate of the upper limit of this delay is 0.25 us at 1 GHz and 0.62 ns at 20 GHz.

The solar plasma in interplanetary space also causes group delay. Measurements made during past deep space missions have provided group delay data leading to an approximation formula for electron density as a function of distance from the Sun, Report 887:

\[ N = 10^{12} \left( \frac{221}{r^6} + \frac{1.55}{r^{2.3}} \right) \]

where

- \( N \): electron density in electrons / meter\(^3\)
- \( r \): distance from center of the Sun, measured in Sun radii (radius of Sun = 6.96 x 10\(^8\) m).

---

1 See Report 564 for practical data on tropospheric scintillation for the frequency range 4 to 112 GHz at low elevation angles.
The group delay for a radio signal passing through interplanetary space is given in Report 263 as:

\[ t = N_s \frac{1.34 \times 10^{-7}}{f^2} \]

where

- \( t \): group delay caused by charged particles, seconds,
- \( f \): frequency, Hz
- \( N_s \): total electrons per meter\(^2\) along the path

Figure 2 shows an example of the range measurement error caused by solar plasma. The figure was obtained by assuming a path of \( 3 \times 10^8 \) km, calculating the group delay as a function of frequency and angle from the Sun, and then multiplying the delay by the speed of light to give a corresponding distance.

4. Equipment considerations

Equipment parameters considered in link performance analysis include transmitter power, antenna gain, and receiving system noise temperature. For additional discussion of these parameters in the context of deep space research, see Report 536.

4.1 Transmitter power

For space station transmitters, the RF output power depends on the amount of primary power that can be provided by the spacecraft, and is further limited by transmitter efficiency. For earth stations, these limitations are much less significant.

For link performance analysis in this Annex, transmitter power is considered to be independent of frequency.

4.2 Antenna gain

Assuming the use of a parabolic reflector antenna, gain is limited by size, surface precision and structural deformation. For space stations, antenna size is limited by space available in the launch vehicle, by the state of development of unfurlable structures, and by the capability of the space station to point the antenna with sufficient precision.

Link analysis in this annex assumes that a fixed diameter antenna for a space station is 60% efficient and has a gain which increases directly as the frequency squared. For the fixed beamwidth (fixed gain) case the gain is assumed to be independent of frequency.

The earth station antenna gain used in the analysis is shown in Fig. 4 of Report 536.
FIGURE 2 – Range error from uncorrected group delay caused by charged particles

\( f \): frequency, GHz
4.3 Receiving equipment noise temperature

The space station receiving system noise temperature is dominated by the input preamplifier and associated preselection filter. Antenna feedline losses are relatively unimportant in their noise contribution. Space station noise temperature used in this Annex is representative of current practice or feasibility utilizing uncooled solid state devices.

At earth stations there is no important size, weight, or complexity limitation, and the most sensitive possible receiver is needed. Cryogenically cooled MASER preamplifiers are commonly used. Link analysis in this Annex assumes that the earth station noise temperatures are as shown in Fig. 1 of Report 536.

5. Link performance

The frequency dependence of link performance may be shown by the variation in the ratio of total received power to noise spectral density, \( P_r/N_0 \) (dB(W/(W/Hz))). Curves of \( P_r/N_0 \) shown in Figures 3 to 6, were calculated by using attenuation and sky-noise temperature data from Figure 1, equipment characteristics described in Report 536, the method given in Report 1119 and the following assumptions:

- Communication distance: \( 8 \times 10^8 \) km
- Diameter of earth station antenna: 70m
- Power of earth station transmitter: 100 kW
- Diameter of space station antenna: 3.7 m
- Power of space station transmitter: 25 W

The important features of the performance curves are the location of maxima and the effects of elevation angle and weather. The absolute values of \( P_r/N_0 \) depend upon the assumed link parameters. Different assumptions about communication distance, antennas characteristics and transmitter power would alter the absolute values but would not significantly change the shape of the curves.

Figures 3 to 6 show curves for clear and rainy weather, and for earth station antenna elevation angles of 15, 30 and 75 deg above the horizon. Figures 3a, 4a, 5a and 6a reflect the limitations imposed by typical equipment of earth and deep space stations.

Figures 3b, 4b, 5b and 6b assume the use of perfect antennas and noiseless receivers. These curves illustrate performance as limited only by natural phenomena. Comparison of the a) and b) curves in each figure shows the potential for better link performance that could result from improvement of equipment technology.
Achievable link performance as limited by equipment characteristics and natural propagation phenomena

Ideal link performance as limited by natural propagation phenomena only

FIGURE 3 — Space-to-Earth link performance, $P_r/N_0$
Fixed diameter earth station and space station antennas

- clear atmosphere, 7.5 gm/m$^3$ water vapor
- atmosphere plus rain, 10 mm/hr

$\Delta$: elevation angle (deg) of earth station antenna
a) Achievable link performance as limited by equipment characteristics and natural propagation phenomena

b) Ideal link performance as limited by natural propagation phenomena only

**FIGURE 4 — Space-to-Earth link performance, $P_p/N_o$**
Fixed diameter earth station antenna, fixed gain space station antenna

- clear atmosphere, $7.5 \text{ gm/m}^3$ water vapor
- atmosphere plus rain, $10 \text{ mm/hr}$

$\Delta$: elevation angle (deg) of earth station antenna
a) Achievable link performance as limited by equipment characteristics and natural propagation phenomena

b) Ideal link performance as limited by natural propagation phenomena only

FIGURE 5 — *Earth-to-Space link performance, \( \frac{P_r}{N_0} \)*
Fixed diameter earth station and space station antennas

- clear atmosphere, 7.5 gm/m\(^3\) water vapor
- atmosphere plus rain, 10 mm/hr

\( \Delta \): elevation angle (deg) of earth station antenna
**FIGURE 6** - *Earth-to-Space link performance, $P_r/N_0$*

Fixed diameter earth station antenna, fixed gain space station antenna

- clear atmosphere, 7.5 gm/m$^3$ water vapor
- atmosphere plus rain, 10 mm/hr

$\Delta$: elevation angle (deg) of earth station antenna

---

*a*) Achievable link performance as limited by equipment characteristics and natural propagation phenomena

*b*) Ideal link performance as limited by natural propagation phenomena only
1. Introduction

The performance of links between earth stations and stations in deep space is affected by the atmosphere of the Earth. Attenuation and emission by the atmosphere generally limits deep-space telecommunications to frequencies below 20 GHz. There are, however, certain frequency bands in the 20 - 120 GHz range where atmospheric attenuation is low enough to permit links between earth stations and deep-space stations. Additionally, there are certain other bands in the 20 - 120 GHz range that would be particularly suitable for links between an earth-orbiting relay station and deep-space stations.

This Report considers the selection of preferred frequency bands for deep-space telecommunications in the 40 - 120 GHz range. The selection of bands in the range 1 to 40 GHz that are preferred for deep-space research is given in Report 683.

1.1 Advantages of higher frequencies

Radio frequencies above 40 GHz can provide advantages for deep-space telecommunications. The advantages are higher link performance, potential for wider bandwidth, reduced errors in measurements that depend on the velocity of propagation, and the possibility of shielding from terrestrial interference.

1.1.1 Increased link performance

For a fixed transmitter power, the power received via a free-space link between perfect antennas with fixed apertures varies in direct proportion to the frequency squared. A practical example of this circumstance is the case of a path between a spacecraft in deep space and a relay satellite in orbit above the atmosphere of the Earth. If technology does not limit the choice of frequency in a particular range that is being considered, the highest frequency in that range will provide the best link performance.

For certain frequencies where the attenuation of the atmosphere is relatively low, links between Earth and space can benefit from the use of frequencies above 40 GHz.

The increased performance of higher frequency links may be utilized for command, telemetering and radiometric functions. Alternatively, the higher performance may be traded for smaller and lighter spacecraft antennas and transmitters.
1.1.2 More accurate measurement of phase and group delay

Accurate navigation of deep-space probes depends upon determination of their position and velocity by means of phase and group delay measurements of received signals. These measurements are influenced by the velocity of propagation along the transmission path. The velocity of propagation is a function of the presence of charged particles along the path. The effect of these particles varies inversely with the square of the frequency and hence higher frequencies are preferable for purposes of navigation and certain other radio measurements.

1.1.3 Shielding from terrestrial interference

In the future it may be desirable to employ a geostationary relay station for signals to and from deep-space probes. The links between such a station and deep-space probes would be free of the perturbing effects of the atmosphere. These links could be protected from terrestrial interference by choosing frequencies where the atmosphere is relatively opaque to radio signals. There are such frequencies in the 40 - 120 GHz range.

1.1.4 The availability of broader bandwidth allows higher data transmission rates. In addition, broader bandwidth permits the use of more complex coding schemes which provide reduced data error rates and reduced susceptibility to interference.

1.2 Basis for frequency selection

Selection of preferred frequencies is based on link performance and by propagation and equipment characteristics. In the next three sections of the Report we examine the factors that influence frequency selection. Some of these factors provide the information needed to calculate an index of link performance. This index may be expressed as \( P_r/N_0 \), the ratio of total received power to noise spectral density for a particular set of propagation conditions and equipment parameters.

2. Frequency dependent characteristics of interplanetary propagation

Interplanetary propagation characteristics determine the performance of links between a deep-space probe and a relay satellite located outside the atmosphere of the Earth. These characteristics, discussed in Report 887, also affect the performance of links between earth stations and deep space.

2.1 Attenuation

A review of gaseous absorption and scattering by dust particles outside planetary atmospheres indicates that neither will attenuate the signal by as much as 0.1 dB in the 40 - 120 GHz range as long as the propagation path is restricted to our solar system. Attenuation by interplanetary space may be considered a negligibly small factor in the selection of preferred bands.
2.2 Sky noise temperature

The sky noise temperature seen by a relay satellite will be determined by the cosmic background (3 K) and quantum noise as shown in curve A of Fig. 1, except when noise from the Earth, other planets or the Sun enters the antenna. The effect of these noise sources is discussed in Report 720.

The sky noise temperature seen by a spacecraft will also be that shown in curve A of Fig. 1. Earth will generally be within the main lobe of a spacecraft antenna pointed at a relay satellite. The presence of Earth within the antenna beam will contribute to the noise temperature. For example, for a spacecraft at $4 \times 10^7$ km from the Earth (the minimum distance to Venus), the Earth subtends an angle of $1.8 \times 10^{-2}$ degrees. If the spacecraft antenna is limited to a minimum beamwidth of 0.15 degrees by pointing accuracy, then the Earth can fill less than $1/69$ of the antenna main lobe. The effect of the black body temperature of the Earth is correspondingly reduced to a value that is small compared to the 600 - 1500 K noise temperature of a typical spacecraft receiving system. (In the frequency range 40 - 120 GHz the black body temperature varies between 210 and 290 K, depending on frequency and sub-spacecraft longitude on the Earth.)

In this frequency range, the noise temperature seen by an antenna pointed in the direction of the Sun is 6000 K. This very large increase in the system noise temperature must usually be avoided and can therefore affect the timing and design of some deep-space missions and experiments.

For calculation of $P_r/N_0$ as a function of frequency, the sky noise temperature seen by a relay satellite or deep-space probe may be considered a negligible part of the system temperature.

2.3 Velocity of propagation

Charged particles along the communication path cause changes in the velocity of propagation. Figure 2 in Report 683 shows an example of the apparent range measurement error as a function of frequency and of the angle between the ray path and a line between the Sun and the earth station. Although the curves in the figure do not include frequencies above 32 GHz, the trend to lower errors continues as frequencies rise to still higher values. It is apparent that high frequencies are desirable for the most precise ranging.

2.4 Scintillation

Amplitude and phase scintillation from solar plasma will be a factor for ray paths close to the Sun. The magnitude of the scintillation decreases with increase in frequency. A discussion of extraterrestrial plasma effects may be found in Report 887.
FIGURE 1 – Sky noise temperature

Curves A: as seen by deep-space station
B: as seen by earth station, antenna at 30° elevation angle

--- Gaseous atmosphere
----- Composite of gaseous atmosphere plus rain exceeded 0.001% of time (55 mm/h rain climate J)
3. Frequency dependent characteristics of propagation through an atmosphere

The foregoing interplanetary propagation factors affect links between deep space and a geostationary relay station. For links between deep space and Earth, the atmosphere plays a dominant role in the selection of preferred frequencies in the 40 - 120 GHz range.

Planetary atmospheres can affect paths that graze or penetrate them.

3.1 Attenuation

3.1.1 Attenuation by the atmosphere of the Earth

Attenuation of signals passing through the ionosphere of the Earth is negligible at frequencies above 40 GHz, but the neutral atmosphere plays a major role at these frequencies. The attenuation for transmission through the atmosphere is shown in Figure 2 (see also Report 719). Above 40 GHz, minimum attenuation on links between Earth and spacecraft would be obtained at frequencies near 90 GHz.

The specific attenuation due to rain at rates greater than a few millimetres per hour is generally larger than that of the gaseous atmosphere and increases monotonically with frequency in the range of interest. The rain rate for 0.01% of the time in a median rain climate is greater than 30 mm/hr (see Report 563). The attenuation in the 40 - 120 GHz region during rain at this rate is so high (Report 721) that telecommunication between the Earth and spacecraft in deep-space is generally not practicable and will not be considered further as a determinant of preferred frequencies.

For relay satellite-to-spacecraft links, the line-of-sight propagation paths will be obscured at times by the interposition of the Earth or some portion of the Earth's atmosphere. From a geostationary satellite, the solid Earth (not including the atmosphere) subtends a solid angle of 17.34 degrees. If the atmosphere from the surface of the Earth up to an altitude of 100 km were opaque to radio waves the obscuration angle would increase by 0.27 degrees. The effect of atmospheric attenuation on the obscuration angle is so small that this factor does not influence the selection of preferred frequency bands.

The objective of protecting the paths between deep-space probes and an earth satellite from terrestrial interference may be satisfied by taking advantage of the high atmospheric attenuation in the 60 and 119 GHz regions (see Report 719). Molecular oxygen absorption lines at these frequencies are responsible for the high attenuation observed in Figure 2.

A pair of links (probe to earth-satellite and vice versa) could be accommodated in the high attenuation region between 54 and 64 GHz. A frequency separation of approximately 7% is required (see Report 683). The absorption line at 119 GHz is much narrower and only one link of a pair could benefit from the maximum shielding. In this case, shielding of the link from the spacecraft to the relay satellite is most important.

3.1.2 Attenuation by atmospheres of other planets

From the standpoint of attenuation, the nature of the atmospheres of other planets does not influence the selection of communication frequencies in the 40 - 120 GHz range. This is not to say that the atmospheres of some planets do not contain spectral lines of scientific interest in this frequency range, for example ammonia.
FIGURE 2 – Attenuation due to the gaseous atmosphere and rain for an antenna elevation angle of 30° at an earth station.

---

- Gaseous atmosphere (7.5 g/m³ water vapour at surface)
- Composite of gaseous atmosphere plus rain exceeded 0.001% of time (55 mm/h rain climate J)
3.2 **Sky noise temperature at earth stations**

Sky noise temperature as seen by an earth station is a function of frequency, elevation angle, and atmospheric conditions (see Report 720). Curves B in Figure 1 are representative of sky noise temperature during clear weather and during heavy rainfall.

When the earth station antenna is pointed near the Sun, the noise temperature will increase.

3.3 **Scintillation**

Amplitude and phase scintillation from the neutral atmosphere is discussed in Report 881 (Geneva, 1982). The effects increase with frequency for a fixed antenna aperture and at 100 GHz may cause signal amplitude fluctuations between 0.4 and 3.8 dB for a 37m parabolic dish antenna.

Scintillation due to the Earth’s ionosphere will not be a selection factor for frequencies above 40 GHz (see Report 263), and the same conclusion can be drawn relative to planetary ionospheres. For some missions, scintillation caused by the solar corona could affect the choice of frequency.

4. **Frequency dependent equipment factors**

Equipment characteristics which determine link performance include transmitter power, antenna size, surface accuracy and pointing accuracy, and receiver noise temperature. These characteristics usually depend upon frequency to some degree. In the frequency range 40 - 120 GHz, for paths between Earth and deep space, the effect of the atmosphere on link performance is so strong that the frequency dependent equipment factors have only a minor effect on the selection of preferred frequencies.

5. **Example of link performance analysis**

Figure 3 illustrates link performance as a function of frequency. Curve A is for a path in free space. Curve B includes the effect of the atmosphere of the Earth. The index of performance $P_r/N_0$ (see 1.2 above) was calculated on the basis of data in Figures 1 and 2 and the following parameter values:

- Communication distance: $8 \times 10^8$ km
- Spacecraft transmitter power: 25 W
- Spacecraft antenna: 3.7 m
- Earth station antenna: 64 m

The antennas are assumed to be ideal with gain that is proportional to frequency squared.
These values are illustrative only; other values could be used. Different numerical results would be obtained, but the shape of the performance curves and the corresponding frequency selection would not change.

Comparison of curves A and B shows the advantage in link performance that results from utilizing higher frequencies when the path is entirely in space. This is a principal reason for establishing a relay station in an earth satellite.

Curve B shows that frequency bands within the 40 - 120 GHz range can provide for transmission through the atmosphere, and for shielding of paths between a relay satellite and deep-space probes from terrestrial signals.

**FIGURE 3** — Link performance ($P_r/N_0$) limited by natural phenomena only; two fixed diameter antennas: 3.7 m on deep-space station, 64 m at receiving station

Curves A: deep space to satellite

B: deep space to earth station
6. **Preferred frequency bands**

The preferred frequency bands for deep-space in the 40 - 120 GHz range are listed in Table I. The bands were selected on the basis of:

- the attenuation and noise temperature characteristics of propagation through the atmosphere;
- the requirement to provide links between a relay satellite and a station in deep space that are shielded from terrestrial signals;
- and the requirement for links that permit communication between a deep-space station and either a relay satellite or an earth station.

The feasibility of band sharing and the existing allocations in the Radio Regulations were not factors in the selection of bands. The frequency dependent characteristics of scintillation and velocity of propagation were not used as determinants of preferred frequency bands. These factors could influence the use of certain allocated bands for particular space research missions, but communication performance was considered the dominant factor in preferred band selection. Similarly, equipment characteristics that vary with frequency were not used to influence band selection. Bands that may be allocated will likely remain for many years, and equipment technology will develop to make best use of those frequencies, as limited by natural phenomena. The bandwidth and frequency separation requirements are discussed in Report 536.

**TABLE I - Preferred frequencies and their uses**

<table>
<thead>
<tr>
<th>Current Allocations</th>
<th>Range of preferred frequencies (GHz)</th>
<th>Application</th>
<th>Other requirements(^{(1)})</th>
</tr>
</thead>
<tbody>
<tr>
<td>There are no current allocations for deep-space research in the 40-120 GHz range.</td>
<td>56-64</td>
<td>Relay satellite to deep space, and deep space to relay satellite, shielded from terrestrial signals</td>
<td>A pair of 500 MHz wide bands spaced at approximately 7% within the 56-64 GHz range</td>
</tr>
<tr>
<td></td>
<td>80-100</td>
<td>Deep space to Earth, and Earth to deep space</td>
<td>A pair of 500 MHz wide bands spaced at approximately 7% within the 80-100 GHz range</td>
</tr>
<tr>
<td></td>
<td>98-110</td>
<td>Relay satellite to deep space (for use in connection with link in the 117.7-119.8 GHz band)</td>
<td>500 MHz bandwidth, spaced at approximately 7% from the space to relay satellite band in the 117.7-119.8 GHz range</td>
</tr>
<tr>
<td></td>
<td>117.7-119.8</td>
<td>Deep space to relay satellite, shielded from terrestrial signals</td>
<td>500 MHz bandwidth</td>
</tr>
</tbody>
</table>

\(^{(1)}\) The requirements shown are based on characteristics of telecommunication systems utilized or planned by several administrations.

**BIBLIOGRAPHY**

1. Introduction

Much of the spectrum suitable for space research is also allocated to one or more other services and consequently frequency sharing between the services is required. This Report discusses factors which affect the susceptibility of systems in the space research service to interference, and specifies appropriate protection criteria for the service in the frequency bands up to about 30 GHz. The protection criteria are for use in coordination and interference analyses when actual system data are unavailable.
2. General considerations

Space research communications are required for four types of functions: telecommand, maintenance telemetering, stored scientific data and real-time scientific data. Interference affects each of these somewhat differently (see Report 548).

For the telecommand function, it is a fundamental design principle of most research spacecraft that no false command should result in a completely aborted mission and that an unalterable state be reached as a result of any command. As there is usually an unavoidable severe dependence on the spacecraft telecommand system during critical mission phases such as during launch and injection sequences or during emergency situations, interference during these critical periods could severely compromise the mission.

Maintenance telemetering can be stored or sampled and transmitted in real time. Except during critical periods, such as launch and injection sequences, emergency situations, or during the transfer of bio-medical data of human occupants, a maintenance telemetry system is fairly tolerant of interruptions and interference. During critical periods, read-outs must of course be highly reliable. The diagnostic use of these data makes it clear that at critical times in a mission there may be long periods (several hours) in which the maintenance telemetry must be protected from harmful interference. For other periods of a mission, however, this class of function can accommodate limited interruption without serious effect.

Stored scientific data can usually be played back more than once for error detection. This is probably the class of data which is most tolerant of interference of limited duration.

Real-time non-stored data are the most susceptible to interference, in that the transmission occurs only once and is unrepeatable. Much of the value of an expensive spacecraft may be represented by such data, so it is imperative that this class be well protected against interruption or degradation. Usually, the time of reception of interesting non-stored data is known in advance to within several hours.

Many space research systems employ PCM-PSK-PM modulating techniques and phase-locked loop circuitry for the demodulation of system carriers and sub-carriers. High data rate transmissions are usually based upon 2-PSK or 4-PSK modulation. Phase-locked loop circuitry is also used during search, acquisition and tracking sequences, and is employed in both ground and spaceborne receivers. Discussion of an experimental investigation into the interference effects in phase-locked loops is presented in Report 544 (Geneva, 1982). In Report 545 (Geneva, 1982), the effects of interference on research spacecraft telemetering (especially binary bit detectors) are discussed.

3. Protection criteria

In a communication link, the permissible ratio of interference to system noise may be determined by the portion of design margin allocated to external interference. In space-to-space and space-to-Earth links, the incentive is to minimize link margins in order to save weight and power, to comply with emission limits, and in the interest of economy. Typical link design margins to allow for the effects of non-ideal conditions are generally in the range of 3 dB to 6 dB for spacecraft operating at frequencies below about 10 GHz. For spacecraft operating at frequencies above about 10 GHz, larger link margins are usually required to offset the effect of weather conditions.

Considering these low link margins, interference can be harmful to typical space research systems if the link threshold performance is decreased by more than 1 dB. This corresponds to a required ratio of system noise spectral density to interference spectral density \((N/I)\) of about 6 dB.

Where it was initially anticipated that channel coding techniques would allow operation with \(N/I\) ratios of \(-10\) dB, it has been found through experience that a value of \(+6\) dB is required (see Report 687).

3.1 Reference bandwidth

The reference bandwidth in which a protection level must be specified depends upon the smallest bandwidth likely to be employed. For earth-station receivers, phase-locked loops may employ bandwidths of a few hertz. The detection bandwidth on the space station is usually greater (1 kHz or more) due to the need for rapid, automatic acquisition of signals from the Earth.
Thus, recommended values for the reference bandwidths for space research receivers are:

- earth-station receivers: 1 Hz
- space station receivers: 1 kHz.

3.2 Reference percentage of time

When considering interference to space research earth stations, it is necessary to note that sporadic interference from man-made sources can be expected due to trans-horizon propagation, fluctuating weather conditions, and the changing gain in the link between the interfering station and the receiving station due to the relative motions of the antennas, etc. Therefore, any criterion of interference which is established must be stringent enough to minimize the possibility of this type of interference.

Further, as propagation data are usually presented in the form of a percentage of time that certain conditions are exceeded, it is necessary to relate outage time with propagation data. For manned space missions, a loss of more than 5 min of communication during critical periods would seriously affect the mission. However, it is usual that propagation conditions are such that the lowest transmission loss between two stations will persist for much longer periods than 5 min. Therefore, to provide protection which will prevent interference for longer than 5 min per day, it is necessary not only to consider the worst hour in the year, but also the worst 5 min within that hour. This is approximately 0.001% of the time. For unmanned missions, where safety of life is not a factor, the reference percentage of time is 0.1%.

3.3 Required protection levels

3.3.1 Earth-station receivers

In the 1-20 GHz region, the total noise temperature of receiving earth stations is typically about 70 K or greater depending on the antenna contribution. This contribution is a function of frequency, antenna elevation angle, existing meteorological conditions and ground and thermal radiation into the antenna side and back lobes. Below about 1 GHz, cosmic noise increases the operating noise temperature of the system at a rate of about 20 dB per decade of decreasing frequency. Therefore, based on the required $N/I$ ratio of 6 dB established in § 3, and a receive noise temperature of 70 K, the following criterion is the most directly appropriate for the protection of earth stations.

In the frequency range 1-20 GHz, harmful interference can occur if the total time during which the power density of noise-like interference or the total power of CW-type interference in any single band or in all sets of bands 1 Hz wide, is greater than $-216$ dB(W/Hz) at the input terminals of the receivers for a period exceeding 0.001% of the time for manned missions, and 0.1% of the time for all other near-Earth space research missions. For frequencies below about 1 GHz, permissible interference may be increased at the rate of 20 dB per decreasing frequency decade. This interference criteria applies to all three of the down-link communication functions discussed in § 2.

3.3.2 Space-station receivers

The total noise temperatures of a typical space-station receiver is generally 600 K or more. These levels are due, in part, to the requirement that the spacecraft antenna points at the Earth (290 K). Based on the required $N/I$ of 6 dB, the following criterion is most directly appropriate for the protection of space stations.

In the frequency range 100 MHz-30 GHz, harmful interference can occur if the power density of noise-like interference or the total power of CW-type interference in any single band or in all sets of bands 1 kHz wide, is greater than $-177$ dB(W/kHz) at the input terminals of the receiver.

Due to the motion of low-orbit spacecraft, which can be susceptible to this level of interference, the amount of time of exposure to the interference is limited to 0.1% of the time for both manned and unmanned missions.
1. Introduction

1.1 General

This Report, based upon work carried out in the United States, deals with some of the statistical and geometric aspects of potential interference from space research spacecraft in low orbit to terrestrial services and to the terrestrial segments of space services.

1.2 Background

The present ITU power flux-density constraints (e.g. Article 28 of the Radio Regulations) were developed primarily on the basis of geostationary space stations interfering with ground communication systems, and as such were based upon a temporally static frequency sharing model (i.e. constant in direction and amplitude of interference). For the sake of generality the expressions “ground communication system”, “ground antenna”, “ground station” etc., refer to systems, antennas, and stations located on the surface of the Earth, regardless of whether they are functioning in a terrestrial or a space service. The increasing use of space stations in circular low orbit in the space research service (and other services) necessitates the development of a dynamic sharing model, in which the potential interference from the space station can be treated as a time varying function. Even for the simplest of dynamic sharing models, at least six specific system parameters must be evaluated to define precisely the primary time dependent statistics of a low-orbit space station as seen from a location on the Earth’s surface.

The time dependent statistics are:
- the longest time of passage of a space station through the main beam of a ground antenna (discussed in § 3 of this Report);
- the long-term percentage of time that the space station spends in various areas of the orbit sphere as seen from the ground station.

The first statistic is important in that it defines the longest continuous duration of noise power into the ground receiving system from the space station. The second set of statistics, after convolution with transmit and receive antenna patterns, and range loss, can be used to develop interference-to-noise ($I/N$) relations as a function of time for the dynamic sharing model. In one sense then, $I/N$ versus time relations can be treated in a method similar to the signal strength versus time relations derived from atmospheric propagation statistics. However, instead of a receiver experiencing change in the signal-to-noise ratio as a statistical function of time, it experiences a change in signal-to-noise-plus-interference ratio, as a statistical function of time, based upon the low-orbit space station model parameters.

The specific parameters which define the long-term visibility statistics of a space station in a low circular inclined orbit (see Note) as seen from a receiving system on the Earth’s surface are:
- altitude of the space station $H$ (km);
- inclination of the space station orbit $i$ (degrees);
- latitude of the ground station $La$ (degrees);
- pointing azimuth of the ground station antenna measured from North $Az$ (degrees);
- pointing elevation of the ground station antenna measured from the local horizontal plane $El$ (degrees);
- angular area of the region of interest $\delta A$.

Note. — This Report only deals with satellite orbits in which the orbital period is not an even multiple of the Earth’s rotational period.

* This Report should be brought to the attention of Study Groups 1, 8 and 9.
The last parameter may take on several different physical interpretations depending upon the purpose of the analysis. For instance, it may be the angular area of the main beam of the ground station antenna or it may be taken as an angular area expressed by an azimuth “width” of $\delta \Delta \theta$ degrees and an elevation “height” expressed as $\delta E \ell$ degrees.

2. Bounding equation

The bounding equation (derived in Annex II of Report 684, Geneva, 1982) is given below and may be used to determine the percentage of time that a low-orbit spacecraft will reside in certain regions visible to a ground station over long periods of time.

$$T (\%) = \frac{\delta \lambda}{2\pi} \left\{ \sin^{-1}\left( \frac{\sin (L + \Delta L)}{\sin i} \right) - \sin^{-1}\left( \frac{\sin L}{\sin i} \right) \right\} \times 100 \tag{1}$$

where,

- $\delta \lambda$ is the longitudinal region on the orbital shell, between the latitude limits of $L$ and $L + \Delta L$ (as seen in Fig. 1) and
- $i$ is the inclination of the satellite orbit

(all angles in radians).

3. The maximum time a satellite spends in the beam of a ground station

This section provides worst case numerical data on one aspect of frequency sharing with low-orbit, inclined orbit satellites. Such sharing is influenced by the amount of time that an “unwanted” and potentially interfering satellite appears within the 3 dB beamwidth of a ground station. This parameter is evaluated for several orbit altitudes and for two “bounding” elevations of the receiving antenna. The numerical results developed in this paper represent an upper bound on the length of time a spacecraft at a given altitude will appear within the beam of a ground station.

The time a satellite spends in a ground station’s beam is a function of the beam’s width, the elevation of the beam and the altitude of the satellite. The worst case, i.e. when the satellite spends the maximum possible time in the beam, occurs when the ground station is located at the equator with a beam of elevation = 0° and the satellite is travelling east along an orbit with 0° inclination. The time the satellite spends in the beam depends upon the satellite’s velocity relative to the velocity of the beam as it rotates with the Earth, and upon the length of the intersection of the orbit with the beam (see Annex III to Report 684, Geneva, 1982).

The maximum time that a spacecraft can spend in the main beam of an antenna is shown in Figs. 2 and 3 for antenna elevations of 0° and 90° respectively, and refers to a variety of orbital altitude and beamwidths.
FIGURE 2 – Maximum time in beam plotted against beamwidth at elevation of 0°

FIGURE 3 – Maximum time in beam plotted against beamwidth at elevation of 90°
4. Conclusions

This Report presents a simple method of calculating the percentage of time that a spacecraft in a circular inclined orbit will be visible within a selected region of the sky, as seen from a point on the Earth's surface. In addition, § 3 and Annex III of Report 684 (Geneva, 1982) presents information on the maximum time that a low-orbit spacecraft can spend in the main beam of a ground antenna.

The two factors mentioned above may be useful in developing sharing models between low-orbit, inclined spacecraft and ground receivers of several services.

REPORT 687-1*

FEASIBILITY OF FREQUENCY SHARING BETWEEN SPACE RESEARCH (NEAR-EARTH) AND FIXED AND MOBILE SERVICES IN THE 7 TO 8 GHz SPECTRAL REGION

(Question 1/2)

(1978–1986)

1. Introduction

The bands near 7 GHz (6425 to 7250 MHz) and near 8 GHz (7750 to 7900 MHz) are currently allocated to the world-wide fixed and mobile services. This Report analyzes the potential for frequency sharing in these bands between the fixed, mobile and space research services. Sharing with space research space-to-Earth transmission is covered in § 2, sharing with Earth-to-space transmissions is covered in § 3 below.

2. Space-to-Earth transmissions in the space research service

2.1 Interference to fixed and mobile line-of-sight receivers from space research satellite transmitters

The power flux-density (pfd) limits used in this analysis are:

-152 dB(W/m²) in 4 kHz for 0° < δ < 5°
-152 + (δ - 5)/2 dB(W/m²) in 4 kHz for 5° < δ < 25°
-142 dB(W/m²) in 4 kHz for 25° < δ < 90°

where

δ : angle (in degrees) of incoming radiation relative to the horizontal.

These pfd limits are identical to those given in Recommendation 358, which were developed for sharing between the fixed-satellite service and the fixed service in this portion of the frequency spectrum.

For the purpose of evaluating the technical feasibility of frequency sharing, the technical characteristics and calculation of pfd of a typical space research satellite emission are given in Table I.

This level of spectral pfd is 2 dB below the limit of –152 dB(W/(m² · 4 kHz)) for low angles of arrival.

* This Report should be brought to the attention of Study Groups 5, 8 and 9.
### TABLE I — Technical characteristics of space-to-Earth transmissions

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmitter power in 100 MHz bandwidth (dBW)</td>
<td>+16</td>
</tr>
<tr>
<td>Maximum antenna gain (') (dBi)</td>
<td>+6</td>
</tr>
<tr>
<td>Allowance for spreading loss (') to satellite horizon (1000 km orbit) (dB)</td>
<td>-142</td>
</tr>
<tr>
<td>Factor for conversion to 4 kHz bandwidth (dB)</td>
<td>-44</td>
</tr>
<tr>
<td>Spectral distribution factor ('') (dB)</td>
<td>+10</td>
</tr>
<tr>
<td>Maximum pfd in a 4 kHz band (dBW/m²)</td>
<td>-154</td>
</tr>
</tbody>
</table>

(') Pattern shaped to provide constant pfd across the satellite field of view.

(2) Defined as the ratio of e.i.r.p. in the direction considered to the power passing in that direction through unit area (1 m²) at the specified distance (3.7 x 10⁶ m in this example).

(3) Defined as the ratio of the maximum power in a 4 kHz band to the mean of the powers in all such bands. The value of 10 dB is assumed to be the worst case for causing interference.

### 2.2 Interference to space research earth station receivers from fixed and mobile transmitters

Table II presents representative technical characteristics of earth stations in the space research service.

### TABLE II — Reception by a space research earth station

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical power flux-density from satellite in a 100 MHz band (') (dB(W/m²))</td>
<td>-120.0</td>
</tr>
<tr>
<td>Allowance for effective area of receiving antenna (') (dB)</td>
<td>+14.4</td>
</tr>
<tr>
<td>Allowance for miscellaneous losses (dB)</td>
<td>-2.0</td>
</tr>
<tr>
<td>Received power, ( P_r ) (dBW)</td>
<td>-107.6</td>
</tr>
<tr>
<td>Receiver noise power, ( kT_B ) (dBW) (( T_B = 150 \text{ K}, B = 100 \text{ MHz} ))</td>
<td>-126.8</td>
</tr>
<tr>
<td>Carrier-to-noise ratio, ( C/N ) (dB)</td>
<td>-19.2</td>
</tr>
</tbody>
</table>

(') For an e.i.r.p. of +22 dBW at a range of 3700 km.

(2) For a parabolic reflector having a diameter of 8 m and an efficiency of 55%.

With this value of \( C/N \), the maximum tolerable value of interference \( P_i \), at the earth station receiver is assumed to be 6 dB below \( kT_B B \), or -132.8 dBW.

The sharing criterion for this interference path is based upon the application of coordination distance procedures to ensure sufficient separation between the two systems. The minimum permissible basic transmission loss to protect the earth station receiver is given by:

\[
L(1\%)^* = P_i + G_t - (P_t - G_t) \quad \text{dB}
\]

where

- \( P_t \): terrestrial transmitter power (dBW)
- \( G_t \): terrestrial antenna gain in direction of earth station (dBi)

\* \( L(1\%) \): the value of minimum acceptable basic transmission loss to be exceeded for all but 1% of the time along the interference path between the terrestrial transmitter and the earth station receiver. The value of 1% is derived from the service probability requirement of the system; and from the statistical variability of \( G_t \) in the case of an earth station tracking a low-altitude, inclined-orbit satellite, and the fact that the earth station would not be continuously active. Coordination distance data is not yet available for \( L(1\%) \).
\(G_r\): gain of earth station antenna in direction of terrestrial station (dBi)

\(P_i\): maximum permissible interference level at earth station receiver input (dBW)

or

\[L(1\%) = P_i + G_r + G_r + 132.8\text{ dB}\]

As the earth station antenna in the space research service is continually tracking a low orbit spacecraft, the value of \(G_r\) is a function of time. If the minimum working elevation angle is assumed to be 5\(^\circ\), the maximum gain in the direction of any terrestrial station would be approximately 32 — 25 \(\log(5^\circ)\) or 14.5 dB. Appendix 28 to the Radio Regulations and Report 382 show a value of \(G_r\) of 10 dB below the level of maximum gain towards the horizon, or 4.5 dB.

\(G_r\), the gain of the terrestrial station antenna in the direction of the earth station is taken to be 47 dBi. Therefore:

\[L(1\%) = 8 + 47 + 4.5 + 132.8\text{ dB}\]

or

\[L(1\%) = 192.3\text{ dB}\]

3. Earth-to-space transmissions in the space research service

3.1 Interference to space research satellites from fixed and mobile emissions

Table III lists technical characteristics of space research earth stations and satellites and derives a carrier-to-noise ratio of 14 dB at the satellite receiver. Considering this \(C/N\) ratio, it is assumed that interference should not be greater than 6 dB below the receiver noise power, or \(-121.5\) dBW in the full 100 MHz band.

The satellite antenna (6 dB gain, 70\(^\circ\) beamwidth) would sweep a 1200 km swath on the surface of the Earth from a 1000 km orbital altitude. The level of interference experienced by a single receiver based on assumed +55 dBW e.i.r.p. of fixed and mobile systems is calculated below. This calculation for worst case analysis assumes that the satellite is in the main beam of the fixed station transmitting antenna.

This received interference power is 5 dB below the calculated receiver noise power. It should be noted that a satellite in a 1000 km near-polar orbit would receive main beam illumination from a single fixed service transmitter for less than 0.008% of the time.

\[
\text{TABLE IIIa} \quad \text{Technical characteristics of the Earth-to-space link in the space research service}
\]

| Typical earth-station transmitter power (dBW) | 8 |
| Earth-station antenna gain (dBi) | 55 |
| Allowance for spreading loss (dB) | -131 |
| Satellite antenna gain (dBi) | 6 |
| Allowance for satellite antenna (10 \(\log\) (antenna area in \(m^2\))) (dB) | -39.5 |
| Received carrier power (dBW) | -101.5 |
| Receiver noise power (dBW) (noise temperature 2000 K, bandwidth 100 MHz) | -115.5 |
| Carrier-to-noise ratio, \(C/N\) at the satellite (dB) | 14.0 |
TABLE IIb — Technical characteristics of the terrestrial station to satellite interference path

| Terrestrial station transmitter power (dBW) | 8 |
| Terrestrial station antenna gain (dBi)    | 47 |
| Allowance for spreading loss (dB)          | -142 |
| Satellite antenna gain (dBi)              | 6 |
| Allowance for satellite antenna (10 log (antenna area in m²)) (dB) | -39.5 |
| Received interference power (dBW)         | -120.5 |

3.2 Interference to fixed and mobile receivers from space research earth station emissions

The sharing criterion for this interference path is the application of coordination distance procedures to ensure sufficient separation between the space research earth station and the fixed or mobile stations. The minimum permissible basic transmission loss to protect the fixed and mobile systems can be calculated by:

\[
L(0.01\%) = P_i + G_t - (P_i - G_t) + \left( B_T \right) dB (2)
\]

where:

- \( P_i \): earth station transmitter power (dBW)
- \( G_t \): gain of terrestrial station in direction of earth station (dBi)
- \( B_T \): receiver bandwidth of terrestrial system (MHz)
- \( B_e \): emission bandwidth of earth station (MHz)
- \( P_i \): maximum permissible interference level at terrestrial receiver input (dBW)

Typical terrestrial systems in this band have the characteristics listed in Table IV.

TABLE IV — Technical characteristics of fixed systems

| Transmitter power (dBW) | 8 |
| Antenna gain (dBi)      | 47 |
| Bandwidth (MHz)         | 20 |
| Receiver noise temperature (K) | 750 |
| Receiver noise power (dBW) | -126.8 |

The assumed maximum interference level at the terrestrial station in this case is 10 dB below the noise power of the receiver, or -136.8 dBW. Therefore:

\[
L(0.01\%) = 8 + 4.5 + 47 + 136.8 - 7 \quad dB
\]

or

\[
L(0.01\%) = +189.3 \quad dB
\]

and the required coordination distance is determined to be 290 km for a 5° earth station elevation angle, assuming no site shielding and Zone A propagation conditions (great circle mode propagation over land). The value of 290 km has been determined using Appendix 28 to the Radio Regulations.
4. Conclusions

Although coordination distance contours for $L(1\%)$ have yet to be developed, it appears that the space research service (near Earth) and (space-to-Earth) can share frequencies in the 6 to 8 GHz spectral region with the fixed and mobile services. This is provided that the pfd limits given in § 2.1 are imposed on the space research satellite and that care is taken in the siting of the space research earth station. This matter is brought to the attention of Study Group 5, with a view to extending the coverage of Report 724.

Regarding Earth-to-space transmission in this spectral region, sharing is possible with fixed and mobile systems provided care is taken in the siting of the earth station and that the space research satellite can accept the possibility of interference from a single fixed or mobile station for up to 0.008% of the time.
REPORT 685-3*

PROTECTION CRITERIA AND SHARING CONSIDERATIONS RELATING TO DEEP-SPACE RESEARCH

(Question 1/2, Study Programmes 1C/2 and 1E/2)


1. Introduction

This Report discusses the sharing of frequency bands between deep-space research stations and stations of other services. Allowable maximum levels of interference are specified for the deep-space research stations. These protection criteria may be used in calculations of coordination distance or for other analysis. The protection criteria are also relevant to studies of sharing within the space research service. Potential interference with other services is considered, and conclusions are drawn about the feasibility of sharing. Future relay satellites for use with deep-space missions are not considered in this Report.

The Report is based on the requirements and characteristics discussed in Report 536, and on the interference susceptibility of receivers typically used for deep-space research, as described in Annex I.

1.1 Interference effects and consequences

The consequence of interference that impairs the proper functioning of an earth-station or space-station receiver can be a reduction or interruption in the ability to navigate and control a spacecraft, and in the ability to receive scientific and engineering data sent by a spacecraft.

The receiver contains several synchronization loops, each of which looks to, and tracks, a particular signal component. With sufficiently strong interference, one or more of the several loops will lose lock on the desired signal. Momentary interference can also cause this unlocking and it may take several minutes in the case of the weakest signals to retain locking. During the critical periods that occur during most deep-space missions, it is essential to transmit and receive scientific data without error or interruption. Loss of lock during these periods results in irretrievable data loss. It is this characteristic that leads to such severe requirements for protection from interference. In contrast, the data communicated by some other radio services are often available for retransmission.

1.2 Loop bandwidth considerations

For some modes of operation, the loop bandwidths are unusually narrow. A particular example is the carrier tracking loop in the earth-station receiver. This loop may be as narrow as 1 Hz. It might be concluded that it would be unlikely that an interfering signal would lie exactly within that bandwidth, but it must be remembered that the frequency of the desired signal is Doppler shifted as a result of Earth rotation. For example, an 8.4 GHz signal will be shifted ± 11 kHz when received during a 24 h period by an earth station located at a latitude of 35°. An interfering signal with a fixed frequency that is anywhere within the Doppler-shifted range of the deep-space signal will appear to sweep through the carrier tracking loop bandwidth, and unlocking can result. In addition, interference does not have to be exactly within the loop bandwidth in order to affect the loop. As long as the interference is near the loop bandwidth and has sufficient power, severe degradation is possible. Interference that is remote from the loop bandwidth can also cause degradation through other mechanisms, such as maser saturation.

* This Report should be brought to the attention of Study Groups 4, 8, 9, 10 and 11.
1.3 Development and application of protection criteria

In the following sections of this Report, protection criteria are developed. These are based on the receiver function that is most sensitive to interference. Since the receivers are tunable throughout the bands allocated for deep-space research, the protection criteria are considered to apply anywhere in those bands. If this is not recognized, the freedom to choose frequencies for new missions is compromised.

In the concluding sections of the Report, the protection criteria are used to analyze the possibilities of band sharing.

2. Deep-space earth station factors pertinent to sharing

2.1 Intersections of satellite orbits and antenna beams from deep-space earth stations

The probability that a satellite will be in the main beam of the antenna of a deep-space earth station strongly affects the possibility of band sharing between the concerned links.

Statistics on antenna pointing at the three deep-space earth stations of the United States network (see Report 536) have been analyzed for a comprehensive set of accomplished and potential deep-space missions. It was found that the earth-station antenna gain in the direction of the geostationary-satellite orbit will be 10 dBi or more for 20% of the time.

Satellites that are not geostationary can pass through one or more deep-space tracking beams each day. Details of visibility statistics and in-beam duration times for satellites in low orbits are contained in Report 684.

2.2 Susceptibility of deep-space earth station receivers to interference

The interference susceptibility of earth-station receivers is discussed in Annex I. There are four receiver sub-systems that are sensitive to interference: maser pre-amplifier, carrier tracking loop, telemetering sub-system, and ranging sub-system. Annex I discusses the effects of CW interference and of noise-like interference on each of the four sub-systems.

2.3 Protection criteria and degradation of performance

To ensure proper operation of the entire receiving system, each of the four sub-systems must be protected against interference. A protection criterion specifies the amount of interference power that will result in a maximum acceptable degradation of performance. The maximum acceptable degradation for each sub-system is given in Table I.

<table>
<thead>
<tr>
<th>Receiving sub-system</th>
<th>Maximum acceptable degradation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maser pre-amplifier</td>
<td>1.0 dB gain compression</td>
</tr>
<tr>
<td>Carrier tracking</td>
<td>10° of loop-static phase error or peak-phase jitter</td>
</tr>
<tr>
<td>Telemetry</td>
<td>1.0 dB equivalent reduction in symbol energy-to-noise spectral density ratio (E/N_0 = 1.0\ dB)</td>
</tr>
<tr>
<td>Ranging</td>
<td>1.0 dB equivalent reduction in ranging signal-to-noise ratio (E/N_0 = 1.0\ dB)</td>
</tr>
</tbody>
</table>
The gain of a maser amplifier is reduced as a function of the input power of very strong signals or interference. This gain compression results in non-linear operation. Strong interference can thus produce non-linear effects on the desired signal, including generation of spurious signals. The maximum acceptable gain compression is considered to be 1 dB. The use of gain compression as a measure of non-linear effects is in agreement with common practice.

The response of the carrier tracking loop to interference is an increase in phase error and jitter. (Very strong interference can cause loss of lock.) The maximum acceptable degradation is considered to be a 10° increase in static phase error or a 10° increase in peak phase jitter.

The degradation of telemetry bit error performance and ranging accuracy as a result of interference can be expressed in terms of a corresponding reduction in signal-to-noise ratio. The maximum acceptable degradation for the telemetry sub-system corresponds to a 1 dB reduction in the symbol energy-to-noise spectral density ratio. This reduction applies to both coded and uncoded telemetry. For the ranging sub-system, the acceptable degradation corresponds to a reduction in ranging signal-to-noise ratio of 1 dB.

The maximum allowable interference for each receiver sub-system is derived from the corresponding maximum acceptable degradation. The protection criterion for the entire receiver is the maximum allowable interference for the most sensitive sub-system.

2.4 Determination of allowable interference

Annex I presents data that describe the susceptibility of the four receiver sub-systems to CW and noise-like interference. Using the criteria listed in Table I, the corresponding maximum interference may be determined.

2.4.1 Maser pre-amplifier

Table II shows the interference power that causes a 1 dB gain compression in the maser pre-amplifier.

<table>
<thead>
<tr>
<th>Interference type</th>
<th>Data source</th>
<th>Maximum interference</th>
</tr>
</thead>
<tbody>
<tr>
<td>CW</td>
<td>Fig. 6</td>
<td>-114 dBW</td>
</tr>
<tr>
<td>Noise (40 MHz bandwidth)</td>
<td>Fig. 6</td>
<td>-190 dB(W/Hz)</td>
</tr>
</tbody>
</table>

2.4.2 Carrier tracking, telemetry, and ranging sub-systems

2.4.2.1 Interference ratios for carrier tracking, telemetry, and ranging

Table III shows the interference-to-carrier ratio (I/C), interference-to-signal ratio (I/S), or interference-to-noise ratio (I/N) that corresponds to the allowable degradation of the carrier tracking, telemetry, and ranging sub-systems. The ratios are found as follows:

For CW interference, the allowable interference ratio for each sub-system may be found directly from curves given in Annex I.

For noise-like interference to the carrier tracking loop, Fig. 12 shows that a reduction in signal-to-noise ratio from 10 dB (the typical minimum operating point) to 5.7 dB results in an additional 10° of phase jitter. The corresponding I/N ratio is given by:

\[
I/N = 10 \log \left( \frac{10^{(CM_0/10)}}{10^{(CM_I/10)}} \right) - 1 \text{ dB (1)}
\]

where:

\( I/N \): interference-to-noise ratio,

\( CM_0 \): carrier margin (dB) without interference,

\( CM_I \): carrier margin (dB) with interference.
For noise-like interference to the telemetry and ranging sub-systems, the allowable interference-to-noise ratio is given by:

\[ I/N = 10 \log \left(10^{(E/N_0)/10} - 1\right) \text{ dB} \]  

(2)

where:
- \(I/N\): ratio of interference noise spectral density to receiver noise spectral density,
- \(E/N_0\): criterion given in Table I and the reduction in equivalent symbol energy-to-noise spectral density ratio or signal-to-noise ratio.

### TABLE III — Maximum allowable \(I/C\), \(I/S\) or \(I/N\) for CW and noise-like interference

<table>
<thead>
<tr>
<th>Sub-system (criterion)</th>
<th>Interference type</th>
<th>Data source</th>
<th>Maximum interference ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Carrier tracking</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(10° added peak phase jitter)</td>
<td>CW</td>
<td>Fig. 7</td>
<td>(I/C = -15) dB</td>
</tr>
<tr>
<td></td>
<td>Noise-like</td>
<td>Fig. 12 and calculation</td>
<td>(I/N = +2.3) dB</td>
</tr>
<tr>
<td><strong>Telemetry</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(1 dB (E/N_0) from interference in carrier tracking loop)</td>
<td>CW</td>
<td>Fig. 9</td>
<td>(I/C = -1.5) dB</td>
</tr>
<tr>
<td><strong>Telemetry</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(1 dB (E/N_0) from interference in telemetry detection bandwidth)</td>
<td>CW</td>
<td>Fig. 8 Calculated</td>
<td>(I/S = -11) dB (I/N = -5.9) dB</td>
</tr>
<tr>
<td><strong>Ranging</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(1 dB (E/N_0) from interference in carrier tracking loop)</td>
<td>CW</td>
<td>Fig. 10</td>
<td>(I/C = -5) dB</td>
</tr>
<tr>
<td><strong>Ranging</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(1 dB (E/N_0) from interference in range estimator bandwidth)</td>
<td>CW</td>
<td>Fig. 11 Calculated</td>
<td>(I/S = -7.1) dB (I/N = -5.9) dB</td>
</tr>
</tbody>
</table>

2.4.2.2 Maximum allowable interference for carrier tracking, telemetry, and ranging

For CW interference, the maximum allowable interference depends upon the \(I/C\) (\(I/S\)) and the minimum carrier (signal) level determined by the receiver design point. If it is assumed that the carrier, telemetry, and ranging signal powers are equal, Table III shows that the maximum allowable CW interference is dictated by the carrier tracking loop because it requires the smallest \(I/C\).

For carrier tracking, the minimum carrier-to-noise ratio is 10 dB. The corresponding allowable interference power for noise-like interference is:

\[ P_I = N_0 + 10 \log B + 10 + I/C \]  

(3)

where:
- \(P_I\): maximum allowable interference power for carrier tracking (dBW),
- \(N_0\): receiver noise spectral density, given in Table IV (dB(W/Hz)),
- \(B\): carrier tracking loop bandwidth, taken as 1 Hz (Hz),
- \(I/C\): interference-to-carrier ratio as given in Table III (dB).
The resulting $P_t$ is $-220.9$ dBW for the 8.4 GHz band, as shown in Table IV. Values are also shown for the other bands allocated to deep-space research.

### Table IV — Maximum allowable interference power to earth-station receivers

<table>
<thead>
<tr>
<th>Band (GHz)</th>
<th>Receiver noise spectral density (dB(W/Hz))</th>
<th>Maximum CW interference power (dBW)</th>
<th>Maximum noise-like interference power spectral density (dB(W/Hz))</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.3</td>
<td>-216.6</td>
<td>-221.6</td>
<td>-222.5</td>
</tr>
<tr>
<td>8.4</td>
<td>-215.0</td>
<td>-220.0</td>
<td>-220.9</td>
</tr>
<tr>
<td>13.0</td>
<td>-214.6</td>
<td>-219.6</td>
<td>-220.5</td>
</tr>
<tr>
<td>32.0</td>
<td>-211.4</td>
<td>-216.4</td>
<td>-217.3</td>
</tr>
</tbody>
</table>

Table III shows that the maximum allowable noise-like interference is dictated by the telemetry and ranging sub-systems because they require the smallest $I/N$. Table IV shows the corresponding maximum allowable power spectral density for this type of interference.

#### 2.5 Protection criteria for deep-space earth station receivers

Table V gives the maximum interference that will not exceed the allowable degradation of earth-station receiver performance. These values are the protection criteria for deep-space earth station receivers. Also shown is the corresponding spectral power flux-density at the aperture of a 70 m antenna.

### Table V — Interference protection for deep-space earth-station receivers

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>Maximum allowable interference power spectral density (dB(W/Hz))</th>
<th>Maximum allowable interference power spectral flux density (dB(W/m²•Hz))</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.3</td>
<td>-222.5</td>
<td>-257.0</td>
</tr>
<tr>
<td>8.4</td>
<td>-220.9</td>
<td>-255.1</td>
</tr>
<tr>
<td>13.0</td>
<td>-220.5</td>
<td>-254.3</td>
</tr>
<tr>
<td>32.0</td>
<td>-217.3</td>
<td>-249.3</td>
</tr>
</tbody>
</table>

To protect earth-station receivers, the spectral power density of noise-like interference, or the total power of CW interference, should not be greater than the amount shown in Table V for an aggregate of 5 min in any one day (5 min per day is generally taken as 0.001% of the time).

#### 3. Deep-space station parameters and protection pertinent to sharing

Space station and earth station receivers for deep-space research function in a similar manner, except that the space station does not include a maser. Space stations are susceptible to interference in ways similar to those described earlier for earth stations.
The criterion for protection of deep-space station receivers is that interference power must be no stronger than receiver noise power. Compared to deep-space earth station criteria, this is less severe and is a consequence of generally larger performance margins on the earth-to-space link. For protection of deep-space stations, the power spectral density of wideband interference, or total power of CW interference, in any 20 Hz band should be no larger than the amount shown in Table VI, for an aggregate of 5 minutes per day. The 20 Hz bandwidth specification is the carrier tracking loop bandwidth of the spacecraft transponder operated with threshold signal strength. The values of noise temperature shown in Table VI are estimates of currently practical systems that could be used in deep space.

Considerations regarding space station transmitter power are given in a later section.

**TABLE VI — Interference protection for receivers in deep-space**

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>Receiver Noise temperature (K)</th>
<th>Maximum allowable interference power spectral density (dB(W/20 Hz))</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>200</td>
<td>- 192.6</td>
</tr>
<tr>
<td>7.2</td>
<td>330</td>
<td>- 190.4</td>
</tr>
<tr>
<td>17.0</td>
<td>910</td>
<td>- 186.0</td>
</tr>
<tr>
<td>34.5</td>
<td>2000</td>
<td>- 182.6</td>
</tr>
</tbody>
</table>

4. **Sharing considerations: Earth-to-space bands**

Table VII and the following paragraphs consider the possibility of interference in the deep-space research Earth-to-space bands.

**TABLE VII — Potential interference in Earth-to-space bands**

<table>
<thead>
<tr>
<th>Source</th>
<th>Receiver</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deep-space earth station</td>
<td>Terrestrial or earth station</td>
</tr>
<tr>
<td>Deep-space earth station</td>
<td>Near-Earth satellite</td>
</tr>
<tr>
<td>Terrestrial or earth station</td>
<td>Deep-space station</td>
</tr>
<tr>
<td>Near-Earth satellite</td>
<td>Deep-space station</td>
</tr>
</tbody>
</table>

4.1 **Potential interference to terrestrial or earth station receivers from deep-space earth station transmitters**

The normal maximum total power for current US deep-space earth stations is 50 dBW. For a typical minimum elevation angle of 10°, the e.i.r.p. directed towards the horizon does not exceed 57 dB(W/4 kHz), assuming the reference earth station antenna radiation pattern of Recommendation 509. For spacecraft emergencies, the maximum total power may be increased to 56 dBW, giving not more than 63 dB(W/4 kHz) at the horizon. These values of e.i.r.p. meet the requirements of No. 2540 of the Radio Regulations.
Aircraft stations within line-of-sight of a deep-space earth station may encounter total power flux-densities as shown in Fig. 1. For an aircraft altitude of 12 km, the maximum line-of-sight distance to an earth station is 391 km and the total power flux-density at the aircraft can never be lower than $-83$ dB(W/m²), again assuming the antenna pattern of Recommendation 509. Depending on distance and earth station antenna direction, the aircraft station may experience much higher flux-densities and interference levels. Coordination with airborne stations is generally not practicable.

Super refraction, ducting, and precipitation scatter may couple emissions from deep-space earth station transmitters into terrestrial receivers, and receivers of other earth stations. Except for airborne terrestrial receivers, coordination for these conditions is generally practicable. See § 5.3 for discussion of interference from airborne transmitters, and § 6 for coordination considerations.

Transmitter: Deep-space earth station
100 kW, 70 m diameter antenna

A: Main beam, 34.5 GHz
B: Main beam, 17 GHz
C: Main beam, 7170 MHz
D: Main beam, 2105 MHz
E: 5 deg off main beam axis (14.5 dBi gain, Rec. 509)
F: > 48 deg off main beam axis (-10 dBi gain, Rec 509)
G: Geostationary orbit altitude: 35,800 km
4.2 Potential interference to satellite receivers from deep-space earth station transmitters

Satellites that come within the deep-space earth station beam will encounter power flux-densities as shown in Fig. 1. When the earth station is tracking a spacecraft whose direction is such that the antenna beam passes through the geostationary satellite orbit, the power flux-density at that point on the orbit will vary with time as shown in Fig. 2.

For example, the total power flux-density will be $-95 \text{ dB(W/m}^2\text{)}$ or more, for 32 minutes. The figure assumes a transmitter power of 50 dBW, a 70 m antenna, and the reference earth station pattern of Recommendation 509.

An important observation is that the minimum power flux-density at the geostationary satellite orbit within line of sight of a deep-space earth station is at least $-122 \text{ dB(W/m}^2\text{)}$, regardless of the antenna pointing direction.

The duration and magnitude of signals from deep-space earth station transmitters which may interfere with satellites in non-geostationary orbits depends upon those orbits and the particular deep-space tracking at that time.

![Figure 2](image)

**FIGURE 2 - Time during which the power flux density at a point on the geostationary satellite orbit may exceed a minimum power flux density.**

Transmitter: Deep-space earth station
100 kW, 70 m diameter antenna, 34.5 GHz

4.3 Potential interference to deep-space station receivers from terrestrial or earth station transmitters

Terrestrial or earth station transmitters within sight of a deep-space station are potential sources of interference. Figure 3 shows the space station distance at which interference power density from such a transmitter equals the receiver noise power density. For example, a transhorizon station with 93 dB(W/10 kHz) e.i.r.p. in the 2.1 GHz band could interfere with a space station receiver at ranges up to $4.1 \times 10^6 \text{ km}$ (600 K noise temperature, 3.7 m spacecraft antenna). The possibility of interference at such a great distance poses a threat to space missions to planets as far away as Uranus. Stations with lower e.i.r.p., or with antennas pointing away from the ecliptic plane, have less potential for interference.
FIGURE 3 - Spacecraft distance from terrestrial transmitter for interference power equal to receiver noise power.

A: Trans-horizon transmitter: 2115 MHz, 93 dB(W/10 kHz) e.i.r.p.; -191 dB(W/20 Hz) receiver noise power
B: Radiolocation transmitter: 34.5 GHz, 48.8 dB(W/Hz) e.i.r.p.; -182.6 dB(W/20 Hz) receiver noise power
C: Radiolocation transmitter: 17 GHz, 40.9 dB(W/Hz) e.i.r.p.; -186 dB(W/20 Hz) receiver noise power
D: Radio-relay transmitter: 7170 MHz, 55 dB(W/10 kHz) e.i.r.p.; -189 dB(W/20 kHz) receiver noise power
E: 1 AU: 1.5 \times 10^8 \text{ km}
F: Inner boundary of deep-space: 2 \times 10^6 \text{ km}

4.4 Potential interference to deep-space station receivers from near-Earth satellite transmitters

Near-Earth satellites typically have antennas directed to the Earth or to other satellites. Interference with deep-space station receivers may occur for those brief periods when the satellite antenna is directed so as to permit main beam coupling. As received at deep-space stations, signals from satellites will usually be relatively weaker than those from earth stations.

5. Sharing considerations: space-to-Earth bands*

Table VIII and the following paragraphs consider the possibility of interference in the deep-space research space-to-Earth bands.

* Report 688 (Geneva, 1982) discusses the feasibility of sharing between space research satellites in eccentric orbits and deep-space research earth stations. The band 2290-2300 MHz was used for the analysis presented in that Report. The Report was originally adopted in 1978. In 1979, the band 2290-2300 MHz was restricted to deep-space research. Report 688 is therefore no longer directly applicable to sharing in that band, but the analysis itself may be of interest.
TABLE VIII — Potential interference in space-to-Earth bands

<table>
<thead>
<tr>
<th>Source</th>
<th>Receiver</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deep-space station</td>
<td>Terrestrial or earth station</td>
</tr>
<tr>
<td>Deep-space station</td>
<td>Near-Earth satellite</td>
</tr>
<tr>
<td>Terrestrial or earth station</td>
<td>Deep-space earth station</td>
</tr>
<tr>
<td>Near-Earth satellite</td>
<td>Deep-space earth station</td>
</tr>
</tbody>
</table>

5.1 Potential interference to terrestrial or earth station receivers from deep-space station transmitters

Figure 4 shows the power flux-density at the surface of the Earth caused by deep-space stations with characteristics as shown in Report 536. These stations typically use low gain, wide beam antennas while near Earth. After a time not exceeding six hours from launching, they are usually at a sufficient distance for the power flux-density at the surface of the Earth to be less than the maximum permitted by the Radio Regulations for protection of line-of-sight radio-relay systems. For example, the Voyager spacecraft used the low gain antenna until $4.2 \times 10^7$ km from Earth, at which time the power flux-density was $-198 \text{dB(W/m}^2\text{)}$ in 4 kHz after switching to the high gain antenna.
When the transmitting space station is using a higher gain directional antenna, there is the potential for interference with sensitive terrestrial receivers if their antennas are directed so as to permit main beam coupling. A space station operating at 2.3 GHz with an e.i.r.p. of 51 dBW at a distance of $5 \times 10^8$ km could create an input of $-168$ dBW to a trans-horizon receiver (27 m antenna, main beam). The duration of such interference would be of the order of a few minutes, once a day, because of the rotation of the Earth.

5.2 Potential interference to near-Earth satellite receivers from deep-space station transmitters

Considerations of this interference are similar to those for the space station to terrestrial receiver case, § 5.1, with the exception of the path geometry. Depending on the changing conditions of that geometry, occasional brief interference is possible.

5.3 Potential interference to deep-space earth station receivers from terrestrial or earth station transmitters

Interference to deep-space earth station receivers may come from terrestrial or earth stations over line-of-sight paths, by tropospheric phenomena, or by rain scatter. For coordination considerations see § 6.

In particular, services utilizing high power transmitters and high gain antennas are potential interference sources. Earth station transmitters are less likely sources of interference, depending on e.i.r.p. in the direction of the deep-space earth station. Coordination should enable adequate protection from radio-relay stations to be provided.

Aircraft transmitters within sight of a deep-space earth station may cause serious interference. At maximum line-of-sight distance in any direction (391 km for an aircraft at 12 km altitude), an e.i.r.p. of $-26$ dB(W/Hz) (for example, 10 dB(W/4 kHz) and 0 dBi antenna) will exceed the earth station interference limit by at least the amount shown in Table IX, assuming the reference earth station antenna pattern.

Airborne radionavigation transmitters that may operate in the 32 GHz region of the spectrum are a particular example of potential sources of harmful interference to deep-space earth-station receivers. This class of transmitter includes a wide variety of characteristics: output power; CW, pulse, or chirp modulation; fixed or scanning antennas with narrow or wide beam patterns. The probability and degree of interference from a particular transmitter can be determined on a case-by-case basis that is beyond the scope of this report. Nevertheless, it is generally true that if an airborne radionavigation transmitter is within line-of-sight of the earth station receiver, the maximum allowable level of interference can be exceeded for a time sufficient to cause degradation to, or interruption of, service.

Coordination with airborne stations is generally not practicable.
TABLE IX – Interference from assumed aircraft transmitter

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>Maximum allowable interference power spectral density (dB(W/Hz))</th>
<th>Amount by which aircraft signal exceeds maximum allowable interference power*1 (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.3</td>
<td>- 222.5</td>
<td>35.0</td>
</tr>
<tr>
<td>8.4</td>
<td>- 220.9</td>
<td>22.1</td>
</tr>
<tr>
<td>13.0</td>
<td>- 220.5</td>
<td>17.9</td>
</tr>
<tr>
<td>32.0</td>
<td>- 217.3</td>
<td>6.9</td>
</tr>
</tbody>
</table>

(1) Aircraft signal less the deep-space earth station interference limit.

5.4 Potential interference to deep-space earth station receivers from near-Earth satellite transmitters

An analysis of the potential for interference in the 2290 - 2300 MHz band from satellites in highly eccentric orbits may be found in Report 688 (Geneva, 1982). It is concluded that sharing is not feasible. This conclusion is also valid for satellites in circular and moderately eccentric orbits.

5.4.1 Satellites transmitting to a geostationary relay satellite.

Table X presents an analysis of a situation where a link between a user spacecraft and a geostationary data relay satellite (DRS) grazes the surface of the Earth near the location of a deep-space earth station. It is assumed that the main beam of the earth station antenna is directed at the user satellite. The negative interference margin means that the protection criterion for the earth station receiver has been violated.

To reduce the negative interference margin shown in the Table to 0 dB, the DRS user satellite must remain at least 1.7 deg away from the main beam axis of the earth station antenna. If the earth station is tracking a particular spacecraft in deep-space each day, and if the DRS user satellite passes through the earth station antenna beam at some time during a given day, then the satellite will pass through the beam at less than 1.7 deg from the beam axis with a frequency ranging between once every 12 days to once each day. The frequency depends upon the satellite orbit period. For example, a satellite with an orbit period of 84 minutes can produce a negative interference margin of up to 0.8 minutes duration every 7th day.
Although an interference interval of less than one minute is relatively unimportant for some radio services, in the Space Research service it can result in irreplaceable loss of scientific data for several minutes. (See § 1.1.)

The analysis presented above is conservative in that it considers only a single user satellite and one deep-space earth station. A greater number of satellites would increase the probability of interference. It may be concluded that band sharing by deep-space research and links between user spacecraft and geostationary relay satellites is not feasible.

TABLE X - Interference from relay satellite link to deep-space earth station

<table>
<thead>
<tr>
<th>DRS user satellite</th>
<th>500.0</th>
<th>1000.0</th>
<th>km</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmitter power</td>
<td>10.0</td>
<td>10.0</td>
<td>dBW</td>
</tr>
<tr>
<td>Bandwidth conversion (300 Mbit/s, QPSK)</td>
<td>- 84.8</td>
<td>- 84.8</td>
<td>dB/Hz</td>
</tr>
<tr>
<td>Transmitting antenna gain</td>
<td>52.0</td>
<td>52.0</td>
<td>dBi</td>
</tr>
<tr>
<td>Off axis gain reduction</td>
<td>- 39.3</td>
<td>- 32.3</td>
<td>dB</td>
</tr>
<tr>
<td>Path loss (32.1 GHz)</td>
<td>- 184.7</td>
<td>- 190.2</td>
<td>dB</td>
</tr>
<tr>
<td>Earth station antenna gain</td>
<td>83.6</td>
<td>83.6</td>
<td>dBi</td>
</tr>
<tr>
<td>Received interference</td>
<td>- 163.2</td>
<td>- 161.7</td>
<td>dBW/Hz</td>
</tr>
<tr>
<td>Harmful interference criterion</td>
<td>- 217.3</td>
<td>- 217.3</td>
<td>dBW/Hz</td>
</tr>
<tr>
<td>Interference margin</td>
<td>- 54.1</td>
<td>- 55.6</td>
<td>dB</td>
</tr>
</tbody>
</table>

6. Discussion

The very high e.i.r.p. and extreme sensitivity of deep-space earth stations usually result in exceptionally large coordination areas.

Sharing with stations that are within line-of-sight (LOS) of deep-space earth stations is not feasible. Stations within LOS will create excessive interference to receivers of deep-space earth stations, or will be exposed to excessive interference from transmitters of these stations. Aeronautical mobile stations and near-Earth satellites frequently come within LOS of deep-space earth stations.

Sharing of deep-space Earth-to-space bands with stations utilizing high average e.i.r.p. is not feasible because of potential interference to stations in deep-space. It is currently considered that stations with an e.i.r.p. that is more than 30 dB below the implemented or planned e.i.r.p. for space research earth stations do not pose a significant problem. From the data in Report 536, this means an average e.i.r.p. no greater than 81 dBW at 2 GHz, and 84 dBW at 7 GHz. The deep-space earth station e.i.r.p. for other frequencies is not now known.
7. **Conclusion**

Criteria and considerations presented in this Report lead to the following conclusions.

7.1 **Sharing of Earth-to-space bands**

With coordination, deep-space research can share Earth-to-space bands with stations in other services except:

- receiving aeronautical mobile stations, receiving satellite stations, and microwave sensor satellites, when any of these may come within line-of-sight, and
- receiving mobile stations that may come within the separation distance required for interference protection, and
- transmitting terrestrial stations having an average e.i.r.p. exceeding 81 dBW in the 2 GHz region and 84 dBW in the 7 GHz region.

7.2 **Sharing of space-to-Earth bands**

With coordination, deep-space research can share space-to-Earth bands with stations in other services except:

- the radioastronomy service;
- transmitting aeronautical mobile stations, transmitting satellite stations and active microwave sensor satellites, when any of these may come within line-of-sight;
- transmitting mobile stations that may come within the separation distance required for the interference protection.

ANNEX I

**INTERFERENCE SUSCEPTIBILITY OF RECEIVING SYSTEMS FOR DEEP-SPACE RESEARCH**

1. **Introduction**

This Annex presents information on the interference susceptibility of receiving systems used for telecommunications associated with deep-space research. Two classes of interference are considered: CW and noise-like interference. The particular receiving systems that have been analyzed are those of the deep-space network (DSN) operated by the United States of America [Yuen, 1983].

The effects of interference on particular parts of a receiver have been examined in Reports 544 and 545 (Geneva, 1982). Report 544 discusses the effect of CW interference on a phase-locked loop. The analysis does not include a bandpass limiter ahead of the loop. Report 545 examines the effect of CW and noise-like interference on the error ratio of a maximum likelihood detector. It does not consider the effect of the interference on the preceding sub-carrier or carrier tracking loops, both of which influence the error ratio of the entire receiver. Although the two Reports provide some understanding of interference effects, they do not accurately characterize the susceptibility of a receiver typically used for deep-space telecommunications.

2. **The receiving system**

The receiving system includes four major elements, each of which must be protected from interference: the maser pre-amplifier, the carrier tracking loop, the telemetry sub-system, and the ranging sub-system. The interference susceptibility of each of these will be discussed in § 4 below. A simplified block diagram of the receiving system is shown in Fig. 5.

3. **Results of interference**

Interference can result in performance degradation, non-linear operation or loss of data. The effect of the interference depends on its strength and separation in frequency from the wanted signal.

At weak-to-moderate power levels, co-channel interference can increase the static phase error and phase jitter of the carrier tracking loop, increase the telemetry bit error ratio, or reduce the accuracy of the range estimate. This performance degradation can generally be expressed as an equivalent reduction in signal-to-noise ratio and can, in theory, be compensated by increasing the power level of the wanted signal. In practice, the power of the wanted signal is usually not adjustable.
FIGURE 5 – Simplified functional block diagram for a typical deep space network receiving system

TLM SS: telemetry sub-system
RNG SS: ranging sub-system
A: antenna
B: maser
C: pre-selector
D: carrier tracking loop
E: carrier demodulation
F: telemetry sub-carrier tracking loop
G: symbol synchronization and data detection
H: dual channel range code correlator
I: range computer
X: telemetry data stream
Y: range delay estimates

Strong interference having a large frequency separation from the wanted signal can result in a performance degradation and simultaneously drive one or more of the receiver components into a non-linear region, resulting in gain compression and the generation of harmonics, spurious signals, and intermodulation products. These non-linear effects are collectively referred to as saturation effects. Unlike performance degradation, saturation effects generally cannot be compensated even if the power level of the wanted signal is increased.

Strong interference having a small frequency separation from the wanted signal can cause the receiving system to lose lock or synchronization, resulting in a total loss of data.

4. Effects of CW interference

The specific interference effects are to be discussed in the following sub-sections for each of the four receiving sub-systems. Although the receiving system is most sensitive to co-channel interference, adjacent-channel interference and even out-of-band interference can sometimes cause detrimental effects. A co-channel interference is one whose frequency is in the passband of the sub-system. The frequency of the interference is assumed to be fixed unless specified otherwise.
4.1 RFI susceptibility of the maser pre-amplifier

The principal interference susceptibility of a maser is saturation (gain compression) by strong signals. The maser is most sensitive to interference that has a frequency in or near the maser passband, or the maser idler frequencies. Interference power that causes 1 dB maser gain compression is shown in Fig. 6 for a typical maser operating at the 8.4 GHz band. This curve is based on [Bautista and Petty, 1981; Hersey and Sue, 1980; Clauss, 1977].

![Figure 6](image_url)

**FIGURE 6 — Signal level required to reduce the gain of a 8.45 GHz maser by 1 dB, versus frequency**

RFI type: CW
A: maser signal bandpass

4.2 CW RFI susceptibility of the carrier tracking loop

The carrier tracking loop is a double heterodyne tracking loop which incorporates a synchronous-detector AGC (automatic gain control) loop and second-order phase-locked loop preceded by a bandpass limiter.

Strong interference can cause the loop to lose lock to the wanted signal, and the loop may lock to the interference [Klinger and Olenberger, 1976]. Both fixed frequency and sweeping (changing frequency) CW interference can result in this effect. If the interference is changing in frequency, the loop may first lose lock to the wanted signal and then lock to the interference as it moves close to the frequency of the wanted signal. As the interference moves through and away from that frequency, the loop then loses lock to the interference and may later re-lock to the wanted signal. The time it takes for the loop to re-lock to the wanted signal depends on the signal strength, the interference strength, and the sweep rate. It may vary from seconds to minutes. If the interference is fixed in frequency, re-locking to the wanted signal may never occur.

As a weaker level, interference can increase the static phase error and the phase jitter in the loop [Bruno, 1973; Blanchard, 1974; Levitt, 1979]. This is true for both fixed and sweeping interference.

Figure 7 shows peak jitter as a function of CW interference-to-carrier ratio.
4.3 **CW RFI susceptibility of the telemetry receiving sub-system**

Telemetry degradation can be expressed as an equivalent reduction in symbol energy-to-noise spectral density ratio \(E/N_0\) which is defined as the amount by which the symbol energy-to-noise spectral density ratio would have to be reduced in the case of no interference in order to obtain a symbol error ratio equal to that in the presence of interference.

The \(E/N_0\) ratio resulting from CW interference that is within the telemetry detection bandwidth is given in Fig. 8.

Telemetry performance can also be degraded by CW interference that falls within the carrier loop bandwidth. Figure 9 shows \(E/N_0\) ratio as a result of carrier loop phase jitter versus interference-to-carrier ratio, for a 10 Hz frequency offset and for a typical receiving mode operating at the 8.4 GHz band.
FIGURE 8 – Equivalent reduction in telemetering signal-to-noise ratio (E/N₀) as a result of interference in the telemetering channel, versus interference-to-signal ratio, for selected values of probability of symbol error.

RFI type: CW

P₀: probability of symbol error.

FIGURE 9 – Equivalent reduction in telemetering signal-to-noise ratio (E/N₀) as a result of carrier loop phase error and jitter, versus interference-to-carrier ratio.

RFI type: CW
Band: 8.45 GHz
Frequency offset: 10 Hz
4.4 CW RFI susceptibility of the ranging sub-system

Interference can degrade the performance of the ranging sub-system by increasing the variance of the range delay estimates. The degradation can be expressed in terms of an equivalent reduction in the effective ranging signal-to-noise ratio.

CW interference in the carrier tracking loop bandwidth affects the ranging system performance, as shown in Fig. 10. The effect of CW interference in the ranging signal bandwidth is shown in Fig. 11. The I/S ratio refers to the ratio of the interference power to the ranging-signal power.
FIGURE 11 – Equivalent reduction in ranging signal-to-noise ratio as a result of interference in ranging channel, versus interference-to-signal ratio

RFI type: CW
5. Effects of noise-like interference

Noise-like interference can saturate the maser pre-amplifier and can degrade the performance of the carrier tracking loop, the telemetry sub-system, and the ranging sub-system. To cause a maser gain compression of 1 dB, the spectral density of the noise-like interference, $I_0$, would have to be $-190$ dB(W/Hz), assuming a maser bandwidth of 40 MHz.

For the carrier tracking loop, the peak phase jitter depends on the carrier margin (Fig. 12). Noise-like interference reduces the carrier margin and hence increases the phase jitter. The carrier margin is related to $I_0/N_0$ by the expression:

$$CM_{RFI} = CM + 10 \log \left( \frac{1}{1 + \frac{I_0}{N_0}} \right)$$

where:

- $CM_{RFI}$: carrier margin in the presence of interference;
- $CM$: margin without interference; and
- $I_0/N_0$: interference-to-noise spectral density ratio.

Given a particular carrier margin without interference, and the acceptable increase in phase jitter, Fig. 12 and the foregoing expression allow the $I_0/N_0$ to be calculated. For example, at a typical margin of 10 dB, an increase of 10° in peak-phase jitter will be caused by interference that reduces the margin to 5.5 dB. The $I_0/N_0$ for this circumstance is 2.3 dB.

---

**FIGURE 12 – Peak phase jitter versus carrier margin**
The effect of a noise-like interference on the telemetry and ranging sub-systems is to reduce the effective symbol energy-to-noise spectral density ratio and thereby increase the telemetry error ratio and the range delay estimate variance.

The reduction in equivalent symbol energy-to-noise spectral density ratio, $E/N_0$, can be expressed as:

$$E/N_0 = 10 \log (1 + I_q/N_0)$$

(5)

where $I_q/N_0$ is the interference spectral density-to-noise spectral density ratio. Knowing the acceptable $E/N_0$ ratio, the corresponding $I_q/N_0$ may be calculated.

6. Conclusion

The susceptibility of a receiving system for deep-space telecommunications has been presented for two kinds of interference, CW and noise-like. Although interference with other spectral characteristics may be encountered, experience has shown that the effects of these two kinds of interference may be used in the determination of criteria needed to ensure protection from harmful interference.

Information in this Annex I is primarily concerned with earth-station receivers. Similar interference effects can be expected for the carrier tracking, command, and ranging functions of a corresponding space station receiver. Numerical values and curves will differ because of differing system noise temperature, the absence of a maser, and different bandwidths.

REFERENCES


BIBLIOGRAPHY


SUE, M. K. [1982] Performance degradation of the block IV telemetry system due to the presence of a CW interference. TDA Progress Report 42-69. Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA.
REPORT 456-3

PREFERRED FREQUENCY BANDS FOR SPACECRAFT TRANSMITTERS
USED AS BEACONS

(Question 10/2)


1. Introduction

Beacon transmitters on satellites are used for scientific experiments and also for several applications in which space techniques are used. The present Report is concerned with beacons used for studies of the atmosphere. Other applications of beacons to geodesy and geodynamics are described in Report 988.

The frequency bands at present allocated to the Space Research Service have been used mainly to satisfy the necessity for receiving telemetered scientific and technological data from spacecraft, and for controlling their movements and condition. Radio transmissions between satellites and the Earth are also used for research into the

* This Report should be brought to the attention of Study Groups 5 and 6.
behaviour of the radio waves themselves rather than the information which they carry as communication links. Some of these activities are described below under four headings. The first three are closely linked in that they depend upon the influence of the ionized and non-ionized regions of the atmosphere on the radio waves. It is convenient to consider them separately because the objectives and frequency requirements are somewhat different.

The first type of study is referred to as radio propagation, its objectives being to determine how waves travel between two points, one of which is on a spacecraft. The second is ionospheric research, with the main objective of determining the characteristics of the ionosphere as a physical medium. The third is research on propagation through the atmosphere, with the objective of determining the propagation characteristics of the atmosphere (ionospheric research, *per se*, is performed within the Meteorological Service). It will be apparent that radio propagation studies will often yield information on the atmosphere, and conversely, atmospheric research will help in the understanding of propagation mechanisms. However, the research discussed here is based on special techniques which have rather specific frequency requirements.

The fourth category of research, the study of orbits, is based on techniques related to those of the other categories; but the atmosphere is a disturbing influence, and frequencies need to be chosen to minimize its effects.

2. Radio propagation

At frequencies mainly in the decametric range, long range propagation between ground stations and satellites of low altitude has been observed up to antipodal distances. It is generally assumed that ducting inside the ionosphere is the important mechanism [Chvojková, 1965]. However, detailed information is lacking and important features such as the exit paths from the duct, leakage, and attenuation need further study. A study of the ducting mechanism is of interest not only for communication with satellites, but also for efficient long distance communication on the Earth by mechanisms without repeated ionospheric and ground reflections. It is therefore, important that suitable experiments be made over a sufficiently long time scale and over a large geographical area. Transmission from a satellite on a suitable selection of frequencies is the best way to allow a great number of earth stations to participate.

As the phenomenon depends in a critical way on ionospheric refraction, a series of frequencies must be used, which extend over a large part of the high-frequency range, say 2 to 20 MHz, taking into account the variations of ionospheric electron density with hour, solar cycle, season and geographical position. The range from about 2 to 5 MHz is suitable for rather low satellite altitudes and for high geomagnetic latitudes, while the higher frequencies are preferable for low latitudes and for the study of very long range propagation.

The requirements have been partially met by secondary allocations to space research at 15.76 and 18.03 MHz and in the standard frequency bands at 2.5, 5, 10, 15, 20 and 25 MHz. It should be noted that the practice of radiating standard-frequency signals at frequencies which are staggered within the allocated bands, may lead to increased interference to space research. It is expected that the propagation problems described above, and similar problems, will be a subject of interest to scientists for many years.

As it becomes increasingly necessary to utilize frequencies above 10 GHz, propagation characteristics in the lower atmosphere become an additional important mechanism needing further study. Propagation effects at millimetre wavelengths can be more severe than at longer wavelengths. These are particularly due to precipitation and to oxygen and water vapour absorption. Several experiments and many theoretical analyses have been conducted on the effects of the atmosphere on radio waves, with varying objectives. Such work can be conveniently considered as beacon-related, and accordingly, is discussed as part of this Report.

3. Ionospheric research

Ionospheric beacon satellites transmitting at harmonically related frequencies have proved to be powerful tools for the investigation of ionospheric electron content; in particular, that of the outer ionosphere. As they can be used by many earth stations simultaneously, the information obtained by the relevant techniques provides complementary data to that obtained with top-side sounders. Two techniques have given most useful results.

Observation of the *differential Doppler-effect* at two harmonically related frequencies allows separate identification of the modification of waves due to the refractive effect of the ionospheric plasma. Moreover, with a simple electronic device the rather small plasma effect can be directly recorded to a high accuracy [Rawer, 1964; Rawer and Suchy, 1967].
A second technique is the observation of the Faraday rotation of waves transmitted through the ionosphere. The Faraday rotation of the plane of polarization is caused by double refraction in the ionospheric plasma situated in a magnetic field. It is possible to apply this technique in the frequency range of 100 to about 1000 MHz, by for example, observing the beacon signals with elaborate equipment which measures the polarization angles to a high degree of accuracy. However, most observations have been made by simpler techniques at lower frequencies, and there will be a continuing need for this type of measurement at many stations all over the world. It should also be mentioned that these observations give, as a side-product, much valuable information concerning the ionospheric propagation phenomenon of scintillation [Aarons et al., 1961; Rawer, 1962]. For evaluation of the electron content these techniques are based on a count of the number of rotations of the plane of polarization. If this number is large, as is the case with frequencies below 100 MHz, changes of the ionospheric electron content can be determined accurately with simple recording of the output of a receiver. However, with only one transmitted frequency in this lower range, the total number of rotations, and hence the total electron content of the ionosphere, cannot be determined absolutely. The addition of a second frequency, differing from the first by only a small per cent, permits the observation of the differential Faraday effect. The total number of rotations is then determined by comparing two time-series of nulls and their relative phases. The fractional frequency difference determines the scale-factor relating the total number of rotations to the number of nulls [Rawer, 1964; Rawer and Suchy, 1967]. In typical ionospheric observations a scale-factor of the order of 30 to 100 is convenient; two frequencies differing by 1 to 3% are therefore technically suitable.

Frequencies usable for both techniques should be high enough to penetrate the ionosphere, but low enough to give appreciable ionospheric refraction effects. In view of the large variations of ionospheric electron density, a satisfactory set of frequencies could be in the range of 15 to 60 MHz. One higher frequency is desirable to provide a phase reference with small refraction effects. Thus a technically suitable series of frequencies for measurements at HF and VHF is:

- three harmonically related frequencies for differential Doppler observations, the two lower ones between 15 and 60 MHz, and one other between 80 and 200 MHz,
- one additional frequency, differing by a few per cent from that of the second of the above frequencies, for differential Faraday observations.

The allocations at 20 and 40 MHz partially meet these requirements. It would be feasible for the highest frequency of the series to be in the space research band just above 400 MHz, but a lower frequency would be preferable. A frequency of 41 MHz has been used with 40 MHz on a non-interference basis for the Faraday rotation work, but there has been no protection at this frequency for these measurements.

Similar techniques are also used in some experiments using rockets. Frequencies of the order of 1 MHz, for example, are suitable for the study of the lower regions of the ionosphere using Faraday rotation. The D region can be explored by measuring the fields in the ionosphere from a low-frequency transmitter on the ground.

4. Research on the non-ionized atmosphere

Some experimental data have been obtained, and extensive theoretical modelling has been done on the efficiency of the atmosphere as a transmission medium for radio waves at frequencies above 10 GHz. The experimental efforts to date, have been at frequencies below 40 GHz. Results have indicated that precipitation in the atmosphere severely degrades transmission, but that by careful selection of earth station sites and orbits, and use of such techniques as site diversity, reliable communication systems may be feasible.

Above 40 GHz, theoretical models have indicated that oxygen absorption becomes the controlling factor in atmospheric transmission, and that attenuation characteristics rapidly increase with frequency. However, the characteristic curves indicate that in certain frequency bands, for example, around 90 GHz and 150 GHz, attenuation may be lower than at neighbouring frequencies.

Accordingly, a technically suitable set of frequencies for conducting atmospheric research is as follows (see Report 205):

- 15 to 20 GHz range
- 30 GHz
- 90 GHz
- 150 GHz.
5. The feasibility of frequency sharing

As far as protection of the frequencies used for space research is concerned, it is shown in the Annex that in many cases, particularly over great distances, the possibility of carrying out measurements is already severely limited by the natural noise level. An increase of the effective noise level by other transmissions would, therefore, lead to intolerable interference. Experiments made at several frequencies indicate that the sharing of these frequencies reduces the measuring possibilities of beacon transmissions to a minimum. Therefore, it must be stated that:

- sharing of beacon frequencies by other services has introduced serious difficulties to the space research service;
- the protection ratios should correspond to those already specified for the reception of telemetering transmissions in space research (Recommendation 364).

6. Conclusion

A continuing need, for many years, is envisaged for space research experiments involving Doppler and Faraday rotation techniques, for measurement of atmospheric transmission characteristics above 10 GHz. Existing allocations in the standard frequency bands from 2.5 to 25 MHz will fulfil some of the need if they prove to be usable without harmful interference. Frequencies below 2 MHz are suitable for some types of experiments but no common requirement on a continuing basis is apparent.

For Doppler measurements an additional frequency is required which is harmonically related to 20 MHz, preferably by a simple multiple, and in the range of 80 to 200 MHz. Faraday measurements can be made with elaborate equipment at frequencies greater than 100 MHz, for example those radiated for tracking purposes, but some of the simpler and more widely used techniques require two VHF transmissions differing by 1 to 3%. In many cases, some frequencies can be common to both Doppler and Faraday measurements.

For atmospheric measurements below 40 GHz, there is a continuing need for frequencies near 15, 20 and 30 GHz. Above 40 GHz it appears frequencies will be needed near 90 and 150 GHz.

The transmissions used in Doppler and Faraday rotation experiments can be accommodated in bandwidths of the order of 0.02% of the frequency.

REFERENCES AND BIBLIOGRAPHY


ANNEX I

SIGNAL STRENGTH AND NOISE CONSIDERATIONS IN BEACON SATELLITE EXPERIMENTS

1. Field strength and Faraday rotation measurements

Field strength observations, mainly as regards the Faraday effect, are made for a relatively large receiving bandwidth of about 3 kHz, on frequencies of about 40 and 41 MHz, which are normally used by most observing stations to obtain reliable amplitude values in spite of the Doppler effect. Although automatic tuning would permit the bandwidth to be reduced considerably, it would require extensive technical expense if locking were to be maintained continuously, even during the deep fading minima.

The different types of application call for varying degrees of protection (signal-to-noise ratio) which depend on the particular measuring parameter to be determined. Experience gained from a long series of measurements indicates that the following values are desirable for the signal-to-noise ratio (relative to the median value of the wanted signal field strength):

- observations of the Faraday effect for determining the electron content: 10 dB;
- observations of ionospheric scintillations: 20 dB;
- observations of the differential absorption from the ratio of the maximum to the minimum value of the Faraday effect: 30 dB.
The use of directional antennas is not feasible for the majority of scientific observation stations, so that, for these stations, a value of 0 dB must be assumed for the gain of the receiving antenna.

As the number of observation stations is large it would not be possible to use directional antennas except on board geostationary satellites. However, even in the case of these satellites, the technical expense of installing directional antennas is prohibitive because of the relatively low frequencies involved. Given the foregoing, and given also the fact that the satellite transmitter power lies between 10 and 50 mW, the range of field strengths shown in the following table can be expected on the ground:

<table>
<thead>
<tr>
<th>Distance from satellite (km)</th>
<th>Transmitter power (mW)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>50</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>1 000</td>
<td>2</td>
</tr>
<tr>
<td>10 000</td>
<td>-18</td>
</tr>
<tr>
<td>40 000</td>
<td>-30</td>
</tr>
</tbody>
</table>

Taking into account the unavoidable cosmic noise, which is, for example, $-18 \, \text{dB(\mu V/m)}$, in a bandwidth of 3 kHz at 40 MHz, these field strength values will frequently not allow the required signal-to-noise ratios to be achieved.

For the small number of better-equipped observation stations, a considerable reduction in noise level can be achieved with the aid of phase-locked frequency tracking (with a separate field-strength recording channel), but the bandwidth must not be less than 30 Hz if rapid variations of field strength are to be reproduced correctly. Compared with a 3 kHz bandwidth, this means an improvement of 20 dB. However, the observation of differential absorption, requiring a protection ratio of 30 dB is of particular interest for these stations, and, for this application, the limits of reception capabilities are reached with respect to cosmic noise, even when using the phase-lock technique, although at greater distances.

Within a few years, new types of application will emerge for beacon techniques at very large planetary distances (greater than 1 astronomical unit). Distances twice as great as that between the Earth and the Sun will be covered by space probes. The same situation will, therefore, still prevail even if much more elaborate systems are in use.

2. Phase measurements

Phase observations, especially by means of the differential Doppler effect, are made both during rocket flight and in satellite operation. While observations of the first type can usually be arranged on a non-interference basis, the observation of satellites requires that many terrestrial receiving stations have the relevant frequencies free of interference.

In the case of the differential Doppler technique, the same receiving antenna is preferably used for both frequencies to minimize direction-dependent phase errors. In any case, non-directional antennas are needed; that is, the gain of the receiving antenna must be assumed to be zero.

The differential Doppler system in itself has a very small bandwidth. This bandwidth should, however, not be too small if rapid changes due to ionospheric irregularities are still to be detectable.

Here, too, such applications are envisaged in planetary missions of space probes (see above).

3. Conclusions

It is pointed out that, even with the present application of beacon satellites, natural noise occasionally limits measuring possibilities. Such limitations will occur even more frequently in envisaged future applications over very large (planetary) distances.
SECTION 2F: EARTH EXPLORATION SATELLITES

REPORT 535-4

TECHNICAL AND OPERATIONAL CONSIDERATIONS FOR THE EARTH EXPLORATION-SATELLITE SERVICE

(Question 12/2)


1. Introduction

The World Administrative Radio Conference (Geneva, 1979) defined the Earth exploration-satellite service as follows: A radiocommunication service between earth stations and one or more space stations, which may include links between space stations, in which:

- information relating to the characteristics of the Earth and its natural phenomena is obtained from active sensors or passive sensors on earth satellites;
- similar information is collected from air-borne or earth-based platforms;
- such information may be distributed to earth stations within the system concerned;
- platform interrogation may be included.

This service may also include feeder links necessary for its operation.

This Report discusses some of the technical and operational parameters of earth resources and earth observation systems which operate within the earth exploration satellite service; it is based upon the characteristics of systems implemented or under study in the United States, Europe, Japan and Canada.

Other technical and operational aspects are discussed in the following reports:

- distribution of data to earth stations: Report 692
- active and passive microwave sensors: Report 693
- meteorological satellite systems: Report 395
- satellite location and data collection systems: Report 538
- satellite systems for geodesy and geodynamics: Report 988.
2. **Earth exploration satellites**

Earth exploration information can currently be categorized according to the following headings:

- agriculture and forestry,
- hydrology and water resources,
- geology and mineral resources,
- geodesy and geodynamics,
- geography and cartography,
- oceanography,
- environmental quality.

Although all of these represent well established disciplines, it is generally recognized that their full potential has not yet been reached. One of the reasons for this has been the lack of technology enabling scientists to acquire data from sufficiently broad regions of the Earth. As satellites offer this capability, they will play an important role in the future. The main advantages offered by satellites are the synoptic view and repetitive coverage of the Earth’s surface. Other advantages include the acquisition of real-time or near real-time data, the use of uniform equipment and methods of calibration and measurements, and the possible reduction in costs of data gathering.

It should be noted that the basic objective of earth exploration satellite systems is the extraction of information for improved decision making in resource and environmental management and not data collection as such. To accomplish this, spacecraft, aircraft and ground systems must play complementary roles. Other important features of an earth exploration system are automated information extraction, the development and utilization of models of the environment and its resources, models with built-in decision capability which can make effective use of data collected by satellite and aircraft.

The technical characteristics of the systems discussed in this Report are only to be considered representative of earth exploration satellites now existing or envisaged in the United States of America, Europe, Japan and Canada.

3. **Present and near future Earth exploration systems**

3.1 **Earth exploration systems**

Earth exploration-satellite systems developed and being considered by the United States of America are discussed in Annexes I and II to this Report. The low-orbit systems comprise the two experimental satellites Landsat-1 and Landsat-2, launched respectively in 1972 and 1975, and Landsat-3 launched in 1977. The operational versions of these Earth resources satellites began with the launches of Landsat-D in 1982 and Landsat-D’ in 1984.

France launched the SPOT-1 Earth observation satellite in 1986. Japan’s first earth observation satellite (MOS-1) was launched in 1987. Japan intends to launch MOS-1b as the successor of MOS-1 in 1990. The European Space Agency is presently designing its remote sensing satellite ERS-1 which will be essentially devoted to ocean and coastal zone observation using active and passive sensors; the target launch date is late 1990. Canada is planning to place an Earth exploration satellite (RADARSAT) in orbit in 1994. Japan is also planning to launch the Japanese Earth Resources Satellite-1 (JERS-1) in 1992.
Most of these future satellites are designed to supply local direct and playback read-out of sensor data and may also be capable of forwarding information to earth stations via geostationary data relay satellites (see Report 982).

SPOT, MOS-1, ERS-1, RADARSAT and JERS-1 are described in Annexes III, IV, V, VI and VII.

3.2 Spectrum considerations for Earth exploration-satellite systems

Earth exploration-satellite systems comprise passive and active sensors sometimes accommodated on board a common space platform. Both use large bandwidths which may occupy several hundreds of megahertz in the case of spaceborne altimeters.

Earth exploration satellites are also characterized by the very high data rates generated by many of their sensors. Typical parameters for the different types of sensor are given in Table I. Projections by Earth resource scientists indicate that it may ultimately be necessary to implement sensors with data rates of up to 600 Mbit/s.

### TABLE I — Typical sensors and parameters for Earth exploration satellites

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Swath width (km)</th>
<th>Resolution</th>
<th>Data rate (bit/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multi-spectral scanners</td>
<td>185</td>
<td>83 m</td>
<td>$15 \times 10^6$</td>
</tr>
<tr>
<td>High resolution pointable imager</td>
<td>48</td>
<td>10 m</td>
<td>$1.2 \times 10^8$</td>
</tr>
<tr>
<td>Visible and infra-red radiometers</td>
<td>2870</td>
<td>2 km</td>
<td>$3.3 \times 10^6$</td>
</tr>
<tr>
<td>Radar scatterometer</td>
<td>500</td>
<td>25 km</td>
<td>$6 \times 10^4$</td>
</tr>
<tr>
<td>Microwave radiometer</td>
<td>1350</td>
<td>10-25 km</td>
<td>$5 \times 10^3$</td>
</tr>
<tr>
<td>Synthetic aperture radar</td>
<td>200</td>
<td>25 m</td>
<td>$2 \times 10^8$</td>
</tr>
<tr>
<td>Radar altimeter</td>
<td>2</td>
<td>5 cm (¹)</td>
<td>$12 \times 10^3$</td>
</tr>
</tbody>
</table>

(¹) Vertical resolution.

In addition, the need to acquire sensor information on Earth by low-cost user data acquisition facilities involves concepts requiring high power flux-densities.

3.2.1 Passive sensors

Passive sensors obtain data on surface or atmospheric phenomena by reception of either emitted or reflected energy. Initially, passive sensing was accomplished at visible and infra-red wavelengths. More recent research and experiments have indicated that passive sensing is effective in the microwave region. One significant advantage of microwave sensors is that the longer wavelengths are much less affected by clouds and precipitation, and can be used to determine brightness temperatures to within 1° in overcast conditions.

Passive earth exploration sensors may utilize bands allocated for radioastronomy and/or for space research (passive). However, it has been found that for certain functions the optimum frequency for a passive sensor does not coincide with allocations for these services. Therefore, studies have been undertaken on the feasibility of sharing frequency bands between passive sensors and services other than radioastronomy and space research (passive). Frequency of operation and bandwidth requirements of passive sensors currently under development are described in Report 693.
3.2.2 Active sensors

Active microwave sensors have two features not found in passive microwave sensors. These are:

- topographic features of land and sea surface can be determined, and
- greater spatial resolutions can be obtained by utilizing a synthetic aperture radar.

As examples of the first feature, petroleum exploration and mineral deposit mapping are two applications for which the capability of active microwave sensors to penetrate surface vegetation could be extremely valuable.

As for the second feature, the resolution expected from the best passive microwave imaging radiometer is of the order of 1 km, while the synthetic aperture radar carried on Seasat had a resolution capability of 25 m.

The capabilities of active microwave sensors have been demonstrated at frequencies ranging from 1.4 GHz to above 30 GHz.

Report 695 shows that frequency bands allocated to the radiolocation service may be shared with active microwave sensors without harmful interference to either the radiolocation service or to the active sensor. This result is reflected in Recommendation 516. Design frequencies and bandwidths of active sensors currently under development and a set of preferred frequencies are contained in Report 693.

3.2.3 Power flux-densities for data communications

Power flux-density limits which are at present in effect may restrict the applications planned for earth exploration satellites. Specifically:

- small, low cost data acquisition facilities are an integral part of the designs of several earth exploration satellite systems. These terminals will be used in order to provide real-time data delivery to the user community. The primary design constraint for these terminals is economic. Costs must be held to a minimum in order to make the facility available to a maximum number of users. Accordingly small antennas must be used for those terminals with a consequent requirement for high power flux-density;

- for certain geometries, a link from an Earth exploration satellite to a tracking and data relay satellite may also require power flux-densities which exceed the currently prescribed limits.

As low orbit satellites provide an inherent method for time sharing, and as studies show that sharing may be feasible between services even with higher power flux-densities, it may be desirable to increase the power flux-densities permitted in the bands to be used by Earth exploration satellites.

3.2.4 Techniques for data communications

3.2.4.1 Transmission modes and data rates

The data will be transmitted from many of the planned satellites to the Earth via three modes:

- direct real-time and playback read-out to major data acquisition facilities;
- direct real-time and playback read-out to local users having lesser data acquisition facilities; and
- through geostationary data relay satellites which will provide a continuous real-time data read-out capability.

The high data rate requirements of existing and planned Earth exploration-satellite programmes (described in the Annexes to this Report) have led to the need to use the 8025 to 8400 MHz frequency band for space-to-Earth links. The LANDSAT programme and future Earth exploration satellites of the United States of America also use the 14.4 to 15.35 GHz frequency band to transmit high rate data through the tracking and data relay satellite (TDRS).

The earth station configuration, together with the high data rates, the expected number of Earth exploration satellites and the characteristics of the atmosphere, should be considered when selecting appropriate regions of the spectrum for the spacecraft-to-Earth data link. It should be noted that actual transmission rate requirements will depend upon the degree of development in the techniques of on-board information extraction.
3.2.4.2 Bandwidth compression

In a data acquisition link for an Earth exploration satellite, the principal requirement for a wide frequency bandwidth is the transmission of two- and three-dimensional observation image data. A number of studies have been made on bandwidth compression techniques with regard to image transmission. Two approaches are possible to reduce the bandwidth required for transmission of earth resource data:
- data compression;
- new modulation techniques.

Application of these techniques can assist in accommodating the very high data rates expected from future Earth exploration sensors.

a) Data compression

Data compression (or source encoding) may play a significant future role in each step of the data acquisition and dissemination chain. The data rate required for transmission to the ground can be reduced by using statistical properties of the image data.

The practicability of applying data compression techniques to earth resource data will depend on a number of factors, including:
- mean squared errors between original and compressed/reconstructed scenes;
- effect on classification accuracy;
- hardware implementation requirements;
- computational requirements;
- subjective image quality.

For geostationary Earth exploration satellites, the transmission rate of image data could be reduced by using the technique of slow scanning or inter-frame coding which is used in data compression of colour television signal transmission [Iijima et al., 1975]. However, a very large spacecraft memory would be required.

b) Modulation techniques

Bandwidth compression can be obtained by the appropriate choice of a modulation system for transmitting the signal. For example, the use of a four-phase PSK modulation system, as in the Landsat-D thematic mapper and SPOT high-resolution visible data, reduces the required bandwidth by a factor of about two in comparison with two-phase modulation systems [Chakraborty, 1975].

REFERENCES


ANNEX I

LANDSAT PROGRAMME

1. Landsat-1, Landsat-2 and Landsat-3

The United States LANDSAT-1, LANDSAT-2, and LANDSAT-3 satellite programme (formerly known as the Earth Resource Technology Satellite) designated as a research and development tool to demonstrate that remote sensing from space is a feasible and practical approach to efficient management of the resources of the Earth. The knowledge gained from the application of data acquired by the three satellites has pointed the way towards development of fully operational and more effective systems for earth resources management. Landsat-1 (launched in 1972), Landsat-2 (launched in 1975), and Landsat-3 (launched in 1977) are no longer operating.
2. LANDSAT follow-on programme

The United States LANDSAT follow-on programme (formerly known as the Earth Observatory Satellite) is intended to continue the research initiated by the LANDSAT-1, LANDSAT-2, and LANDSAT-3 series. Landsat-D and Landsat-D' were launched in 1982 and 1984 respectively. The objectives of the programme are, firstly, to define advanced remote sensing instrumentation, Earth observation systems and missions required for:

- surveying and monitoring of Earth's resources;
- identification and monitoring of surface and atmospheric pollutants;
- understanding the physical behaviour of the oceans, water/atmosphere interaction and coastal processes;

and secondly, to support requirements of user organizations by providing data on these topics.

2.1 Initial mission payloads

The initial mission in the LANDSAT follow-on programme has application to the disciplines of earth resources survey and pollution measurement. Sensors include a six-channel thematic mapper (TM) scanning a 185 km swath with 30 m resolution, and a five-channel multi-spectral scanner. Coverage of the Earth survey function is real-time, direct data transmission only, with no on-board recording capability.

2.2 Orbit considerations and attitude control

Systematic, repetitive Earth coverage is required to maximize the utility of the multi-spectral images collected by the different sensors. The nominal LANDSAT orbit is circular, Sun-synchronous, and near-polar at an altitude of 705 km. The orbital period is 99 min, resulting in an entire Earth scan every 16 days.

During normal operation, the attitude control sub-system (ACS) is capable of pointing the observatory continuously to the Earth's centroid to an accuracy of better than 0.01°. Attitude perturbation is less than 2 s and the rate of attitude drift is less than $2 \times 10^{-6}$ degrees/s.

2.3 High-data-rate communications

LANDSAT follow-on satellites contain the thematic mapper (TM) and the multi-spectral scanner (MSS) sensors and produce a composite data rate of approximately 84 Mbit/s.

Three wideband data communications links are:

- the primary wideband data link to the ground is via the TDRS. The composite data at 84 Mbit/s are transmitted to the TDRS on a frequency of 15.0034 GHz;
- the 84 Mbit/s TM data are transmitted directly to Earth at a frequency of 8215.5 MHz. Quadriphase modulation is utilized with a resultant bandwidth of approximately 100 MHz. A wide-angle spacecraft antenna designed to produce maximum gain in the direction of maximum slant range is used to maximize data acquisition by participating earth stations;
- MSS data are transmitted directly to Earth at a rate of 15 Mbit/s. This sub-system operates in band 9 and is identical to the wideband telemetering sub-system utilized on Landsat-1, Landsat-2 and Landsat-3. This data link is included in the LANDSAT follow-on programme in order to provide continuity of data for existing earth stations that are currently acquiring MSS data from Landsat.

2.4 Communications and data handling (CDH) sub-system

The CDH sub-system provides means for ground and on-board control of all spacecraft and instrument functions and for retrieval of low-rate telemetry data. This sub-system contains communication equipment composed of the RF transmitters and receivers, and data handling equipment composed of a command group, a telemetry group, and an on-board computer.

For more detailed information, see Annexes I and II to Report 535 (Geneva, 1982).

ANNEX II

SEASAT PROGRAMME

The primary objective of the SEASAT programme was to determine the applicability of satellite-borne remote sensing techniques to oceanographic problems. The Seasat spacecraft was launched in 1978 into a near-polar orbit. It circled the Earth 14 times daily collecting data from 95% of the Earth’s oceans every 36 h. Although planned for a year’s flight, a catastrophic failure occurred in the satellite power sub-system which resulted in communications with the satellite being terminated after three months of its operation. However, a thorough evaluation of all the data acquired during the mission has met virtually all the programme objectives and, in particular, the concept of microwave measurements of oceanographic features has been demonstrated.
The Seasat spacecraft was the first major step in developing and demonstrating a global ocean dynamics monitoring system using relevant measurement techniques from a space platform. It carried an experimental instrumentation payload intended to validate concepts for monitoring and measuring ocean features, in particular for predicting general ocean circulation, for synoptic monitoring and the predicting of transient surface phenomena. The objectives also included measurements of the geoid, earthquake damage monitoring, charting ice fields, and measuring precise sea-surface topography as well as the global monitoring of wave height, surface wind speed and direction, ocean current patterns and ocean surface temperature.

The satellite instrument complement included three active sensors: a radar altimeter, a wind field scatterometer and a synthetic aperture radar, all of which normally operated full-time over the ocean and were switched off over land. A scanning radiometer operated in the visible and infra-red regions of the spectrum.

The spacecraft was placed into a nearly circular orbit at an altitude of approximately 800 km. The orbit was inclined 108° to the equator with a period of 6045 s, resulting in about 14 1/3 revolutions per day. The orbit was not Sun-synchronous and was designed to precess during a day/night cycle in approximately 3.5 to 5.5 months.

The Seasat spacecraft control, tracking and data transmission complement included a receiver and four transmitters. The dual redundant receiver operated in band 9. Two of the transmitters, although used for tracking, were primarily utilized for data transmission. The wideband data transmitter required a 20 MHz bandwidth in band 9 for the data stream from the synthetic aperture radar. The narrow-band data transmitter required a 5 MHz bandwidth in band 9. Real-time or recorded data from the other sensors were transmitted over this link.

Two other transmitters operated in band 8 and band 9 and transmitted stable signals containing no modulation. The signals from these transmitters were used for range-rate tracking measurements. The use of two separate frequencies permits compensation for ionospheric effects.

The radar altimeter operated in band 10 and transmitted peak power of 2.5 kW. The scatterometer operated in band 10, separated by about 1000 MHz from the radar altimeter, with 100 W peak power. The synthetic aperture radar operated in the middle of band 9 with a peak power of 800 W.

The normal mode of operation for the radar altimeter and scatterometer was only over seas. Illumination of any one spot on Earth would occur a maximum of 2.4 s per day and 2 min per day for the altimeter and scatterometer respectively.

The illumination of any one spot on Earth from the synthetic aperture radar occurred a maximum of 2 s per day.

For more detailed information, see Annex III to Report 535 (Geneva, 1982).

ANNEX III

SPOT PROGRAMME

1. Introduction

The SPOT-1 satellite is the first of a generation of Earth observation satellites that France brought into operation in 1986. The main objective of this first satellite is to establish, store and make available a high-resolution, remote-sensing data base for a large part of the world, in order to:

- study soil utilization and the evolution of the environment;
- evaluate renewable natural resources (agriculture-forests);
- contribute to the exploration of mineral resources;
- carry out medium-scale (1/100 000) mapping, revise maps having scales of about 1/50 000, and prepare new types of maps.
Two sensors operating in the visible portion of the spectrum, have been designed to attain these specific objectives:

- a 3-channel multiband sensor, (0.5-0.59 μm, 0.61-0.68 μm, 0.79-0.89 μm),
- a high resolution panchromatic sensor. (0.51-0.73 μm).

Two identical picture-taking instruments are equipped with these two sensors, each instrument being capable of taking multiband and panchromatic pictures independently of the other. These HRV (High Resolution Visible) instruments are mounted on a platform designed not only for the initial mission but also for future missions.

Two satellites (SPOT-2 and 3) having identical characteristics as SPOT 1 are scheduled to succeed SPOT-1. France is preparing a second generation of Earth observation satellites, the first of which (SPOT-4) should be launched in 1992.

2. Satellite and orbit characteristics

The spacecraft is so designed that the payload constitutes an independent entity, with the result that the platform design can be re-used for future missions. In addition, the general structure of the spacecraft is modular, thus providing a certain flexibility of use.

SPOT-1 is in a circular Sun-synchronous near-polar orbit at a nominal altitude of 822 km and circles the Earth in 101.3 min, completing an entire Earth scan every 26 days. Moreover, the HRV instruments are equipped with a device enabling them to observe the Earth's surface on either side of the local vertical in a plane perpendicular to the absolute velocity vector of the satellite. The repetition of observations over a selected area can thus be increased considerably. For example, the lateral boresight device makes it possible to observe the same equatorial Earth zone 8 times in 26 days.

3. Communications and data handling system

A system of communications and data handling provides for all the flow of information between the spacecraft and the earth stations. It comprises three separate sub-systems:

- localization, telecommand and telemetering: a platform sub-system;
- wideband telemetering: a payload sub-system;
- wideband video tape recorders: another payload sub-system.

3.1 Telemetering, telecommand and tracking sub-system

This sub-system collects telemetering maintenance data from the spacecraft and transmits them to the earth stations. It retransmits tracking data and receives orders from the earth stations which it executes on board the spacecraft.

The telemetering maintenance data are PCM signals, NRZ-M coded, with biphase modulation of the carrier. The data are transmitted in the band 2200-2290 MHz at 2048 bit/s.

The telecommand orders are PCM signals, coded in NRZ-L or M, also with biphase modulation of a carrier. They are transmitted in the band 2025-2110 MHz at 2 kbit/s.

Tracking is effected:
- by two-way range measurements, obtained by measuring phase differences on sinusoidal modulations, allowing for sequential sense finding;
- or by range-rate measurement as between the transmitted frequency and the received frequency after an earth station-spacecraft round trip;
- or by a combination of both types of measurement in accordance with orbit recovery requirements.

3.2 Wideband telemetering

The wideband telemetering sub-system receives and processes data supplied by the two HRV instruments or by the two wideband video tape recorders. This sub-system consists of a transmitter with a power of 20 W operating in the band 8025-8400 MHz. It allows for the simultaneous transmission of data coming from the HRV instruments, either directly or via the recorder in the replay mode. When one of the two instruments is not operating, the missing data are replaced by a pseudo-random code without any particular significance.
Each information channel associated with an HRV instrument consists of a PCM signal, NRZ-L coded, and transformed by Gray differential coding. The bit rate per channel is 25 Mbit/s. The two channels are multiplexed, so that the data transmission rate is 50 Mbit/s. After multiplexing, the data are either recorded or transmitted to earth. The data are transmitted to earth by quadruphase modulation of a carrier.

The transmitting antenna diagram is shaped so as to compensate for the dynamic range of the signal between 5° and 90° elevation as far as possible.

3.3 Wideband video tape recording

Two wideband video tape instruments record and reproduce the data coming from the two sensors. When working, one of the recorders is always in the replay mode, while the other is in the recording mode. The data stream from the two instruments is therefore always recorded or retransmitted by one and the same recorder. The maximum recording duration is 22 min per recorder. The recording and replay speeds are the same (50 Mbit/s).

4. Continuation of the SPOT programme

A second generation is being developed with the preparation of the SPOT-4 and 5 satellites. Its main objectives being:

- to improve the satellite's general performance, particularly with regard to its life (raised to five years);
- to extend the high-resolution mission (additional infrared band: 1.58-1.75 μm);
- to introduce a "new Vegetation" payload for high-repetitivity observations in the visible spectrum (bands identical to the main instrument and additional band around 0.45 μm).
1. Introduction

Japan's first Earth observation satellite MOS-1 is an experimental satellite to collect information on earth surface (colour and temperature of sea surface, land use, etc.) and to establish the fundamental technologies.

The conceptional designs and the preliminary design of MOS-1 were completed in 1979 and 1981 respectively. The satellite was launched by the N-II launch vehicle in 1987. Japan intends to launch MOS-1b as the successor of MOS-1 in 1990.

1.1 Mission objectives

The mission objectives of the MOS-1 programme are as follows:

- establishment of fundamental technologies which are common to both marine and land observation satellites;
- observation of the state of sea surface and atmosphere using visible, infra-red and microwave radiometers and verification of the performance of these sensors.

1.2 Mission equipment

1.2.1 Sensors

In MOS-1, a Multispectral Electronic Self-Scanning Radiometer (MESSR), the Visible and Thermal-Infra-red Radiometer (VTIR) and a Microwave Scanning Radiometer (MSR) are to be installed. MESSR is a high resolution, visible and near-infra-red radiometer with push-broom scanning method using charge coupled devices (CCD's).

VTIR is a mechanical scanning type of radiometer to measure sea surface temperature etc.

MSR is a Dicke type radiometer to measure the content of water vapour in the atmosphere.

The anticipated characteristics of these radiometers are summarized in Table II.

1.2.2 DCS (Data Collection System) transponder

In order to perform the fundamental experiments concerning collection of the data acquired by many DCP's (Data Collection Platforms) via a satellite and locating the DCP's, MOS-1 is to carry a transponder for the experimental DCS.

2. Launch and orbit

The operational orbit of MOS-1 is Sun-synchronous, with a 17-day recurrent period. The nominal altitude is 909 km. The local time of the descending node is kept between 10:00 h and 11:00 h.

3. Communication system

A schematic diagram of the communication system is shown in Fig. 1. The 8 GHz band has been selected for transmission of the data obtained by MESSR and VTIR, and the data rate is about 9 Mbit/s. MSR data are transmitted by the 2 GHz link. Characteristics of the communication system are shown in Table III.
### TABLE II — Characteristics of MOS-1 sensors

<table>
<thead>
<tr>
<th>Sensor</th>
<th>MESSR</th>
<th>VTIR</th>
<th>MSR</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Item</strong></td>
<td><strong>Measurement objective</strong></td>
<td><strong>Wavelength (µm)</strong></td>
<td><strong>Frequency (GHz)</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sea-surface colour</td>
<td>0.5 to 0.59</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.61 to 0.69</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.72 to 0.80</td>
<td>23.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.80 to 1.1</td>
<td>31.4</td>
</tr>
<tr>
<td></td>
<td><strong>Water content of atmosphere</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>6 to 7</td>
<td>10.5 to 11.5</td>
<td>11.5 to 12.5</td>
</tr>
</tbody>
</table>

(°) Instantaneous field of view.
(²) Signal-to-noise ratio excluding quantization noise.

---

**FIGURE 1 — Communication system of MOS-1**
### TABLE III — Characteristics of communication system of MOS-1

<table>
<thead>
<tr>
<th>Link</th>
<th>Space-to-Earth</th>
<th>Earth-to-space</th>
</tr>
</thead>
<tbody>
<tr>
<td>Function</td>
<td>MESSR and VTIR</td>
<td>MSR</td>
</tr>
<tr>
<td>Item</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frequency</td>
<td>8025-8400 MHz</td>
<td>2200-2290 MHz</td>
</tr>
<tr>
<td>Modulation</td>
<td>MSK</td>
<td>PCM-PSK-PM</td>
</tr>
<tr>
<td>Data rate</td>
<td>8.78 Mbit/s</td>
<td>2 kbit/s</td>
</tr>
</tbody>
</table>

### ANNEX V

ERS REMOTE SENSING SATELLITE PROGRAMME

1. **Introduction**

ERS-1 is the first of a family of remote sensing satellites of the European Space Agency (ESA) and is planned to be launched by mid-1989. It is planned to develop derived satellites later for operational applications in meteorology, oceanography and advanced land observations.

ERS-1 is mainly an oceanographic mission, aiming at:

- the development and promotion of applications related to a better understanding of ocean, sea and ice parameters and their status;
- improvement of scientific knowledge about coastal zones and ocean processes.

2. **Orbit**

ERS-1 will be launched into a Sun-synchronous circular orbit at a nominal altitude of 777 km and with a descending node at 1015 local time. The accuracy of the ground track repetition is expected to be within ± 1 km across track.

During the 3-year mission, the baseline repeat cycle can be altered for experimental purposes, which will cause some orbit parameters to change.

3. **ERS-1 payload**

Priority in the payload has been given to a comprehensive set of radar instruments designed mainly to observe the oceans. They consist of:

- an active microwave instrument (AMI) combining a synthetic aperture radar (SAR) and a wind scatterometer; and
- a radar altimeter (RA).

In addition, the following instruments are included in the payload:

- an along track scanning radiometer and microwave sounder (ATSR-M);
- a precise range and range rate experiment (PRARE);
- a laser retro-reflector.
3.1 The active microwave instrument

3.1.1 SAR imaging and wave modes

The synthetic aperture radar of the AMI uses much common equipment for both the imaging and wave modes. Table IV summarizes the relevant SAR characteristics.

<table>
<thead>
<tr>
<th>TABLE IV — ERS-1 SAR characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (MHz)</td>
</tr>
<tr>
<td>Bandwidth (MHz)</td>
</tr>
<tr>
<td>PRF (Hz)</td>
</tr>
<tr>
<td>Pulse duration (µs)</td>
</tr>
<tr>
<td>Peak power (kW)</td>
</tr>
<tr>
<td>Polarization</td>
</tr>
</tbody>
</table>

This Table applies to both the SAR imaging and wave modes. When in the imaging mode, data are collected from nearly 100 km wide swaths for no more than 10 min per orbit. In the wave mode, data are collected from 5 km wide swaths (anywhere within the imaging swath capability) for 5 km along track, every 200 or 300 km.

3.1.2 Wind scatterometer

In the wind scatterometer mode, the AMI uses a 3-beam antenna, which is described in Table V.

<table>
<thead>
<tr>
<th>TABLE V — ERS-1 wind scatterometer characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (MHz)</td>
</tr>
<tr>
<td>Peak power (kW)</td>
</tr>
<tr>
<td>Polarization</td>
</tr>
<tr>
<td>Beam</td>
</tr>
<tr>
<td>Pulse duration (µs)</td>
</tr>
<tr>
<td>Pulse repetition interval (ms)</td>
</tr>
<tr>
<td>Orientation (degrees)</td>
</tr>
</tbody>
</table>

Data collection is made over a 500 km swath. It is expected that the wind speed can be determined with 10% accuracy over the range 4 m/s to 24 m/s and wind direction with 20° accuracy. The wind scatterometer and the wave modes are operated alternately.

3.2 Radar altimeter

The ERS-1 radar altimeter will have the characteristics described in Table VI below.

<table>
<thead>
<tr>
<th>TABLE VI — ERS-1 radar altimeter characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (GHz)</td>
</tr>
<tr>
<td>Bandwidth (MHz)</td>
</tr>
<tr>
<td>Pulse duration (µs)</td>
</tr>
<tr>
<td>RF peak power (W)</td>
</tr>
<tr>
<td>Pulse repetition frequency (Hz)</td>
</tr>
<tr>
<td>Antenna gain (dBi)</td>
</tr>
</tbody>
</table>
The expected accuracy of the altitude measurement is 10 cm over water and 40 cm over ice. The significant wave height measurement is expected to have an accuracy of 10% over the range 1 to 20 m.

3.3 Along track scanning radiometer and microwave sounder

The ATSR-M is a purely passive instrument for the following observations:
- sea surface temperature;
- images of land surface temperature; and
- clouds, aerosols, haze and total water vapour content of the atmosphere.

The instrument consists of an infra-red radiometer and a microwave radiometer, the latter operating at 23.8 GHz and 36.5 GHz.

3.4 Precise range and range rate experiment (PRARE)

This equipment extends the ERS-1 mission to geodetic and geodynamic applications: PRARE aims at determining the satellite orbit radial component to a precision of the order of 10 cm. Table VII summarizes its RF characteristics.

<table>
<thead>
<tr>
<th>TABLE VII — ERS-1 PRARE characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Up link</strong></td>
</tr>
<tr>
<td>Frequency (MHz)</td>
</tr>
<tr>
<td>Bandwidth (MHz)</td>
</tr>
<tr>
<td>System noise figure (dB)</td>
</tr>
<tr>
<td><strong>Down link 8 GHz</strong></td>
</tr>
<tr>
<td>Frequency (MHz)</td>
</tr>
<tr>
<td>Bandwidth (MHz)</td>
</tr>
<tr>
<td>Power transmitted (W)</td>
</tr>
<tr>
<td>Modulation rate (PSK) (Mbit/s)</td>
</tr>
<tr>
<td>Maximum antenna gain (dB)</td>
</tr>
<tr>
<td><strong>Down link 2 GHz</strong></td>
</tr>
<tr>
<td>Frequency (MHz)</td>
</tr>
<tr>
<td>Bandwidth (MHz)</td>
</tr>
<tr>
<td>Power transmitted (W)</td>
</tr>
<tr>
<td>Modulation rate (PSK) (Mbit/s)</td>
</tr>
<tr>
<td>Maximum antenna gain (dBi)</td>
</tr>
</tbody>
</table>

The 7/8 GHz band is used for range measurement and the 2 GHz band for ionospheric correction.

Further information on geodetic and geodynamic satellites is contained in Report 988.

4. Communication and data handling system

4.1 Telemetry tracking and command

The housekeeping data have a bit rate of 2048 kbit/s and uses PCM-PSK-PM to modulate a 2225 MHz carrier.

The telecommand uses a 2048.85 MHz carrier with PCM-PSK-PM modulation at a 2000 bit/s data rate.

4.2 Payload data transmission

The AMI SAR imaging mode data are transmitted in real-time to the ground by means of a 105 Mbit/s 4-PSK link in the 8 GHz band, called link I. This link will operate for only about 10 min per orbit.
All other instrument data are either transmitted in real time or recorded on board, for subsequent play-back using link II. The overall instrument data rate is 800 kbit/s. The real-time data are convolutionally encoded which results in a data rate of 3.2 Mbit/s. In addition, over the prime stations, the on-board recorder is played back at 15 Mbit/s and modulates together with the real-time data the link II carrier.

Table VIII summarizes the transmission characteristics.

**TABLE VIII — ERS-I 8 GHz band transmission**

<table>
<thead>
<tr>
<th>Link I</th>
<th>8140</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier frequency (MHz)</td>
<td>8140</td>
</tr>
<tr>
<td>Modulation</td>
<td>4-PSK differentially encoded</td>
</tr>
<tr>
<td>Bit rate (Mbit/s)</td>
<td>105</td>
</tr>
<tr>
<td>Radiated power (dBW)</td>
<td>11.9</td>
</tr>
<tr>
<td>Maximum antenna gain (dBi)</td>
<td>8.5</td>
</tr>
<tr>
<td>Polarization</td>
<td>Right hand circular</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Link II</th>
<th>8040</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier frequency (MHz)</td>
<td>8040</td>
</tr>
<tr>
<td>Modulation (')</td>
<td>a) SPL/2-PSK</td>
</tr>
<tr>
<td>Bit rate (')</td>
<td>b) U4-PSK (with unbalance factor 1/4)</td>
</tr>
<tr>
<td>Radiated power (dBW)</td>
<td>a) 3.2 Mbit/s</td>
</tr>
<tr>
<td>Maximum antenna gain (dBi)</td>
<td>b) SPL 3.2 Mbit/s and NRZ 15 Mbit/s</td>
</tr>
<tr>
<td>Polarization</td>
<td>Right hand circular</td>
</tr>
</tbody>
</table>

(') Either a) or b) are operated, exclusively.

**ANNEX VI**

**RADARSAT**

1. **Introduction**

Canada has embarked on a national programme to develop and operate RADARSAT, a remote sensing satellite system. Radarsat will be a 3-axis stabilized polar orbiting satellite with a payload consisting of a synthetic aperture radar, a scatterometer and an optical instrument. The payload will be mounted on a low-orbit derivative of a platform which was conceived for the geostationary Olympus satellite. The satellite is designed for a 5-year life in orbit following a launch by the NASA Space Shuttle in mid-1991. The operational life is expected to be extended to more than 8 years after in-orbit servicing during the fifth year.

2. **Objectives**

The mission objectives of Radarsat are to monitor and to predict the location and type of sea ice; to provide scientific information for sea-ice analysis; to aid ship-route planning, off-shore drilling and production, and fishing fleet and oil slick monitoring; to manage agriculture, forestry and hydrology resources; and to update geological maps.

3. **Orbit**

Radarsat will be placed in a Sun-synchronous, near-polar, circular orbit with a descending node local time of 0944. The period will be 105.21 min at a mean height of 1004 km. The entire Earth scan is repeated every 16 days.
4. **Payload**

The RADARSAT payload will consist of the following instruments.

4.1 **Synthetic aperture radar (SAR)**

The SAR will provide raw data for high-resolution imagery from a swath width greater than 100 km. This swath will be one of four selectable swaths in a 500 km accessible swath. The fully-calibrated SAR system will generate 500 W mean RF power at 5.3 GHz which will be used to coherently illuminate a swath to the left of the nadir by means of a planar array antenna. The characteristics of the SAR are listed in Table IX. The SAR instrument will be operated up to 20 min in sunlight and 8 min in eclipse during each orbit.

4.2 **Scatterometer (RSCAT)**

The RSCAT instrument will be a modified Navy remote ocean sensing system (N-ROSS) scatterometer. The Radarsat version will generate 35 W mean RF power at 14 GHz which will be used to illuminate 670 km swaths on each side of nadir. The RSCAT characteristics are listed in Table IX. This instrument will be operated over oceans and large inland waters but may be operated continuously, if desired.

**TABLE IX — Radarsat SAR and RSCAT characteristics**

<table>
<thead>
<tr>
<th>Feature</th>
<th>SAR</th>
<th>RSCAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Azimuth resolution (m)</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>Range resolution (m)</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>Incidence angle range (degrees)</td>
<td>20-45</td>
<td>20-56</td>
</tr>
<tr>
<td>Accessible swath (km)</td>
<td>500</td>
<td></td>
</tr>
<tr>
<td>Swath width (km)</td>
<td>140</td>
<td>670</td>
</tr>
<tr>
<td>Number of swaths</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Operating frequency (GHz)</td>
<td>5.3</td>
<td>13.995</td>
</tr>
<tr>
<td>Bandwidth (MHz)</td>
<td>11.3</td>
<td>1</td>
</tr>
<tr>
<td>Peak transmitted power</td>
<td>10 kW</td>
<td>110 W</td>
</tr>
<tr>
<td>Pulse width</td>
<td>55 μs</td>
<td>5 ms</td>
</tr>
<tr>
<td>Pulse repetition rate (p/s)</td>
<td>1160-1360</td>
<td>62</td>
</tr>
<tr>
<td>Raw data rate (Mbit/s)</td>
<td>120</td>
<td></td>
</tr>
<tr>
<td>Antenna polarization</td>
<td>vertical</td>
<td>4 vertical, 2 horizontal</td>
</tr>
<tr>
<td>Antenna length (m)</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>Antenna height (m)</td>
<td>1.8</td>
<td></td>
</tr>
<tr>
<td>Antenna gain (dBi)</td>
<td></td>
<td>32</td>
</tr>
<tr>
<td>Antenna beamwidth (degrees)</td>
<td>0.5 x 25</td>
<td></td>
</tr>
<tr>
<td>Wind speed accuracy</td>
<td>2 m/s or 10%</td>
<td></td>
</tr>
<tr>
<td>Wind direction (degrees)</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Spatial resolution (km)</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>Sampling interval (km)</td>
<td></td>
<td>25</td>
</tr>
</tbody>
</table>

4.3 **Optical imaging sensors**

Radarsat will have two optical sensors on board. The advanced very high resolution radiometer (AVHRR) will have a resolution of 1.1 km in each of six optical and infra-red bands. In addition the modular opto-electronic multi-spectral system will have four optical channels with a swath width of 400 km and a pel size of 30 m.

5. **Communications and data handling**

The Radarsat communications and data handling systems consist of telemetry, telecommand and tracking, low data rate and high data rate sub-systems.
5.1 Tracking telemetry and telecommand sub-systems

This sub-system collects spacecraft and payload instrument status data and transmits them to earth stations. This sub-system also receives, decodes and distributes telecommand data and retransmits tracking data.

The telemetry data are NRZ coded PCM signals at 2048 bit/s. These signals phase-shift-key sub-carrier oscillators which phase-modulate a down-link carrier in the 2200 to 2290 MHz band.

The telecommand data are NRZ coded PCM signals phase-shift-keying a sub-carrier oscillator which phase modulates an up-link carrier in the 2025 to 2110 MHz band.

A tracking station acquires spacecraft range data by measuring the phase differences of returned sinusoidal tones (maximum frequency of 100 kHz) which phase modulate the up and down links. Range-rate data are acquired by measuring the 2-way Doppler shift of the up and down links using a coherent transponder in the spacecraft.

5.2 Low data rate sub-system

The 3.2 kbit/s RSCAT data will be down-linked via a transmitter in the 1.7 GHz band. On-board recording devices will permit acquisition of these data when Radarsat is out of the range of a data acquisition station.

5.3 High data rate sub-system

The 120 Mbit/s SAR and the optical imaging data will be down-linked via two transmitters in the 8.025 to 8.400 GHz band, each with a bandwidth of 75 MHz. In addition, on-board tape recorders will permit the acquisition of some of these data when out of range of a data acquisition station.

ANNEX VII

Japanese Earth Resources Satellite-1 (JERS-1)

1. Introduction

JERS-1 project is to establish remote sensing technology from space by a synthetic aperture radar (SAR) and optical sensors (OPS) as well as primarily to explore non-renewable resources and also to collect information for agriculture and fishery, environmental preservation, coastal activities, etc. during two-year mission life time.

Conceptual study of JERS-1 was undertaken in FY 1980, and preliminary design was completed in 1987.

1.1 JERS-1 Mission objectives

The mission objectives of JERS-1 are as follows:

1. to establish the fundamental technology of remote sensing from space by synthetic aperture radar and optical sensors.
2. to primarily explore non-renewable resources, and also to monitor land-use, agriculture, forestry, fishery, environmental preservation, prevention of natural disasters, surveillance of regions, etc.
1.2 Mission Equipments

Mission equipments are:
- L-band synthetic aperture radar (SAR) to take all-weather images of earth surface.
- Optical sensors (OPS) with multi-spectral bands, and stereoscopic observation capability which consists of visible and near-infrared radiometer (VNIR) and short wavelength infrared radiometer (SWIR)

Mission equipments characteristics are shown in Tables X and XI.

### TABLE X - Synthetic Aperture Radar (SAR)

<table>
<thead>
<tr>
<th>ITEM</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>1275 MHz</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>15 MHz</td>
</tr>
<tr>
<td>Modulation</td>
<td>FM-chirp</td>
</tr>
<tr>
<td>Polarization</td>
<td>H-H</td>
</tr>
<tr>
<td>Spatial Resolution</td>
<td>18 m x 18 m</td>
</tr>
<tr>
<td>Swath Width</td>
<td>57 Km</td>
</tr>
<tr>
<td>Off Nadir Angle</td>
<td>35 deg.</td>
</tr>
<tr>
<td>Antenna Size</td>
<td>2.2 m x 12 m (electrical dimension)</td>
</tr>
</tbody>
</table>

### TABLE XI - Optical Sensors (OPS)

<table>
<thead>
<tr>
<th>ITEM</th>
<th>VNIR</th>
<th>SWIR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>0.4 - 0.9 μm</td>
<td>1.6 - 2.4 μm</td>
</tr>
<tr>
<td>IFOV</td>
<td>4 bands</td>
<td>4 bands</td>
</tr>
<tr>
<td>Swath Width</td>
<td>18 m</td>
<td>18 m</td>
</tr>
<tr>
<td>Stereoscopic Image</td>
<td>75 Km</td>
<td>75 Km</td>
</tr>
<tr>
<td></td>
<td>One band in near-infrared wavelength</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(stereoscopic viewing angle= 15 deg.)</td>
<td></td>
</tr>
</tbody>
</table>

2. Launch and Orbit

JERS-1 will be launched by the H-I launch vehicle from Tanegashima Space Center in early 1992, and the operational orbit parameters are shown in TABLE XII.
TABLE XII - Orbit Parameters

<table>
<thead>
<tr>
<th>ITEM</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbit</td>
<td>Sun-synchronous, circular</td>
</tr>
<tr>
<td>Altitude</td>
<td>568 Km</td>
</tr>
<tr>
<td>Inclination</td>
<td>98 deg.</td>
</tr>
<tr>
<td>Recurrent Period</td>
<td>44 days</td>
</tr>
<tr>
<td>Mean Local Time at Desending Node</td>
<td>10:00 - 11:00</td>
</tr>
</tbody>
</table>

3. Communications system

A schematic diagram of the communications system is shown in Figure 2. Two 8 GHz bands are used for transmitting the data obtained by SAR and OPS, and the data rate is 60 Mbps per each band. Characteristics of the communications system are shown in Table XIII.
TABLE XIII - Characteristics of communications system of JERS-1

<table>
<thead>
<tr>
<th>LINK</th>
<th>Space-to-Earth</th>
<th>Earth-to-Space</th>
</tr>
</thead>
<tbody>
<tr>
<td>Function</td>
<td>Item</td>
<td>Item</td>
</tr>
<tr>
<td>Item</td>
<td>TLM</td>
<td>R&amp;RR</td>
</tr>
<tr>
<td>Frequency</td>
<td>2200-2290</td>
<td>2200-2290</td>
</tr>
<tr>
<td>(MHz)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Modulation</td>
<td>PCM-PM</td>
<td>PCM-PSK-PM</td>
</tr>
<tr>
<td>Data rate</td>
<td>2048 bps</td>
<td>60 Mbps</td>
</tr>
<tr>
<td></td>
<td>32768 bps</td>
<td>/band</td>
</tr>
</tbody>
</table>

3.1 Tracking, Telemetry and Command subsystem

This subsystem is compatible with Unified S-band (USB) systems, and each tone (sinusoidal/rectangular) modulation is usable for Range and Range Rate (R&RR) measurement.

The real time housekeeping telemetry data are 2048 bps PCM (biphase-L) signals with phase modulation of the carrier, and reproduced housekeeping telemetry data are 32768 bps PCM signals, with phase modulation of the subcarrier.

The command data are 500 bps PCM (NRZ-L) signals, with phase shift keying modulation of the subcarrier.

3.2 Image Data Transmitting subsystem

The wideband Image Data Transmitting subsystem is composed of a high data rate recorder and two wide band transmitters operating in two bands (8025-8175 MHz and 8215-8400 MHz).

SAR data, OPS data and both reproduced data are 60 Mbps (30 Mbps x 2 channels) signals, switched and transmitted in both bands by QPSK modulation with band suppression.
METHOD FOR DERIVING PERFORMANCE CRITERIA FOR
THE EARTH EXPLORATION-SATELLITE SERVICE

(Question 12/2)

1. Introduction
This report describes a method for establishing EES service performance
criteria. The method involves the following steps, each of which is
further described in the sections below:

- Establishment of a Hypothetical Reference System;
- Characterization of representative systems
  - definition of representative system transmission and operating
    parameters and
  - quantification of intra-system performance degradations;
- Establishment of performance criteria on the basis of:
  - requirements for resolution, accuracy, reliability, and availability
    of data and
  - assessment of performance achievable with representative systems.

2. Hypothetical reference systems
In order to define EES system elements which are relevant to the establishment
of performance criteria and derivation of interference and sharing criteria, it
is useful to establish a Hypothetical Reference System (HRS) that generally
defines the major significant subsystems. The diverse operational functions in
the EES service (Table I) result in numerous possible subsystems. All of these
are not necessarily included in all systems. Figure 1 depicts an HRS for the
EES service.

<table>
<thead>
<tr>
<th>TABLE I - Operational functions in the EES service</th>
</tr>
</thead>
<tbody>
<tr>
<td>o Active Remote Sensing</td>
</tr>
<tr>
<td>o Passive Remote Sensing</td>
</tr>
<tr>
<td>o Data Collection</td>
</tr>
<tr>
<td>o Direct Data Readout (Real Time)</td>
</tr>
<tr>
<td>o Recorded Data Acquisition</td>
</tr>
<tr>
<td>o Processed Data Dissemination</td>
</tr>
<tr>
<td>o Satellite Tracking, Telemetry and Telecommand</td>
</tr>
</tbody>
</table>
The Hypothetical Reference System (HRS) of Figure 1 includes all major EES subsystems needed to establish performance, interference and sharing criteria. The earth stations are specifically designated for uplink or downlink functions because many earth stations are used only for transmission or only for reception. Processing subsystems which provide baseband signals to transmitting earth stations are not included, but the characteristics of the baseband signals present at this interface are of concern to the establishment of performance objectives. Likewise, data processing and display subsystems that utilize the baseband signals from receiving earth stations are not included, but consideration of the baseband signal quality requirements and associated operational needs is necessary. The media being observed by active or passive sensors are included in the HRS only when the sensor operates at radio frequency wavelengths; however, the sensor baseband output characteristics are included in all cases.

3. Characteristics of representative systems

Typical characteristics of the transmission subsystems must be established to facilitate system performance assessments. Although the satellite and each functional type of earth station may have diverse designs, a generic system is desired for derivation of performance criteria. In some cases, where differing interference criteria might result, it may be appropriate to consider more than one set of parameters to characterize a given system element (e.g., large and small aperture earth stations for direct data readout). In such cases, each representative system should be separately addressed to determine its appropriate specific performance criteria. Values are needed for the parameters listed in Table II.
TABLE II - Required system transmission and operating characteristics

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>SYSTEM ELEMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EARTH STATION</td>
</tr>
<tr>
<td>Propagation characteristics</td>
<td>X</td>
</tr>
<tr>
<td>Receiver noise temperature</td>
<td>X</td>
</tr>
<tr>
<td>Receiver bandwidth</td>
<td>X</td>
</tr>
<tr>
<td>Antenna gains/patterns</td>
<td>X</td>
</tr>
<tr>
<td>Line losses</td>
<td>X</td>
</tr>
<tr>
<td>Transmitter output power</td>
<td>X</td>
</tr>
<tr>
<td>Orbit altitude(s)/inclination</td>
<td>X</td>
</tr>
<tr>
<td>Modulation type/data rate</td>
<td>X</td>
</tr>
<tr>
<td>Processing/coding gain</td>
<td>X</td>
</tr>
<tr>
<td>Multiple access technique</td>
<td>X</td>
</tr>
<tr>
<td>Multiplexing technique</td>
<td>X</td>
</tr>
<tr>
<td>Number of satellites accessed</td>
<td>X</td>
</tr>
<tr>
<td>Minimum Antenna Elevation Angle</td>
<td>--</td>
</tr>
<tr>
<td>Coverage Area</td>
<td>--</td>
</tr>
<tr>
<td>Percent of time in operation</td>
<td>X</td>
</tr>
</tbody>
</table>

("X" entry indicates parameter value or description might be needed)

Table III lists several intra-system degradation factors that might significantly affect performance. Both variable and constant degradations are of concern because normal and unusually degraded performance must be evaluated for the representative system(s) where possible.

TABLE III - Potentially significant intra-system degradation factors and their nature

<table>
<thead>
<tr>
<th>DEGRADATION AND CORRESPONDING SYSTEM ELEMENT</th>
<th>GENERAL COMMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propagation losses on desired signal paths (for small time percentages)</td>
<td>Precipitation, clouds, water vapor and refraction effects cause short term attenuations that generally increase in severity at lower path elevation angles and are highly dependent on frequency and climate. Multipath can introduce severe short term fading at elevation angles below about 10° and is highly dependent on antenna and antenna site parameters (See Report 564).</td>
</tr>
<tr>
<td>Antenna thermal noise from atmosphere and terrain at a receiving earth station (for small time percentages)</td>
<td>Thermal noise increases with atmospheric attenuation, thus being correlated with several fading mechanisms. (See Reports 564 and 208). Noise contributions from the terrain increase with decreasing antenna elevation angle, thus being correlated with multipath effects in earth stations tracking non-geostationary satellites.</td>
</tr>
</tbody>
</table>
### Mean propagation losses on desired signal paths
Predominantly determined by free space loss and, when significant, atmospheric absorption. Mean loss increases with decreasing antenna elevation angle, although this might be somewhat offset by the satellite antenna gain pattern shaping.

### Mean thermal noise in the receiver system
Includes receiver, antenna and environmental contributions.

### Implementation losses in demodulators
Degradations caused by frequency instabilities, unwanted non-symmetry in digital signals, carrier tracking errors, bit synchronization errors and other demodulator factors.

### Modulation loss on data links
Arises from residual carrier or other emissions from the data transmitter not carrying desired information.

### Polarization mismatch loss in data link antennas
Arises from polarization mismatch in antennas and is in some cases induced by propagation phenomena.

### Pointing loss of the earth station antenna
Dependent on method of tracking and antenna beamwidth.

### Errors in satellite and earth station data handling systems
Arises from multiplexing and demultiplexing operations and temporary storage which introduces noise and/or bit errors.

### Adjacent frequency channel interference in data links
Arising in FDM data links. (TDM adjacent time channels considered in implementation loss for demodulator).

### Quantization error in satellite and earth station equipment
In digital systems, error introduced in analog-to-digital and digital-to-analog conversions.

### Intersymbol interference in data links
In digital systems, corruption of symbols caused by residual energy of preceding symbols (e.g., from filters or multipath).

### Blocking of data collection platform transmissions
Arising in random or demand access systems.

#### Establishment of performance criteria

Previous sections of this report have introduced the hypothetical reference system for EES, have discussed system transmission and operating characteristics in relationship with performance criteria, and have discussed the need to harmonize performance criteria with the limits on performance imposed by intra-system degradation factors.
This section presents a series of steps which comprise a method for establishing performance criteria for the EES service:

Step 1

Determine the performance objectives of the ultimate users of the data produced by the EES. For reception of data at an EES earth station, it will be necessary to specify the objectives for the accuracy, the availability, the resolution and the reliability. For passive sensors that use the radio spectrum, it is also necessary to determine the dynamic range and precision of the physical measurement which will be derived from the sensor data. This information must be transformed into the equivalent range and sensitivity of microwave temperature measurements made by the sensor. Similar objectives can be formulated for the remaining operational functions found in Table I. On completion of step 1, performance objectives will have been defined for each element in the hypothetical reference system.

Step 2

Define one or more representative systems which include the satellite, the earth station and, as appropriate, sensors and systems for data collection, data relay, and data dissemination. The relevant transmission and operating characteristics in Table II must be considered.

Step 3

Evaluate the degradation in performance of the representative system caused by intra-system factors. A list of factors that can cause potentially significant intra-system degradation is found in Table III.

Step 4

Taking intra-system degradations into account, assess the performance achievable with the representative systems.

Step 5

If necessary, repeat steps 2, 3 and 4 until either the performance objectives determined in step 1 are satisfied or the performance objectives are modified to be harmonized with achievable performance when intra-system degradations are taken into account.

Step 6

Establish performance criteria. These criteria should take into account both the requirements imposed by the performance objectives and the performance achievable with representative systems. For regulatory purposes, one, or at most a few, generic systems must be considered that encompass the range of system parameters found within the EES service. For example, performance criteria might be specified for earth stations with small antennas as well as for those with large antennas.
5. **Available performance criteria**

The percentage of time for data readout downlinks, during which the minimum acceptable basic transmission loss on the interfering signal path need not be exceeded, is given as 1% in Report 540-1. A performance criteria for bit error rate for data readout of $10^{-6}$ is inferred in several Reports but is not explicitly stated. Further study is needed to establish performance criteria for EES data readout links.

For the command link, a percentage of time of 0.1% and a bit error rate of $10^{-7}$ can be inferred from Recommendation 514 as being the applicable performance criteria.

Report 693, Table IV, provides sensitivity criteria for passive sensors. Report 850 implies a percentage of time of 5% loss for performance criteria for passive sensors in the 18.6–18.8 band. Measurement sensitivity derived from needed resolution in sensed parameters is a valid way to express passive sensor performance requirements. Availability in shared bands would appear to be best expressed in terms of percentage of locations where sensed data can be obtained. A suitable performance criteria would be that, in shared frequency bands, availability of passive sensor measurements which meet the specified sensitivity criteria should exceed 95% of all locations in the sensed area.

No performance criteria appear to exist for EES data relay, for platform data, or for active sensors. Study, using the method contained in this Report, is needed to determine suitable performance criteria for these systems.

6. **Conclusions**

A Hypothetical Reference System (HRS) has been established to define the principal EES system elements needed to determine performance criteria and interference criteria.

A method for establishment of performance criteria has been described.

Performance criteria for EES systems are currently available for passive microwave sensors and for command links. Further study is needed to establish performance criteria for data readout, both direct and via data relay, for platform data and for active sensors.
1. **Introduction**

This report presents a method for determining interference criteria for the EES service. These criteria will define the total power level of all interfering signals that can be accepted in representative EES receivers. The method results in separate criteria for satellite and earth station receivers. Interference criteria are derived on the basis of:

1) **assessment of representative system performance**, and

2a) computation of the margin between a minimum specified performance objective and the performance achievable in the absence of interference, or

2b) determination of an acceptable degradation in system performance resulting from interference.

2. **Long-term and short-term interference criteria**

In many communications systems, the desired signal and noise power levels vary with operating and environmental conditions such that system performance is a statistical parameter. Similarly, interfering signal power levels vary with such system operating and environment conditions as earth station antenna pointing and propagation mechanisms. Consequently, interference criteria typically consist of at least two components: (1) a threshold which defines a limit on interfering signal power density and (2) a time percentage which defines the amount of time during which the threshold may be exceeded. There is a third criterion that is useful for services involving area coverage such as the terrestrial land mobile and broadcasting services, and for active and passive sensors in the EES service.
This criterion establishes the maximum percentage of locations within the coverage area where interference levels may make communications or measurements unobtainable.

The temporal (and location) variabilities of the desired signal, interfering signal and noise power levels are sufficiently great in most cases to necessitate the use of at least two sets of interference criteria, each with two components. Two sets are needed because one set of criteria which specifies an interference power and one time percentage does not necessarily assure acceptable performance for all other percentages of time. For example, specification of acceptable levels of interference for only 50% of the time might not prevent unacceptably high interference levels for 1% of the time.

Two sets of interference criteria as described below are typically specified for interactions involving highly variable propagation over terrestrial paths (see Report 448):

- "Long-term" criteria which establish the maximum permissible interference which can be exceeded for no more than 20% of the time. These criteria specify interfering signal levels to protect desired signals which are faded to levels existing only for small percentages of time.

- "Short-term" criteria which establish the maximum permissible interference which can be exceeded for no more than p% of the time, where p is less than about 1%. These interference levels are not likely to be present when desired signals are faded to the level where barely acceptable performance is achieved. This set of criteria specifically protects operations under conditions involving interfering signal enhancement at the same time that desired signals are near their median value.

3. Derivation of interference criteria

The "long-term" total received interference power level must be accommodated during all operating conditions of the desired system, including periods of fading of the desired signal on data links or times when sensors are operating near their sensitivity thresholds. More liberal "short-term" interference criteria can be safely established because there is negligible probability that interference will be enhanced to levels experienced for only small percentages of time while the desired signal is also faded to levels existing for only small percentages of time.

Figure 1 depicts these concepts for an example system. The example system has two performance criteria. The criterion for availability is 99.9% of the time and the criterion for C/(N+I) is 10.7 dB. Interference may degrade the performance by up to 2.7 dB for small percentages of time without compromising the integrity of the sample system. In the absence of interference, the example system achieves a C/N ratio of 13.4 dB for median path loss and environmental conditions. The C/N ratio is reduced to 11.5 dB when the desired signal is faded to the value existing for 0.1% of the time (again in the absence of interference). The margin between the performance objective and the performance level achieved for a small percentage of time in the absence of inter-system interference can be reduced by long-term interference without compromising the integrity of the system.
Cumulative distribution of the achieved carrier-to-noise power ratio in the absence of interference (I = 0).

- Minimum performance objective, including all inter-system interference (I ≠ 0).

A: Long term system performance margin, in the absence of inter-system interference, which can be allocated for short term degradations from inter-system interference.

B: Short term system performance margin, in the absence of inter-system interference, which can be allocated for long term degradations from inter-system interference.

FIGURE 1

Illustration of the determination of long-term and short-term interference criteria
Achievable performance of each element in the Hypothetical Reference System (see Report 1120) can be predicted using representative system characteristics as discussed in Report 1120. For up-link satellite receivers or down-link earth station receivers, link analyses can be performed to determine bit error ratios and carrier-to-noise ratios for conditions existing for large and small percentages of time in the absence of interference. For examples, see Report 1121. The long-term analysis should evaluate the performance exceeded for all but 20% of the time, which corresponds to near-median signal levels. The short-term analysis should evaluate the performance exceeded for all but p% of the time, where p is the short-term time percentage associated with a performance objective.

For passive and active microwave sensors, the performance analyses should make it possible to determine quality criteria such as the r.m.s. measurement uncertainty. Interference criteria could again be derived based on the margin between the performance possible in the absence of interference and the required performance. For sensors, one performance criterion can be defined in terms of a percentage of locations where sensing is possible. The analyses must consider this criterion in addition to, or instead of percentage of time availability.

In addition to insuring that performance objectives are met, it is appropriate to consider the relationship of degraded performance caused by inter-system interference to that due to intra-system limitations. In selecting interference criteria, it is important to preserve a high degree of system design control of overall performance. Simply stated, the incremental degradation due to inter-system interference should not exceed some fraction of the intra-system degradation. However, it must be borne in mind that a system should tolerate the maximum practicable interfering signal power levels that are conducive to sharing (Radio Regulations Article 5).

The fixed-satellite service (FSS), for which orbit/spectrum resources are in high demand and use, permits 35% of the total system noise to result from inter-system interference. This interference allowance which amounts to about 54% of the intra-system degradation (0.35 external/0.65 internal degradation), results in what is often referred to as "interference limited" performance. This high allowance has evolved from lower values (33% in the year 1978 and 25% in earlier years) because of a need to accommodate more systems in FSS frequency bands and because improved multiplexers, higher transmission powers and other advances have reduced intra-system degradation. By way of contrast, the "safety services" such as aeronautical radio navigation generally demand the highest performance that can be practicably achieved. Even in those cases, some allowance has been made for degradation caused by interference (e.g., see Report 927).

3.1 Long-term criteria

Whether based on meeting minimum performance objectives or on acceptable degradation of performance otherwise achievable, the long-term interference criterion can be specified as the interfering signal power level, to be exceeded for no more than 20% of the time. This relationship is defined in equations (1) and (2) [ORI 1987] below. For example, with a given C/(N+I) objective, an allowance of 25% of the short-term intra-system noise power for inter-system interference (I/N = -6 dB) corresponds to a 1 dB reduction in performance. An allowance of 25% of the intra-system degradation for interference would appear to be generally acceptable and would permit system designers to retain effective control over system performance. The short-term time percentage p to be used in the performance analysis is the percentage of
time corresponding to the unavailability, i.e., the percentage of time that system performance may be degraded below the performance objective. In the absence of such an objective, p should be taken to be 0.1% but further study of this assumption and the permissible incremental degradation allowance is required.

\[
\left(\frac{c}{n+1}\right)_p = \left(\frac{c}{n}\right)_p \times \left(\frac{n}{n+1}\right)_p \times \left(\frac{n}{n+i}\right)_p \times \left(\frac{n}{n+c}\right)_p
\]

\[
i_{20} = n \times \left[\left(\frac{c}{n}\right)_p \times \left(\frac{n+i}{c}\right)_p\right] - n
\]

where:

c : carrier (W);
n : noise (W);
i : interference (W);
p : p1 + p2 (unavailability, percent of time);
p1 : percentage of time that intra-system degradation may result in performance below the performance objective (for example, p1 = 0.075%);
p2 : percentage of time that inter-system interference may degrade performance below the performance objective (for example, p2 = 0.025%).

Equation (1) states that short-term carrier-to-noise plus interference performance equals the short-term carrier-to-thermal noise multiplied by long-term noise-to-noise plus interference.

Equation (1) is equivalent to an identity which states that \(c/(n+i) = c/n \times n/(n+i)\). This formulation makes possible the assignment of short-term and long-term percentages of time to the terms involving c and i, because these parameters are mutually independent in a statistical sense. An assumption is made that the variability of \(c/n\) dominates the determination of \(i(20)\) while \(n/(n+i)\) is near its mean value.

Equation (2) results from rearrangement of the terms in equation (1) to solve for the permissible interference to be exceeded for no more than 20% of the time.

3.2 Short-term criteria

The short-term interference criteria can be specified as the interfering signal power level to be exceeded for no more than a small percentage of time (p2). Equations (3) and (4) [ORI 1987] describe this relationship. The time percentage p2 should be taken to be 0.25 p in order to again allow the system designer to maintain control over system performance. This value of p2 also assures that the probability remains small that interference will be enhanced and desired signal will be faded simultaneously.

\[
n/(n+i) (p2) = c/(n+i) (20) \times n/c (20)
\]

\[
i (p2) = n \times [(n+i)/c (20) \times c/n (20)] - n
\]
3.3 Generalization of interference criteria for receiving earth stations

The long-term and short-term interference criteria are determined using equations (2) and (4) with values for c/n determined in the analysis of performance achievable in the absence of inter-system interference. This performance analysis is necessarily based on a representative standard system and the interference criteria calculated using equations (2) and (4) apply to the standard system. For EES space-to-Earth links, the values calculated for interference criteria are dependent on the antenna gain of the receiving earth station. Since interference criteria are needed that are valid for all EES systems in a given frequency band which performs the same function, a method is needed to adjust the criteria calculated for the standard system to obtain criteria for systems that differ from the standard system. A method to modify the interference criteria for the standard system so as to apply to earth stations having different antennas is given in Annex I.

4. Available interference criteria

Protection (interference) criteria for EES receiving earth stations are contained in Recommendation 514: for frequencies between 1 and 10 GHz, the power spectral density of noise-like interference or the total power of CW-type interference in any single band or in all sets of bands shall not exceed -154 dB (W/MHz) at the receiver input for more than 1% of the time; for frequencies less than 1 GHz, the permissible interference may increase at the rate of 20 dB per decreasing frequency decade.

Protection (interference) criteria for near-Earth EES spacecraft command receivers are contained in Recommendation 514: for frequencies between 300 MHz and 10 GHz, the power spectral density of noise-like interference or the total power of CW-type interference in any single band or in all sets of bands 1 kHz wide shall not exceed -161 dB (W/kHz) at the receiver input for more than 0.1% of the time; for frequencies less than 300 MHz, the permissible interference may increase at the rate of 20 dB per decreasing frequency decade.

Interference criteria for passive microwave sensors are contained in Report 694. The criteria are based on a degradation of $\Delta T_e$ by 20% due to long-term interference. However, additional study is needed to determine a suitable reference bandwidth for bands which exceed 100 MHz in width.

Based on the performance criteria discussed in Report AB/2, loss of the ability to obtain passive sensor measurements due to interference in shared frequency bands should not exceed 5% of all possible locations in the sensor service area. In bands shared with the fixed-satellite service, this loss could occur when the sensor satellite passes through the fixed-satellite main-beam or from fixed-satellite signals reflected from the Earth. In bands shared with the fixed service, this loss could occur when the main-beam of the fixed service transmitter illuminates the sensor satellite or when the sensor antenna main-beam or near side-lobes illuminate the fixed service transmitter.

No interference criteria appear to exist for EES data relay, for platform data, or for active microwave sensors. Study, using the method contained in this report, is needed to determine suitable interference criteria for these systems.
5. Conclusions

A method for deriving interference criteria has been described which is based on consideration of performance criteria as well as on degradation of performance caused by interference in relation to performance achievable in the absence of interference.

It should be noted that the interference criteria resulting from application of this method apply to the total noise-like interference from all sources external to the ESS system and thus cannot be directly applied as sharing criteria for any individual interferer.

REFERENCE


ANNEX I

GENERALIZED INTERFERENCE CRITERIA FOR RECEIVING EARTH STATIONS

This annex presents methods for scaling the interference criteria of the standard EES space-to-Earth link to apply to links having earth station antenna sizes different from that of the standard link. Two methods are given below. Method 1 applies if the interference criteria have been established as a percentage of the total noise power that would cause the performance achieved to equal the performance required. Method 2 applies if the criteria have been established to yield performance in the presence of interference that just equals the performance objective. For an example application of these methods, see Annex I to Report 1121.

When permissible levels of interference are specified as a percentage of the total noise power that would cause the receiver performance level to equal that of the performance objective, the interference criteria may be scaled in direct proportion to the gain of the receiving antenna compared to that of the standard system. Equation (1) may be used for this purpose.

\[ i = \frac{i_s}{g} \]  \hspace{1cm} (1)

where:

\[ i \] : permissible level of interference power (W) for the specific earth station under consideration;

\[ g \] : antenna gain of the specific earth station under consideration;

\[ i_s \] : permissible level of interference power (W) for the standard link;

\[ g_s \] : antenna gain of the standard link.
When the permissible level of interference is that which would cause the performance achieved in the absence of interference to be degraded to a level which just equals the performance objective, equation (2) may be used.

\[ I = I_s \times \left( \frac{g}{g_s} \right) - n \times \left( 1 - \frac{g}{g_s} \right) \]  

(2)

where:

\[ n \]: intra-system noise power (W) of the standard system.

Equations (1) and (2) are valid as long as the earth station antenna size is sufficiently large that the performance objective can be met in the absence of interference. They cannot be used for smaller antenna sizes.
1. Introduction

The Radio Regulations provide two mechanisms that could be considered to protect earth exploration-satellite systems from harmful interference. For the case of terrestrial transmitters interfering with satellite receivers, sharing criteria in the form of power, e.i.r.p. and antenna pointing limits can be placed on the terrestrial stations. Other modes of interference, such as terrestrial transmitters interfering with receiving earth stations, are controlled by coordination on a case-by-case basis when a potentially unacceptable level of interference is predicted (i.e. a "coordination threshold" is exceeded). This report presents a method for deriving these sharing criteria and coordination thresholds from appropriate interference criteria for the EES service.

The objective of sharing criteria and coordination procedures is to ensure that the total interference from all sources will not violate the interference criteria of the affected service. This objective can be accomplished by subdividing the interference criteria into interference allocations for each interferer. When both space services and terrestrial services contribute to the interference environment, an initial apportionment of the interference criteria can be made prior to the further subdivisions needed to establish sharing criteria or coordination thresholds for individual interferers. A general approach for accomplishing these subdivisions of short-term and long-term interference criteria is presented in section 2. Specific consideration is given to earth station and satellite receivers in succeeding sections.

* This Report should be brought to the attention of Study Groups 1, 5 and 9.
2. **Initial division of interference criteria among space and terrestrial services**

Space-to-Earth and Earth-to-space allocations for EES generally require sharing with systems in terrestrial services and in some cases with systems in other space services. Similar sharing situations are encountered in many of the EES active and passive sensor allocations. Spurious emissions from space and terrestrial systems operating outside bands allocated for EES can also be significant sources of interference. An initial division of the short-term (enhanced) and long-term (near median) interference criteria can be made to establish separate interference budgets for the space service and the terrestrial service. This procedure facilitates the determination of appropriate sharing criteria and coordination thresholds for space and terrestrial systems, which are generally present in differing numbers and which might pose interference potentials of different severity. The following equations can be used for this subdivision:

\[
i_s(20) = i(20) \times (A_s/100) \tag{1}
\]

\[
i_t(20) = i(20) - i_s(20) \tag{2}
\]

where:

- \(i_s\): interference (W) budget for space service;
- \(i_t\): interference (W) budget for terrestrial service;
- \(A_s\): percent of total interference power budget allotted to space service;
- \(i(20)\): Total permissible level of interference power (W) to be exceeded for no more than 20% of the time.

\[
i_s(p_s) = i(p) - i_t(20) \tag{3a}
\]

\[
i_t(p_t) = i(p) - i_s(20) \tag{3b}
\]

\[
p_s = p \times (a_s/100) \tag{4a}
\]

\[
p_t = p - p_s \tag{4b}
\]

where:

- \(p\): percentage of time associated with the short-term interference criteria;
- \(p_s\): percentage of time that space services may exceed the interference threshold;
- \(p_t\): percentage of time that terrestrial services may exceed the interference threshold;
- \(a_s\): portion (percent) of the percentage of time \(p\) allocated to space services;
Total interference power level (W) to be exceeded for no more than \( p \% \) of the time (i.e. the short-term interference criteria).

In Equations (1) and (2), the long-term interference criteria are subdivided on a power basis among space and terrestrial service interference categories. This is justified in that these long-term space and terrestrial interference levels can be expected to be present simultaneously.

The short-term interference criteria are subdivided in Equations (3) and (4) on a percentage of time basis among space and terrestrial service interference categories. Short-term enhanced interference levels are not likely to occur simultaneously for both space and terrestrial services owing to the uncorrelated mechanisms which cause these enhancements. However, the interference from the space service at its long-term level must be considered when the short-term interference budget is established for the terrestrial service and vice versa.

The percentages of time in Equations (1) to (4) are specified as percentages of reception time. In cases where reception occurs for only a portion of the time (e.g. earth stations tracking low-earth-orbit satellites), consideration should be given to the joint probability of interference and reception as discussed in section 5.

Values for the interference apportionment \( i_s \) and \( i_t \) and time apportionment \( p_s \) and \( p_t \) in Equations (1) to (4) should be selected so as to correspond with interference levels that can be expected from a typical environment of terrestrial and space service interferers in order to minimize constraints resulting from adoption of sharing criteria.

### 3. Single entry sharing criteria

Subdivisions of the aggregate interference and time allowances for space and terrestrial interferers can be made to establish appropriate permissible levels of interference from individual interferers (i.e. "single entry" interference). Equations (5) and (6) below can be used for this purpose:

\[
\begin{align*}
  i_X'(20) &= \frac{i_X(20)}{n} \\
  i_X'(p_X') &= \frac{i_X(p_X)}{yn} - \left[ i_X(20) \times (1 - y) \right] \\
  p_X' &= \frac{p_X}{(1-y)n}
\end{align*}
\]

where primed (') parameters denote single entry values and:

- \( i_X(20) \): total permissible interference power level (W) budgeted for space or terrestrial services, to be exceeded for no more than 20\% of the time;
- \( i_X(p_X) \): total permissible interference power level (W) budgeted for space or terrestrial services, to be exceeded for no more than \( p_X \% \) of the time;
Equations (5) and (6) are similar in nature to Equations (1) to (4) [ORI 1987]. Long-term interference allowances are subdivided on a power basis and short-term interference allowances are subdivided on a percentage of time basis. In Equation (6), only some of the interference entries are assumed to be enhanced to their short-term values and therefore correlated. While these interference entries are at an enhanced level, all other entries are assumed to be at their long-term levels. The sum of these long-term levels is assumed to be \((n - yn)\) times the long-term single entry interference allowance.

4. Coordination thresholds and sharing criteria for earth stations sharing with terrestrial transmitters

4.1 Appendix 28 method and provisions

Appendix 28 of the Radio Regulations contains a method for the determination of the coordination area around an earth station in frequency bands shared between space services and terrestrial services. This topic is also the subject of Report 382. The procedures contained in these documents are based on parameters typical of radio relays for the terrestrial system. Large coordination areas (minimum distance = 100 km) are the result of use of these parameters. However, the number of interfering stations is assumed to be small.

The procedure can be used to determine coordination areas in frequency bands shared by EES and radio-relay systems upon adoption of specific parameter values for EES that are needed to apply the procedure. That such values are not available is conspicuous since the relevant tables in Appendix 28 contain columns for EES and METSAT but no values. This section explains how values for these parameters can be determined.

For earth stations operating with satellites in low earth orbits, Appendix 28 and Report 382 both apply simplified methods for taking into account the variability of earth station antenna gain on the statistics of interference. This report presents an alternative method for treating these effects which is more accurate than the present method.

While Appendix 28 has proven satisfactory for the initial purpose, it cannot be satisfactorily used to evaluate sharing feasibility or coordination area when the terrestrial systems consist of a large number of very low power transmitters (e.g. certain mobile or fixed services). Further study is required to develop a method that can be used for those cases.
4.2 Generalized coordination parameters for EES earth station receivers

One of two sets of generalized coordination parameters must be supplied for EES/METSAT earth station receivers in order to apply Appendix 28. These are:

1. \( P_0, P_r(p), M_0(p_0), n, B \)
2. \( P_0, n, J, M_0(p_0), W, T_e, B \)

where all terms are as defined in Appendix 28. In set 1, the short-term interference allowance must be expressed as a maximum permissible level of interference \( P_r \) which is to be exceeded from one interferer for no more than \( p \% \) of the time \( (p < 1) \). The factor \( B \) is the reference bandwidth. The factor \( M_0(p_0) \) is the difference in dB between the long-term (20%) and short-term (p%) interference allowances which, when considered with the factor \( y_n \) from Equation (6a) (number of correlated interference entries), establishes the following relationship (in dB):

\[
P_r(20) = P_r(p) - M_0(p_0) - 10 \log n \quad (7)
\]

The factor \( p_0 \) comes directly from the short-term interference allowance for the terrestrial station-earth station interaction (Equation (4b)). It is the cumulative percentage of time during which terrestrial stations are permitted to exceed the short-term interference threshold. The percentage of time \( p_0 \) is subdivided among \((1-y)n\) uncorrelated interference entries from terrestrial services to determine the permissible percentage of time \( p \) associated a single interferer.

Since the concern in Appendix 28 is with terrestrial transmitters whose interference entries can exceed the short-term threshold, the value of \( n \) is typically small. A terrestrial station would have to direct an e.i.r.p. of about 55 dBW in the reference bandwidth \( B \) toward an EES earth station in order to be a member of \( n \). Appropriate \( n \) values would lie in the range from 1 to 3.

In the second parameter set, the parameter \( J \) is the aggregate interference-to-thermal noise power ratio. Values for \( J \) may be determined from the long-term aggregate allowance for interference from terrestrial services (Equation (2)) and the thermal noise power assumed in the representative system (Report AE/2). The factor \( W \) adjusts the \( J \) values to account for the differences in degradation between thermal noise and the worst-case interfering signal modulation type. Typically, interfering signals produce degradation that is no worse than thermal noise of equal power and \( W \) would equal 0 dB. Only desired signals using high-index FM modulation would appear to warrant a higher \( W \) value \((W = 4\) for such systems in Appendix 28). The parameter \( T_e \) is the thermal noise power of the earth station receiving system at the antenna output port.

The difference between using the first and second sets of parameters is that with the second set of parameters, the actual thermal noise temperature of the earth station is applied. In any case, the threshold of permissible interference power may be adjusted in accordance with the antenna gain of the earth station using the method of Annex 1 to Report 1123.
5. Method to account for visibility and orbit statistics of satellites in low earth orbit

Both Appendix 28 and Report 382 recognize that the variations in gain due to variable pointing of earth station antennas which track low-orbiting satellites should be taken into account when calculating interference resulting from propagation conditions that occur for only small percentages of time. The methods given for accomplishing this adjustment substitute a time-invariant gain for earth station antenna gain towards the horizon. The gain to be used is either the value which is exceeded for 10% of the time (if known) or the value which is 10 dB less than the maximum gain, whichever is greater in the direction of interest. Annex I shows that these methods, while being simple to apply, result in coordination distances which are unnecessarily large.

In addition to variation in pointing direction, earth stations operating with low-orbiting satellites cannot operate 100% of the time because visibility to the satellites is limited by the satellite orbits. The probability that an earth station will be operating at the same time that propagation conditions cause enhanced interference should also be taken into account in the coordination area computations.

This section addresses an alternative procedure for evaluating interference based on the probability that enhanced interference, pointing in a particular direction, and earth station operation will all occur simultaneously.

5.1 Consideration of earth station operating time

Many earth exploration satellites are in polar, sun-synchronous orbits with altitudes between 500 and 1,000 km. The operation schedules for four user stations tracking four such satellites (two NOAA and two COSPAS satellites) were analysed [Texas Instruments, 1977]. The probability of tracking, averaged over five-day periods, ranged between 15% and 18% for earth stations near mid-latitudes. Thus, earth stations operating with several EES satellites in low-earth-orbit may typically receive transmissions for about 20% of the time or less.

The propagation model used in Report 382 is taken from Report 724. It predicts the relatively low transmission losses expected to occur on great-circle and rain-scatter paths for no more than a small percentage of the average year. Although the EES earth station may be receiving for about 20% of the time or less, the statistics of basic transmission losses occurring during reception can, as a worst case, be assumed to be the same as those occurring during the average year. Under this assumption, it is not necessary to make an adjustment to convert propagation statistics for the average year to account for the limited time of reception.
5.2 Alternative procedure for determining antenna gains toward the horizon for earth stations operating with satellites in low earth orbit

Appendix 28 and Report 382 provide simple methods for accounting for the variation in antenna gain of an earth station in the direction of the horizon when computing coordination distance on great-circle propagation paths. Annex I shows that this method overestimates the statistical effect of antenna gain and consequently results in unnecessarily large coordination distances. Further, if those methods were applied in a more detailed analysis of the probability of interference in the course of coordination (e.g. as in Report 448), the probability of interference would be overestimated.

Example calculations have shown that the simplified method of Appendix 28 overestimates the minimum required basic transmission loss by as much as 30 dB for time percentages between 0.01% and 0.1%. An error of this magnitude leads to coordination distances that are far greater than necessary. For example, using the new method resulted in reduction of coordination distance from 1,000 km to the minimum distance of 100 km for a path at 1700 MHz. For an example path at 7550 MHz, the reduction was from 270 km to 100 km.

Annex II presents an alternate method for treating earth station antenna gain in the determination of coordination distances resulting from great-circle propagation mechanisms. This method takes advantage of the fact that the propagation mechanisms are independent of the antenna gain of the earth station in the direction of a terrestrial station to make a more precise prediction of the statistics of interference. The greater complexity of this method is justified by the smaller coordination distances that result and the concomitant elimination of unnecessary coordinations. This alternate method is also applicable to analyses of the probability of interference, such as those conducted in the course of coordination.

6. Available sharing criteria

Sharing criteria to protect passive sensor operations in the 10.60 - 10.68 GHz band are prescribed in Footnote 831 of the Radio Regulations. The criteria contained in the footnote do not apply in certain countries.

Sharing criteria are suggested in Report 850 which would permit sharing in the 18.6 - 18.8 GHz band between passive sensors and the fixed service, the mobile service, and the fixed-satellite service.

No other sharing criteria pertaining specifically to the earth exploration-satellite service appear to exist. Further study is needed to determine suitable criteria for the EES.

7. Conclusions

A method for deriving sharing criteria and coordination thresholds has been described. It is based on subdivision of EES interference criteria among interferers to arrive at criteria to be applied to individual interferers. An approach to adoption of values needed to carry out coordination using Appendix 28 is given.
A new method is presented for determining coordination distances on great-circle paths from earth stations operating with satellites in low-earth-orbit. This method applies the statistics of earth station antenna pointing to arrive at smaller coordination distances for those earth stations without sacrificing the conservative nature of the present methodology in Appendix 28.

The methods contained in this report can be applied to develop sharing criteria and coordination thresholds for the earth exploration-satellite service.

REFERENCES


TEXAS INSTRUMENTS [1977] - Study of satellite emergency locater systems for the NASA Goddard Space Flight Center. Texas Instruments, Inc., Dallas, TX, USA.

ANNEX I

EFFECTS OF EARTH STATION ANTENNA TRACKING OF SATELLITES IN LOW EARTH ORBIT ON THE STATISTICS OF INTERFERENCE TO OR FROM TERRESTRIAL STATIONS

1. Introduction

Interference between terrestrial stations and earth stations tracking satellites in low Earth orbit is dependent on parameters whose values change with time. Specifically, the gain of the earth station antenna in the direction of a terrestrial station and the propagation losses vary in a statistically independent but predictable manner. This annex considers the effects of these parameters on interference and evaluates the accuracy of the approximate methods given in Report 382 and Appendix 28 of the Radio Regulations for treating these effects in the calculation of coordination distances.

2. Earth station antenna gain toward the horizon

The probability distributions of antenna gain toward the horizon have been analyzed for representative earth stations having the following characteristics:

- Earth Station Latitudes: 0, 35 and 65 degrees.
- Satellite Orbit: 825 km altitude, circular, 98.89 degrees inclination.
- Minimum Earth Station Elevation Angle: 3 degrees.
- Minimum Time of Visibility (above 3 degrees) During Which Tracking is Attempted: 1 minute.
Earth Station Antenna Diameters and Operating Frequencies:
2.44 meters, 1.7 GHz; 25.9 meters, 1.7 GHz and 7.55 GHz.
Earth Station Antenna Pattern: as given in Appendix 28.
Physical Horizon Angle (angle measured to the Earth horizon from a horizontal plane at the earth station antenna): zero degrees in all azimuths.

Figure 1 presents the results of the analyses for an interferer at an azimuth angle of 20 degrees in the Northern hemisphere. Among all azimuths and at all latitudes, this azimuth angle was found to result in the highest gain values for a given probability. It can be seen that higher gains become more probable at higher earth station latitudes and for small antennas.

The probabilities shown in Figure 1 are with respect to the time that a satellite is visible from the earth station which, for the given orbit is 3.05%, 3.73%, and 8.48% of the time for latitudes of 0, 35, and 65 degrees, respectively.

The coordination distance calculations of Report 382 (and Appendix 28) substitute a time-invariant earth station antenna gain for the actual gain. This gain is either 10 dB less than the maximum gain towards the horizon or is the gain exceeded for no more than 10% of the time, whichever is the greater. Table I presents the gain resulting from use of these methods for an azimuth of 20 degrees. For the situations analyzed, the gain used in Report 382 is consistently the value that is 10 dB less than the maximum gain toward the horizon.

TABLE I - Time-invariant antenna gain as calculated for use in Report 382 and Appendix 28.

<table>
<thead>
<tr>
<th>Antenna Diameter (meters)</th>
<th>Maximum Gain Towards the Horizon less 10 dB (dBi)</th>
<th>Gain (dB) Exceeded for No More Than 10% of the Time, for Latitudes:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0 degrees</td>
</tr>
<tr>
<td>2.44</td>
<td>18.6</td>
<td>5.1</td>
</tr>
<tr>
<td>25.9</td>
<td>10.1</td>
<td>-3.5</td>
</tr>
</tbody>
</table>

3. Minimum permissible basic transmission loss

Coordination distance is determined in Report 382 from the minimum permissible basic transmission loss given by the following equation:

\[ L_b(p) = P_t + G_t + G_r - P_r(p) \]  \hspace{1cm} (1)
where:

\( L_b(p) \): minimum permissible basic transmission loss (dB) to be exceeded for all but \( p \% \) of the time;

\( P_t \): maximum transmitter power (dBW) in the reference bandwidth at the input to the antenna of the interfering station;

\( G_t \): gain (dBi) of the transmitting antenna of the interfering station;

\( G_r \): gain (dBi) of the receiving antenna of the interfered-with station;

\( P_r(p) \): permissible level of interference (dBW) in the reference bandwidth to be exceeded for no more than \( p \% \) of the time at the terminals of the receiving antenna of the interfered-with station.

Annex II contains a more precise approach to treat the variability of earth station antenna gain which applies the estimated joint statistics of earth station antenna gain and basic transmission loss using an alternate form of Equation 1:

\[
I_r(p) = P_t + G_t + [G_r - L_b](p)
\]  

(2)

where:

\( I_r(p) \): interfering signal power (dBW) exceeded for \( p \% \) of the time.

Using the method of Annex II, the coordination distance is the distance at which the \([G_r - L_b](p)\) value in Equation 2 causes \( I_r(p) \) to equal the permissible level of interference to be exceeded for no more than \( p \% \) of the time.

Figure 2 presents cumulative distributions of basic transmission loss for the example 1.7 GHz and 7.5 GHz cases analyzed here for a distance of 100 km.

Figure 3 presents the cumulative distributions of \([G_r - L_b]\) (p) for the cases that have been analyzed. All results are for an azimuth of 20 degrees in the Northern hemisphere.

A comparison of values of \([G_r - L_b]\) (p) obtained with the more precise method of Annex II and the approximate approach of Appendix 28 and Report 382 (using Table I and Equation 1) reveals that the approximate approach overestimates the minimum required basic transmission loss by as much as 30 dB for time percentages between 0.01% and 1%. An error of this magnitude leads to coordination distances that are far greater than necessary. For example, if the method of Annex II were to result in a coordination distance of 100 km, the approximate approach of Report 382 with a 30 dB error leads to overly conservative coordination distances of about 1000 km and 270 km on the 1.7 GHz and 7.55 GHz paths of Figure 1, respectively.
FIGURE 1 - statistics of the gain towards the horizon for the assumed earth station.
FIGURE 2 - Basic transmission losses assumed for the analysis (100 km path)

1 : 1.7 GHz, climatic zone C         2 : 7.55 GHz, climatic zone A2
FIGURE 3 - statistics of gain minus loss (20 degree azimuth).
4. Discussion of results

The approximate method in Report 382 and Appendix 28 used to adjust the antenna gain of earth stations tracking low Earth orbit satellites (e.g., 825 km, 98.9 degree inclination) results in overly conservative coordination distances. The more precise method contained in Annex II requires the computation and convolution of the statistics of earth station antenna gain toward the horizon and basic transmission losses on great-circle signal paths. The added complexity of this approach is compensated by the smaller coordination distances achieved and the reduced administrative burden of coordination.

ANNEX II

METHOD FOR DETERMINING COORDINATION DISTANCES ON GREAT-CIRCLE PATHS FOR EARTH STATIONS OPERATING WITH SATELLITES IN CIRCULAR LOW-EARTH-ORBITS

1. Introduction

This annex presents a step-by-step procedure for determining coordination distances on great-circle paths for earth stations operating with satellites in low-Earth-orbit. This method requires iteration of estimated distances in each azimuth to determine the distance at which the interfering signal power exceeds the permissible level of interference for no more than p% of the time. A summary of the steps involved is presented, approaches for performing the calculations are given, and an example is provided.

2. Summary of the procedure

Step 1. Determine the statistics of gain of the earth station antenna, toward the horizon, in the azimuths for which coordination distances will be calculated (e.g., every five degrees). This can be accomplished using a reference antenna gain pattern for the earth station (e.g., as given in Appendix 28, or a measured pattern) and a computer simulation of tracking by the earth station antenna of the anticipated satellites. (See Section 3).

Step 2. For a selected azimuth, make an initial estimate of the coordination distance using the method of Report 382, but with the assumption that the earth station antenna gain toward the horizon is at its minimum value.

Step 3. For the interference path determined in Step 2, compute the cumulative distribution of basic transmission loss using the methods of Report 724 for percentages of time less than 1% and the methods of Report 569 for other percentages of time. Insofar as the minimum coordination distance is 100 km, and many details of the potential interference situation are not known when computing coordination distance, it is reasonable to assume that the cumulative distribution of basic transmission loss is symmetric about its mean value (i.e., calculations need be made only for time percentages of 50% or less). Further, a sufficiently accurate distribution can be interpolated and extrapolated from values calculated for 50%, 20%, 10%, 5%, 1%, 0.1%, 0.01% and 0.001% of the time.
Step 4. For the path of Step 3, determine the cumulative distribution of the earth station antenna gain minus basic transmission loss by performing convolution of the statistics determined in Steps 1 and 3. (See Section 4).

Step 5. For the path of Step 3, compare the permissible level of interference with the interference level calculated in Step 4 for the percentage of time \( p \) associated with the permissible level of interference. The following Equations should be used for this purpose (based on Equation 2 of Report 382):

\[
I(p) = P_T + G_{\text{terr}} + [G_{\text{es}} - L](p) \tag{1}
\]

\[
e = P_T(p) - I(p) \tag{2}
\]

where:

- \( I(p) \): Interference power (dBW) predicted to occur for no more than \( p\% \) of the time;
- \( P_T \): Transmitter power (dBW), in the reference bandwidth, at the input to the antenna of the interfering station;
- \( G_{\text{terr}} \): Antenna gain (dBi) of the terrestrial station towards the earth station;
- \([G_{\text{es}} - L](p)\): Earth station antenna gain minus basic transmission loss exceeded for no more than \( p\% \) of the time (from Step 4);
- \( e \): Amount (dB) by which the permissible level of interference \( P_T(p) \) exceeds the level of interference predicted for the path.

Step 6. Increase or decrease the estimated coordination distance (e.g., from Step 2) for negative or positive values of the parameter \( e \), respectively, to make the value for the parameter \( e \) converge to zero. Steps 3 through 5 must be performed in iterative fashion using adjusted distance estimates until \( e \) becomes sufficiently small. A good estimate for a new value of distance to use is that distance different from the preceding value by an amount which increases or decreases \( L \) by about \( "e" \) dB. The distance which results in \( 0 < e < 1 \) dB is the mode 1 coordination distance for the selected azimuth.

Step 7. Repeat Steps 2 through 6 for other azimuths at 5 degree increments. Depending on the variations encountered in radio climatic zones and the physical horizon angle from azimuth to azimuth, a good first estimate of coordination distance (Step 2) may be based on the coordination distance determined for the adjacent azimuth.

3. Determination of antenna gain statistics (Step 1)

3.1 Coordinate system used for analysis

The coordinate system used for satellite orbital computations is inertial (i.e., fixed with respect to the Earth's centre and non-rotating). The origin is the Earth's centre. The unit vectors in the coordinate system are defined with respect to the earth at time 0 in the problem. The x-direction is through the
point 00 degrees north, 000 degrees east at time 0, (i.e., the
equator at the Greenwich meridian). The y-direction is through
the point 00 degrees north, 090 degrees east at time 0. The z-
direction is through 90 degrees north, (i.e., the north pole).
Units of length are kilometers, but Earth radii are also
typically used.

It is convenient to convert from the inertial coordinate system to an
Earth-fixed, (non-inertial) rotating coordinate system. This system
rotates eastwards about the inertial z-axis at the Earth’s rate of
rotation and is considered to be coincident to the inertial system at
time 0. In addition, for the case of a sun-synchronous orbit, we make
a correction to the Earth rotation rate to account for the non-
Keplerian precession of the orbit.

### 3.2 Satellite position at time \( t \)

For circular orbits, such as this case, the following Keplerian
orbital parameters are used:

- \( R_s \): Orbital radius - the distance from the Earth center to
  the satellite.

- \( i \): Inclination angle (degrees) - angle between the orbital plane
  and the Earth’s equatorial plane. The angle is less than 90
  degrees if the satellite is heading eastwards as it
  crosses the equatorial plane from south to north;
  greater than 90 degrees if it is heading westward; and
  exactly 90 degrees for a polar orbit.

- \( \Omega \): Longitude (degrees) of ascending node - angle in the
  equatorial plane between the y unit vector and the satellite
  as it crosses the equatorial plane from south to north.
  If \( i = 0 \), set \( \Omega \) to 0.

- \( M(0) \): Mean anomaly (radians) - angle in the satellite orbital plane
  from the point where the satellite crosses the equatorial
  plane from south to north to the satellite position at time
  0. If \( i = 0 \), \( M(0) \) is measured from the x unit vector to the
  satellite position at time 0.

In addition, for sun-synchronous satellites, a non-Keplerian
parameter is used:

- \( \Delta L \): Precession of longitude of ascending node, measured in
  degrees eastward per year. For a sun-synchronous
  satellite,

\[
\Delta L = 2\pi \text{ radians/year} = 1.9911 \times 10^{-7} \text{ radians/sec}
\]

The inertial position of the satellite at time \( t \),
\( \text{SI}(t) = (S_{ix}, S_{iy}, S_{iz}) \), is calculated as follows. The orbital period
of the satellite is given by:

\[
T_s = \text{orbital period} = O_{\text{const}} \times R_s^{-1.5} \tag{3}
\]

\[
\Delta M = \text{mean orbital rate} = 1 / T_s \tag{4}
\]

where:

\[
O_{\text{const}} = \text{orbital constant} = 1 / (9.952004586 \times 10^{-3}) \text{ sec/(km}^{1.5}\text{)}
\]
Then:

\[ M(t) = \text{Mean anomaly at time } T = \Delta M \times t + M(0) \]  

(5)

and, finally:

\[ S_{IX} = R_s \times \cos(\mu) \times \cos(M(t)) \]
\[ S_{IY} = R_s \times \sin(\mu) \times \cos(i) \times \sin(M(t)) \]
\[ S_{IZ} = R_s \times \sin(i) \times \sin(M(t)) \]

(6a)  

(6b)  

(6c)

We then rotate the inertial position \( S_I(t) \) westward to the Earth-fixed rotating coordinate system to obtain the satellite position \( S(t) = (S_X, S_Y, S_Z) \), as follows:

\[ S_X = \cos(\Delta E \times t) \times S_{IX} - \sin(\Delta E \times t) \times S_{IY} \]
\[ S_Y = \sin(\Delta E \times t) \times S_{IX} + \cos(\Delta E \times t) \times S_{IY} \]
\[ S_Z = S_{IZ} \]

(7a)  

(7b)  

(7c)

where:

\[ \Delta E = \Delta E' - \Delta L \]  

(8)

\[ \Delta E' = \text{actual rotation rate of earth eastward in inertial frame} \]
\[ = 7.292115856 \times 10^{-5} \text{ radians/sec} \]

It should be noted that for non-circular orbits, the calculation of the satellite position \( S(t) \) is much more complicated. A highly recommended technique adapted for computer use is the universal variable formulation given in chapter 4 of [Bate et al., 1971]. The calculations shown here are also described in Bate, chapters 1, 2, and 4.

3.3 Earth station geometrical parameters

Given an earth station at Lat degrees north latitude and Lon degrees east longitude, let

\[ R_e = \text{radius of the Earth} \]

If the Earth station position is \( E = (E_X, E_Y, E_Z) \), then

\[ E_X = R_e \times \cos(\text{Lon}) \times \cos(\text{Lat}) \]
\[ E_Y = R_e \times \sin(\text{Lon}) \times \cos(\text{Lat}) \]
\[ E_Z = R_e \times \sin(\text{Lat}) \]

(9a)  

(9b)  

(9c)

Let \( H(a, el_T) = (H_X, H_Y, H_Z) \) be a unit vector from the earth station toward the terrestrial horizon, where:

\[ a: \text{azimuth toward the point on the horizon, degrees} \]
\[ el_T: \text{elevation angle of the terrestrial horizon above the local horizontal of the earth station, degrees} \]
Then:

\[
H_x = -\cos(Lon) \times \sin(Lat) \times \cos(a) \times \cos(elt) \\
+ \cos(lat) \times \cos(lon) \times \sin(elt)
\]

\[
H_y = -\sin(Lon) \times \sin(Lat) \times \cos(a) \times \cos(elt) \\
+ \cos(Lon) \times \sin(a) \times \cos(elt) \\
+ \cos(lat) \times \sin(lon) \times \sin(elt)
\]

\[
H_z = \cos(Lat) \times \cos(a) \times \cos(elt) \\
+ \sin(lat) \times \sin(elt)
\]

Given \( S(t) \) and \( E \), then \( S(t)-E \) is the vector from the earth station to the satellite.

The off-axis angle \( \varphi(t) \) is the angle between the antenna mainbeam at time \( t \) and a point of interest (transmitting or receiving terrestrial station), measured at the location of the earth station antenna. If the antenna is at location \( E \), pointing at the satellite at \( S(t) \), and the terrestrial station is considered to be in the direction "a" of the unit vector \( H(a) \) pointing at the horizon from the earth station, then

\[
\varphi(t) = \cos^{-1} \left[ \frac{(S(t)-E) \cdot H(a)}{|S(t)-E|} \right]. 
\]

The antenna elevation angle at time \( t \) is

\[
el(t) = \sin^{-1} \left[ \frac{E \cdot (S(t)-E)}{R_e \times |S(t)-E|} \right]
\]

where:

\((S(t)-E) \cdot H(a)\) is the scaler product of two vectors

\(|S(t)-E|\) is the length of the vector

3.4 Statistics of antenna gain toward a point on the horizon

Antenna gain \( G(\varphi(t)) \) at off-axis angles \( \varphi(t) \) may be determined using a relevant reference pattern (e.g., that given in Annex II of Appendix 28).

We are interested in the function \( P(g) \), where \( P(g) \) is the probability that the gain \( G(\varphi(t)) \) of the earth station \( E \) in the direction \( H(a) \) of the horizon point exceeds some arbitrary value, \( g \), given that the satellite position \( S(t) \) is above some minimum elevation angle, \( \text{elmin} \). Suppose we observe the value of \( G(\varphi(t)) \) for some period of time, \( T \). Then we can estimate \( P(g) \) by

\[
P(g) = \frac{\text{Total time } G(\varphi(t)) \geq g \text{ and } el(t) \geq \text{elmin}}{\text{Total time } el(t) \geq \text{elmin}}
\]
A more formal expression for \( P(g) \) is

\[
P(g) = \lim_{T \to \infty} \frac{\int_{0}^{T} x(g,t) \times y(t) \, dt}{\int_{0}^{T} y(t) \, dt}
\]  

(14)

where, when solved using numerical integration,

\[
x(g,t) = \begin{cases} 
1 & \text{if } g - \epsilon < G(\Phi) \leq g + \epsilon \\
0 & \text{otherwise}
\end{cases}
\]

\[
y(t) = \begin{cases} 
1 & \text{if } e(t) \geq e_{\text{min}} \\
0 & \text{otherwise}
\end{cases}
\]

There is no closed form solution for \( P(g) \), and thus we must integrate the equation numerically. The solution is facilitated by the definition of \( x(g,t) \) because gain statistics can be accumulated into bins (e.g., bins 1 dB wide) between the maximum and minimum values of gain. If the satellite repeats its ground track periodically, equation (14) can be integrated over the period and a solution found. In general, \( T_e \) and \( T_s \) will not have a common periodicity. In this case, we can form a double integral: the inner integrated with respect to time between the limits of 0 and \( T_s \); the outer integrated with respect to \( \Phi \) (longitude of the ascending node) between the limits of 0 and 360 degrees.

\[
P(g) = \int_{0}^{360} \left[ \int_{0}^{T_s} x(g,t) \times y(t) \, dt \right. \\
\left. \quad \int_{0}^{T_s} y(t) \, dt \right] \, d\Phi
\]  

(15)

Efficiency and accuracy in solving for \( P(g) \) requires judicious choice of step size for time \( (dt) \) and longitude of the ascending node \( (d\Phi) \). For satellites in highly inclined orbits, good results can be achieved with the following steps for \( d\Phi \):

- 0.25 degrees for earth station latitudes less than 35 degrees
- 0.3 degrees for earth stations between latitudes of 35 and 55 degrees
- 0.4 degrees for earth station latitudes greater than 55 degrees.

Smaller steps in \( d\Phi \) should be used for satellite orbits inclined less than 70 degrees or more than 110 degrees.

Appropriate choice of steps for \( dt \) can be made using the following equation:

\[
dt = d\Phi/\Delta M
\]  

(16)
The values of gain probability $P(g)$ obtained from equation (15) define the probability density function of gain. This function is used to determine the statistics of gain minus loss.

4. Determination of statistics of antenna gain minus basic transmission loss (Step 4)

Given the statistics of antenna gain ($P(g \leq G_{es})$) and basic transmission loss ($P(l \leq L)$), values for the parameter $[G_{es} - L](p)$ in Equation 1 are obtained from a reverse cumulative distribution function defined as follows:

$$P(g - l \geq Z): \text{reverse cumulative distribution function (dB),}$$

(i.e., the probability that a value for the random variable $(g-1)$ is greater than or equal to some arbitrary level $Z$);

$g$: antenna gain (dBi), a random variable;

$l$: basic transmission loss (dB), a random variable;

$Z$: arbitrary value (dB) for the parameter $(g - l)$;

The reverse cumulative distribution $P(g - l \geq Z)$ can be determined by a convolution of $P'(g \leq G_{es})$ and $P(l \leq L)$ (where $P'(g)$ is the density function of $P(g \leq G_{es})$, i.e., $d/dg P(g \leq G_{es})$) as follows:

$$P(g - l \geq Z) = 1 - P(g - l \leq Z) \quad (17a)$$

$$= 1 - \begin{cases} P'(g \leq G_{es}) \times P(l \geq G_{es} - Z) \, dg & \text{if } G_{es} = G_{max} \\ G_{es} = G_{min} \\ G_{es} = G_{max} \end{cases} \quad (17b)$$

$$= 1 - \begin{cases} P'(g \leq G_{es}) \times (1 - P(l \leq G_{es} - Z)) \, dg & \text{if } G_{es} = G_{min} \\ G_{es} = G_{max} \end{cases} \quad (17c)$$

where:

$G_{min}$: minimum level of antenna gain (dBi) towards the horizon;

$G_{max}$: maximum level of antenna gain (dBi) towards the horizon;

$P'(g \leq G_{es})$: density function of antenna gain (dBi), (i.e., from Equation 15).

5. Computer implementation of Step 1 (gain statistics) and Step 4 (determination of statistics for gain minus loss)

Two computer programs have been developed for accomplishing Steps 1 and 4 and are available through the ITU, [ARC, 1989]. They are coded in ANSI FORTRAN 77 (with the additional use of "INCLUDE" statements available in most FORTRAN compilers) in source-code suitable for implementation on virtually any computer having a FORTRAN compiler.
The first program provides statistics of earth station antenna gain toward the horizon. The second program produces statistics of gain minus basic transmission loss. The results of useful intermediate calculations are also optionally available. Default values are automatically used (but optionally adjusted) for parameters affecting the accuracy of all integrations. The following inputs are required:

- Azimuth(s) for which calculations will be done and associated physical horizon angles;
- Earth station latitude and longitude;
- Minimum earth station antenna elevation angle at which transmission or reception will take place and the minimum time that a satellite must be above that angle;
- Frequency and antenna diameter (for use with Appendix 28 reference antenna pattern);
- Orbit altitude and inclination;
- Annual precession of the longitude of the ascending node;
- Set of basic transmission losses vs. % of time (obtained in Step 3).

The programs can be exercised with a PC class computer having a minimum memory size of 128 k (if the compiled code supplied with the reference is used, a math co-processor is required). This configuration will handle 24 azimuths in one run of program 1 (program 2 makes calculations for one azimuth at a time). On a PC XT type computer, program one can calculate gain statistics for 24 azimuths in 10-15 minutes. Program 2 will calculate gain minus loss statistics for one azimuth in much less than one minute.

6. Example calculation of coordination distance

An example of the calculation of coordination distance for a great circle path is presented below for an earth station in the meteorological-satellite service. The station is located at the equator. An antenna diameter of 25.9 m operating at 1700 MHz has been used. The interfering signal path has no terrain blockage (i.e., a physical horizon angle of zero degrees), is contained in radio-climatic zone A2 (i.e., land not near a large body of water), has a type 1 equatorial climate, and has an azimuth of 20 degrees from the earth station (clockwise, from north). The satellite is in a circular orbit at an altitude of 825 km and inclination of 98.89 degrees. Further, the minimum antenna elevation angle is 3 degrees, and the minimum time of satellite visibility (above 3 degrees elevation) required is one minute. Other assumptions are stated where used in the following step-by-step presentation.
6.1 Step 1: antenna gain statistics

The reference antenna gain pattern of Annex II of Appendix 28 is used with the method given in Section 3 of this Annex to compute the statistics of antenna gain toward the horizon. The orbital period $T_S$ is found from Eq. 3 to be $6.086 \times 10^3$ sec (101.44 minutes), the satellite is sun-synchronous giving a precession of the ascending node $L$ of $2\pi$ radians/year, and the orbital rate $M$ is found from Equation 4 to be 0.059 degrees per second.

Equation 10 is solved to determine the unit vector $H(a)$ in the azimuth $\theta$ of 20 degrees from the earth station. Equations 6 and 7 are now solved to determine satellite positions $S(t)$, and Equations 12 and 11 are solved for the associated elevation angles $\theta(t)$ and off-axis angle to the horizon ($\phi(t)$). These angles are used to calculate the gains $(G(\phi(t)))$ using the reference antenna pattern.

Equation 15 is used for each satellite pass with time intervals $(dt)$ of 0.25 seconds to determine the cumulative time that the gain falls in each one dB increment between $-10$ dB ($G_{\min}$) and 20.1 dB ($G_{\max}$). The results are accumulated if the elevation angle exceeds 3 degrees and if the elevation angle is greater than 3 degrees for at least one minute. The variable $\alpha$ is incremented by 0.25 degrees and the process is repeated over the range of $\alpha$ over 0 to 360 degrees.

The result of carrying out the procedure described above is the density function of gain toward the selected horizon point. Curve 1 in Figure 1 of Annex I shows the cumulative distribution of antenna gain toward the horizon which results from applying the method of this annex to the example case described in this Section.

6.2 Step 2: initial estimate of coordination distance

Equation 6 of Report 382 is used to make the initial estimate of the coordination distance. This Equation is as follows (using parameters defined in Report 382):

$$L_X(p_X) = 120 + 20 \log f + d(0.01 + B_0 + B_V + B_Z) + A_h$$

Equation 11 of Report 382 is used to determine a value for the parameter $L_X(p_X)$, assuming that $p_X = p$. Note that $p$ is the percentage of time associated with the short-term permissible level of interference, $P_T(p)$. The assumption of $p = p_X$ is reasonable for the assumed earth station according to Report 724, in that the difference between permissible levels of interference for $p$% of the time and 20% of the time is less than 15 dB (e.g. see Report AC/2). Using this assumption, Equation 11 of Report 382 would be as follows:

$$L(p) = P_T + G_e + 42 + \Delta G - P_T(p)$$

Based on Report AC/2, the permissible level of interference, $P_T(p)$, is taken to be -124 dBW/5.334 MHz. This level is to be exceeded for no more than $p = 0.006$% of the time. The antenna gain of the terrestrial station transmitter ($42 + \Delta G$) is 42 dBi according to Report 382 (for line of sight systems), and its antenna input power level $P_T$ is assumed to be 13 dBW in the reference bandwidth of 5.334 MHz. The 13 dBW power level is given in Report 382 as the level in a one MHz reference bandwidth, but is assumed here to be applicable for the wider reference bandwidth. The earth station antenna gain toward the horizon, $G_e$, is taken to be -10 dBi from Figure 1 of Annex 1. Thus, from Equation 19 above, $L(p) = 169$ dB.
For Equation 18, the total specific attenuation, (i.e. the distance coefficient, dB/km, 0.01 + 2B) is computed using Equations 7 to 9 of Report 382. For the assumed path in zone A2, the distance coefficient is 0.11 dB/km. The coordination distance estimated from Equation 18 (assuming no terrain shielding, i.e. $A_h - 0$ dB) is 403 km.

6.3 Step 3: distribution of basic transmission loss

The statistics of basic transmission loss were determined for a path of 403 km using the methods of Report 724 for percentages of time of 1% or less and Report 569 for other time percentages. For percentages of time greater than 1%, the tropospheric forward scatter mode of propagation is found to produce lower values of basic transmission loss than the other possible modes of propagation defined in Report 569. In order to determine basic transmission loss for this mode, "Method I" of Report 238 is applied with the assumption of 0 dB of aperture-to-medium coupling loss, an equatorial (type 1) climate, an annual mean refractivity (Ns) of 350, and antenna heights of 30 m and 100 m for the earth station and terrestrial station, respectively. These assumptions lead to conservatively low values of basic transmission loss, consistent with the purpose of coordination distances. The resulting losses are shown in Table I for the first (and second and third) estimated coordination distances.

![Table I - statistics of basic transmission loss](image)

6.4 Step 4: distribution of gain minus loss

The method of Section 4 is used to determine the statistics of gain minus loss for the estimated coordination distance of 403 km. Using the density function of earth station antenna gain toward the horizon (from Equation 15) and interpolation of the basic transmission losses given in Table I, Equation 17 is used to determine the cumulative distribution of gain minus loss. The resulting value of gain minus loss associated with 0.006% of the time is found to be -172 dB.
6.5 Step 5: comparison of predicted and permissible interference

The value calculated in Section 6.4 for gain minus loss is used with Equation 1 of Section 2 to determine the interference predicted to occur for no more than 0.006% of the time. This interference power level is -117 dBW, which is 7 dB higher than the permissible level, i.e., the parameter "e" from Equation 2 is 7 dB.

6.6 Step 6: adjustment of estimated coordination distance

Since the permissible interference power level is 7 dB less than the interference level predicted for the estimated coordination distance of 403 km, it is clear that the second estimate of coordination distance must be somewhat larger. A tentative second estimate of 440 km was made and the associated statistics of basic transmission loss were determined under Step 3 (see Table I). By comparing these statistics with those for the initial estimated distance of 403 km, it is seen that the losses are generally increased by less than the value for "e". Thus, the estimated distance was further increased to 460 km to increase the basic transmission losses before proceeding to Step 4. The losses associated with the 460 km estimate are greater than those for the 403 km path by amounts near the "e".value of 7 dB, so 460 km is used as the second estimate in repeating Steps 4 and 5.

The 460 km distance results in a value for (G - L)(0.006) of -179 dB in Step 4. In Step 5, the associated prediction of interference power (0.006) is -124 dB W, which equals the permissible level of interference. Accordingly, the coordination distance in the azimuth under consideration is 460 km.

In computing a coordination distance for the next azimuth, the 460 km distance would be used as the initial estimate, provided that the radio climatic zone(s) and physical horizon angle remains unchanged. In that case, only the statistics of antenna gain (Step 1) might change. (However, note that the statistics of antenna gain are essentially independent of azimuth for earth stations near the equator, as in this example). In other cases where climatic zones or physical horizon angles change from azimuth to azimuth, the anticipated effect of these changes can be used to deduce a good first estimate of coordination distance on the basis of the coordination distance for the adjacent azimuth.

REFERENCES

ARC [1989] - Computer programs for determining and applying the statistics of interference between terrestrial stations and earth stations operating with satellites in low-earth-orbit. Atlantic Research Corporation, Landover, MD, USA

PREFERRED FREQUENCY BANDS AND POWER FLUX-DENSITY
CONSIDERATIONS FOR EARTH EXPLORATION SATELLITES
(Questions 11/2 and 12/2, Study Programme 12A/2)
(1978-1982-1986)

1. Introduction

In recognition of the potential usefulness of Earth exploration satellites, frequency bands have been
allocated in the Radio Regulations for telemetering data from Earth exploration satellites in Bands 9 and 10
(2200 to 2290 MHz and 8025 to 8400 MHz) for direct read-out and 25.25 to 27.5 GHz for acquisition of data via
data relay.

Applications planned for Earth exploration satellites may be restricted by the power flux-density limits
which apply to the frequency bands used by the satellites' radiocommunication systems.

The purpose of this Report is to present the factors which influence the selection of frequencies for
transmissions of wideband data from Earth exploration satellites as well as to present the power flux-density levels
needed by Earth exploration satellite applications.

This Report does not deal with selection of operating frequencies for satellite housekeeping telemetry. It
also does not deal with frequency selection for microwave sensors or with power flux-densities produced by active
microwave sensors which are discussed in Report 693.
2. Frequency selection criteria

There are several important criteria which must be satisfied in choosing frequencies for transmission of wideband data from Earth exploration satellites.

- Adequate bandwidth must be available for present and future sensor data requirements.
- Harmful interference must not exist either to or from services sharing common frequency bands.
- Power flux-densities must be permitted which are sufficiently high that Earth exploration satellite applications are not significantly compromised.
- Spacecraft and ground station data acquisition systems must be technically and economically viable.

3. Sensor data rate requirements

Basic to the problem of frequency selection is the need to provide sufficient bandwidth for the data output of the spacecraft sensors. The data rates produced by Earth exploration satellite sensors are extraordinarily high, and hence bandwidth requirements are much greater than for many other space systems.

It is also necessary to ensure that there is no overlap between the frequencies used in the spacecraft communications system and the spectral region covered by the sensors.

Sensors include a thematic mapper which produces data at a rate of 84 Mbit/s. This sensor is used in the LANDSAT programme.

Future sensors under consideration include a High Resolution Pointable Imager (HRPI) which will have a data rate of around 120 Mbit/s.

It will be necessary to multiplex data when a satellite carries two or more sensors. A satellite carrying a thematic mapper and an HRPI will generate a composite data rate of 204 Mbit/s. The bandwidth required for this signal, a guard band, and a 20 Mbit/s signal for transmission to low cost data acquisition facilities is approximately 350 MHz.

Earth resources scientists predict that data rate requirements for optical type sensors may ultimately reach rates five times that of the present thematic mapper. This could result from either increased scan width or resolution. Such an increase would produce data rates up to 600 Mbit/s from a single sensor, requiring bandwidths of the order of 800 MHz.

4. Spacecraft and ground station consideration

4.1 Major data acquisition facilities

Among the factors influencing design of Earth exploration satellites are the availability and the costs of data acquisition facilities to operate the satellites. Earth exploration satellite communication links in the United States have been designed for 9 m diameter data acquisition antennas. In addition to the economic advantage of using existing data acquisition antennas, there are technical reasons why 9 m diameter antennas are near optimum for Earth exploration satellites. Communication link requirements can be satisfied using available, convenient components on board the satellite. Above 10 GHz, the surface accuracy and the control system accuracy of the data acquisition antenna, become limiting factors on the design of the communications link. At frequencies near 20 GHz, 9 m approaches the limiting size for an economical antenna constructed using conventional techniques. For these reasons, 9 m will be used as a given parameter for the size of the data acquisition antenna in determining power flux-density requirements for the radiocommunications link from Earth exploration satellite to major data acquisition facility.

With the technology available today, a viable communications link cannot be accommodated above 20 GHz because of the required data rates. At low elevation angles, link losses under moderate rain conditions are about 28 dB greater near the 20 GHz band than in the 8025 to 8400 MHz band. Existing ground station antennas designs provide insufficient gain and control systems accuracy to satisfy the communications requirement with available spacecraft components. On the other hand, technology is available to provide the spacecraft e.i.r.p. required to meet mission requirements in the 8025 to 8400 MHz Earth Earth exploration-satellite allocation. At the present time, the upper limit of technically suitable frequencies for transmission of Earth exploration-satellite data to Earth is approximately 20 GHz.
Another problem would occur if frequencies near sensor operating frequencies were used for data communications. For example, one of the sensors developed by earth resources scientists is a microwave radiometer which utilizes frequencies near the 22.235 GHz water vapour line to measure atmospheric water vapour. Technology does not exist to shield the radiometer from interference from the communications transmitter if it were to operate just above 20 GHz. It would not be possible to operate the radiometer and the data communications system simultaneously.

4.2 Low cost data acquisition facility

Small, low-cost data acquisition facilities are under consideration for future Earth exploration-satellite systems. These terminals will be used in order to provide real-time data delivery to the user community. The satellites will transmit selected data to these terminals at reduced data rates. Twenty Mbit/s data rates are contemplated for these communications links.

Since local users will acquire data over limited regions, receiving antenna angles will never be less than 30° above the horizon. Data error ratios are required to be no greater than $10^{-5}$.

The primary design constraint for these terminals is economic. Costs must be held to a minimum in order to make the facility available to a maximum number of users.

Cost can be minimized by increasing the satellite e.i.r.p. to reduce the required ground antenna size and quality of the preamplifier. Impact of costs for these components is assumed to be negligible if they comprise less than 10% of the total cost of the low cost data acquisition facility. This criterion can be achieved if the ground antenna is limited in size to a 0.3 m diameter parabola and a preamplifier noise temperature of 200 K is used for the frequency bands being considered.

These two parameters (0.3 m diameter ground antenna, 200 K preamplifier noise temperature) will determine the power flux-density required at the Earth's surface for the communications link from Earth exploration satellites to low cost data acquisition facilities.

4.3 Tracking and data relay satellite

A research tracking and data relay satellite (TDRS) designed by the United States of America provides two-way radiocommunications to and from experimental Earth exploration satellites and other research Earth satellites. The system relays these communications and data to one or more fixed earth stations within view of the relay satellites. At the same time, the research satellites which receive communications relay support from the TDRS, may require communication of some of the data directly to and from fixed earth stations not associated with the TDRS.

Operational Earth exploration satellites may require a similar data relay satellite for data acquisition. Preferred frequencies and sharing aspects of an operational relay satellite system in the Earth exploration satellite service are discussed in Report 982.

The design of the TDRS is such, that user satellite data rates up to 300 Mbit/s will be accommodated. Equivalent isotropically radiated power (e.i.r.p.) of 60 dBW will be required from the user for 300 Mbit/s data rates. A 2.5 m parabolic antenna having $-10$ dBi median backlobe and sidelobe pattern which follows the CCIR equation, $32 - 25 \log \theta$, is representative of the antenna that will be needed on the Earth exploration satellite.

5. Power flux-density (pfd) analysis

Radiocommunication link parameters contained in Table I were used to determine power flux-density levels commensurate with Earth exploration satellite applications. The analysis was carried out for the allocated frequency bands of 8025 to 8400 MHz as well as in the vicinity of 20 GHz.

Values given in Table I are based on 120 Mbit/s quadruphase shift keyed data on the path from the Earth exploration satellite to the major data acquisition facility and 20 Mbit/s bi-phase shift keyed data on the path from Earth exploration satellite to low cost data acquisition facility. These signals were chosen as representative of systems currently being designed in the United States. A change of data rate, however, would not affect the requirements for pfd. The analysis assumed an error ratio requirement of $10^{-5}$ during moderate rainfalls of 4 mm per hour. Appropriate link design and pfd limits should be considered for regions of the world with higher rainfall rates to maintain satisfactory performance.
Values determined for satellite e.i.r.p. are contained in Table I.

<table>
<thead>
<tr>
<th>Radiocommunication link</th>
<th>Frequency bands</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>8025 to 8400 MHz Major facility</td>
</tr>
<tr>
<td>System temperature (K)</td>
<td>266</td>
</tr>
<tr>
<td>System noise (dBm)</td>
<td>−93.6</td>
</tr>
<tr>
<td>System margin (dB)</td>
<td>−3.0</td>
</tr>
<tr>
<td>Required S/N (dB)</td>
<td>12.0</td>
</tr>
<tr>
<td>Required receive signal (dBm)</td>
<td>−78.6</td>
</tr>
<tr>
<td>Nominal ground antenna gain (dB)</td>
<td>55.5</td>
</tr>
<tr>
<td>Antenna surface tolerance loss (dB)</td>
<td>−0.3</td>
</tr>
<tr>
<td>Antenna pointing loss (dB)</td>
<td>−0.5</td>
</tr>
<tr>
<td>Receive circuit loss (dB)</td>
<td>−0.5</td>
</tr>
<tr>
<td>Free space loss (dB)(1)</td>
<td>−181.0</td>
</tr>
<tr>
<td>O\textsubscript{2}/H\textsubscript{2}O absorption loss (dB)</td>
<td>−0.6</td>
</tr>
<tr>
<td>Precipitation loss (4 mm/h) (dB)</td>
<td>−0.8</td>
</tr>
<tr>
<td>Cloud loss (dB)</td>
<td>−1.9</td>
</tr>
<tr>
<td>Satellite antenna pointing loss (dB)</td>
<td>−3.0</td>
</tr>
<tr>
<td>Satellite required e.i.r.p. (dBm)</td>
<td>53.9</td>
</tr>
</tbody>
</table>

(1) Calculation based on a 1000 km orbit. Loss calculated at 5° elevation angle link to major data acquisition facility and at 30° elevation angle for link to low cost data acquisition facility. Elevation angle of low cost acquisition facility angle is restricted to values above 30°.

The calculation for the resultant pfd is performed for the maximum value, ignoring variable increases in propagation losses as well as pointing error of the satellite antenna:

\[
pfd_{\text{max}} = 10 \log (4 \text{ kHz}) + \text{e.i.r.p.} - 10 \log \frac{BR}{2} - 10 \log 4\pi D^2
\]

(1)

for quadriphase modulation, and

\[
pfd_{\text{max}} = 10 \log (4 \text{ kHz}) + \text{e.i.r.p.} - 10 \log BR - 10 \log 4\pi D^2
\]

(2)

where:

\[BR\] bit rate
\[D\] distance

for bi-phase modulation. Both equations assume phase-shift keying (PSK) transmission and non-return to zero (NRZ) coding format.

Since the Earth exploration satellite may have a mode of transmission where one wideband sensor is turned off and therefore the data rate is reduced by a factor of 2 while the same power will be radiated within only half the bandwidth, the calculated pfd must be increased by 3 dB for the link to the major data acquisition facility.
The results of the analysis are shown below:

<table>
<thead>
<tr>
<th>Region</th>
<th>8025 to 8400 MHz</th>
<th>In the region of 20 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>pfd max (major data facility)</td>
<td>-145.8 dB(W/(m^2 \cdot 4 kHz))</td>
<td>-98.9 dB(W/(m^2 \cdot MHz))</td>
</tr>
<tr>
<td></td>
<td>(at 90°)</td>
<td>(at 90°)</td>
</tr>
<tr>
<td>pfd max (low cost facility)</td>
<td>-123.8 dB(W/(m^2 \cdot 4 kHz))</td>
<td>-92.1 dB(W/(m^2 \cdot MHz))</td>
</tr>
<tr>
<td></td>
<td>(at 90°)</td>
<td>(at 90°)</td>
</tr>
<tr>
<td>Present pfd limits*</td>
<td>-140 dB(W/(m^2 \cdot 4 kHz))</td>
<td>-105 dB(W/(m^2 \cdot MHz))</td>
</tr>
<tr>
<td></td>
<td>(25° to 90°)</td>
<td>(25° to 90°)</td>
</tr>
</tbody>
</table>

Due to increased path length attenuation at low elevation angles from low orbit satellites, the pfd limit above 25° determines the allowable satellite e.i.r.p. Present pfd limits as given in the Radio Regulations and Report 358, and discussed in Report 387, are derived from detailed analyses of interference to the fixed service, based essentially on the use by the fixed-satellite service of geostationary satellites. Further detailed examination may be required to verify an extension of their applicability to include non-geostationary satellites.

The maximum pfd generated at the Earth's surface for an Earth exploration satellite transmitting data to a TDRS, occurs when the satellite is at the Earth's horizon with respect to TDRS as shown in Fig. 1. The distance from the satellite to the point on the Earth where maximum pfd occurs is 3080 km for a 705 km orbit as is planned for the LANDSAT programme. The pfd for this worst-case condition would be -102.6 dB(W/(m^2 \cdot MHz)). In practice, transmission paths to TDRS closer to the surface of the Earth than 50 km will not be used. The worst pfd which would occur in this case, would be -124.2 dB(W/(m^2 \cdot MHz)).

The results show that the pfd in the 8025 to 8400 MHz band is within the pfd limit for the link to the major data acquisition facility but exceeds the limit by 16.2 dB for the link to the low cost data acquisition facility. In the region of 20 GHz, the pfd limit for the link to a major data acquisition facility would be exceeded by 6.1 dB and on the link to a low cost data acquisition facility by 12.9 dB.

### 6. Conclusion

The 8025 to 8400 MHz band is well suited for telemetering data from near-future Earth exploration satellites directly to major data acquisition facilities. The 8025 to 8400 MHz band has insufficient bandwidth to accommodate future developments in satellite borne sensors. In addition, the power flux-density limit in the 8025 to 8400 MHz band will severely restrict the use of low cost data acquisition facilities which are needed for real time distribution of satellite data to the user community.

* There is no proposal to increase the present pfd limits. The calculations above merely compare those limits with the pfd that would be required for low-cost facilities.
Increased atmospheric and precipitation losses at frequencies above 20 GHz preclude configuration of a satisfactory radiocommunications down link with current spacecraft and ground data acquisition technology for the high data rates generated by Earth exploration satellites. The power flux-density limit imposed on the band also prevents a satisfactory link. Mutual interference would preclude use of a radiometer operating at the 22.235 GHz water vapour line on a satellite whose data communications system operated just above 20 GHz.

The practical economic upper limit of frequencies useful for telemetering wide-band data from Earth exploration satellites directly to Earth is approximately 20 GHz. Above this frequency, technology is not available at low cost to overcome high atmospheric and precipitation losses. The power flux-density limit at 20 GHz would constrain the design of the link to major data acquisition facilities and would severely restrict the use of low cost data acquisition facilities.

BIBLIOGRAPHY


REPORT 540-1*

FEASIBILITY OF FREQUENCY SHARING BETWEEN AN EARTH EXPLORATION-SATELLITE (EES) SYSTEM AND FIXED SATELLITE, METEOROLOGICAL SATELLITE AND TERRESTRIAL FIXED AND MOBILE SERVICES

(Study Programme 12A/2)

(1974-1982)

1. Introduction

According to the Radio Regulations, the frequency band 8025 to 8400 MHz is allocated on a shared basis to the Earth exploration-satellite service (space-to-Earth).

However, the allocation in Regions 1 and 3 is made only on a secondary basis, with the exception of a number of countries whose names are included in a footnote and which may have primary status subject to an agreement reached in accordance with the procedure envisaged in Article 14 of the Radio Regulations.

The band is shared in the three Regions with the terrestrial fixed and mobile services and with the fixed-satellite service (Earth-to-space). The sub-band 8175 to 8215 MHz is further shared with the meteorological-satellite service (Earth-to-space).

The technical feasibility of frequency sharing between Earth exploration satellite and terrestrial fixed and mobile services, fixed satellites and meteorological satellites is discussed in this Report. The basic conclusions that can be drawn from the analyses of the sharing possibilities are:

1.1 Sharing between an Earth exploration satellite system and a line-of-sight radio-relay system is feasible provided that the power flux-density produced at the surface of the Earth by the satellite is limited to the Radio Regulation values (see Article 28, Section IV) for a fixed-satellite service sharing with a line-of-sight radio relay; and provided that the earth resources system earth station is coordinated with line-of-sight radio-relay transmitters according to established procedures.

1.2 Frequency sharing between space-to-Earth links of an Earth exploration satellite system using a low orbit and the Earth-to-space links of either a geostationary fixed satellite or a geostationary meteorological satellite is feasible, provided that the power flux-density produced at the geostationary orbit by any Earth exploration satellite does not exceed $-174 \, \text{dB}(W/m^2)$ in any 4 kHz band and that the earth station of the Earth exploration satellite is coordinated with the Meteorological and Fixed Satellite Service earth stations according to established procedures.

* This Report should be brought to the attention of Study Groups 4, 5, and 9.
2. Interference potentiality from EES space stations to line-of-sight radio-relay receivers

For the purposes of evaluating the technical feasibility of this aspect of sharing, the applicable technical characteristics of a planned United States Earth exploration satellite are given in Table I.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>R (km)</th>
<th>Numerical value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_t$, space station (dBW)</td>
<td></td>
<td>+ 16</td>
</tr>
<tr>
<td>Max. $G_t$, space station ('') (dB)</td>
<td></td>
<td>+ 6</td>
</tr>
<tr>
<td>Max. e.i.r.p. ('') (dBW)</td>
<td></td>
<td>+ 22</td>
</tr>
<tr>
<td>Spreading loss, $1/4 \pi R^2$ (dB) (')</td>
<td>5400</td>
<td>145.6</td>
</tr>
<tr>
<td></td>
<td>3600</td>
<td>142.0</td>
</tr>
<tr>
<td>Power flux-density at surface of the Earth (dB(W/m²))</td>
<td></td>
<td>- 123.6</td>
</tr>
<tr>
<td></td>
<td>3600</td>
<td>- 120.0</td>
</tr>
<tr>
<td>Spectral power flux-density ('') (dB(W/m²) in 4 kHz)</td>
<td></td>
<td>- 157.6</td>
</tr>
<tr>
<td></td>
<td>3600</td>
<td>- 154.0</td>
</tr>
</tbody>
</table>

(1) Objective of EES antenna design is to provide constant flux density within the field-of-view of the satellite.

(2) Horizon distance for 1800 km orbit altitude.

(3) Horizon distance for 900 km orbit altitude.

(4) Assuming a 100 MHz emission bandwidth and a maximum "peaking factor" of 10 dB above mean spectral distribution level.

(5) If this expression is used for calculating spreading loss, $R$ is expressed in metres.

The values of power flux-density in 4 kHz given above, allowing 10 dB for non-uniform spectral distribution, still allow margins of 5.6 and 2.0 dB, respectively, without exceeding $-152$ dB(W/m²) in 4 kHz at low elevation angles.

Characteristics for the French SPOT satellite are given in Annex I.

3. Interference from EES space station transmitters to fixed service satellite or meteorological satellite receivers

For the purpose of evaluating the technical feasibility of sharing with other space stations, applicable technical characteristics of the projected Earth exploration satellite are given in Table I.

The geometrical relationship between the near-polar (100° retrograde) orbit of the Earth exploration satellite and the geostationary satellite orbit is shown in Fig. 1.

![Geometric relationship between geostationary satellite orbit and circular-inclined orbit of altitude 1800 km, inclination 100°](image-url)
Since the Earth exploration satellite will direct its maximum e.i.r.p. at the horizon of its coverage, it follows that this maximum e.i.r.p. will be directed at the corresponding part of the geostationary satellite orbit.

The interference potential of the Earth exploration satellite can be evaluated by comparing its e.i.r.p. with that of earth stations operating with meteorological and communication satellites in this band.

The general case is defined by the equation for the carrier-to-interference ratio of the fixed or meteorological service receiver:

\[ \frac{C}{I} = P_{TW} + GTW - (P_{TU} + GTU) + \Delta L_p + 10 \log \left( \frac{B_y}{B_w} \right) \]  

where:

- \( P_{TW}, GTW \): transmitter power and antenna gain of wanted earth station,
- \( P_{TU} + GTU \): e.i.r.p. of the earth resources satellite in the direction of the interfered-with satellite,
- \( \Delta L_p \): differential path loss between the desired and undesired signals,
- \( B_w \) and \( B_y \): emission bandwidths of the unwanted and wanted signals.

As an example, we assume that the minimum earth station e.i.r.p. anticipated for an earth station in the Fixed Satellite Service, \( P_{TW} + GTW \), is +45 dBW in an emission bandwidth of the order of 0.25 MHz \( B_w \). Thus, the \( C/I \) ratio at the fixed service satellite is, to a reasonable approximation:

\[ \frac{C}{I} = 45 - (P_{TU} + GTU + \Delta L_p + 10 \log (B_y/0.25)) \]  

If the maximum undesired e.i.r.p. is +22 dBW, \( \Delta L_p \), the differential path loss between the desired and undesired signals, is \( \leq 3 \) dB, \( B_w \), the receiver bandwidth required for the desired signal, is \( \approx 0.25 \) MHz, \( B_U \), the bandwidth of the EES transmission is 100 MHz, the minimum acceptable \( C/I \) becomes:

\[ 45 - 22 - 3 + 26 = 46 \text{ dB} \]

The factor 10 \( \log \left( \frac{100}{B_w} \right) \) assumes uniform spectral distribution for both signals; if actual spectra are known, they should be used in determining the bandwidth factor. Allowing 10 dB for non-uniform spectral distribution of EES emission, \( C/I \) min = 36 dB.

When \( \Delta L_p = -3 \) dB, the earth exploration spacecraft is directly beneath a geostationary or near-geostationary satellite. However, at that point, the e.i.r.p. in the direction away from the Earth will be less than +22 dBW, and \( C/I \) will therefore be greater than 36 dB.

\( P_{TU} + GTU \) will in general be considerably greater than +45 dBW, so that the minimum value of \( C/I \) is expected to exceed 36 dB.

For meteorological satellites, typical minimum values of \( C/I \) are tabulated in Table II.

### TABLE II – Technical characteristics of meteorological satellite earth stations

<table>
<thead>
<tr>
<th>Meteorological satellite earth stations</th>
<th>e.i.r.p. (dBW)</th>
<th>( B_w ) (MHz)</th>
<th>Minimum ( C/I ) (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDA (stretch data)</td>
<td>73-4</td>
<td>3-5</td>
<td>52-9</td>
</tr>
<tr>
<td>CDA (facsimile)</td>
<td>73-4</td>
<td>0-026</td>
<td>74-3</td>
</tr>
<tr>
<td>CDA (command link)</td>
<td>56-4</td>
<td>0-03</td>
<td>56-5</td>
</tr>
<tr>
<td>CDA (ranging data)</td>
<td>64-4</td>
<td>1</td>
<td>49-4</td>
</tr>
<tr>
<td>TARS (stretch data)</td>
<td>45-0</td>
<td>1</td>
<td>30-0</td>
</tr>
</tbody>
</table>

(1) Values of \( C/I \) are based on:

\[ P_{TU} + GTU = +22 \text{ dBW} \]
\[ \Delta L_p = -3 \text{ dB} \]

and 10 \( \log B_U/10 B_w \), to account for non-uniform spectral distribution of \( B_U \).

(2) CDA: Command and data acquisition (station).

(3) TARS: Turn-around ranging station.
The foregoing analyses of interference in terms of protection ratios \((C/I)\) lead to the conclusion that meteorological and fixed satellite receivers in the geostationary satellite orbit can tolerate the power flux-density which results when the full e.i.r.p. of the low-altitude EES satellite is directed toward the geostationary orbit. This can be translated to a power flux-density limit as follows:

\[
\text{Power flux-density} = P_t + G_t - L_p - 10 \log B_Y \quad \text{dB}(W/(m^2 \cdot 4 \text{ kHz}))
\]

where:
\[
P_t + G_t: \text{EES e.i.r.p.} + 22 \text{ dBW},
\]
\[
L_p: \text{the spreading loss at minimum range of EES is 162 dB},
\]
\[
B_Y: \text{the equivalent emission bandwidth of EES for interference purposes, expressed in kHz; for this case } B_Y = 10 \text{ MHz} = 10^4 \text{ kHz},
\]

therefore:

\[
\text{Power flux-density} = +22 - 162 - 34 = -196 + 22 = -174 \quad \text{dB}(W/(m^2 \cdot 4 \text{ kHz}))
\]

4. Interference from terrestrial fixed service transmitters to EES earth station receivers

The sharing criterion for this interference path is the coordination distance required to ensure adequate separation between the terrestrial service transmitters and the EES earth station receivers.

The minimum permissible basic transmission loss to protect the earth station can be stated as:

\[
L_b (1\%) = P_t + G_t - (P_t - G_R) \quad \text{dB}
\]

where:
\[
P_t: \text{terrestrial service transmitter power (dBW)},
\]
\[
G_t: \text{terrestrial service antenna gain in the direction of the earth station (dB)},
\]
\[
G_R: \text{gain of the earth station antenna in the direction of the terrestrial station (dB)},
\]
\[
P_t: \text{maximum permissible interference level at the earth station receiver input (dBW)},
\]
\[
L_b (1\%): \text{the value of minimum acceptable basic transmission loss to be exceeded for all but 1\% of the time along the interference path between the terrestrial transmitter and the earth station receiver.}
\]

The value 1\% is derived from the service probability requirement of the EES system, and from the statistical variability of \(G_R\) in the case of an earth station tracking a low-altitude inclined-orbit satellite, and the fact that the earth station would not be active 100\% of the time.

The minimum value of \(L_b\) is derived as follows, using as an example a frequency of 8 GHz and the following parameters:

Space station e.i.r.p. (dBW) \(+22\)

Free space path loss, \(L_p, (D = 5400 \text{ km})\) (dB) \(+185\)

Receiving antenna gain, \(G_R\) (8 m parabola, 55\% eff) (dB) \(+53.8\)

With such a low value of \(C/N\), the maximum tolerable value of interference, \(P_t\), at the EES earth station receiver is assumed to be 6 dB below \(kT_b B\), or \(-132.6\) dBW; therefore:

\[
L_b (1\%) = P_t + G_t + G_R + 132.6 \quad \text{dB}
\]

5. Interference from fixed satellite or meteorological satellite earth station transmitters to EES earth station receivers

For purposes of evaluating the technical feasibility of sharing, the applicable technical characteristics of a proposed USA Earth exploration-satellite earth station are given in Table III using a frequency of 8 GHz as an example.
TABLE III – Technical characteristics of the proposed earth exploration satellite earth station receiver

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_e$ (K)</td>
<td>150</td>
</tr>
<tr>
<td>Receiver bandwidth, $B$ (MHz)</td>
<td>100</td>
</tr>
<tr>
<td>$kT_e B$ (100 MHz) (dBW)</td>
<td>-126.6</td>
</tr>
<tr>
<td>Power flux-density (1) (dB(W/m²))</td>
<td>-123.6</td>
</tr>
<tr>
<td>Effective area of receiving antenna, $A_r$ (m²)</td>
<td>+14.4</td>
</tr>
<tr>
<td>10 log $A_r$ (2)</td>
<td>2.0</td>
</tr>
<tr>
<td>Miscellaneous losses (dB)</td>
<td>-111.2</td>
</tr>
<tr>
<td>$C/N$ (dB)</td>
<td>15.4</td>
</tr>
</tbody>
</table>

(1) For e.i.r.p. of +22 dBW at a range of 5400 km.
(2) For a parabolic reflector having a diameter of 8 m and an efficiency of 55%.

The procedure presently used for ensuring protection of a fixed-satellite service earth station receiver from a terrestrial line-of-sight radio-relay transmitter operating in shared bands, is to establish a coordination distance. This procedure can be applied to determine the required separation between up-link earth station transmitters and down-link earth station receivers, as outlined below.

The minimum permissible basic transmission loss to protect the earth station receiver can be stated as:

$$ L_b (1\%) = P_i + G_i - (P_i - G_R) \quad \text{dB} $$

where:

- $P_i$: space service up-link transmitters power (dBW),
- $G_i$: space service up-link antenna gain in the direction of the EES earth station (dB),
- $G_R$: gain of the EES earth station antenna in the direction of the interference (dB),
- $P_i$: maximum permissible interference level at the EES earth station receiver input (dBW),
- $L_b (1\%)$: the value of minimum basic transmission loss to be exceeded for all but 1% of the time along the interference path between the terrestrial transmitter and the earth station receiver. 1% derives from the service probability requirement of the EES system, and from the statistical variability of $G_R$ in the case of an earth station tracking a low-altitude inclined-orbit satellite.

As indicated in Table III, the noise power in the earth station receiver is -126.6 dBW, and the carrier-to-noise ratio, $C/N$ is 15.4 dB. With such a low value of $C/N$, the maximum tolerable value of interference, $P_i$, at the EES earth station receiver is 6 dB below $kT_e B$, or -132.6 dBW. If we assume that the maximum gain in the horizontal direction of the EES earth station antenna at a minimum elevation angle of 5° will be +15 dB,

$$ L_b (1%) = P_i + G_i + 147.6 \quad \text{dB} $$

(7)
ANNEX I

POSSIBILITIES OF FREQUENCY SHARING BETWEEN THE EARTH EXPLORATION-SATELLITE SERVICE AND THE FIXED SERVICE (LINE-OF-SIGHT RADIO RELAY SYSTEMS) AROUND 8 GHz

1. Introduction

The following calculation method does not replace the method given in Appendix 28 to the Radio Regulations. It is not intended to be used in evaluating coordination distances. It allows the a priori evaluation of an order of magnitude for acceptable separation distances between an earth station and a terrestrial station, on the basis of a number of parameters. For this purpose, the calculation of the attenuation over the interference path is based not on the worst case but on an average case, with reference exclusively to diffraction caused by an obstacle situated between the two stations. The separation distance thus calculated gives a realistic idea of practical sharing possibilities between the space service and the terrestrial service.

2. Technical characteristics

2.1 Characteristics of the space stations concerned

For the purposes of this analysis, the characteristics of the SPOT Earth observation satellite project developed by France have been taken as the basis.

These are as follows:
- frequency: 8.25 GHz
- e.i.r.p. (equivalent isotropically radiated power): +14.5 dBW
- modulation: 4-phase PSK
- passband: 50 MHz
- polarization: circular
- orbit altitude: 822 km

These characteristics result in power flux-density values conforming to the limitations imposed by the Radio Regulations in this band.

2.2 Characteristics of the radio-relay systems concerned

The standard characteristics are as follows:
- power emitted per channel: 9 dBW
- number of channels in 100 MHz: 3
- \( P_T \) = Maximum power emitted in 100 MHz: 14 dBW
- \( G_T \) = Antenna gain less losses: see Fig. 2

2.3 Characteristics of the earth station concerned

The SPOT Earth observation satellite project developed by France has the following characteristics:

Bandwidth: 100 MHz

\( P_I \) = Maximum permissible interference power for less than 1% of the time: -134 dBW

\( G_e \) = Antenna gain of the earth station: The gain in the axis is 55.4 dBi; the gain values at more than 1° from the axis are given by the formula \( G_e = 32 - 25 \log \varphi \) (in accordance with Recommendation 509).

3. Method of calculation

3.1 Principle

3.1.1 The minimum permissible transmission loss for protecting the earth station receiver is given by the relation:

\[
L(1\%) = P_T + G_T - P_i + G_e = 148 + G_T + G_e
\]
Since the earth station operates exclusively above an angle of elevation of 5°, the antenna gain must be as at \( \theta = (5 - \epsilon)° \) in elevation when the physical horizon is at \( \epsilon° \) in elevation, less 10 dB to allow for the diversity of the angular positions occupied by the satellite in sight of the earth station (see Fig. 3).

\[
L(1\%) = 148 + G_T + 32 - 25 \log (5 - \epsilon) - 10 = 170 + G_T - 25 \log (5 - \epsilon) \tag{9}
\]

3.1.2 The calculation of the loss on the interference path takes the following into account:
- free space propagation loss: \( A_d \)
- loss due to diffraction by an obstacle between the two stations: \( A_h \).

The value of the first loss coefficient expressed in dB is obtained by calculating the relation:

\[
A_d = 20 \log \left( \frac{4\pi d}{\lambda} \right) \tag{10}
\]

where:
\( d \): distance between the earth station and the terrestrial station (m)
\( \lambda \): wavelength of the terrestrial station transmitting frequency (m).
FIGURE 3 — Configuration of terrestrial stations in relation to the earth station for the study of practical sharing possibilities

- \( d \): distance OA
- \( \varepsilon \): angle of elevation of the earth station's physical horizon
- \( O \): earth station
- \( AB \): line-of-sight radio-relay link
- \( \theta \): offset angle

The value of the second loss coefficient expressed in dB is obtained by calculating the relation:

\[
A_h = 20 \log [1 + (4.5 f^{1/2} \varepsilon)] + f^{1/2} \varepsilon
\]  

(see Report 724 (Geneva, 1982))

where:

- \( f \): terrestrial station transmitting frequency (GHz)
- \( \varepsilon \): the elevation of the earth station's physical horizon in the direction of the terrestrial station.

3.1.3 The interference level of the earth station is then considered to be below the permissible level provided the minimum permissible transmission loss \( L(1\%) \) is smaller than the loss on the interference path \((A_d + A_h)\). The condition which must be met is expressed by the following inequality:

\[
L(1\%) < A_d + A_h
\]  

(12)
3.2 Construction of a nomogram

The practical possibilities of sharing between the space service and the terrestrial service are analyzed with the aid of a nomogram (Fig. 4). The nomogram is based on observance of the inequality referred to in the preceding paragraph.

If, for example, the special technical characteristics described above are taken into account, it is interesting to convert that inequality and to use it in the following form for the construction of the nomogram:

\[ G_T(\theta) \leq 25 \log (5 - \varepsilon) + 20 \log \left( \frac{4\pi d}{\lambda} \right) + 20 \log \left[ 1 + (4.5 f^{1/3} \varepsilon) \right] + f^{1/3} \varepsilon - 170 \]  \hspace{1cm} (13)

3.2.1 First stage

The free space propagation loss \( A_d \), is calculated for a particular arbitrarily chosen distance:

\[ A_d = 20 \log \left( \frac{4\pi d}{\lambda} \right) = 144.75 \text{ dB} \quad (d = 50 \text{ km}, \lambda = 0.0364 \text{ m}, f = 8.25 \text{ GHz}) \]

such that:

\[ G_T(\theta) \leq 25 \log (5 - \varepsilon) + 20 \log [1 + (4.5 f^{1/3} \varepsilon)] + f^{1/3} \varepsilon - 25.25 \]

3.2.2 Second stage

The two elements of the second term of the inequality which depend on \( \varepsilon \) (angle of elevation of the earth station's physical horizon in the direction of the terrestrial station) are calculated.

<table>
<thead>
<tr>
<th>( \varepsilon )</th>
<th>0.5°</th>
<th>1°</th>
<th>2°</th>
<th>3°</th>
<th>4°</th>
</tr>
</thead>
<tbody>
<tr>
<td>( A_h = 20 \log \left[ 1 + (4.5 f^{1/3} \varepsilon) \right] + f^{1/3} \varepsilon ) (dB)</td>
<td>18.47</td>
<td>24.9</td>
<td>32.62</td>
<td>38.05</td>
<td>42.52</td>
</tr>
<tr>
<td>( A = 25 \log (5 - \varepsilon) ) (dB)</td>
<td>16.33</td>
<td>15.05</td>
<td>11.9</td>
<td>7.53</td>
<td>0</td>
</tr>
<tr>
<td>( (A_h + A) ) (dB)</td>
<td>34.8</td>
<td>39.95</td>
<td>44.55</td>
<td>45.58</td>
<td>42.52</td>
</tr>
</tbody>
</table>

It will be found that the sum of these two terms \( (A_h + A) \) presents a maximum value equal to 45.58 dB for a value of \( \varepsilon \) equal to 3°.

3.2.3 Third stage

In the circumstances we may, for a particular value of the distance between the earth station and the terrestrial station associate a value of the terrestrial station gain in the direction of the earth station with a value of the angle of elevation of the earth station's physical horizon.

Table V shows this correspondence in the particular case under study:

<table>
<thead>
<tr>
<th>( \varepsilon )</th>
<th>0.5°</th>
<th>1°</th>
<th>2°</th>
<th>3°</th>
<th>4°</th>
</tr>
</thead>
<tbody>
<tr>
<td>( G_T(5 - \varepsilon) ) (dB)</td>
<td>9.55</td>
<td>14.7</td>
<td>19.30</td>
<td>20.33</td>
<td>17.27</td>
</tr>
</tbody>
</table>

To obtain the slope of the lines represented in Fig. 4 the arbitrarily chosen distance used in the calculations is doubled. The new value of the terrestrial station gain in the direction of the earth station is obtained from the values already calculated to which 6 dB is added.
FIGURE 4 — Field of interference to the Earth station by a radio-relay system in line-of-sight

$d$: distance between the earth station and the terrestrial station

$G_T(\theta)$: gain of the terrestrial station in the direction of the earth station

$\epsilon$: angle of elevation of the earth station's physical horizon in the direction of the terrestrial station

A: area in which interference is improbable

B: area in which interference is probable

Characteristics of the earth station

- Maximum permissible interference power for less than 1% of the time: $-134$ dBW
- Bandwidth: 100 MHz
- Reception: digital

Characteristics of the radio-relay systems

- Interfering power emitted in 100 MHz: 14 dBW
- Transmission: analogue
3.3 Use of the nomogram

The nomogram shows, for example, that the interference level of the earth station is below the permissible level if:

- the relief around the earth station offers a protection of 0.5° to 4° in elevation;
- the distance between the two stations is above 50 km;
- the axis of the radio-relay system is more than 10° out of line with the direction joining the terrestrial station to the earth station.

4. Conclusion

Without prejudice to the coordination procedure described in Appendix 28 to the Radio Regulations, it is often necessary to make a swift analysis of the practical conditions for siting an earth station in an already existing radio-relay network. There is a simple graphical method (Fig. 4) for making such analyses and provisionally determining the best sites for the earth station in relation to those of terrestrial stations in the radio-relay system.

Applied specifically to the French SPOT Earth observation satellite, the method used quickly reveals that application of the coordination procedure in Appendix 28 to the Radio Regulations should not involve intolerable constraints as regards the siting of the earth station.

REPORT 693-3

TECHNICAL AND OPERATIONAL CONSIDERATIONS FOR THE EARTH EXPLORATION-SATELLITE SERVICE

Preferred frequency bands for active and passive microwave sensors
(Question 12/2 and Study Programme 12B/2)


1. Introduction

In the area of Earth exploration for earth resources, meteorology and oceanography, new satellite programmes currently developed in Europe, Canada and the United States are expected to extend the useful remote sensing spectrum into the microwave region, using both passive and active devices. Based on this work, the purpose of this Report is to present the preferred frequency bands and the expected characteristics of microwave sensors under development for these satellites.

2. Passive microwave radiometry

Energy at microwave frequencies is emitted and absorbed by the surface of the Earth and by the atmosphere above the surface. The transmission properties of the absorbing atmosphere vary as a function of frequency, as shown in Fig. 1. This figure depicts calculated one way zenith (90° elevation angle) attenuation values for oxygen and water vapour [Crane, 1971]. The calculations are for a path between the surface and a satellite. These calculations reveal frequency bands for which the atmosphere is effectively opaque and others for which the atmosphere is nearly transparent. The regions or windows that are nearly transparent may be used to sense surface phenomena; the regions that are opaque are used to sense the top of the atmosphere.
The power received by a radiometer on a satellite looking down at the Earth may be calculated from the equations of radiative transfer, [Crane, 1971; Staelin, 1969]. For a nonscattering medium,

$$T_a(v) = \frac{P(v)}{kB} = \frac{1}{4\pi} \int_0^{4\pi} g(\Omega) \left[ T_0(v) e^{-t(\Omega)} + \int_0^L T(s) \beta(s) e^{-\tau(s)} ds \right] d\Omega$$

(1)

where:

- $T_a$: antenna temperature (K)
- $P$: received power (W)
- $v$: centre frequency (Hz)
- $B$: receiver bandwidth (Hz)
- $k$: Boltzmann's constant (J/K)
- $g$: antenna gain (numeric ratio)
- $\Omega$: solid angle about the antenna (steradian)
- $T_0$: surface brightness temperature (emission plus scattering) (K)
- $\tau$: optical depth (nepers)
- $\beta$: absorption coefficient (nepers/km)
- $L$: path length from satellite to ground (km)
- $s$: position along the path (km)

and $T(s)$: atmospheric temperature at point $s$ along the path (K)

The optical depth is simply related to the attenuation as follows:

$$\tau(s) = \int_0^s \beta(x) dx = \int_0^s \left[ \frac{\sigma(x)}{4.34} \right] dx = \frac{A(s)}{4.34}$$

(2)
where

\( A \): attenuation (one way) (dB)

and \( a \): specific attenuation (dB/km).

Equations (1) and (2) display the essential features of remote sensing using microwave frequencies. The surface brightness temperature, the atmospheric temperature at points, \( s \), along the path and the absorption coefficients are unknown and to be determined from measurements of the antenna temperature, \( T_A \). The surface brightness temperature and the absorption coefficients in turn, depend upon the physical properties of the surface or atmosphere that are to be sensed. A single observation at a single frequency cannot be used to estimate a single physical parameter. Observations must be made simultaneously at a number of frequencies and combined with models for the frequency dependence and physical parameter dependence of the surface brightness temperature and of the absorption coefficient, before the integral equation (1), may be solved.

The equation may be simplified for application at frequencies in the atmospheric windows where the attenuation is less than 1 dB. For an antenna system with a narrow beam and for an absorber at a constant temperature, \( T \), the equation reduces to:

\[
T_A(s) = T_s e^{-a(s)} + T_r (1 - e^{-a(s)})
\]

(3)

\[
T_A(s) = T_0 (1 - \tau(s)) + T_r \tau(s)
\]

(4)

This result shows that even in the windows, the effect of the atmosphere above the surface must be considered.

Radiometric receivers sense the noise-like thermal emission collected by the antenna and the thermal noise of the receiver. By integrating the received signal the random noise fluctuations can be reduced and accurate estimates can be made of the sum of the receiver noise and external thermal emission noise power. Expressing the noise power per unit bandwidth as an equivalent noise temperature, the effect of integration in reducing measurement uncertainty can be expressed as given below, [Kraus, 1966]:

\[
\Delta T_e = \frac{\alpha (T_A + T_N)}{\sqrt{Bt}}
\]

where:

\( \Delta T_e \): r.m.s. uncertainty in the estimation of the total system noise, \( T_A + T_N \)

\( T_A \): antenna temperature

\( T_N \): receiver noise temperature

\( B \): bandwidth

\( t \): integration time

\( \alpha \): receiver system constant.

The sensitivity of microwave receivers is improving rapidly due to the development of improved solid-state components. At wavelengths longer than 3 cm, receiver noise temperatures of less than 150 K can be obtained with solid-state parametric amplifiers. At wavelengths shorter than 3 cm, the most common type of receiver is the superheterodyne with noise temperatures ranging from several hundred degrees at 3 cm wavelength to perhaps 2000 K at 3 mm wavelengths. Improvements in Schottky-barrier diodes show promise of reducing superheterodyne noise temperature to a few hundred degrees for wavelengths as short as 5 mm.

With the receiver noise temperatures that can be obtained with current technology, significant reductions in the \( \Delta T_e \) values (or increased sensitivity) can only be accomplished in spaceborne radiometers by increased system bandwidths. Low orbit spaceborne radiometers are limited to integration times on the order of seconds or less, due to the spacecraft relative velocity and high spatial resolution requirements.
3. Active sensors

Active sensors differ from passive sensors in that they illuminate the object under observation and respond to the reflected energy.

There are three basic types of active sensors:
- scatterometers
- altimeters
- imagers

Radar scatterometers are useful for determining the roughness of large objects. When operating at frequencies higher than 300 MHz, the scatterometer measures the amount of backscatter from the surface roughness in broad categories ranging from smooth to very rough. At frequencies around 200 MHz, reflectivity depends upon the dielectric constant of the object; at lower frequencies, reflectivity depends primarily upon electrical conductivity. These lower frequencies can be used to penetrate the surface of the earth to detect subsurface structures.

Radar altimetry has yielded three possible operational concepts for practical systems. One of these techniques is based upon the use of a very narrow beamwidth (2 mrad) and a very short transmitted pulse (2 ns). Timing of the round-trip delay of the transmitted pulse leading edge, is used to provide altitude information. A technique that is similar to the short pulse system, is the pulse compression technique. A short impulse pulse generates a longer frequency modulated pulse and the return, which has a wide bandwidth, is compressed back to a short pulse which is then leading edge detected. The third technique requires moderate antenna size and spacecraft stabilization, with radar return from the nadir point obtained by a time-gating technique. In this system, altitude information is extracted by measuring the centroid of the early portion of the radar waveform rather than the leading edge of a very short pulse.

Radar imaging systems are employed to produce high resolution images required by users in such fields as geology, oceanography, and agriculture. To achieve reasonable resolution from space, synthetic aperture focused radars will be employed for many applications as they have resolutions independent of range. In the area of meteorology scanning Doppler radars may also be employed.

4. Present and near future microwave sensors

Characteristics of passive and active sensors currently in use and under development are shown in Tables I and II respectively.
<table>
<thead>
<tr>
<th>Sensor</th>
<th>Frequency (GHz)</th>
<th>Bandwidth (MHz)</th>
<th>Sensitivity $\Delta T_s$ (K)</th>
<th>Sensitivity (dBm)</th>
<th>Operation date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiometer (L-band)</td>
<td>1.4</td>
<td>27</td>
<td>1</td>
<td>-124</td>
<td>1972</td>
</tr>
<tr>
<td>Nimbus-5 microwave spectrometer</td>
<td>22.23 ; 31.4 ; 53.65 ; 54.9 ; 58.8</td>
<td>220</td>
<td>1</td>
<td>-115</td>
<td>1972</td>
</tr>
<tr>
<td>Scanning microwave spectrometer</td>
<td>22.23 ; 31.65 ; 52.85 ; 53.85 ; 55.45</td>
<td>220</td>
<td>1 to 1.5</td>
<td>-115</td>
<td>1975</td>
</tr>
<tr>
<td>Tiros-N microwave sounding unit</td>
<td>50.3 ; 53.74 ; 54.95 ; 57.95</td>
<td>200</td>
<td>0.3</td>
<td>-121</td>
<td>1978</td>
</tr>
<tr>
<td>Electronic scanning microwave radiometer</td>
<td>37 (Nimbus-6)</td>
<td>250</td>
<td>1</td>
<td>-114</td>
<td>1975</td>
</tr>
<tr>
<td>19.35 (Nimbus-5)</td>
<td>300</td>
<td>250</td>
<td>1</td>
<td>-114</td>
<td>1972</td>
</tr>
<tr>
<td>Scanning multi-channel microwave radiometer</td>
<td>6.6 ; 10.69 ; 17.96 ; 21.0 ; 37.0</td>
<td>250</td>
<td>0.9 to 1.5</td>
<td>-113</td>
<td>1978</td>
</tr>
<tr>
<td>Microwave limb sounder (UARS)</td>
<td>63, 119, 183, 205, 231</td>
<td>To be determined</td>
<td>To be determined</td>
<td>To be determined</td>
<td>1986</td>
</tr>
<tr>
<td>Radiometer (S-band)</td>
<td>2.65</td>
<td>100</td>
<td>0.1</td>
<td>-129</td>
<td>1970</td>
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<tr>
<td>Microwave temperature sounder</td>
<td>53.331</td>
<td>600</td>
<td>1</td>
<td>-111</td>
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<tr>
<td>52.85</td>
<td>120</td>
<td>120</td>
<td>1</td>
<td>-118</td>
<td>1978</td>
</tr>
<tr>
<td>53.85</td>
<td>120</td>
<td>120</td>
<td>1</td>
<td>-118</td>
<td>1978</td>
</tr>
<tr>
<td>55.45</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Radiometer (L-band)</td>
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<td>0.1</td>
<td>-130</td>
<td>1975</td>
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<tr>
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<tr>
<td>Passive microwave imaging system</td>
<td>10.69</td>
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<td>1.2</td>
<td>-115</td>
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<tr>
<td>Multi-frequency microwave radiometer</td>
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<tr>
<td>18.0</td>
<td>200</td>
<td>200</td>
<td>1</td>
<td>-115</td>
<td>1975</td>
</tr>
<tr>
<td>22.05</td>
<td>200</td>
<td>1</td>
<td>-112</td>
<td></td>
<td></td>
</tr>
<tr>
<td>37.0</td>
<td>500</td>
<td>1</td>
<td>-112</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sensor</td>
<td>Frequency (GHz)</td>
<td>Bandwidth (MHz)</td>
<td>Sensitivity $\Delta T_s$(K)</td>
<td>Sensitivity (dBm)</td>
<td>Operation date</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------</td>
<td>-----------------</td>
<td>-----------------------------</td>
<td>-------------------</td>
<td>----------------</td>
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<td>Large antenna multi-frequency microwave radiometer (ICEX)</td>
<td>1.4; 4.3; 5.1; 6.6; 10.7; 18.5; 21.5; 36.5; 92</td>
<td>100 MHz-1 GHz</td>
<td>~ 1</td>
<td>-109 to -119</td>
<td>To be determined</td>
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<td>Advanced microwave moisture sensor</td>
<td>91, 65, 183, 15</td>
<td>1 GHz, 2-9 GHz</td>
<td>2, 6</td>
<td>-106</td>
<td>1979</td>
</tr>
<tr>
<td>Advanced microwave sounding unit</td>
<td>18.5; 22.23; 31.65; 50.30; 52.85; 53.40; 54.35; 54.90; 55.50; 57.968 (6 channels), 90, 150, 183.311 (3 channels)</td>
<td>2.5-7000</td>
<td>0.25 (chan. 1-12), 0.40 (chan. 13), 1.0 (chan. 14), 2.2 (chan. 15), 0.5 (chan. 16), 0.6 (chan. 17-20)</td>
<td>-91 to -98</td>
<td>1993</td>
</tr>
<tr>
<td>Microwave radiometry using ATSR-M*</td>
<td>23.8; 36.5</td>
<td>400; 1000</td>
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<td></td>
<td></td>
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</table>

* ATSR-M - Along the Track Scanning Radiometer - Microwave
<table>
<thead>
<tr>
<th>Sensors</th>
<th>Frequency (GHz)</th>
<th>Beamwidth (degrees)</th>
<th>Sensitivity (dBm)</th>
<th>E.i.r.p. (dBW)</th>
<th>Operation date</th>
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<tr>
<td>Skylab altimeter</td>
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<td>1.4</td>
<td>-88</td>
<td>72</td>
<td>1972</td>
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<tr>
<td>Skylab scatterometer</td>
<td>13.9</td>
<td>1.4</td>
<td>-88</td>
<td>52</td>
<td>1972</td>
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<td>GFOV C altimeter</td>
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<td>2.6</td>
<td>-80</td>
<td>73</td>
<td>1975</td>
</tr>
<tr>
<td>Seasat synthetic aperture radar</td>
<td>1.275</td>
<td>5 x 1</td>
<td>-98.5</td>
<td>64</td>
<td>1978</td>
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<tr>
<td>Seasat scatterometer</td>
<td>14.6</td>
<td>25 x 5.5</td>
<td>-128</td>
<td>55</td>
<td>1978</td>
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<tr>
<td>Seasat altimeter</td>
<td>13.5</td>
<td>1.5</td>
<td>-81</td>
<td>75</td>
<td>1978</td>
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<td>AAEF multispectral active microwave imaging system</td>
<td>3.0</td>
<td>6</td>
<td>-98</td>
<td>67</td>
<td>1977</td>
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<td>Surface contour radar</td>
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<td>-82</td>
<td>45</td>
<td>1977</td>
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<tr>
<td>Radiometer/scatterometer</td>
<td>13.9</td>
<td>1.5</td>
<td>-90</td>
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<td>1970</td>
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<tr>
<td>Radar pulse compression experiment</td>
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<td>15</td>
<td>-107</td>
<td>21</td>
<td>1977</td>
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<tr>
<td>Shuttle imaging radar</td>
<td>10</td>
<td>1.3 x 8</td>
<td></td>
<td>75</td>
<td>1982</td>
</tr>
<tr>
<td>Microwave pressure sounder</td>
<td>29.25; 26.55; 44.87; 50.80; 67.31; 73.01</td>
<td>1.3 x 0.17; to 0.52 x 0.07</td>
<td></td>
<td>79</td>
<td>1982</td>
</tr>
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<td>Spacelab SAR/scatterometer</td>
<td>9.65</td>
<td>2.4 x 1.25</td>
<td>-90</td>
<td>60</td>
<td>1983</td>
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<tr>
<td>SAR</td>
<td>9.65</td>
<td>2.4 x 1.25</td>
<td>-90</td>
<td>64</td>
<td>1983</td>
</tr>
<tr>
<td>Scatterometer</td>
<td>5.3</td>
<td>3.3 x 0.8</td>
<td>-134.5</td>
<td>49 (max = 56)</td>
<td>1989</td>
</tr>
<tr>
<td>ERS 1 wind scatterometer</td>
<td>5.3</td>
<td>5 x 0.3</td>
<td>-98.5</td>
<td>62.4 (max = 72)</td>
<td>1989</td>
</tr>
<tr>
<td>ERS 1 SAR/wave scatterometer</td>
<td>5.3</td>
<td>5 x 0.3</td>
<td>-100</td>
<td>67.2 (max = 76.8)</td>
<td>1989</td>
</tr>
<tr>
<td>SAR</td>
<td>13.2</td>
<td>1.6</td>
<td>-83.2</td>
<td>48 (max = 68)</td>
<td>1989</td>
</tr>
<tr>
<td>IRS 1 altimeter</td>
<td>13.65</td>
<td>1.1</td>
<td>-82</td>
<td>max = 51</td>
<td>1992</td>
</tr>
</tbody>
</table>
5. Preferred frequency bands

5.1 Passive sensors

Operating frequencies for passive microwave sensors are primarily determined by the phenomena to be measured. For certain applications, such as those requiring measurements of microwave emissions from atmospheric gases, the choice of frequencies is quite restricted and is determined by the spectral line frequencies of the gases. Other applications have broad frequency regions where the phenomena can be sensed.

5.1.1 Atmospheric measurements*

Atmospheric attenuation does not occur within a single atmospheric layer of constant temperature. Figure 2 (see Report 719 (Geneva, 1982)) displays the variation of attenuation with frequency and height. Equation (1) indicates that the measured antenna temperature depends mostly upon the temperature in the region along the path where the attenuation (total to the satellite) is less than 10 dB, and little upon temperatures in regions where the attenuation is very small, or the total attenuation to the satellite is large. The temperature values can be sensed at different heights or distances along the path by selecting frequencies near the edges of the opaque regions with different attenuations, which provide different weighting functions or multipliers of $T(s)$ in equation (1). The broad opaque region between 50 and 70 GHz is composed of a number of narrow absorption (opaque) lines and observations may be made either at the edges of the complex of lines or in the valleys between the lines. The range of attenuation values, peak to valley for the complex of lines, are indicated as shaded areas on Figs. 1 and 2.

A number of different frequencies may be chosen to provide a reasonable set of weighting functions for atmospheric temperature, water vapour, ozone, chlorine oxide, nitrous oxide and carbon monoxide profile measurements. For the last four molecular measurements, each individual line does not have enough fine structure, as in the $O_2$ temperature profiling band, or enough width, as in the water vapour band about 22.235 GHz, to allow for profile measurements about a line, given the satellite constraints on integration time. Hence, in order to achieve profiling information on these constituents, multiple line measurements will be necessary.

Sample calculations for a set of frequencies in the oxygen line complex are given in Fig. 3. Calculations for the channels corresponding to the lowest five frequencies in Fig. 3, performed using a statistical procedure for inverting equation (1), show that for a 0.3 K radiometer sensitivity the expected r.m.s. uncertainty in the estimated temperatures is less than 2 °C for heights above 1 km at mid-latitudes over the ocean.

Clouds and rain can provide additional attenuation when they occur along the path. Both rain and clouds may be sensed in the atmospheric windows between 5 and 150 GHz. Multiple observations over a wide frequency range are required to separate rain from cloud and to separate these effects from surface emission.

5.1.2 Land and ocean measurements

Emission from the surface of the Earth is transmitted through the atmosphere to the satellite. When the attenuation values are high, this emission cannot be sensed. When it is low, as required to sense the temperature of the lowest layer of the atmosphere, both the surface and atmospheric contributions are combined. Additional measurements within the window channels are required to separate the two types of contributions. Surface emission is proportional to the temperature and emissivity of the surface. The latter are related to the dielectric properties of the surface and to the roughness of the surface. If the emissivity is less than unity, the surface both emits and scatters radiation. The scattered radiation originates from downward atmospheric emission from above the surface. In a window channel with very small attenuation values this latter contribution is negligible; otherwise it must be considered in the solution of equation (1).

* See also the sections on Radiometeorology (5C), Space Telecommunications (5F) and Interference (5G) of Volume V.
FIGURE 2 - Theoretical vertical one-way attenuation from specified height to top of the atmosphere for a moderate humid atmosphere (7.5 g/m³ at the surface)

A: Starting heights (km)
B: Minimum values for paths starting at indicated heights (km)
C: Range of values for the path from the surface to 80 km
Surface brightness temperatures do not show the rapid variation with frequency exhibited by emission from atmospheric absorption lines. The relatively slow frequency variations of the effects of surface parameters require simultaneous observations over a broad frequency range within the atmospheric windows to determine their values. Separation of the parameters can only be accomplished when the parameters have different frequency dependences. Figures 4, 5, and 6 depict the frequency dependence of the several parameters affecting the brightness temperature of the ocean surface, salinity, temperature, and wind. The wind affects the brightness temperature by roughing the surface and by producing foam which has dielectric properties different from the underlying water. These figures show that salinity is best sensed at frequencies below 3 GHz and, if extreme measurement accuracy is required, at frequencies below 1.5 GHz. Sea surface temperature is best sensed using frequencies in the 3 to 10 GHz range, with 5 GHz being near optimum. Wind affects observations at all frequencies but is best sensed at frequencies above 15 GHz.
Surface layers of ice or oil floating on the ocean surface have dielectric properties different from water and can be sensed due to the resultant change in brightness temperature. Oil slicks can change the brightness temperature above 30 GHz by more than 50 K [Hollinger and Mennella, 1973] and ice can change the brightness temperature by more than 50 K at frequencies from 1 to 40 GHz. Although ice and oil spills can provide a large change in brightness temperature, a number of observations in each of the atmospheric windows are required to separate the effects of ice and oil from rain and clouds.

The moisture content of the surface layers can be detected at microwave frequencies [Schmugge et al., 1974]. The brightness temperature of snow and of soil both change with moisture content and with frequency. In general, the lower the frequency, the thicker the layer that can be sensed. Since the moisture at the surface is related to the profile of moisture below the surface, observations at higher frequencies can
also be useful. In sensing the melting of snow near the surface, observations at 37 GHz and higher, provide the most information. For sensing soil, especially soil under a vegetation canopy, frequencies below 3 GHz are of most interest. In practice, a number of frequencies are required, first to classify the surface as to roughness, vegetation cover, sea ice age, etc., and, second, to measure parameters such as ice thickness or moisture content. Figures 7 and 8 present sensitivity curves versus frequency for ice and soil moisture. In particular, Fig. 7 presents actual measurements over ice for various frequencies and polarizations.

Table III presents the preferred frequency bands for passive microwave sensing measurements. The primary measurements which require each frequency band are also listed as well as necessary bandwidths to provide sufficient measurement accuracy and usable areas of coverage.

![Figure 5](image1.png)  
**FIGURE 5** - Change in brightness temperature with surface temperature (salinity 36 parts per thousand)

- $\Delta T$ : Physical surface temperature change (K)
- $\Delta T_0$ : Brightness temperature change (K)

![Figure 6](image2.png)  
**FIGURE 6** - Change in brightness temperature with wind speed (nadir)

- $\Delta U$ : Wind speed change (m/s)
- $\Delta T_0$ : Brightness temperature change (K)
FIGURE 7 – Brightness temperatures of ice at various wavelengths and polarizations

A: Large multiyear ice floe
B: Refrozen leads
C: Temperature difference range indication

<table>
<thead>
<tr>
<th>Curve</th>
<th>$\lambda$ (cm)</th>
<th>Pol.</th>
<th>Curve</th>
<th>$\lambda$ (cm)</th>
<th>Pol.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>21.1</td>
<td>V,H</td>
<td>6</td>
<td>0.81</td>
<td>V</td>
</tr>
<tr>
<td>2</td>
<td>11.2</td>
<td>V,H</td>
<td>7</td>
<td>0.81</td>
<td>H</td>
</tr>
<tr>
<td>3</td>
<td>6.01</td>
<td>V,H</td>
<td>8</td>
<td>0.32</td>
<td>H</td>
</tr>
<tr>
<td>4</td>
<td>2.81</td>
<td>V,H</td>
<td>9</td>
<td>10,\mu m (Infra-red)</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>1.55</td>
<td>V,H</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

FIGURE 8 – Apparent temperature of a smooth surface uniform vegetation for various frequencies

40° Incidence
Vertical polarization
Density = 3.0%
Canopy height = 50 cm
5.1.3 Technical parameters of passive sensors

Studies have been performed to determine sensor sensitivity requirements, spatial resolution requirements, and non-scanning bandwidth requirements [NASA 1976a and 1976b]. The results of the studies are summarized in Table IV for each of the preferred frequencies contained in Table III. Also presented in Table IV is the coverage width that can be achieved with the suggested bandwidths in Table III by use of scanning sensors. It should be noted that 185 km coverage widths result in total Earth coverage in about 18 days for a typical EES orbit such as that used by the Landsat series of satellites. Updating at a period of less than every 18 days is required to fully satisfy the requirements of environmental scientists and meteorologists.

5.2 Active sensors

Since the 1940's, it has been apparent from ground-based and airborne experiments and operations, and recently from experiments aboard satellites, that active microwave sensing of atmosphere, ocean and land parameters is feasible and economically useful. Active remote sensing in the microwave region offers several advantages over visible region sensors and passive microwave sensors. Besides being uniquely sensitive to several land/ocean/atmosphere variables (e.g., plant moisture and cloud height), active sensing can, for instance, penetrate the surface and vegetation, operate on an all-weather, day/night basis, attain high spatial resolution (synthetic aperture radar, SAR), enhance features by changing the illumination angle, and operate over broad spectral ranges independent of emissions from narrow-band phenomena.

Active sensors illuminate the object under observation and respond to reflected energy. In order to gather information concerning the Earth's surface from space, the transmitted signal must traverse the atmosphere twice. As a result the electromagnetic absorption and scattering properties of the atmosphere play an important role in determining the spectral regions suitable for active remote sensors.

Severe atmospheric attenuation is confined to the shorter wavelengths, and for this reason, active sensors usually operate below the 60 GHz oxygen absorption region and also avoid the spectral region near the 22 GHz water vapour line.

Electromagnetic scattering by precipitation and clouds can present a more serious problem than atmospheric absorption. Echoes from water droplets increase with droplet diameter and decrease with increasing wavelength. Thus, at longer wavelengths clouds give little echo, but precipitation can give somewhat stronger echoes because of the larger particle diameters of the raindrops.

Seasat, launched by the United States in 1978, had an active sensor complement (see Table II) designed to study ocean dynamics and physical properties on a global basis.

The Canadian SURSAT programme [Department of Energy, Mines and Resources, 1980] was begun in April, 1977 as a step towards the utilization of satellite microwave remote sensors to provide oceanographic data. One consequence of this programme has been the proposal for the satellite Radarsat as described in Annex VI to Report 535.

5.2.1 General frequency considerations for active sensor measurements

The following have been identified as being of prime importance for the application of spaceborne radar:

- soil moisture;
- vegetation mapping;
- snow distributions, depth and water content;
- geological mapping;
- land use mapping;
- ice boundaries, depth, type and age;
- ocean wave structure;
- ocean wind speed and directions;
- mapping of ocean circulation (currents and eddies);
- oil spills;
- geodetic mapping;
- rain rates;
- cloud height and extent;
- surface pressure.

Studies [NASA, 1974] have identified a number of frequency bands that are needed in order to obtain the measurements listed above.
### TABLE III - Preferred frequency bands for passive microwave sensors

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>Bandwidth (MHz)</th>
<th>Measurement(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Near 1.4</td>
<td>100</td>
<td>Soil moisture; salinity</td>
</tr>
<tr>
<td>Near 2.7</td>
<td>60</td>
<td>Salinity; soil moisture</td>
</tr>
<tr>
<td>Near 5</td>
<td>200</td>
<td>Estuarine temperature</td>
</tr>
<tr>
<td>Near 6</td>
<td>400</td>
<td>Ocean temperature</td>
</tr>
<tr>
<td>Near 11</td>
<td>100</td>
<td>Rain; snow; lake ice; sea state</td>
</tr>
<tr>
<td>Near 15</td>
<td>200</td>
<td>Water vapour; rain</td>
</tr>
<tr>
<td>Near 18</td>
<td>200</td>
<td>Rain; sea state; ocean ice; water vapour</td>
</tr>
<tr>
<td>Near 21</td>
<td>200</td>
<td>Water vapour; liquid water</td>
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<td>22.235</td>
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<td>Water vapour; liquid water</td>
</tr>
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<td>Near 24</td>
<td>400</td>
<td>Water vapour; liquid water</td>
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<td>Near 30</td>
<td>500</td>
<td>Ocean ice; water vapour; oil spills; clouds; liquid water</td>
</tr>
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<td>Near 37</td>
<td>1000</td>
<td>Rain; snow; ocean ice; oil spills; clouds</td>
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<tr>
<td>Near 55</td>
<td>250 multiple(1)</td>
<td>Temperature</td>
</tr>
<tr>
<td>Near 90</td>
<td>6000</td>
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<td>100.49</td>
<td>2000</td>
<td>Nitrous oxide</td>
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<tr>
<td>110.80</td>
<td>2000</td>
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<td>Carbon monoxide</td>
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<tr>
<td>118.70</td>
<td>2000</td>
<td>Temperature</td>
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<td>125.61</td>
<td>2000</td>
<td>Nitrous oxide</td>
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<td>150.74</td>
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<td>164.38</td>
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<td>167.20</td>
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<td>175.86</td>
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<td>380.20</td>
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</table>

(1) Several bands each of 250 MHz bandwidth.
### Table IV - Technical considerations for passive spaceborne sensors

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>Primary application</th>
<th>Required $\Delta T_e$ (K)</th>
<th>Resolution (km)</th>
<th>System noise temp. (K)</th>
<th>Non-scan bandwidth (MHz)</th>
<th>Suggested bandwidth (MHz)</th>
<th>Coverage width (km)</th>
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<tbody>
<tr>
<td>Near 1.4</td>
<td>Soil moisture, salinity</td>
<td>0.1</td>
<td>20</td>
<td>450</td>
<td>42</td>
<td>100</td>
<td>48</td>
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<tr>
<td>Near 2.7</td>
<td>Salinity, soil moisture</td>
<td>0.1</td>
<td>2</td>
<td>450</td>
<td>60</td>
<td>60</td>
<td>2</td>
</tr>
<tr>
<td>Near 5</td>
<td>Estuary surface temperature</td>
<td>0.3</td>
<td>2</td>
<td>450</td>
<td>45</td>
<td>200</td>
<td>9</td>
</tr>
<tr>
<td>Near 6</td>
<td>Sea surface temperature</td>
<td>0.3</td>
<td>20</td>
<td>450</td>
<td>5</td>
<td>400</td>
<td>1600</td>
</tr>
<tr>
<td>Near 11</td>
<td>Rain, snow, ice, wind</td>
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<td>1</td>
<td>1000</td>
<td>60</td>
<td>100</td>
<td>2</td>
</tr>
<tr>
<td>Near 15</td>
<td>Water vapour, rain</td>
<td>0.2</td>
<td>2</td>
<td>1000</td>
<td>180</td>
<td>200</td>
<td>2</td>
</tr>
<tr>
<td>Near 18</td>
<td>Rain, snow, ice, wind, water vapour(1)</td>
<td>0.2</td>
<td>2</td>
<td>1000</td>
<td>180</td>
<td>200</td>
<td>2</td>
</tr>
<tr>
<td>Near 21</td>
<td>Water vapour, liquid water</td>
<td>0.2</td>
<td>2</td>
<td>1000</td>
<td>180</td>
<td>200</td>
<td>2</td>
</tr>
<tr>
<td>22.235</td>
<td>Water vapour, liquid water</td>
<td>0.4</td>
<td>2</td>
<td>1000</td>
<td>45</td>
<td>300</td>
<td>13</td>
</tr>
<tr>
<td>Near 24</td>
<td>Water vapour, liquid water</td>
<td>0.2</td>
<td>2</td>
<td>1000</td>
<td>180</td>
<td>400</td>
<td>4</td>
</tr>
<tr>
<td>Near 30</td>
<td>Ice, oil spills, clouds</td>
<td>0.2</td>
<td>2</td>
<td>1000</td>
<td>180</td>
<td>500</td>
<td>6</td>
</tr>
<tr>
<td>Near 37</td>
<td>Rain, snow, ice</td>
<td>1.0</td>
<td>1</td>
<td>2300</td>
<td>230</td>
<td>1000</td>
<td>4</td>
</tr>
<tr>
<td>Near 55</td>
<td>Atmospheric temperature profiling</td>
<td>0.3</td>
<td>10</td>
<td>2300</td>
<td>235</td>
<td>Multiple(2)</td>
<td>10</td>
</tr>
<tr>
<td>Near 90</td>
<td>Clouds, oil spills, ice, snow</td>
<td>1.0</td>
<td>1</td>
<td>2300</td>
<td>230</td>
<td>6000</td>
<td>26</td>
</tr>
<tr>
<td>Above 100</td>
<td>Nitrous oxide, $\text{O}_3$, CO, $\text{H}_2\text{O}$, CLO, temperature</td>
<td>0.2</td>
<td>1</td>
<td>4300</td>
<td>1850</td>
<td>2000</td>
<td>1</td>
</tr>
</tbody>
</table>

(1) Parameters given for this application.
(2) Several bands around 55 GHz.
Several aspects of active sensor research, particularly as it relates to the choice of frequencies for measuring Earth-oriented variables from a space platform, are presented below. It should be noted in determining optimal frequencies that, due to the broad frequency response range of various phenomena of interest, there is often a need for simultaneous measurements at several frequencies so that contributions of the radar return from different sources can be separated.

The radar return from any surface is a function of radar frequency, surface roughness, surface dielectric properties, angle of incidence and aspect, and sub-surface microstructure. In each of the applications listed earlier, the energy reflected back to a radar sensor is strongly affected by at least one backscattering mechanism related to the measured phenomenon. In general, these are: oceanic roughness (used in the study of ocean structure and winds over sea surfaces); O$_2$ absorption (used in determining surface pressure over oceans); and surface roughness and dielectric constant variations (used in studies of ice, snow and land parameters).

5.2.2 Active sensing of ocean and ocean winds

Oceanic active sensor studies are dominated by wave structure determination, sea-surface wind measurements and ocean current investigations. Generally the reflected microwave energy is due to ocean roughness; specifically, the radar return is a function of diffraction effects from both large gravity waves and small capillary, surface-tension ripples riding the large-scale waves, and foam. The amount of reflected radiation due to each of these effects observed by an active sensor depends on the sea state and the particular active measurement technique.

Theoretical, laboratory, and pre-satellite field work at several frequencies in band 10 have shown that the effects of large gravity waves dominate at near-normal incidence and those of capillary waves at incidence angles greater than 20° [Wright, 1968]. Thus to sense sea roughness (a function of the very breeze-dependent ripples) and the size and direction of long-lived gravity waves (coarse sea structure), a two-component concept is used. In the study of ocean surface winds (important in weather prediction models), the underlying principle is that ocean roughness is a gauge by which wind variables can be inferred, since the small roughness elements which convey the transfer of momentum from the wind to the sea are in at least near equilibrium with the wind. Using variable frequencies, polarizations and incidence angles, investigators were able to infer details of ocean surface wind, significant wave height and mean square wave slopes, an accomplishment beyond the capabilities of passive sensing [Claasen et al., 1973; Price, 1976; Weissman and Johnson, 1977]. Table V illustrates the history of wind studies using scatterometers which infer ocean roughness from backscatter measurements.

The Skylab S-193 radiometer/scatterometer/altimeter (RADSCAT) experiment was the first attempt to gather data using spaceborne, active microwave systems. Following this, the GEOS-3 altimeter provided measurements of mean sea level and ocean wave heights and the Seasat scatterometer provided data on the relationship between radar backscatter, ocean surface roughness, wind speed and incidence angle. The Seasat scatterometer (14.6 GHz) was able to provide wind estimates by taking pairs of orthonormal measurements [Price, 1976]. Experiments have shown that good wind speed sensitivity is obtained at the Seasat scatterometer frequency of 14.6 GHz and that there is a reduced sensitivity to wind speed at 1.3 GHz. The Seasat scatterometer used a Doppler filtering technique, and both the peak power (100 W) and bandwidth (800 kHz) requirements were moderate.

SARs are now showing promise in coarse ocean structure measurements (average significant wave height). An advanced SAR program (ASAR) will employ four frequency bands in the 1 to 10 GHz range and three polarizations with wide-swath and multiple-incidence angle capabilities as a further step in the development of SARs. The Seasat SAR collected data on ocean wave length and direction, which are currently being processed [Frost et al., 1980]. Ocean oil slicks suppress short-wavelength ocean waves and therefore the slick area can be discriminated from the surrounding clean surface by microwave imaging radars. This technique has been demonstrated to be a practical method for oil spill surveillance from aircraft, and may be extended to SAR observation from space [Fujita et al., 1986].
While the first generation of operational radars will probably utilize a bandwidth comparable to that used by the Seasat SAR (19 MHz), it is probable that greater bandwidths will be required in the future to improve the range resolution. Also, because of the desirability of larger incident angles and higher resolution, it is possible that higher peak power output will be required than that used by the Seasat SAR (800 W).

**TABLE V — Compendium of experiments concerning the active sensing of ocean/water surface structure and winds**

<table>
<thead>
<tr>
<th>Type of measurement and organization</th>
<th>Frequency (GHz)</th>
<th>Polarizations (1) combinations</th>
<th>Approximate range of angles of incidence (degrees)</th>
<th>Range of winds or waves</th>
</tr>
</thead>
<tbody>
<tr>
<td>Space borne experiments:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NASA</td>
<td>13.9</td>
<td>VV, VH, HV and HH</td>
<td>0 to 53</td>
<td>2.1 m/s to more than 28.3 m/s</td>
</tr>
<tr>
<td>Airborne experiments:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Naval Research Laboratory</td>
<td>1.2; 4.4; 8.9</td>
<td>VV, VH, HV and HH</td>
<td>0 to 89</td>
<td>2.1 m/s to 24.7 m/s</td>
</tr>
<tr>
<td>NASA</td>
<td>13.3</td>
<td>VV</td>
<td>0 to 60</td>
<td>3.1 m/s to more than 28.3 m/s</td>
</tr>
<tr>
<td>NASA</td>
<td>13.9</td>
<td>VV, VH, HV and HH</td>
<td>0 to 60</td>
<td>3.1 m/s to 20.6 m/s</td>
</tr>
<tr>
<td>CRPE (2)</td>
<td>5.3</td>
<td>VV, VH, HV and HH</td>
<td>0 to 60</td>
<td>0 to 25 m/s</td>
</tr>
<tr>
<td>From platform bridges:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Naval Research Laboratory</td>
<td>9.4; 35</td>
<td>VV</td>
<td>0 to 80</td>
<td>0 to 12.9 m/s</td>
</tr>
<tr>
<td>CNES</td>
<td>3 to 18</td>
<td>HH, VV, HV and VH</td>
<td>0 to 60</td>
<td>0 to 25 m/s</td>
</tr>
<tr>
<td>Wave tank measurements:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Naval Research Laboratory</td>
<td>9.375</td>
<td>VV and HH</td>
<td>10 to 86</td>
<td>Millimetre waves of wavelengths from 1.6 to 6 cm</td>
</tr>
</tbody>
</table>

(1) VV: vertical transmit/vertical receive  
VH: vertical transmit/horizontal receive  
HH: horizontal transmit/horizontal receive  
HV: horizontal transmit/vertical receive.  
(2) Centre de recherches en physique de l'environnement terrestre et planétaire.
Altimeters have been used successfully from a number of satellites over the world's oceans. The Seasat altimeter was designed to operate at 13.5 GHz and to measure ocean wave heights on a track directly beneath the satellite. A very large bandwidth (360 MHz) and relatively high peak power (= 2.5 kW) were required in order to achieve a precision of 10 cm. For oceanographic satellites such as TOPEX-POSEIDON, currently being developed in cooperation between the United States of America and France, an altimeter system having an overall range measurement precision better than 2 cm is required. To achieve 2 cm precision will require removal of the range errors due to ionospheric electron content which cause errors as great as 22 cm at 13.5 GHz [Goldhirsh and Rowland, 1982]. A two-frequency altimeter system [Goldhirsh and Rowland, 1982] can eliminate the range uncertainty due to the ionosphere. A two-frequency altimeter system can also provide accurate measurements of continuous swaths of the ionospheric electron content, measurements which are not available today over large regions of the Earth's oceans. A region of the spectrum, separated by more than an octave from the 13.4 - 14 GHz band, would be a suitable choice for the second frequency. The second frequency could be selected around 5 GHz, with the main frequency remaining near 14 GHz. It is thought that in the longer term, higher frequencies around 35 GHz could be used. TOPEX-POSEIDON also carries a single-frequency altimeter entirely constructed using solid state technology.

It can thus be seen that several frequencies have proven useful for the remote active sensing of ocean-wave structure. Due to high wind speed dynamic range and the relative absence of atmospheric effects, wind speed measurement technology is converging on the 10 to 15 GHz region.

5.2.3 Active sensing of ice-covered surfaces

Airborne investigations of Arctic ice fields at 400 MHz, and 1.2, 9.4, 10, 13.3 and 34.9 GHz [Anderson, 1966; Parashar, 1974] have found that ice variables which most affect radar return are surface roughness, material microstructure, ice liquid content, temperature and brine volume. A summary of all these investigations indicates that the following types of ice variables are amenable in varying degrees to active microwave sensing: ice-type (young, old, etc.), surface roughness, concentration, floe size and number, water openings, drift, surface topography, pressure characteristics, thickness and changes in nature and in distribution of types. Based on these studies, a frequency in band 10 appears to be the best for determining sea-ice types. Band 9 radar is useful in resolving ambiguities resulting from measurements of thin ice, especially when utilized in conjunction with band 10 radars. Higher frequencies are under study.

The most important spaceborne active microwave sensors for sea-ice application are the SAR, radar altimeter and radar scatterometer. Satellite research on sea-ice has been primarily carried out by Seasat. Airborne synthetic aperture radar imagery (1.3 GHz and 9.1 GHz) has shown that in some cases, including sea-ice mapping, the higher frequency channel is preferable. However, there are currently technical problems and risks associated with the development of a 9 GHz spaceborne synthetic aperture radar and the most probable frequency for the near-term development of spaceborne radars is near 1.3 GHz or 5 GHz with the possibility of future development at 9 GHz or even higher frequency. Although the interpretability of sea-ice imagery does improve with higher frequencies, there is no question of the usefulness of the product at 1.3 GHz. Altimeters have been used to map sea-ice parameters and the height of the Greenland ice-cap.

The usefulness of active microwave sensing of ice-cover parameters will be better understood as Seasat data continue to be analyzed.
5.2.4 Meteorological observations

The knowledge gained in ground-based and airborne measurement of rainfall, storm features and pressure fields in weather prediction models is being extended to spaceborne systems. The techniques are based upon changes in clear atmosphere refractive index due to rain-related features or differential reflectivities of multi-frequency echoes. Studies carried out with orthogonally polarized radars and multiple, narrow-beam coverage at several frequencies between 2 and 37.5 GHz [Skolnik, 1974; Goldhirsh and Katz, 1974; Atlas and Ulbrich, 1973; Okamoto et al., 1982] have been able to measure precipitation rate, intensity, spatial distribution, drop size and surface pressure over oceans, and wind movements within storms. The results of flight experiments for rain-rate measurements by an airborne microwave scatterometer/radiometer system suggest the potential of spaceborne sensors for global mapping of rain rate [Okamoto et al., 1982]. In the estimation of rain rate, it is desirable to complement radar measurements by data from radiometers [Masuko et al., 1981]. There are several factors constraining frequency choices. A combination of bands must be chosen to match minimum rainfall sensitivity, yet not be swamped by Earth echo at needed viewing angles. Only downward-looking scanning pencil beams (as opposed to azimuthal or cross-track fan beams) have the capacity to infer rainfall intensity from altimeter estimates of the freezing layer. A multi-frequency approach to measurement of rain attenuation has potential for deriving rain rates from satellites. This has been verified by an experiment using an airborne dual wavelength radar [Menegheni et al., 1989].

5.2.5 Active sensing of vegetation cover and soil moisture

Interest in active sensing of soil moisture arose due to the limited spatial resolution of passive sensors. The amount of reflected radar power from the soil depends on soil roughness and dielectric constant, vegetation cover and incidence of the transmitted microwave beam. Early laboratory studies showed that soil moisture affects reflectivity of the soil due to changes in soil dielectric constant [Lundien, 1966]. Aircraft measurements of backscatter coefficient which show the effect of irrigation on the backscatter coefficient are plotted in Fig. 9. Usually, incidence angles less than 45° help distinguish roughness returns from moisture returns, whereas polarization regimens appear to offer little prospect of improving these results. Research, which utilized 4.7, 5.9 and 13.3 GHz [King, 1973; Ulaby et al., 1974, 1975; Ulaby and Batliwalla, 1976] indicates that a satellite scatterometer system operated at 4.7 GHz with 5° to 17° incidence angles could adequately distinguish soil moisture returns from those of vegetation cover and roughness. However, additional frequencies are needed when vegetation cover is a factor or when sub-soil measurements are required.
On the other hand, vegetation cover has been studied as an objective, particularly in crop identification experiments, where soil returns become an obscuring factor. Both imagers and scatterometers have been used with the reflected power from vegetation being related to vegetation roughness, moisture and dielectric constant, and viewing angle. Results of these investigations indicate that satellites can be useful in active sensor identification of crops and forests, of land use patterns (range, forest, etc.) and of watershed parameters. Multi-spectral, multi-polarization, multi-temporal schemes of observation at high incidence angles (to minimize soil returns) have yielded promising results in research at 1.3, 5.9, 9.0, 9.4, 13, 16 and 35 GHz [De Loor et al., 1974; Havalick et al., 1970; Schuchman and Drake, 1974; Ulaby and Moore, 1973]. In crop studies in the 8 to 18 GHz range [Ulaby and Bush, 1975; Ulaby, 1976], crop classification was improved by taking growing periods into account, by employing several frequencies and by repeating measurements over several weeks. It can be seen in Fig. 10 that HH polarization yielded improved results over VV and a combination of HH and VV polarizations gave the best single-frequency results. The identification statistics can be improved to 91% using a combination of three frequencies (8.6, 13.3 and 16.6 GHz).
5.2.6 Bandwidth requirements for active sensing

Bandwidth requirements for active sensors vary with the type of sensor, i.e., synthetic aperture radar, real aperture radar, scatterometer or altimeter. In all cases, the bandwidth is determined by the required range resolution and is equal to:

\[ B = \frac{c}{\tau} = \frac{1}{2\Delta R \cos \theta_d} \]  

where:

- \( B \): bandwidth (Hz)
- \( \Delta R \): range resolution (m)
- \( c \): speed of light (m/s)
- \( \theta_d \): depression angle from satellite, or equivalently, arrival angle at Earth
- \( \tau \): effective pulse duration (equivalent to the inverse of the pulse compression bandwidths) (s).

As an example, the synthetic aperture radar on Seasat had a range resolution of 25 m, a \( \tau \) of 53 ns and a \( \theta_d \) of 70°. The required bandwidth was therefore 19 MHz, which is the inverse of the effective pulse duration.
Applications envisaged by scientists using synthetic aperture radars will require greater bandwidth than the active sensors used on Seasat. A bandwidth of 100 MHz would be compatible with a large majority of applications.

Altimeters, used in applications such as geodetic mapping, require a greater bandwidth than do other types of active sensors. For example, the Seasat altimeter had a bandwidth of 360 MHz. Allowing for more precise future measurements, a bandwidth of 600 MHz would be appropriate for use by spaceborne altimeters.

5.2.7 Summary of preferred frequencies for active sensing

Although active microwave sensing technology is advancing rapidly and much still needs to be learned, a set of preferred frequencies can be defined which satisfy the specific measurement requirements discussed in § 5.2.2 and provide for multi-frequency measurements needed to separate signal contributions from different sources. Sharing considerations (Report 695 (Kyoto, 1978)) dictate that specific frequency bands for active sensors should be in bands shared with the radiolocation service. Thus, preferred frequencies for active spaceborne sensor measurements of the phenomena discussed in § 5.2.2 to 5.2.5 fall near 1, 3, 5, 10, 14, 17, 35 and 76 GHz. A bandwidth of 100 MHz is appropriate for all applications using active sensor instruments other than altimeters. Altimeter measurements may need up to 600 MHz bandwidth to satisfy accuracy requirements, but, at present, this requirement can be accommodated only in the band allocated near 14 GHz for active sensing. A second frequency band, with 600 MHz bandwidth would achieve 2 cm precision for the application of altimeters to oceanography. Two frequency bands which would be useful for achieving this precision are, for instance, around 5 GHz and 35 GHz. A variety of active microwave sensing instruments is summarized in Table II.

REFERENCES


NASA [1976a] Frequency band justifications for passive sensors 1-10 GHz. National Aeronautic and Space Administration, USA.


BIBLIOGRAPHY


1. Introduction

The purposes of this Report are to evaluate the possibilities of sharing frequency bands between passive microwave sensors and stations of other services, and to develop sharing criteria where sharing is determined to be feasible.

Frequency bands ranging from below 1 GHz to above 300 GHz are needed to carry out microwave sensing applications being developed for earth exploration in earth resources, meteorology and oceanography. The extent to which sharing with other services is feasible will determine the need for dedicated or shared frequency bands and will affect the development of operational remote sensing systems.

Three potential methods for sharing common frequency bands between microwave sensors and other services are:
- simultaneous operations,
- time sharing,
- geographical separation.

Simultaneous sharing requires no operational constraints on the sharing services and is preferred. In bands where simultaneous sharing is not feasible, service characteristics may permit time sharing.

The third technique, geographical separation of interfering stations, may be applicable to certain remote sensing applications which are needed over areas of limited extent, such as estuarine salinity.

More detailed analysis of the sharing situations discussed in this Report can be found in the Annexes to Report 694-2, Dubrovnik, 1986.

2. Microwave sensor factors pertinent to sharing

2.1 Harmful interference criteria

Radiometer sensitivities are generally expressed as a temperature differential (Report 224). This sensitivity is given by:

$$\Delta T_r = \frac{\alpha T_n}{\sqrt{Bt}} \quad (K) \quad (1)$$

where:
- $B$: receiver bandwidth (Hz)
- $t$: total time of observation (s)
- $\alpha$: receiver system constant
- $T_n$: operating noise temperature (the sum of the receiver noise referred to the antenna terminal and that noise entering via the antenna) (K).

* This Report should be brought to the attention of Study Groups 4, 8 and 9.
The radiometer threshold, or minimum discernible power change, is given by:

\[ \Delta p = k \Delta T_e B \quad (\text{W}) \]  

(2)

where: \( k = \text{Boltzmann's constant}, 1.38 \times 10^{-23} \text{ J/K.} \)

Harmful interference occurs when the unwanted signal at the receiving antenna is on a level comparable with \( \Delta p \). The criterion used in this analysis is that interfering signal levels of greater than 20% of \( \Delta p \) constitute the threshold interference level \( (p_H) \). Therefore:

\[ p_H = 0.2 k \Delta T_e B \quad (\text{W}) \]  

(3)

2.2 Sensor performance parameters

Key sensor characteristics which must be known in order to analyze interference potential include:

- interference threshold,
- antenna gain and pattern,
- geographical coverage requirements,
- frequency of measurements,
- spatial resolution,
- orbit.

3. Analysis approach

Preferred frequency bands for passive microwave sensors are listed in Recommendation 515. The potential for sharing between sensors and other services has been analyzed for each frequency band. Typical equipment parameters for the stations of other services were used in the analyses. In bands where equipment has not yet been developed potential systems were postulated following applicable CCIR guidelines.

3.1 Gain range factor analysis \((g, g_r / R^2)\)

The gain range model is based upon a parametric analysis of potential interference situations. The harmful interference power, \( p_H \), seen at the passive radiometric receiver is given by equation (3).

In relation to the interfering source,

\[ p_H = \frac{p_t g_t g_r}{4\pi R^2} \left( \frac{\lambda^2}{4\pi} \right) \]  

(4)

where:

- \( g_t \) : numerical gain of transmitting antenna,
- \( p_t \) : power of transmitting source (W),
- \( g_r \) : numerical gain of receiver antenna,
- \( \lambda \) : wavelength (m),
- \( R \) : range (m).

Rearranging equation (4):

\[ \frac{p_H (4\pi)^2}{p_t \lambda^2} = \frac{g_t g_r}{R^2} \]  

(5)

A computer simulation of the right-hand side of equation (5) can be performed if the characteristics of the interference source are known and the interference threshold and orbit of the sensor are known. The gain range factor \((g, g_r / R^2)\) analysis determines the percentage of time and areas of geographical coverage lost to a spaceborne sensor when in view of a single terrestrial station.
3.2 Random interference analysis programme

The random interference analysis programme was developed to determine the cumulative effects of numerous terrestrial stations simultaneously visible to a spaceborne radiometer.

This technique utilizes a random number generator to place terrestrial stations within the field of view of the radiometer. The terrestrial stations are located at random great circle distances from the spacecraft sub-satellite point, and assigned a random pointing direction. Based upon the terrestrial and radiometer antennas and range to the spacecraft, the interference power at the input to the radiometer is calculated.

The random interference analysis programme is used to determine the probability of interference to a sensor as a function of the population of interfering stations.

4. Sharing considerations

Sensor interference thresholds, corresponding to the preferred frequency bands contained in Recommendation 515 together with applicable bandwidths related to the interference thresholds are given in Table I below. The values for the interference thresholds are determined using equation (3), the values for $\Delta T_e$ are given in Table IV of Report 693, and the values for bandwidth are given in Table I of this Report and Table III of Report 693.

The following paragraphs consider the feasibility of sharing between passive microwave sensors and stations in other services.

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>Interference threshold (dBW)</th>
<th>Bandwidth (MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Near 1.4</td>
<td>-165</td>
<td>100</td>
</tr>
<tr>
<td>Near 2.7</td>
<td>-166</td>
<td>60</td>
</tr>
<tr>
<td>Near 5</td>
<td>-158</td>
<td>200</td>
</tr>
<tr>
<td>Near 6</td>
<td>-158</td>
<td>400</td>
</tr>
<tr>
<td>Near 11</td>
<td>-156</td>
<td>100</td>
</tr>
<tr>
<td>Near 15</td>
<td>-160</td>
<td>200</td>
</tr>
<tr>
<td>Near 18</td>
<td>-152</td>
<td>200</td>
</tr>
<tr>
<td>Near 21</td>
<td>-160</td>
<td>200</td>
</tr>
<tr>
<td>22.237</td>
<td>-155</td>
<td>300</td>
</tr>
<tr>
<td>Near 24</td>
<td>-157</td>
<td>400</td>
</tr>
<tr>
<td>Near 30</td>
<td>-156</td>
<td>500</td>
</tr>
<tr>
<td>Near 37</td>
<td>-146</td>
<td>1000</td>
</tr>
<tr>
<td>Near 55</td>
<td>-157</td>
<td>250</td>
</tr>
<tr>
<td>Near 90</td>
<td>-138</td>
<td>6000</td>
</tr>
<tr>
<td>Above 100</td>
<td>-150</td>
<td>2000</td>
</tr>
</tbody>
</table>
4.1 Sharing between passive sensors and the fixed service

Each of the preferred frequency bands for passive sensors has been analysed using the gain range factor \((g/R^2)\) analysis programme and the random interference analysis programme.

Simultaneous sharing between passive sensors and fixed service systems has been determined to be generally not feasible much below 10 GHz.

Time sharing with the fixed service is generally not feasible since operation of this service is usually continuous. Limited exceptions might be found where the fixed service is limited to day-time hours. In that case, sensors could operate during the night, so time sharing could be used.

Large areas of the Earth are, at present, interference-free for all bands because of the concentrated locations of the fixed stations. However, sensing applications cannot be performed over some major areas of interest, because of fixed service transmitters.

Above 20 GHz frequency sharing between passive sensors and the fixed service appears feasible due to increased atmospheric attenuation and assumptions as to the technical characteristics of the, as yet, undeveloped fixed service, which is expected to use low power wideband modulation techniques. Small areas of interference would occur for a direct overhead pass. Based on the assumptions and analyses performed, the resultant interference would have negligible impact on passive sensor operations.

Frequency sharing with the fixed service at 10 GHz would be feasible provided the maximum e.i.r.p. of a fixed or mobile station does not exceed 38 dBW and that the power delivered by a transmitter to the antenna of the fixed station does not exceed –1 dBW. Near 18 GHz the results of analysis, based on the assumptions used in Report 850 indicate that sharing would be feasible if the fixed service operated with gains greater than 40 dBi (beamwidth less than 1.6°) and powers less than 0 dBW (see Report 850 for details of sharing analysis and criteria near 18 GHz).

It would be necessary for future analyses near 18 GHz to model a high capacity route in a north-south orientation to consider the effects of low capacity distribution systems and to explore the effects at additional values of terrestrial antenna gain.

4.2 Sharing between passive sensors and the mobile service

Sharing between passive sensors and the mobile service below 10 GHz is generally not feasible.

Above 10 GHz sharing becomes progressively more feasible as frequency increases. However, in the 10-20 GHz range sharing criteria would be required if mobile systems were to operate in the fixed/mobile allocations jointly shared with passive sensors. See Report 850 for details of sharing analysis, and criteria for 18 GHz.

4.3 Sharing between passive sensors and the fixed-satellite service (space-to-Earth)

The feasibility of frequency sharing between sensors and fixed-satellite space-to-Earth transmissions has been analysed in the vicinity of 18 GHz and 37 GHz. Details of the 18 GHz analysis are contained in Report 850.

The analysis was first performed assuming that the fixed-satellite e.i.r.p. would result in the maximum allowable pfd at the Earth's surface. Under this condition, interference to the sensor at 18 GHz would be 10 dB above the sensor interference threshold when the sensor is in the fixed-satellite main beam. Simultaneous operations at 18 GHz would therefore not be feasible.

An analysis was also performed to determine suitable sharing criteria that would allow frequency sharing between passive sensors and the fixed-satellite space-to-Earth link. It was determined that sharing is feasible provided that the gain of the fixed-satellite antenna is at least 52 dBi (beamwidth less than 0.4°) and the pfd limit is reduced by 10 dB. Other sets of sharing criteria are also possible (see Report 850).
The constraint on the fixed-satellite service to avoid harmful interference to passive sensors appears compatible with requirements of the international carriers, such as INTELSAT, where large size (27 < $G/T$ < 40) earth stations are employed.

Sharing with the fixed-satellite service (space-to-Earth) at 37 GHz is feasible.

4.4 Sharing between passive sensors and the fixed-satellite service (Earth-to-space)

Sharing between passive sensor and fixed-satellite up-links was analysed in the vicinity of 2.6 GHz, 37 GHz and 50 GHz.

Simultaneous sharing at 2.6 GHz is not feasible, since loss of coverage due to interference from each fixed-satellite earth station would be 27% of the visibility sphere. Time sharing might be feasible if it is assumed that the fixed-satellite service uses this band only for thin-route, on-demand, low duty cycle operations.

Loss of coverage from a single fixed-satellite earth station in the vicinity of 37 GHz would be 2% of the visibility sphere and at 50 GHz would be only 0.24%. Results of the random interference analysis programme show that significant loss of data would occur if more than 15 earth stations were within the sensor field of view. Simultaneous operations in these bands are feasible if the fixed-satellite system employs a small number of earth stations.

4.5 Sharing between passive sensors and the inter-satellite service

The feasibility of frequency sharing by passive sensors and the inter-satellite service has been analysed in the region of 50 to 70 GHz and near 115 GHz. The analysis considered three possible configurations of inter-satellite link geometry:

- geostationary-to-geostationary satellite links;
- geostationary-to-low-orbit satellite links, and
- low-orbit-to-geostationary links.

Localized areas of interference could be encountered by a spaceborne sensor when:

- passing through the down-link tracking beam of the geostationary satellite,
- in close proximity to an up-link transmitting low-orbit satellite,
- pointing (for a limb sounder) directly at the geostationary satellite.

Cumulative side lobe interference from multiple inter-satellite links is not expected to be an important factor.

The technical characteristics assumed for the inter-satellite service are based on a hypothetical system model.

4.5.1 Interference due to geostationary-to-geostationary satellite links

Interference could occur only when the geostationary satellites are separated by more than 70 degrees of the geostationary arc. However, orientation of both nadir-pointing and limb sounding sensors will preclude the antenna couplings which would produce interference. No interference to sensor operations would occur.

4.5.2 Interference due to geostationary-to-low-orbit satellite links

Interference could occur for a limb sounding passive sensor but not for a nadir-looking passive sensor. In the former case, interference would occur for short periods of time if the sensor antenna were pointed at the main beam or side lobes of the geostationary satellite antenna. This situation would occur infrequently and be of short duration. The loss of data would be negligible; typically, less than 0.02%.

4.5.3 Interference due to low-orbit-to-geostationary satellite links

The only potential for large areas of interference would be due to side lobe to side lobe coupling between the passive sensor antenna and the low orbit satellite antenna. Interference would occur only if the two satellites were separated by less than 150 km. The probability of this occurrence is negligible.
4.5.4 Conclusion

Sharing on a simultaneous operational basis between passive sensors and the inter-satellite service is feasible.

4.6 Sharing between passive sensors and the Aeronautical Radionavigation and Radiolocation Services

Sharing between passive sensors and the Aeronautical Radionavigation and Radiolocation Services has been analysed for frequency bands near 1.4 GHz, 15 GHz, and above 100 GHz.

Transmitters in the Aeronautical Radionavigation and Radiolocation Services are typically pulse type radars.

The gain range factor analysis programme was used to simulate couplings between the passive sensor and transmitter antennas. The loss of coverage area for the passive sensor was found to be 100 per cent of the visibility sphere around the terrestrial stations. The population of transmitters is typically large in the bands that were analysed resulting in large areas of the Earth where passive sensing would not be possible.

Frequency sharing between passive sensors and either the aeronautical radionavigation service or the radiolocation service is in general not feasible. An exception to this conclusion is discussed in § 4.9.

4.7 Sharing between passive sensors and the broadcasting-satellite service

Sharing between passive sensors and the broadcasting-satellite service near 2.6 GHz was analysed.

There are two possible interference paths from a broadcasting-satellite to a low orbit satellite. Interference could either be received through the low-orbiting satellite antenna back lobe, or through reflection from the surface of the Earth into the radiometer main beam.

Calculations for the above cases show that interference to the passive sensor would be 22 to 33 dB above the sensor interference threshold.

Calculations for a broadcasting-satellite with side lobe gain discrimination meeting CCIR Recommendations and operating 3 time zones away from the sensor position show that interference would still exceed the sensor interference threshold. Therefore, time sharing is not feasible.

Sharing between passive sensors and the broadcasting-satellite service is not considered feasible either on a simultaneous operation or on a time sharing basis. Improved side lobe discrimination of the broadcasting-satellite could possibly permit time sharing on a limited scale.

4.8 Sharing between passive sensors and the Mobile-Satellite Service

Sharing between passive sensors and Mobile-Satellite Services has been analysed for frequency bands near 20 GHz, 37 GHz, and 50 GHz.

4.8.1 Space-to-Earth mobile-satellite links

Sharing calculations were based on a model of a hypothetical mobile-satellite system, using spread spectrum techniques.

Interference levels were determined to be below the sensor interference threshold so long as the mobile-satellites do not produce pfd levels at the surface of the Earth, in excess of $-128$ dB(W/(m$^2$ · MHz)) at 20 GHz and $-117$ dB(W/(m$^2$ · MHz)) at 37 GHz.

Sharing between passive sensors and mobile-satellite sensors is feasible if the mobile-satellites conform to the pfd limits given above.
4.8.2 **Earth-to-space mobile-satellite links**

The maximum interference level at the sensor occurs when the sensor is in the main beam of the mobile earth station. Interference levels of the order of 40 dB above the sensor threshold result.

An analysis of the gain range factor shows that approximately 2 per cent of the visibility sphere would be lost to the passive sensor at 37 GHz due to a single source of interference. At 50 GHz the corresponding loss would be 0.24 per cent.

The loss of data to a passive sensor would depend on the population of mobile-satellite earth stations and the percentage of time that each station may transmit.

Sharing between passive sensors and Earth-to-space mobile-satellite links is feasible for small numbers of mobile-satellite earth stations. Since loss of coverage would result and since the numbers of earth stations is largely unknown, sharing with mobile-satellite Earth-to-space links is undesirable and should be avoided.

4.9 **Sharing between passive sensors and airborne radio altimeters**

Sharing between passive sensors and radio altimeters operating in the aeronautical radionavigation service in the 4.2 to 4.4 GHz band has been analysed.

Both CW and pulsed type altimeters operate in this band. The two systems have average e.i.r.p. levels of approximately 5 dBW. Estimates of future use of the band indicate that of the order of 50,000 units may be in operation by the year 2000. A small percentage of these units may be configured to allow precision range finding as well as radar altimetry (see No. 789 of the Radio Regulations).

The passive sensor interference threshold would not be exceeded unless more than 3000 aircraft were simultaneously in view of the sensor. This is well above the predicted maximum number of 750 in view over coastal and ocean areas. Between 2000 and 4500 radar altimeter/precision range finding systems having characteristics as used in the analysis could also operate without exceeding the interference threshold of -158 dBW.

Simultaneous sharing with radio altimeters is therefore feasible. The criterion for sharing is that transmitters in the Aeronautical Radionavigation Service employ average output powers of the order of –5 dBW.

4.10 **Sharing between passive sensors and radioastronomy**

The only potential for interference to the Radioastronomy Service would be due to local oscillator leakage and emission through the spacecraft antenna. Based on radioastronomy sharing criteria as presented in Report 224, the analysis indicated that no harmful interference would occur to the Radioastronomy Service. Hence simultaneous sharing is feasible.

Radio astronomers have suggested that, if practicable, designers should choose local oscillator frequencies so that they lie on the upper side of those radioastronomy bands in which line emission has been detected from distant galaxies by the use of high gain antennas (Recommendation 314).
5. Conclusions

Frequency sharing between passive sensors and the fixed service appears feasible above 20 GHz.

Frequency sharing with the fixed service at 10 GHz is feasible only provided that the maximum e.i.r.p. of a station in the fixed service does not exceed 38 dBW, and that the power delivered by a transmitter to the antenna of a station in the fixed or mobile service does not exceed about −1 dBW. Other sets of sharing criteria are possible. For example, sharing is feasible for an e.i.r.p. of 40 dBW and a maximum transmitter output power of −3 dBW, the fixed service limits in the 10.6-10.68 GHz band. Near 18 GHz the results of analysis, based on the assumptions used in Report 850, indicate that sharing is feasible with the fixed service if the antenna gain is at least 40 dBi and the transmitter power less than 1 W. Sharing is feasible with the mobile service if the transmitter power is less than −5 dBW. However, there are fixed systems operating in the 10 GHz range, other than the 10.6-10.7 GHz band, which exceed these criteria by at least an order of magnitude. Also, present regulations permit operation of fixed and mobile systems with 10 dBW input power to the antenna except at 10.6-10.68 GHz. If these maximum allowable levels are used, sharing would not be feasible. Further improvement of prototype fixed systems around 20 GHz might also result in parameters which would exceed the criteria. Analysis shows, however, that many fixed and mobile applications are compatible with the stated criteria.

Frequency sharing with the fixed and mobile services much below 10 GHz is generally not feasible. However, large areas of the Earth's oceans will be interference-free for passive sensing in common frequency bands.

Frequency sharing with fixed-satellite and mobile-satellite space-to-Earth links between 15 GHz and 20 GHz is feasible provided the gain of the fixed-satellite antenna is at least 52 dBi and the pfd limit is reduced by 10 dB. Other sets of sharing criteria are also possible (see Report 850).

Sharing with fixed and mobile-satellite Earth-to-space links is of limited feasibility and should be avoided if possible, the amount of data loss being highly dependent upon the number of earth stations in the fixed and mobile-satellite systems.

Sharing with the broadcasting-satellite service is not feasible, except that time sharing may be feasible on a limited basis if the broadcasting-satellite employs state-of-the-art antenna side-lobe control.

Sharing with the radiolocation and aeronautical radionavigation services is feasible only in bands used exclusively for radio altimeters.

Future studies of the feasibility of passive sensor sharing with active services near 18 GHz should include analysis of factors described in the conclusion of Report 850.
FREQUENCY SHARING BY PASSIVE SENSORS WITH THE FIXED, MOBILE 
EXCEPT AERONAUTICAL MOBILE, AND FIXED-SATELLITE SERVICES 
IN THE BAND 18.6-18.8 GHz

Minimum restrictions to other services in order to ensure 
satisfactory operations of passive sensors
(Study Programme 12B/2)

(1982-1986)

1. Introduction

Recommendation No. 706 of the WARC-79 requests that the CCIR study sharing between services 
allocated in the 18.6-18.8 GHz band in order to develop sharing criteria which would ensure satisfactory 
operations of passive sensors without jeopardizing the other services likely to use this frequency band.

This Report is a partial answer to Recommendation No. 706. In particular, it examines the question of the 
minimum restrictions which might be applied to the fixed, mobile, except aeronautical mobile, and fixed-satellite 
(space-to-Earth) services in order to ensure the satisfactory operation of passive sensors.

2. Interference criteria

The interference threshold for a passive sensor having a sensitivity of 1 K and a radio-frequency 
bandwidth of 200 MHz (Report 694) is:

$$P_H = 0.2k \Delta T_e B = -152 \text{ dBW}$$

where:

- $\Delta T_e$: radiometer sensitivity, 1 K,
- $k$: Boltzmann’s constant, $1.38 \times 10^{-23} \text{ J/K}$,
- $B$: radio-frequency bandwidth, 200 MHz.

A second criterion is that, for viable passive sensor operations, the data loss caused by interference levels 
above the interference threshold must be less than 5%. This amount of data loss could be composed of data loss 
when the passive sensor antenna points directly at an interference source, or conversely, when the sensor is within 
the main beam of an interfering source.

3. Passive sensor characteristics

The passive sensor satellite orbit, utilized for the analyses that follow, is a 500 km circular, polar orbit.

The sensor’s antenna pattern is substantially better than usual CCIR patterns, since one purpose of the 
sensor antenna is to suppress as much energy outside of its main beam as possible. Approximately 90% of the 
energy received by the sensor comes through the main beam. Figure 1 represents the sensor antenna pattern. The 
gain of the antenna was selected to be 57 dBi, resulting in a spatial resolution of 2 km and a half-power 
beamwidth of 0.16°. A sensor can utilize a number of different types of scanning modes. These modes are:

- a) nadir looking only;
- b) conical scanning;
- c) cross-track scanning; and
- d) "push-broom" scanning.

When scanning, the angle off nadir is generally no greater than 45°. For modes a), b) and c), only one 
antenna/receiver combination is employed. The "push-broom" mode processes in parallel each resolution element 
in its swath, and thus requires many receivers to cover a given swath.

* This Report should be brought to the attention of Study Groups 4, 8 and 9.
The harmful interference threshold as previously calculated is $-152$ dBW. Half of the allowable interference power ($-155$ dBW) was allocated to the fixed and mobile services and half was allocated to the fixed-satellite service. The sensor characteristics are summarized in Table I.

**TABLE I — Passive sensor characteristics**

<table>
<thead>
<tr>
<th>Satellite altitude</th>
<th>500 km</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antenna gain</td>
<td>57 dBi</td>
</tr>
<tr>
<td>Resolution</td>
<td>2 km</td>
</tr>
<tr>
<td>Half-power beamwidth</td>
<td>0.16°</td>
</tr>
<tr>
<td>Interference threshold</td>
<td>$-152$ dBW</td>
</tr>
<tr>
<td>Receiver RF bandwidth</td>
<td>200 MHz</td>
</tr>
</tbody>
</table>

4. Analysis of the feasibility of sharing with the fixed and mobile services

A parametric study has been performed to determine the effects on sharing potential of varying the population, antenna gain and transmitter power of the terrestrial transmitters. Instead of using a randomly distributed transmitter population, a more representative distribution of transmitters clustered around the 30 largest population centres in the United States and Canada was utilized in this study. Interference levels were determined for transmitter populations of 1000, 5000 and 10 000, transmitter antenna gains of 0, 10, 20, 30 and 40 dBi and transmitter powers of $-10$, $-5$, 0, $+5$ and $+10$ dBW.

A computer model was developed to determine interference levels at orbital altitude for all combinations of the above variables. The computer model used random azimuths for transmitter antenna pointing angles, assuming a uniform distribution of headings between 0 and 360°. The total number of emitters, the transmitter antenna gain, and the transmitter output power were treated as parameters, with assigned values. The interference which would have occurred to a sensor at the centre of each $2° \times 2°$ latitude/longitude cell was computed for each transmitter in view, using the angular difference between the antenna centre line and the direction of the cell from the transmitter to determine transmitter antenna gain. Transmitter antenna gains were estimated using a standard CCIR side-lobe envelope approximation ($S_2 = 10 \log D/\lambda - 25 \log \varphi$ for $D/\lambda < 100$, see Report 391).
The combined effects of multiple interference input paths were then summed and compared with the sensor interference threshold. There are three types of interference paths, namely: terrestrial antennas main beams to sensor antenna side lobes, terrestrial antennas side lobes to sensor antenna main beams, and terrestrial antennas side lobes to sensor antenna side lobes (see Report 694). Those cells which had a cumulative interference level above the interference threshold were lost data areas. The total area of data loss was accumulated for each combination of input parameters and the results are plotted in Fig. 2.

It should be noted that the $2^\circ \times 2^\circ$ cells over-estimate the data loss when that loss is small ($< 3\%$), but not when considering losses comparable to $5\%$ or greater. The over-estimation is significantly reduced for the $< 3\%$ loss region when scattering is considered.

![Graphs]

FIGURE 2 – Loss of coverage area versus FS transmitter population, FS transmitter power, and FS transmitter antenna gain

- (a) 10 000 transmitters
- (b) 5 000 transmitters
- (c) 1 000 transmitters
- (d) 250 transmitters

Frequency = 18.6 GHz
4.1 Analysis of results

Figure 2 confirms that higher transmitter power and larger numbers of transmitters cause increased loss of sensor coverage area. Passive sensor interference criteria can be satisfied, resulting in satisfactory passive sensor operations, if the fixed and mobile services use combinations of transmitter power and antenna gains which maintain the loss of coverage area below the 5% data-loss level. For example, as shown in Fig. 2, the sensor's criteria would be met, when 10,000 transmitters are within line of sight to the passive sensor satellite, if each transmitter were to use a transmitter power of 0 dBW and an antenna gain of 40 dBi.

Permissible values of transmitter power and antenna gain depend on the total population of transmitters that are visible to the sensor satellite. In the United States, the 18.6-18.8 GHz band is used by the private operational-fixed microwave service. Based on the number of transmitters presently in operation in the 18.6-18.8 GHz band, and on market projections of growth in demand for this service, 10,000 appears to be a reasonable estimate of the total number of transmitters that might operate in this band. Current systems in the United States utilize transmitter powers of —12 dBW and antenna gains of 43 dBi. Sharing between passive sensors and the current systems in the United States is feasible, as can be seen from Fig. 2.

Further analyses of fixed systems have been undertaken covering high-capacity North-South systems, low-capacity distribution systems and scattering effects. Annex I presents an analysis of a high-capacity North-South system, designed and being implemented in Japan. Annex II analysed a low-capacity digital distribution system called a digital termination system (DTS), while Annex III analyses the effects of surface scattering on sensor data loss.

The feasibility of frequency sharing between passive sensors and fixed-service systems was found to be independent of the length and orientation of the fixed-service system (see Annex I). Low-capacity distribution systems having transmission parameters as shown in Annex II were found to have no adverse effect on the feasibility of sharing.

Surface scattering is shown in Annex III to increase the interference received by passive sensors. The additional interference due to the scattered component was found to be about 75% of the level due to the direct-path component.

The type of scan employed by the passive sensor was found not to affect the results of the interference analysis.

4.2 Possible approach to sharing*

Figure 2 would indicate that fixed systems with transmitter power as high as 0 dBW, and station population as great as 10,000 within line of sight to the sensor satellite, would permit sharing with passive sensors so long as the fixed systems used minimum antenna gains of 40 dBi. When scattering is taken into account, the compatible station population would be reduced by approximately 45%.

Based on the assumptions used in this Report, the results of the analysis would indicate that an approach to permit sharing between passive sensors and the fixed service in the 18.6-18.8 GHz band, would be to limit fixed service transmitter power to a maximum of 0 dBW and to limit antenna gain to a minimum of 40 dBi.

The mobile service typically employs low gain, hemispherical antennas (3 dBi). Sharing criteria which would permit sharing between passive sensors and the mobile service in the 18.6-18.8 GHz band could be established by limiting the maximum transmitter power of mobile systems to —5 dBW. No limits on antenna gain or e.i.r.p. would be required.

5. Analysis of the feasibility of sharing with the fixed-satellite service (FSS)

The results of this analysis are independent of sensor antenna pointing and therefore of the sensor scan configuration, since for a given surface PFD, the power received at the sensor is independent of range. This fact is shown in the following derivation.

Two interference paths are possible between a passive sensor and an FSS space-to-Earth link:

- coupling of the down-link signal via the back lobe of the sensor antenna, and
- coupling of the down-link signal into the main lobe of the sensor antenna by scattering from the Earth's surface.

* In Japan, systems are planned which may not satisfy the criteria discussed in this section.
The FSS satellite e.i.r.p. which will produce interference at the sensor threshold level can be calculated as follows for the case of coupling via the back lobe of the sensor antenna:

Sensor interference level \(-155 \text{ dBW}\)

Effective area of sensor antenna (back lobe), \(S\) in m\(^2\); \(10 \log S = -63\)

Therefore power flux at sensor \(-92 \text{ dB(W/m}^2\)\)

Spreading loss \(-162 \text{ dB/m}^2\)

Maximum FSS satellite e.i.r.p. \(70 \text{ dBW}\)

The maximum FSS satellite e.i.r.p. which avoids interference into the sensor's back lobes is thus 70 dBW and the corresponding power flux-density limit (PFD) at the Earth's surface \(-92 \text{ dB(W/m}^2\)\) in the 200 MHz sensor bandwidth. This PFD is 10 dB lower than the value derived from the limit of \(-105 \text{ dB(W/m}^2\)\) in any 1 MHz band for angles of arrival greater than 25° above the horizontal plane, the value permitted by the Radio Regulations. The above comparison presumes that the FSS satellite radiates uniformly over the entire 200 MHz sensor bandwidth.

Interference to the sensor from FSS satellites employing e.i.r.p. greater than 70 dBW would occur whenever the sensor satellite is in the main beam of the FSS satellite. Note also that the above calculation corresponds to the case where the sensor satellite is within the main beam of one FSS satellite having a total e.i.r.p. of 70 dBW in a 200 MHz bandwidth. If the sensor satellite were in the main beams of multiple FSS satellites, loss of coverage would result for FSS satellite e.i.r.p.s of 70 dBW. The percentage of area loss for both situations would depend on the FSS satellite antenna beamwidth and the population of FSS satellites.

A more severe interference problem results from the fixed-satellite signal scattered from the Earth's surface into the main lobe of the sensor antenna. The interference power received by the sensor is:

\[
P_R = \left( \frac{P_T G_T}{4 \pi R_{TE}^2} \right) \left[ \frac{A_r}{R_{ER}^2} \right] \sigma_0
\]

where:

\(P_T G_T\): FSS satellite transmitter e.i.r.p.,

\(R_{TE}\): range from the fixed-satellite transmitter to Earth,

\(\sigma_0\): scattering coefficient,

\(A_r\): footprint area of the sensor antenna on the Earth,

\(R_{ER}\): range from the Earth to the sensor receiver,

\(A_r\): effective area of the sensor antenna.

The above equation can be expressed as:

\[
P_R = \left( \frac{P_T G_T}{4 \pi R_{TE}^2} \right) \frac{\lambda^2 \pi}{64 \cos \theta} \sigma_0
\]

where \(\theta\) is the incidence angle of the sensor antenna and \(\lambda\) is the wavelength.

Since the first term on the right side of the above equations is the PFD produced by the FSS satellite, the maximum PFD which will not cause interference can be determined from:

\[
P_{FDF} = \frac{P_R (64 \cos \theta)}{\lambda^2 \pi \sigma_0}
\]

by substituting the sensor interference level for \(P_R\).

The value of \(\sigma_0\) is a function of the angle of incidence, soil humidity, soil roughness, vegetation cover, soil type and terrain slope.
The results in Annex III can be presented in terms of the maximum PFD which would permit sharing, as a function of $\sigma_0$. The PFD necessary to maintain interference below the sensor interference threshold, for a one beam (50 dBi) FSS satellite, is:

$$PFD = -106 \text{ dB}(W/(m^2 \cdot 200 \text{ MHz})) - \sigma_0$$

and when $\sigma_0$ is $-5$ dB (see Annex III), then the maximum PFD would be:

$$PFD = -101 \text{ dB}(W/(m^2 \cdot 200 \text{ MHz}))$$

For a 10 beam (50 dBi each) FSS satellite, the allowable PFD would have to be reduced by another 3 dB.

5.1 Areas of passive sensor data loss for Earth coverage FSS systems

An Earth-coverage FSS satellite operating at the PFD limit specified in the Radio Regulations ($-105 \text{ dB}(W/(m^2 \cdot \text{ MHz}))$) would result in interference to a passive sensor anywhere within line of sight. A value of $-22$ dB for $\sigma_0$ would be required to limit interference to small areas, and as Fig. 3 shows, values of $\sigma_0$ as low as $-22$ dB are not expected.

A decrease in PFD of $22$ dB would result in interference only for values of $\sigma_0$ greater than $0$ dB. These values of $\sigma_0$ can occur only when geometrical relationships result in specular reflection. This requires that the sensor antenna must be aligned within $10^\circ$ of the specular direction of the reflected fixed-satellite signal.

The alignment of the sensor's main beam along the specular direction to the FSS satellite will happen infrequently and these areas can still be sensed at other orbit passes where such alignment does not occur.

![FIGURE 3 — Differential scattering coefficient measured at various sites in the United States with Skylab S-193 scatterometer during summer of 1973. (Vertical polarization) [Purduski, 1978]:](image-url)
5.2 Areas of passive sensor data loss for spot beam fixed satellite

At 18 GHz, fixed-satellite systems are likely to employ spot beams to keep transmitter power at achievable and reliable levels, and to meet fade margin requirements due to high rainfall attenuation.

A developmental fixed-satellite system being considered in the United States for operation in the 17.7-19.7 GHz band [NASA, 1981] would contain 10 spot beams to provide high capacity service between major population centres plus two scanning spot beams for lower rate service. Each beam would have a beamwidth of 0.3° and a peak gain of 55 dBi.

Area C in Fig. 4 is the area lost to passive sensing based on the current PFD limits. Clearly, the large area lost would seriously affect the full operation of the passive sensor at 18 GHz under the current allowable PFD. If the PFD were reduced by 16 dB, the area lost would be reduced from area C in Fig. 4 to area A where PFD levels as high as $-102\,\text{dB(W/(m}^2\cdot\text{1 MHz})}$). The loss would occur regardless of the orientation of the sensor antenna with respect to the direction of specular reflection from the FSS satellite. A further reduction of PFD by 6 dB to 22 dB below the current limit would result in the loss to the passive sensor occurring only when the sensor antenna is aligned within $\pm 10^\circ$ of the specular direction. A still further reduction of PFD by an additional 8 dB would eliminate interference even when the sensor is aligned with the direction of specular reflection from the FSS satellite.

**FIGURE 4 - PFD contours and passive sensor data loss areas due to interference from a ten-beam fixed satellite system**

Areas A: $\text{PFD} > -108\,\text{dB(W/(m}^2\cdot\text{1 MHz})}$
B: $\text{PFD} > -115\,\text{dB(W/(m}^2\cdot\text{1 MHz})}$
C: $\text{PFD} > -125\,\text{dB(W/(m}^2\cdot\text{1 MHz})}$
D: $\text{PFD} > -135\,\text{dB(W/(m}^2\cdot\text{1 MHz})}$

*Note.* – Crossed hatched area (C) is the data loss area for the current PFD limit. Area (A) is the data loss area for a PFD 16 dB or 22 dB below the current limit.
5.3 Selection of sensor scan angle to minimize interference

Regardless of the scanning method, whether conical, cross-track, or "push-broom" scanning, wide area interference will not be affected as it is not a function of look angle (see derivation, § 5). There would be certain areas where data may be lost due to specular reflection even if the PFD were reduced by 22 dB (see Annex III). However, these areas would not be large and the data could be collected at other "look" angles away from the specular direction.

5.4 Use of fixed-satellite guard channels for sensors

A fixed-satellite channel plan which placed a guard channel at 18.7 GHz would reduce the power flux-density in the 18.6-18.8 GHz band without other impact to fixed-satellite systems. Figure 5 shows the amount of PFD reduction which would result between channels with the filter response being studied for the United States developmental satellite system although these particular filters would have little effect at 18.6-18.8 GHz.

![Figure 5 - Input multiplexer filter response](image)

5.5 Possible approaches to sharing*

Operation of passive sensors in the 18.6-18.8 GHz frequency band would be severely compromised by unconstrained emissions from space stations in the fixed-satellite service at or near the maximum permissible power flux-density.

In order to ensure satisfactory operations of passive sensors it would be necessary to employ lower power flux-densities, minimize the areas on Earth subjected to high power flux-densities, or to use a combination of both steps.

Power flux-density could be reduced either by reduced fixed-satellite e.i.r.p. or by adoption of a channel plan having a guard channel at 18.7 GHz.

6. Conclusions

Recommendation No. 706 of the WARC-79 requests the CCIR to study sharing criteria which would ensure satisfactory operations of passive sensors without jeopardizing the other services likely to use the 18.6-18.8 GHz band.

The question of minimum restrictions which might be applied to the fixed, mobile except aeronautical mobile, and fixed-satellite (space-to-Earth) services consistent with satisfactory sensor operations has been examined in this Report.

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* The developmental fixed-satellite system being considered in the United States for operation in the 17.7-19.7 GHz band would produce power flux-densities more than 22 dB below maximum levels permitted by the Radio Regulations and would employ a peak antenna gain greater than 52 dBi. However, existing Japanese communication satellites are using about 40 dBi peak antenna gain to cover all of Japan. Although existing Japanese satellites also produce power flux-densities more than 22 dB below the maximum permitted levels, this value cannot be confirmed for future satellites.
Based on the assumptions used in this Report, the results of the analysis would indicate that an approach to permit sharing between passive sensors and the fixed service would be to limit fixed service transmitter power to a maximum of 0 dBW and to require the antenna gain to be 40 dBi or greater.

Restrictions which would permit sharing between passive sensors and the mobile services in the 18.6-18.8 GHz band could be established by limiting the maximum transmitter power of mobile systems to —5 dBW. No other restrictions would be required.

Based on the assumptions used in this Report, the results of the analysis indicate that an approach to permit sharing between passive sensors and the fixed-satellite service would be to reduce the allowable PFD in the 18.6-18.8 GHz band by at least 22 dB, or to adopt a channel plan providing at least 22 dB of isolation.

REFERENCES


BIBLIOGRAPHY

PURDUSKI, S. [June, 1978] Distribution tests five percentile values and autocorrelation coefficients of Skylab S-193 overland radar data. RSL Tech. Memo. 2923-9, University of Kansas, Lawrence, KA, USA.

ANNEX I

SHARING BETWEEN PASSIVE SENSORS AND LONG-HAUL, NORTH-SOUTH MICROWAVE RELAY SYSTEMS

1. Introduction

In the analyses of interference from fixed systems in this Report, the interference to passive spaceborne sensors from a short-haul microwave relay system was modelled. Since a long-haul, high-capacity digital, North-South* fixed system covering the 18.6-18.8 GHz band has been designed and partially implemented for Japan [Nakamura et al., 1977] a model of this system was developed and an analysis to determine the compatibility of such a system with passive sensors was performed [Nicholas et al., 1983]. This Annex contains the results of the analysis.

2. Description of a Japanese long-haul fixed system

The Japanese fixed system is designed to operate as a long-haul system over a 2500 km distance in the 17.7-21.2 GHz band. Repeater stations are to be separated by distances varying from about 2 km to 6 km over the length of Japan. System design elements include an interleaved frequency arrangement in which 320 MHz wide channels alternate between vertical and horizontal polarization. Transmitter power of the repeater stations that have been implemented is —8 dBW per channel. The antennas have approximately 48 dBi gain.

3. Description of the interference model

The model employed is similar to that described in § 4 of this Report. A region of the Earth encompassing Japan was divided into 2° × 2° latitude-longitude cells. The number of radio-relay transmitters placed at the centre of each cell was determined from information presented in [Nakamura et al., 1977]. A population of 2000 radio relays operating with both polarizations in the 200 MHz passive sensor band was used as an upper bound for the fully implemented system. A standard CCIR fixed-service side lobe envelope pattern was assumed for system transmit antennas. The average trendline for the backbone system was chosen to be 40° clockwise from 0° N, and two spurs were positioned at 90° from that trendline. Fixed-system antennas were pointed within a 30° variance of the backbone trendline or spur trendline.

The interference that would arrive at a sensor in each orbital position in view of the modelled system was computed and compared to sensor interference threshold of —155 dBW. The 320 MHz channel widths and overlapping polarized channel structure were included in the calculation algorithm. Sensor coverage loss was determined in the same manner as described in § 4 of this Report.

* Actually, the Japanese system runs 40° off due North. The analysis presented in [Nicholas et al., 1983] shows that the results presented in this Annex are independent of trendline direction.
4. Sensor coverage loss results

Study results indicate that:

- for the −8 dBW per channel transmit power used by the actual system, sensor coverage loss would be less than 2% for 2000 transmitters;
- for the 0 dBW per channel transmit power suggested as a possible limit in this Report, sensor coverage loss would still be less than 2% for 2000 transmitters.

These predicted coverage losses are below the 5% level given as acceptable in the main body of this Report.

As discussed in [Nicholas et al., 1983] when transmit stations are confined to a trendline, the modelled loss of 2° cells exaggerates the actual sensor coverage loss. Even taking into account the interference contributions from scattering (see Annex III), study results indicate that coverage loss due to a long-haul, North-South radio-relay system with 2000 repeaters would be limited to 0.6% for transmit powers as high as 0 dBW and antenna gains of 48 dBi. Data loss would thus be substantially below the criterion given in § 2 of this Report.

5. Discussion of results

As in the case of the model developed for short-haul systems in this Report, a rapid increase in loss of sensor coverage area occurs above a threshold transmit power. For both short-haul and long-haul cases, the threshold occurs near 5 dBW for a population of 2000 transmitters.

The one main conclusion to be drawn from this study is that the feasibility of frequency sharing between passive sensors and fixed-service systems is unaffected by the length and orientation of the fixed-service system.

The total number of fixed transmitters, their transmitted power and antenna gain, are the critical parameters for determining sharing feasibility for both long-haul, North-South oriented fixed systems and short-haul systems with random orientation. The relationships between these parameters and sensor data loss are discussed in this Report.

REFERENCES


ANNEX II

FREQUENCY SHARING BETWEEN PASSIVE SPACEBORNE SENSORS AND DIGITAL TERMINATION SYSTEMS IN THE 18.6-18.8 GHz BAND

1. Introduction

The possibility exists that point-to-point, point-to-multipoint combination systems might be implemented in the 18 GHz region. Such a system has been referred to as a digital termination system (DTS) [Manichaikul et al., 1983].

Since DTS systems are not currently implemented, and not all the parameters of interest are well specified, a parametric analysis based on existing fixed-service hardware and DTS systems being considered at 10 GHz, was developed for each of the various DTS links. Based on these transmission parameters, the model described in § 4 of this Report was utilized to determine the feasibility of sharing between DTS and passive sensors.

2. Description of the DTS

A DTS system would comprise multiple users (subscribers) clustered around a nodal station. Transmission to the nodal station would be as point-to-point, but the reverse transmission would be point-to-multipoint. The nodal stations could be interconnected by a typical fixed-service point-to-point link (possibly with multiple hops), or space relay or cable linkage could be used. The DTS concept is presented in Fig. 6.

Subscriber antennas are envisaged to be high gain, of the order of 40 dBi. Nodal antennas for transmission to subscribers are envisaged to be effectively omnidirectional in azimuth with 19 dBi gain, through the use of several 19 dBi "sector" antennas. Node-to-node transmission is expected to use antennas similar to other fixed systems at 18 GHz with gains of at least 40 dBi.
A channel plan and transmit power requirements for an 18 GHz DTS system have not been established. Consequently, each DTS link has been analysed separately as if only that link occupied the 18.6-18.8 GHz band. The transmit power requirements are critical to the nodal span and outage times for a DTS system. Transmit power, distance and outage-time trade-off calculations were made using DTS link parameters based on existing United States and Japanese fixed systems. DTS link parameters are presented in Table II. The results along with the resultant total power in the sensor’s 200 MHz bandwidth and the number of compatible nodal stations are presented in Table III.

**TABLE II — DTS system parameters**

<table>
<thead>
<tr>
<th>Subscriber-to-node:</th>
<th>40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gain (dBi)</td>
<td>1% (0.1%)</td>
</tr>
<tr>
<td>Outage time</td>
<td>10 dB (20 dB)</td>
</tr>
<tr>
<td>Fade margin</td>
<td>0.000025 W/250 kHz</td>
</tr>
<tr>
<td>Transmit power</td>
<td>(0.00025 W/250 kHz)</td>
</tr>
<tr>
<td>Maximum link distance (km)</td>
<td>10</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Node-to-subscriber:</th>
<th>19</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gain (dBi)</td>
<td>1% (0.1%)</td>
</tr>
<tr>
<td>Outage time</td>
<td>10 dB (20 dB)</td>
</tr>
<tr>
<td>Fade margin</td>
<td>0.000025 W/250 kHz</td>
</tr>
<tr>
<td>Transmit power</td>
<td>(0.00025 W/250 kHz)</td>
</tr>
<tr>
<td>Maximum link distance (km)</td>
<td>10</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Node-to-node hop length:</th>
<th>43</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gain (dBi)</td>
<td>0.01%</td>
</tr>
<tr>
<td>Outage time</td>
<td>40 dB</td>
</tr>
<tr>
<td>Fade margin</td>
<td>0.0015 W/250 kHz</td>
</tr>
<tr>
<td>Transmit power</td>
<td>3</td>
</tr>
<tr>
<td>Maximum link distance (km)</td>
<td></td>
</tr>
</tbody>
</table>

* For the node-to-subscriber and subscriber-to-node links, a two-phase coherent PSK with a $C/N = 14$ dB (probability of error ($P_e$) < $10^{-9}$) was assumed. The fade margins 10 dB (20 dB) for these two links allows for at least 1% (0.1%) in rain regions A to M (see Reports 382 and 721).
TABLE III — DTS system-sensor compatibility results

<table>
<thead>
<tr>
<th>DTS link node</th>
<th>Spectral transmitter power density/250 kHz</th>
<th>Total power per 200 MHz per node (W)</th>
<th>Link distance (outage time) (km)</th>
<th>Number of compatible nodes (1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subscriber-to-node</td>
<td>0.000025</td>
<td>0.2</td>
<td>10 (0.1%)</td>
<td>&gt; 10000</td>
</tr>
<tr>
<td></td>
<td>0.000025</td>
<td>0.02</td>
<td>10 (1%)</td>
<td>&gt; 10000</td>
</tr>
<tr>
<td>Node-to-subscriber</td>
<td>0.000025</td>
<td>0.2</td>
<td>10 (0.1%)</td>
<td>&gt; 10000</td>
</tr>
<tr>
<td></td>
<td>0.000025</td>
<td>0.02</td>
<td>10 (1%)</td>
<td>&gt; 10000</td>
</tr>
<tr>
<td>Node-to-node</td>
<td>0.0015</td>
<td>1.2</td>
<td>3 (per hop)</td>
<td>10 000</td>
</tr>
</tbody>
</table>

(1) Each node represents full utilization of the 200 MHz passive sensor band of interest. For example, if each subscriber had 250 kHz of bandwidth, then there could be 800 subscribers per node. If subscribers were to time-share a channel, substantially more subscribers would be utilizing the DTS system.

3. Conclusion

Based on the envisaged link parameters for a DTS system, sharing with passive sensors would be feasible with any link. Sharing with any combination of links within the passive sensor's 200 MHz bandwidth would, by implication, also be feasible.

DTS systems now under consideration in Canada would use outage times of 0.01% and fade margins of 25 to 30 dB. The compatibility of such a fixed system with passive sensors has still to be determined.

REFERENCES


ANNEX III

EFFECTS OF TERRAIN SCATTERING ON SHARING WITH FIXED AND FIXED-SATELLITE SYSTEMS

1. Introduction

In the analyses contained in this Report, including Annexes I and II, no consideration has been given to scattered energy from fixed transmitters, and only a very general consideration to scattered energy from FSS satellites. The analysis of this Annex is based on a recent model [Nicholas et al., 1983] for analysing surface scattering. This model is an extension of work by [Beckmann, 1963].

2. Scattering analysis for the case of the fixed service

The type of terrain over which a fixed-service transmitter operates is crucial for determining the power scattered towards a passive sensor. Based on the model presented by [Nicholas et al., 1983] and data presented in [Long, 1975] the average surface normalized scattering coefficient, $\sigma_0$, would be around $-10$ dB for urban and residential areas. For heavily forested regions, $\sigma_0$ falls in the range of $-18$ to $-10$ dB; however, to provide a reasonable conservative bound, a $\sigma_0$ of $-10$ dB is used in the following analysis.
The power received by a spaceborne sensor due to scattering will be:

\[ P_R = \sum P_i = \sum P_T G_T \cdot \frac{1}{4\pi (r_{1i})^2} \cdot \sigma_0 A_i \cdot \frac{1}{4\pi (r_{2i})^2} \cdot G_R \frac{\lambda^2}{4\pi} \]  

(1)

where:

- \( r_{1i} \): distance from the transmitting antenna to the scattering surface (m),
- \( r_{2i} \): distance from the elementary scattering surface to the spacecraft (m),
- \( P_R \): power received (W),
- \( P_i \): power received due to scattering from an elemental area \( A_i \) (W),
- \( A_i \): elemental area of the scattering surface (m\(^2\)),
- \( P_T G_T / 4\pi (r_{1i})^2 \): pfd arriving at the elemental scattering surface (W/m\(^2\)),
- \( \sigma_0 \): scattering coefficient (dB),
- \( 1/4\pi (r_{2i})^2 \): spreading loss to the spacecraft (m\(^{-2}\)),
- \( G_R \lambda^2/4\pi \): effective area of the sensor antenna in the direction of the scattering surface (m\(^2\)).

The summation is performed over the complete scattering surface \( A \) to determine the signal power entering the sensor side lobes, and over the sensor main-beam footprint on the Earth to determine the signal power entering the sensor main beam.

In order to obtain the scattered signal PFD at the Earth's surface, it is necessary to determine the gain contours of the fixed-service antenna on the surface of the Earth. This was done for a typical fixed-service antenna of 40 dBi gain, pointing horizontally and mounted 20 m above the Earth. The gain contours of 25 dBi, 10 dBi, 0 dBi and —5 dBi are plotted in Fig. 7. The line-of-sight distance for a 20 m antenna height is 16 km.

2.1 Side-lobe case

The line-of-sight region, a circle of 16 km radius, was divided into areas with sizes of 0.5 x 0.5 km, 1 x 1 km and 2 x 2 km in order to accurately perform the summation over the gain contours. The total power summation was then calculated over the complete area \( A \). For a fixed-service transmitter power of 1 W, the area within the \( G_T = 25 \) dBi contours was found to contribute the equivalent of a 0.15 W transmitter with an omnidirectional antenna located at the centre of \( A \). The balance of the total scattering area contributes 0.10 W for a total of 0.25 W omnidirectionally distributed.

For the direct path from the fixed transmitter to the sensor, the power associated with the fixed transmitter —5 dBi side lobes is equivalent to a 0.32 W omnidirectionally distributed transmitter. Thus, scattering will cause the effective side lobe-to-side lobe interference to increase by 2.6 dB. Consequently, the number of 1 W transmitters which would just meet the criterion contained in this Report would be reduced from 10 000 to 5555.

Another way to envisage the results of this analysis is that a line-of-sight transmitter emits half of its power towards the Earth’s surface where some is absorbed and some scattered. This analysis indicates that half of the power incident on the Earth’s surface is absorbed and half scattered for surfaces with \( \sigma_0 = -10 \) dB.

2.2 Sensor main beam-to-scatter surface case

Without consideration of scattered energy, an area the size of the sensor’s resolution, 2 x 2 km, is “lost” due to interference when the main beam of the passive sensor’s antenna is pointed at a fixed service transmitter. Figure 7 shows the area “lost” to sensing due to scattering for the conditions given in § 2.1 and a \( \sigma_0 \) of —10 dB. As indicated by \( C \), an area substantially larger than 2 x 2 km around the site is lost.

* The antenna pattern for fixed services is presented in Report 614. Note that the far back-lobe level is stated to be 0 dBi; however, a footnote to § 5 indicates that where multiple entries from fixed transmitters are to be considered, —5 dBi appears to be a more appropriate level.
The conclusions drawn in the Report are unaffected, however, since the modelled 2° by 2° cells (220 x 220 km at the equator) used in the model over-estimate the actual loss. The over-estimation is only significant when considering small percentage area loss (< 3%), but not for area loss comparable to 5%, or greater, data loss. The over-estimation is significantly reduced for the < 3% loss region when scattering is considered.

3. Fixed-satellite service spot beam scattering analysis

The scattering model presented [Nicholas et al., 1983] was used to determine the power scattered from the Earth's surface by a fixed satellite at 18 GHz.

At 8/7 GHz (x band), the values of $\sigma_0$ presented in [Nicholas et al., 1983] indicate that typical Earth land surfaces have $\beta_0$ values of 6° to 12° and $H$ values of 1/5 to 1/13. The term $\beta_0$ is defined as arc tan ($2\sigma/T$) where $\sigma$ is the surface roughness and $T$ is the surface horizontal correlation distance. The term, $H$, is defined as $4\pi\sigma/\lambda$. Projecting these $\beta_0$ and $H$ values to 18 GHz yields $\beta_0 = 12°$ to 24° and $H = 2/5$ to 2/13. Confirmation of these values can be seen in Skylab 15 GHz back-scatter data, which produce values of $\beta_0$ of 12° to 24° and $H = 0.5$ to 0.25 [Nicholas et al., 1983]. The values of $\sigma_0$ for all three-dimensional directions was calculated utilizing these values for $\beta_0$ and $H$, and for incoming angles of arrival from a fixed satellite of from 10° to 90°. The model presented in [Nicholas et al., 1983] yielded $\sigma_0$ values that ranged from $-25$ dB to $+3$ dB. In order to provide a conservative bound, the maximum $\sigma_0$ value in all directions was determined. It was found that $\sigma_0$ was less than $-5$ dB in all directions except for $\pm 10°$ about the specular direction, in which case $-5 < \sigma_0 < 3$ dB.
The reflected power that a sensor will receive (in dB) is:

$$P_R = PFD + BW_s + \sigma_0 + A_s + G_s + \frac{\lambda^2}{4\pi} + \frac{1}{4\pi R^2}$$

where:

- \(PFD\): fixed-satellite PFD (dB(W/(m² · MHz)));
- \(BW_s\): sensor bandwidth relative to 1 MHz (23 dB);
- \(\sigma_0\): average normalized radar scattering cross-section (dB);
- \(A_s\): area within sensor 3 dB beamwidth and Earth intersection (66 dB(m²));
- \(G_s\): sensor antenna gain (57 dBi);
- \(\lambda^2\): wavelength (—36 dB(m²));
- \(\frac{1}{4\pi R^2}\): spreading loss (—125 dB(m⁻²)).

The power received then can be simplified to:

$$P_R = PFD - 26 + \sigma_0 \quad \text{dBW}$$

A sensor interference level of —155 dBW implies that \(\sigma_0\) must be less than —24 dB for sharing to be feasible when the PFD is —105 dB(W/(m² · MHz)), the present limit. Based on the scattering model for 18 GHz and the Skylab data, such values would virtually never occur. In fact, —5 dB is a more typical value for the vast majority of surfaces at 18 GHz. Thus a reduction of 19 dB in PFD would be required to limit data loss to small angles around the specular direction. Figure 8 illustrates the area (A + B) lost due to one fixed satellite having a 50 dBi spot-beam antenna and operating at the current PFD.

---

**FIGURE 8 — PFD contours and data loss areas due to a system operating at the current PFD limit utilizing one FSS satellite beam \((G_T = 50 \, \text{dBi})\)**

Areas:
- A: PFD \(\geq -115 \, \text{dB}(\text{W}/(\text{m}^2 \cdot 1 \, \text{MHz}))\)
- B: PFD \(\geq -125 \, \text{dB}(\text{W}/(\text{m}^2 \cdot 1 \, \text{MHz}))\)
- C: PFD \(\geq -135 \, \text{dB}(\text{W}/(\text{m}^2 \cdot 1 \, \text{MHz}))\)
- D: PFD \(\geq -145 \, \text{dB}(\text{W}/(\text{m}^2 \cdot 1 \, \text{MHz}))\)
- E: PFD \(\geq -155 \, \text{dB}(\text{W}/(\text{m}^2 \cdot 1 \, \text{MHz}))\)

*Note.* — Crossed hatched areas represent data loss regions.
Since a satellite at 18 GHz would likely have more than one spot beam, a 10-beam satellite system was analysed based on the proposed system for the United States of America discussed in the main text. Area C in Fig. 4 is the area lost to passive sensing based on the current PFD limits. Clearly, the large area lost would seriously affect the full operation of the passive sensor at 18 GHz under the current allowable PFD. If the PFD were reduced by 16 dB, the area lost would be reduced from area C in Fig. 4 to area A where PFD levels as high as $-102 \text{ dB(W/(m}^2 \cdot \text{MHz})$ are found. The loss would occur regardless of the orientation of the sensor antenna with respect to the direction of specular reflection from the FSS satellite. A further reduction of PFD by 6 dB to 22 dB below the current limit would result in the loss to the passive sensor occurring only when the sensor antenna is aligned within $\pm 10^\circ$ of the specular direction. A still further reduction of PFD by an additional 8 dB would eliminate interference even when the sensor is aligned with the direction of specular reflection from the FSS satellite.

4. Conclusions

In the case of the fixed service, scattering reduces, almost by half, the number of possible transmitters operating on a shared basis at the criteria proposed in this Report. However, this lower number is still expected to exceed the number of transmitters actually in service in the visibility area of the passive sensor. Hence, sharing at the proposed criteria would be feasible.

In the case of the fixed-satellite service, scattering considerations would require a 22 dB reduction in the PFD limit in order to permit satisfactory operation of passive sensors. A further 8 dB reduction would preclude interference occurring in the specular direction.

REFERENCES


REPORT 987

INTERFERENCE TO SPACEBORNE REMOTE PASSIVE MICROWAVE SENSORS FROM ACTIVE SERVICES IN ADJACENT AND SUB-HARMONIC BANDS

(Question 12/2 and Study Programme 12B/2)

(1986)
Input or RF filters are not typically used on sensors because of the extremely low power levels being detected. Input passband characteristics are therefore determined by the IF bandwidth, antenna, antenna switch, and waveguide characteristics. It is estimated that the input passband of a typical sensor can be modelled by use of the passband characteristics of a 4-pole Butterworth filter. For a description of Butterworth filters, see [ITT, 1972].

3. Terrestrial interferer characteristics

Data required to characterize typical terrestrial transmitting stations include bandwidth, transmit power, main beam gain, number of units, and allocated band within which all units of the particular station class can be found. Values of these parameters were chosen to best represent all assignments. Knowing the main-lobe gain of a particular station, side-lobe gains can be predicted with the patterns given in Report 391.

An upper bound for harmonic output power from interfering stations can be predicted from the table of maximum permitted spurious emission power levels in Appendix 8 to the Radio Regulations. Because of the uncertainty in predicting interferer characteristics at high harmonics, especially those of antennas, this study was limited to the first two sub-harmonics of the sensing bands. The gain of antennas up to the third harmonic was assumed to be constant because of the offsetting effect of the increased antenna effective area as opposed to the increased antenna surface tolerance losses, and the decreased antenna feed efficiencies with increasing frequency.

After reviewing the ITU and domestic United States of America regulations it was determined that a 3-pole Butterworth filter characteristic would best represent the interferer spectrum for out-of-band emissions. The number and characteristics of interferers used in the analysis were determined from statistics compiled from the frequency assignments in the United States of America.

4. Spaceborne interferer characteristics

It was determined that a 3-pole Butterworth filter characteristic is suitable for modelling spaceborne transmitters.

For spurious emission power levels, it was assumed that the levels contained in Appendix 8 to the Radio Regulations could be extended to apply to space services.

5. Out-of-band rejection factor (OBRF)

An out-of-band rejection factor, OBRF, can be defined as the fraction of interference power that is accepted by the sensor. It is of the form:

\[
OBRF = \frac{\int_{0}^{\infty} B(f) df}{\int_{0}^{\infty} A^2(f) B(f) df}
\]  

where:

- \( f \): frequency (Hz),
- \( A(f) \): normalized sensor receiver amplitude response,
- \( B(f) \): normalized interference spectrum.

If both the sensor receiver passband and the interferer spectrum can be modelled by a Butterworth filter characteristic, then:

\[
A^2(f) = \frac{1}{\left(\frac{2(f - f_c)}{B_c}\right)^{2N_r} + 1}
\]

\[
B(f) = \frac{1}{\left(\frac{2(f - f_c)}{B_i}\right)^{2N_i} + 1}
\]

where:

- \( B_c \): -3 dB receiver bandwidth (Hz),
- \( N_r \): number of receiver filter poles,
- \( f_c \): receiver centre frequency (Hz),
- \( B_i \): interference bandwidth (Hz).
In order to evaluate these integrals using numerical techniques, it was assumed that the receiver filter has a maximum rejection of 70 dB. Similarly, it was assumed that the interferer power is contained within ±10 times its −3 dB bandwidth.

Figure 1 shows the relationship between OBRF, the number of poles in the receiver filter, and the guard band (i.e. the separation between the −3 dB frequencies of the sensor and the interferer) for an interferer having the indicated characteristics. A new set of curves is required for each different combination of receiver and interferer bandwidths.

6. Interference modes

This Report analyses interference levels into passive sensors from both terrestrial stations and space stations using techniques similar to those in Report 694. Interference from terrestrial stations is computed using a uniform distribution model.

6.1 Interference modes in the case of transmitting terrestrial stations

There are three separate modes of interference that must be evaluated. Interference can occur when a terrestrial transmitter is within the main beam and near side-lobes of the sensor antenna. Interference can also occur when the main beam of a terrestrial transmitter illuminates the sensor. In both these cases, a single transmitter can cause the loss of data over a small area of the Earth corresponding to the area within the beam of
the sensor during the time that interference occurs. To determine if interference occurs, the spreading loss and the OBRF are applied to the transmitted power of the interferer to determine the interference power received by the sensor. This power is compared to the interference threshold to determine if harmful interference exists. To determine the percentage of area lost to remote sensing, all individual lost areas are summed and the sum is compared to the total area.

The third mode of interference involves small interference contributions from all transmitters within line-of-sight of the sensor. Similar calculations to those above permit determination of the interference power from each transmitter and contributions from all interferers are summed to determine if the harmful interference threshold is exceeded. If the threshold is exceeded in this mode, all the visible area is lost.

6.2 Interference modes in the case of transmitting space stations

Two interference modes are considered in the assessment of interference from space stations: interference into sensor back-lobe from the interferer main-lobe and interference into the sensor main-lobe and near side-lobes from energy reflected from the Earth. Sample calculations of the interfering power levels into a sensor from fixed-satellite space stations in the adjacent band and shown in Table I.

<table>
<thead>
<tr>
<th>TABLE I — Adjacent band interference from the fixed-satellite service into the 18 GHz sensor band</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contribution from back-lobe</td>
</tr>
<tr>
<td>Interferer e.i.r.p. (including OBRF) (dBW)</td>
</tr>
<tr>
<td>Allowance for spreading loss (dB(m²))</td>
</tr>
<tr>
<td>Back-lobe effective area (dB(m²))</td>
</tr>
<tr>
<td>Receiver power (dBW)</td>
</tr>
<tr>
<td>Contribution from main-lobe and near side-lobes</td>
</tr>
<tr>
<td>Interferer e.i.r.p. (including OBRF) (dBW)</td>
</tr>
<tr>
<td>Allowance for spreading loss to Earth (dB(m²))</td>
</tr>
<tr>
<td>Allowance for reflection loss (dB)</td>
</tr>
<tr>
<td>Allowance for spreading loss (4πR², R in m)</td>
</tr>
<tr>
<td>Sensor footprint (dB(m²))</td>
</tr>
<tr>
<td>Effective area (dB(m²))</td>
</tr>
<tr>
<td>Received power (dBW)</td>
</tr>
<tr>
<td>Total received power (dBW)</td>
</tr>
</tbody>
</table>

7. Results

7.1 Interference from terrestrial stations

Using the previously described models, an assessment of the interference from adjacent and sub-harmonic bands to remote passive microwave sensors was made for conditions representative of those over the United States of America. For the case of sensor receivers which have 4-pole Butterworth filter characteristics, the total interference levels from terrestrial stations in adjacent and sub-harmonic bands are tabulated in Table II. Each row in Table II lists the sensor frequency band, the interference threshold (from Report 694), the calculated level of total interference power into the sensor far side-lobes (mode 3) and the percentage of area loss. In those cases where the interference received in the far side-lobes exceeds the interference threshold, 100% of the visible area is lost to passive sensor operations. If this condition does not pertain, the percentage of area loss is that resulting from modes 1 and 2.
### TABLE II — Interference levels from terrestrial stations — 4-pole receiver filter characteristics

<table>
<thead>
<tr>
<th>Sensor frequency</th>
<th>Interference threshold (dBW)</th>
<th>Interference received into far side-lobes (dBW)</th>
<th>Percentage of area lost (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1400-1427 MHz</td>
<td>-171.0</td>
<td>-139.0</td>
<td>100.0</td>
</tr>
<tr>
<td>1406-1421 MHz</td>
<td>-174.0</td>
<td>-162.1</td>
<td>100.0</td>
</tr>
<tr>
<td>4200-4400 MHz</td>
<td>-158.0</td>
<td>-148.5</td>
<td>100.0</td>
</tr>
<tr>
<td>4225-4390 MHz</td>
<td>-159.0</td>
<td>-159.0</td>
<td>3.4</td>
</tr>
<tr>
<td>6425-7075 MHz</td>
<td>-158.0</td>
<td>-150.7</td>
<td>100.0</td>
</tr>
<tr>
<td>6425-6625 MHz</td>
<td>-158.0</td>
<td>-158.9</td>
<td>11.8</td>
</tr>
<tr>
<td>6445-6645 MHz</td>
<td>-158.0</td>
<td>-181.0</td>
<td>0.4</td>
</tr>
<tr>
<td>6650-6850 MHz</td>
<td>-158.0</td>
<td>-158.0</td>
<td>3.8</td>
</tr>
<tr>
<td>6845-7045 MHz</td>
<td>-158.0</td>
<td>-146.3</td>
<td>100.0</td>
</tr>
<tr>
<td>6875-7075 MHz</td>
<td>-158.0</td>
<td>-170.5</td>
<td>0.6</td>
</tr>
<tr>
<td>10.600-10.700 GHz</td>
<td>-156.0</td>
<td>-164.8</td>
<td>0.6</td>
</tr>
<tr>
<td>15.200-15.400 GHz</td>
<td>-152.0</td>
<td>-166.9</td>
<td>0.2</td>
</tr>
<tr>
<td>18.600-18.800 GHz</td>
<td>-160.0</td>
<td>-186.3</td>
<td>0.0</td>
</tr>
<tr>
<td>22.210-22.500 GHz</td>
<td>-155.0</td>
<td>-189.1</td>
<td>0.0</td>
</tr>
<tr>
<td>23.600-24.000 GHz</td>
<td>-157.0</td>
<td>-175.0</td>
<td>0.5</td>
</tr>
<tr>
<td>31.300-31.800 GHz</td>
<td>-156.0</td>
<td>-192.4</td>
<td>0.1</td>
</tr>
<tr>
<td>36.000-37.000 GHz</td>
<td>-146.0</td>
<td>-189.8</td>
<td>0.0</td>
</tr>
<tr>
<td>50.200-50.400 GHz</td>
<td>-157.0</td>
<td>-264.9</td>
<td>0.0</td>
</tr>
<tr>
<td>51.400-59.000 GHz</td>
<td>-157.0</td>
<td>-336.8</td>
<td>0.0</td>
</tr>
<tr>
<td>55.100-55.300 GHz</td>
<td>-157.0</td>
<td>-336.8</td>
<td>0.0</td>
</tr>
<tr>
<td>58.800-59.000 GHz</td>
<td>-157.0</td>
<td>-336.8</td>
<td>0.0</td>
</tr>
<tr>
<td>64.000-65.000 GHz</td>
<td>-157.0</td>
<td>-336.8</td>
<td>0.0</td>
</tr>
<tr>
<td>64.000-64.200 GHz</td>
<td>-157.0</td>
<td>-300.5</td>
<td>0.0</td>
</tr>
<tr>
<td>64.400-64.600 GHz</td>
<td>-157.0</td>
<td>-300.5</td>
<td>0.0</td>
</tr>
<tr>
<td>64.800-65.000 GHz</td>
<td>-157.0</td>
<td>-300.6</td>
<td>0.0</td>
</tr>
<tr>
<td>86.000-92.000 GHz</td>
<td>-138.0</td>
<td>-187.0</td>
<td>0.0</td>
</tr>
<tr>
<td>100.000-102.000 GHz</td>
<td>-150.0</td>
<td>-204.0</td>
<td>0.0</td>
</tr>
<tr>
<td>105.000-126.000 GHz</td>
<td>-150.0</td>
<td>-229.7</td>
<td>0.0</td>
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<tr>
<td>114.500-116.500 GHz</td>
<td>-150.0</td>
<td>-230.5</td>
<td>0.0</td>
</tr>
<tr>
<td>124.000-126.000 GHz</td>
<td>-150.0</td>
<td>-231.2</td>
<td>0.0</td>
</tr>
<tr>
<td>150.000-151.000 GHz</td>
<td>-150.0</td>
<td>-270.1</td>
<td>0.0</td>
</tr>
<tr>
<td>164.000-168.000 GHz</td>
<td>-150.0</td>
<td>-261.6</td>
<td>0.0</td>
</tr>
<tr>
<td>182.000-185.000 GHz</td>
<td>-150.0</td>
<td>-342.2</td>
<td>0.0</td>
</tr>
<tr>
<td>217.000-231.000 GHz</td>
<td>-150.0</td>
<td>-227.9</td>
<td>0.0</td>
</tr>
<tr>
<td>275.000-277.000 GHz</td>
<td>-150.0</td>
<td>-334.3</td>
<td>0.0</td>
</tr>
</tbody>
</table>

In those cases where allocated bands are wider than the sensor bandwidth, for example the 51.4-59.0 GHz band, the 64-65 GHz band and the 105-126 GHz band, the analysis was carried out at the lower edge of the band, at the centre of the band, and at the upper edge of the band.

For all bands above 10 GHz the received interference in the far side-lobes (mode 3) is below corresponding interference thresholds and the percentage of area lost by modes 1 and 2 is below 5%.

At the lower end of the 6425-7075 MHz band, i.e., 6425-6625 MHz, and at the high end, i.e., 6875-7075 MHz, the interference level in the far side-lobes is above threshold. Interference is below threshold within the range of 6445-7045 MHz. Note, however, that harmful interference may result from fixed-service transmitters operating throughout the 6425-7075 MHz band (see Report 694) and the question of interference from transmitters in adjacent bands may be of secondary importance.

For the 4200-4400 MHz band, the received interference power in the far side-lobes (mode 3) exceeds the threshold by 9.5 dB and the percentage of area lost is therefore 100%. However, for a sensor bandwidth reduced from 200-165 MHz, and centred on 4308 MHz, the interference level due to mode 3 is below threshold and the area lost by modes 1 and 2 is 3.4%.
For the 1400-1427 MHz band, the interference in the far side-lobes exceeds the threshold by 31.7 dB. For a reduced sensor bandwidth of 15 MHz, centred at 1414 MHz, the interference level still exceeds the threshold, in this case by 11.9 dB. Note that the calculated percentage of area lost is valid only near land areas with a density of interferers such as that which exists in the United States of America (see Report 694, Annex I).

The analysis of sensor operation was further refined for the 1400, 4200 and 6400 MHz bands by considering the effect of a 10-pole receiver filter. These results are shown in Table III.

### Table III — Interference levels from terrestrial stations — 10-pole receiver filter characteristics

<table>
<thead>
<tr>
<th>Sensor frequency (MHz)</th>
<th>Interference threshold (dBW)</th>
<th>Interference received into far side-lobes (dBW)</th>
<th>Percentage of area lost (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1406-1421</td>
<td>-174.0</td>
<td>-163.1</td>
<td>100.0</td>
</tr>
<tr>
<td>4200-4400</td>
<td>-158.0</td>
<td>-152.4</td>
<td>100.0</td>
</tr>
<tr>
<td>4210-4400</td>
<td>-158.0</td>
<td>-160.4</td>
<td>1.2</td>
</tr>
<tr>
<td>6425-6625</td>
<td>-158.0</td>
<td>-154.9</td>
<td>100.0</td>
</tr>
<tr>
<td>6430-6630</td>
<td>-158.0</td>
<td>-160.4</td>
<td>3.7</td>
</tr>
<tr>
<td>6650-6850</td>
<td>-158.0</td>
<td>-181.1</td>
<td>0.3</td>
</tr>
<tr>
<td>6865-7065</td>
<td>-158.0</td>
<td>-158.4</td>
<td>1.3</td>
</tr>
<tr>
<td>6875-7075</td>
<td>-158.0</td>
<td>-149.7</td>
<td>100.0</td>
</tr>
</tbody>
</table>

In the 1400 MHz band, the reduced sensor bandwidth of 15 MHz centred on 1414 MHz combined with the use of a 10-pole filter results in interference, primarily due to interferers in sub-harmonic bands, which exceed the threshold by 10.9 dB.

In the 4200 MHz band, use of a 10-pole filter permits operation with a sensor bandwidth of 190 MHz centred on 4305 MHz with an interference level due to mode 3 which is below threshold and with an area loss due to modes 1 and 2 of 1.2%.

Finally, the range where interference from adjacent bands is not a factor in the 6400 MHz band expands up to 6430-7065 MHz when a 10-pole receiver filter is used.

### 7.2 Interference from space stations

Calculations of interference levels into sensors due to space stations in adjacent and sub-harmonic bands were performed for each of the allocated sensor bands using interferer characteristics representative of all classes of space stations in the respective adjacent and sub-harmonic bands. The results show that interference from space stations in adjacent and sub-harmonic bands is below the harmful threshold in all cases. Note, however, that there is a potential in-band interference problem in the band 18.6-18.8 GHz which is considered in Report 850.

### 8. Conclusions

8.1 For sensor operation in allocated bands above 10 GHz, the calculated interference levels due to terrestrial transmitters in adjacent and sub-harmonic bands are below threshold and the percentage of area lost is less than 5% using only a 4-pole receiver filter. For these frequency bands, harmful interference from transmitters in adjacent and sub-harmonic bands does not constitute a problem.

In the 6425-7075 MHz band, transmitters in adjacent bands would cause harmful interference to sensors operating near the lower and higher edges of the band.

In the 4200-4400 MHz band, sensor operation with a full 200 MHz bandwidth results in interference levels above threshold. Provision of guard bands can improve this result. Interference levels due to mode 3 are below threshold. Area loss due to modes 1 and 2 of less than 5% result from sensor bandwidth and filter types, for example, of:
- sensor bandwidth of 165 MHz centred at 4308 MHz using a 4-pole filter, and
- sensor bandwidth of 190 MHz centred at 4305 MHz using a 10-pole filter.
In the 1400 MHz band, calculated interference levels exceed the threshold for both of the receiver filter types examined in this study:
- a 27 MHz sensor bandwidth or a 15 MHz bandwidth centred at 1414 MHz using a 4-pole receiver filter, and
- a 15 MHz bandwidth centred at 1414 MHz using a 10-pole receiver filter.

The predominant form of interference in the 1400 MHz band is due to interferers in sub-harmonic bands.

8.2 Interference to passive sensors in allocated bands from space stations transmitting in adjacent and sub-harmonic bands was determined to be below the harmful interference threshold in all cases.

8.3 Note that the analyses described above are considered to be for the worst geographic case situation. For much of the world’s land and ocean surface areas, not within or near the United States of America, the observed levels of interference are likely to be less than those calculated in this Report. However, the use of passive sensors at 1400 MHz near land areas having a large number of transmitters in sub-harmonic bands should be approached with caution because of the possibility of harmful interference.

The analyses given in this Report are based on the extrapolation, above 17.7 GHz for terrestrial services and above 960 MHz for space services, of the maximum permitted spurious emission power levels contained in Appendix 8 to the Radio Regulations.

REFERENCES

FEASIBILITY OF FREQUENCY SHARING BETWEEN SPACEBORNE RADARS
AND TERRESTRIAL RADARS IN THE RADIOLOCATION SERVICE

(Question 12/2 and Study Programme 12B/2)


I. Introduction

This Report documents the feasibility of radio frequency sharing between spaceborne active sensors on Earth exploration satellites and terrestrial radars in the radiolocation service.

It has been assumed that spaceborne active sensors may operate in bands allocated to the radiolocation service. The WARC-79 allocated several frequency bands to that effect between 1 and 30 GHz either in the Table of Frequency Allocations, or in Footnotes Nos. 713, 828, 897 and 912. However, no formal studies of sharing feasibility are known to have been documented. The purpose of this Report is to fill this gap.

2. Background

Although many of the active microwave sensor efforts to date have been concentrated in laboratory and aircraft experimentation, several active microwave systems have been flown on spacecraft. The Skylab Earth Resources Experiment Packages (EREP) flown in 1973, contained a microwave radiometer/scatterometer and altimeter. The GEOS-3 launched in 1975 also carried an altimeter. Seasat, launched in 1978, carried an altimeter, scatterometer and synthetic aperture radar (SAR) (see Report 535). Additional active microwave sensors are being considered by the United States of America for flight missions in the 1980’s. For example, active microwave sensor experiments are planned for the Severe Storm Observation Satellite. It can also be expected that future Shuttle/Spacelab missions will have payloads containing active microwave sensors for Earth exploration.

3. Study approach

The approach adopted for this study was to determine the amount of harmful interference that can occur between very susceptible terrestrial and spaceborne radars. The reasoning used for this approach was that sharing will be generally feasible between spaceborne and terrestrial radars if the most susceptible radars can operate on a shared basis.

The spaceborne radar selected for the analysis was the SAR, since this type of radar is likely to be the most abundant and susceptible spaceborne radar. More specifically, the Seasat (SAR) was chosen since its technical operating parameters are typical of spaceborne SAR radars.

The terrestrial radar mode utilized in the analysis was based on two air route surveillance radars, the ARSR-1 and ARSR-2. Although this analysis pertains to radio location devices and the ARSR-1 and ARSR-2 operate in a different service (the radionavigation service), where a minute amount of interference may be harmful, the ARSR-1 and ARSR-2 were used for the terrestrial radar model for the following reasons:

– current use: these ARSR radars employ normal and Moving-Target-Indicator (MTI) radars which are commonly employed by both the aeronautical radionavigation and radio location services, and hence a generic radar model can be constructed which is representative of a large variety of radars;
– interference susceptibility: normal and MTI radars could be highly susceptible to interference from a spaceborne radar;
– interference potential: these ARSR radars have peak powers up to 5 MW, which is as high as, or higher than, other radars in the vicinity of SAR operations.

Report 827 discusses some of the parameters utilized in various radars. Based on this information and a US survey of the preferred frequency bands for active sensors (Report 693), the following can be concluded:

– a worst-case terrestrial radar output power is about 5 MW;
– typical main beam antenna gains are around 35 dBi;

* This Report should be brought to the attention of Study Groups 1 and 8.
– the vast majority of bandwidths are between 1 to 10 MHz, tending toward the lower end;
– the pulse duration (PD) varies mostly between 0.2 and 2 μs;
– the emission is typically PON or PXN.

Radar processing is of particular concern in a radar sharing analysis. In order to make the model as
general as possible, four types of radar processing modes were considered: normal, MTI, integrated and digital
modes.

4. System characteristics

4.1 Spaceborne radar

The spaceborne radar, the Seasat SAR, had the following emission and orbit characteristics [NASA, 1976]:

4.1.1 Emission characteristics

– frequency: 1.285 GHz centre frequency
– power: 800 W peak (nominal)
– gain: 35 dB
– beam shape: 6.3° cross track, 0.9° wide; pointed 20° off nadir and
  perpendicular to the spacecraft's velocity vector
– swath width: 100 km (−3 dB points of antenna)
– pulse repetition rate: 1464, 1540 or 1647 pps
– pulse duration: 33.8 μs
– modulation: chirp 0.562 MHz/μs
– polarization: horizontal
– bandwidth of emission: 19 MHz
– spectrum density over bandwidth: approximately uniform

4.1.2 Orbit characteristics

– altitude: 800 km
– period: 100.75 min
– inclination: 108°

4.2 Radiolocation radar

The relevant technical characteristics of a generic radiolocation radar were based on the ARSR-1 and
ARSR-2 [FAA, 1964 and 1973].

The ARSR is a pulsed radar having three analogue processing modes and one digital processing mode. These modes are:
– normal video
– integrated normal video
– MTI video
– digital processed video

In order to overcome clutter in normal video, techniques such as integration, MTI, or digital processing
are employed.

Other characteristics of the ARSR-1 and ARSR-2 are:

4.2.1 Transmitter

– frequency: co-channel
– power: 4 MW and 5 MW peak (minimum)
– pulse repetition rate: 360 pps or 3 pulse staggered (13:14:15) mode, averaging 360 pps
– pulse width: 2 μs
4.2.2 Receiver
- bandwidth: normal (1 MHz) and MTI (3 MHz)
- sensitivity: normal (—113 dBm), MTI (—111 dBm) and integrated (—116 dBm)
- minimum detectable signal: ARSR-1 (normal (—109 dBm), MTI (—107 dBm) and integrated (—112 dBm)); ARSR-2 (—111, —109, —114 dBm respectively)
- system noise figure: less than 4 dB
- subclutter visibility (MTI): 27 dB
- cancellation ratio (MTI): 33 dB

4.2.3 Digital processor
- special digital processing of normal or MTI video

4.2.4 Antenna
- gain: 34 dB along axis of maximum radiation
- beamwidth: horizontal 1.35° and vertical 6.2° for ARSR-1 and 1.2 by 4° for ARSR-2. Beam in elevation is a modified cosecant squared pattern
- polarization: horizontal or circular
- scan rate: 6 r.p.m.

5. Sharing analysis

5.1 Down-link analysis

There are four primary considerations regarding interference experienced by the terrestrial radar and, consequently, the ability to share with a spaceborne SAR. These considerations are:
- processing effects on interference,
- amount of time, expressed as a percentage, that the spaceborne SAR produces power in the terrestrial radar receiver bandwidth exceeding the minimal detectable signal (MDS). This amount of time is based on long-term antenna “couplings” between these radars,
- amount of time that the SAR emissions exceed the MDS on individual passes,
- form of the interference, as presented on an operator’s planned position indicator (PPI).

5.1.1 Normal and MTI modes

In the normal mode, the processing is such that any interference pulse, on the same centre frequency, will be detected when above the receiver MDS. In the MTI mode, the MTI canceller, whose delay time is not equal to the interferer interpulse period, can in general produce several interference pulses for each interference pulse above MDS.

The power received by a pulsed terrestrial radar from a pulse compression spaceborne transmitter is given by:

\[ p_r = \left( \frac{p_t g_t g_r}{4\pi R^2} \right) \left( \frac{\lambda^2}{4\pi} \right) \left( \frac{B_{Wr}}{B_{Wt}} \right) \left( \frac{T_2}{T_1} \right) \times (0.42), \]

for \( B_{Wr} < B_{Wt} \)

where:
- \( p_r \): power of transmitter source (W),
- \( g_t \): gain of transmitting SAR antenna,
- \( g_r \): gain of terrestrial radar receiving antenna,
- \( R \): range (m),
- \( \lambda \): wavelength (m),
- \( B_{Wr} \): bandwidth of the terrestrial radar receiver (Hz),
- \( B_{Wt} \): bandwidth of the SAR transmitter (Hz),
- \( T_1 \): pulse duration of the terrestrial radar,
- \( T_2 \): pulse duration of the SAR.
Rearranging (1):

\[ \frac{p_r (4\pi)^2}{p_i \lambda^2} \times \left[ 2.38 \left( \frac{BW_i}{BW_r} \right) \left( \frac{T_i}{T_r} \right) \right] = \frac{g_i g_r}{R^2} \]  \hspace{1cm} (2)

If the value of received power used, is the minimum detectable signal, the parameters on the left-hand side are then all system constants, while those on the right-hand side are a function of geometrical relationships. A computer program was developed to calculate \( \frac{g_i g_r}{R^2} \) curves as a function of time. The resultant curves for the terrestrial radar and SAR antennas, and Seasat orbital parameters, are presented in Fig. 1.

![Figure 1](image-url)

**Figure 1** — \( \frac{g_i g_r}{R^2} \), long term couplings between spaceborne side-looking fan beam antenna and terrestrial radars for the Seasat orbital parameters

- — typical 360° scan terrestrial radar
- — — typical tracking terrestrial radar

The harmful values of \( \frac{g_i g_r}{R^2} \), utilizing SAR and terrestrial radar system parameters, equal \(-122.6 \, \text{dB}\) in the normal mode and \(-120.6 \, \text{dB}\) in the MTI mode. From the curves of Fig. 1, it can be seen that these values are exceeded for 0.094% and 0.075% of the time respectively.
Figure 2 characterizes the display of detected interference pulses on an operator's PPI. The interference pattern generated is called a "running rabbit" pattern and is common among pulsed radars. For a given SAR orbit, the duration of the pattern depends basically on the elevation of the satellite SAR from the terrestrial radar and the mutual antenna couplings as the terrestrial radar antenna rotates.

A near-overhead satellite pass produces the worst-case short-term PPI interference situation. In the normal mode, interference patterns could last for as much as 30 s for the worst-case pass; however, this pass occurs only once every 18 days for each typical Earth exploration satellite.
The more common type of interference mode will occur at low elevation angles from the terrestrial radar. Near the horizon, the terrestrial radar would experience approximately 1 s of interference per sweep (i.e. 10% of PPI display), for as long as the spaceborne radar is in line-of-sight – which is about 1 min for a near horizon pass. For a pass occurring near 50° elevation from the terrestrial radar, the interference time reduces to 0.1 s per sweep (i.e. 1% of PPI display) for as long as the spaceborne radar is in line-of-sight, which is approximately 12 min. On a daily average basis, two passes will occur during the day-time and two during the night-time period. However, as previously calculated, the overall long-term interference occurs for less than 0.094% of the time for either the normal or MTI modes [NASA, 1977].

5.1.2 Integrated normal video and digital processing mode

Integration is a method of summing a number of consecutive radar returns for the purpose of improving detection. Interference pulses, whether random or in a pulse train, will not add in a reinforcing manner in the integrator, unless their pulse period equals or is a multiple of the transmitting radar. Also, no single pulse could be large enough to trigger the threshold detector due to input limiting. However, pulse interference does slightly raise the probability of a false alarm from noise.

The digital processor, as commonly employed, performs a function similar to the analogue integrator, except that the digital processing is better able to reject clutter and interference through digital decision processes.

Thus, when in the digital processing or integrated modes, potential interfering pulses should be neither processed nor should appear on an operator's PPI display.

5.1.3 Parametric analysis of interference for normal and MTI modes

Figure 3 presents the results of a parametric computer simulation of normal and MTI mode interference times, the parametric variables being satellite power, receiver sensitivity (or MDS) and the number of satellites in orbit. The curves are all derivations of the \( \frac{g_{gr}}{R^2} \) curve (Fig. 1). The satellites are assumed to be co-channel with the terrestrial radar for a worst-case interference situation. Also, atmospheric attenuation was not included so that one curve, for all frequencies, could be presented. Thus, the curves present an upperbound worst-case situation.

The following examples illustrate the use of Fig. 3:

**Example 1:** If the maximum acceptable percentage of the time for terrestrial radar interference were 0.1% and two satellites were operating co-channel, the upper limit of the maximum satellite transmitter power-to-receiver sensitivity (or MDS) ratio, to avoid harmful interference, would be 158 dB. If the receiver sensitivity (or MDS) were approximately \(-130 \text{ dBW}\), then the maximum allowable satellite transmitter power would be 29 dBW, or 800 W.

**Example 2:** If the maximum acceptable percentage of the time for interference were 1%, and all other factors were the same as in Example 1, then the maximum allowable satellite transmitter power would be 49 dBW or 100 kW.

**Example 3:** If there were 10 satellites and all other factors were the same as in Example 2, then the maximum allowable satellite transmitter power would be 35 dBW or 3 kW.

5.1.4 Tracking and sector scan radars

In addition to the terrestrial radars which scan the horizon in a 360° search pattern, there are pulsed radars which utilize narrow circular beams to track airborne targets. Characteristics of these radars can be considered identical to the search radar described previously with the exception of the following antenna parameters:

- gain \(45 \text{ dBi}\)
- beamwidth \(0.9° \text{ circular}\)
- back-lobe gain \(-10 \text{ dBi}\)
The tracking radar was assumed to be pointed with equal probability within 0 to 30° of elevation and in any azimuth direction. Following the same procedure as described in § 5.1.1, a graph of $g_t g_r / R^2$ versus the long term percentage of time was obtained by computer simulation. The results for tracking radars are shown in Fig. 1. The higher gain and higher elevation angles of the tracking radar results in a value of $g_t g_r / R^2$ that exceeds, for small percentages of time, the value of $g_t g_r / R^2$ for a 360° scanning radar. This means that interference levels at the tracking radar receiver will be higher for small percentages of time, than in the case of the 360° scanning radar. However, Fig. 1 shows that the harmful level of $g_t g_r / R^2$ (−122.6 dB/m² for the model parameters) is exceeded for a somewhat lower percentage of time. It can be concluded that the long term percentage of time that the tracking radar would experience interference signals above the receiver threshold is of the same magnitude as for the 360° scanning radar case. Radar processing techniques for tracking radars, which are not accounted for in this analysis, could further reduce the effect of the interfering signal as they do in the case of the scanning radar digital and integrator modes.
Sector scan radars are similar to 360° scan radars in that they have a fan-shaped, low elevation beam that scans in a search pattern, except that the radar scan is restricted to a certain azimuthal sector around the antenna. The $g/r/R^2$ curve and long term interference percentage of time are identical to the 360° scan radar case, with the exception of a radar scanning only the sector directly north (south in the southern hemisphere) of the antenna. In that case, the satellite orbit statistics result in higher long term interference percentage of time than would result in the case of a 360° scanning radar. The percentage of time that the receiver threshold would be exceeded is approximately twice that for the 360° scanning radar.

5.2 Up-link analysis

The same considerations regarding interference, as presented in the down-link analysis, apply to this analysis with the exception that interference effects on an image, rather than PPI, must be considered.

The SAR processes reflected signals in range and azimuth. High resolution in range is achieved by pulse compression techniques while azimuth resolution is achieved through "synthesizing" a long antenna by utilizing coherent processing.

Consequently, the analysis requires consideration of the SAR system range and azimuth processing outputs which include the wanted signal, an interfering signal from a terrestrial radar and system noise.

5.2.1 Range processing

Range processing is accomplished through the use of a matched filter. The output of the filter is the convolution of the input and filter transfer function. However, an "ambiguity function" can be substituted and is more useful since the derived output will be a function of not only input delay, but Doppler effect also.

The complex ambiguity function, in its most general form, is defined as:

$$
\chi_{12}(\tau, v) = \frac{1}{2} \int_{-\infty}^{\infty} \mu_1(t) \mu_2^*(t - \tau) e^{j\pi v \tau} dt
$$

where:
- $\tau$: delay
- $v$: Doppler frequency
- $^*$: complex conjugate

and,

- $\mu_1(t)$: input signal
- $\mu_2(t)$: signal for which the filter is matched.

When the input signal is matched to the filter, the ambiguity function is called the auto-ambiguity function. When the input is mismatched, the function is called the cross-ambiguity function. In both cases, the function represents the output, $Y(t)$, of the filter for a given Doppler shift of the input.

$$
Y(t) = C_0 |\chi(t, v = \text{constant})|
$$

For the desired signal, the auto-ambiguity function for a chirp signal is well known [Berkowitz, 1965; Cook and Bernfeld, 1967; Rihaczek, 1969] and is:

$$
|\chi(\tau, v)| = B \frac{\sin \left[ \pi T (k \tau + v) (1 - |\tau|/T) \right]}{\pi T (k \tau + v) (1 - |\tau|/T)}
$$

where:
- $B$: bandwidth
- $T$: period
- $k$: chirp rate
If the input signal to the matched filter had an amplitude $A$, then the maximum output of the matched filter would be $\sqrt{\frac{B}{T}} \times A$. Thus, the peak power gain for a matched filter is $BT$. For the Seasat SAR, the desired output pulse from the matched filter has a power gain ($BT$) of 28 dB and a duration, defined as the 3 dB points $(1/B)$, of 53 nanoseconds.

For an interfering, non-chirp pulsed signal, the cross-ambiguity function is:

$$|\chi_{12}(t,v)| = \frac{1}{2} \left[ (C(Z_1) + C(Z_2))^2 + (S(Z_1) + S(Z_2))^2 \right]^{1/2}$$

(6)

where $C$ and $S$ are the Fresnel integrals. The resulting matched filter output for a terrestrial interference pulse, based on numerical evaluation, has a 2.28 dB gain, and a time extent at the 3 dB points, of the order of 2 μs.

For noise, since the matched filter is designed so that its frequency transfer function is $\frac{1}{H(f)} = 1$ over bandwidth, the filter gain is 0 dB.

5.2.2 **Azimuth processing**

Azimuth processing is accomplished through the summation of returns received from different positions of the real antenna.

For the wanted signals, an $N$-summation yields an output that is $N$ times the originally received signal — an output power gain of $20 \log N$.

For noise, an $N$-summation yields an output of only $10 \log N$, since samples from the same random process add incoherently.

For the interfering signal, the analysis of the azimuth processing is analytically difficult. However, it is possible to simulate and approximate the effect of the interfering signal. A computer programme was written to simulate successive range scans and the cumulative azimuth integration process.

The simulated time relationships, for interference pulses falling within the same pulse with a tolerance of ± 2 μs of successive range scans, are shown in Fig. 4. The bottom curve in Fig. 4 is the cumulative effect of azimuth processing summation of the various interference pulses over the chosen range. The oscillatory nature of this curve will be repetitious over the complete processed azimuth range scan due to the periodic nature of the radar signal. Also, the “phase” of each succeeding completely processed range scan will differ due to the time differences between the terrestrial radar and SAR PRF's and the SAR azimuth integration time. Such out-of-phase oscillations in line-video systems produces an interference effect that looks like a “wood grain” pattern.

The voltage oscillations in the azimuth processed range scan vary between one and approximately three times the peak voltage of one interference pulse out of the matched filter, as shown in Fig 4. Consequently, instantaneous peak powers for azimuth processed interference pulses vary between 0 and 9.5 dB above the matched filter output for one interfering pulse.

5.2.3 **Input/output system comparisons and summary**

Table I summarizes the input/output power relationships as determined by system processing gains.

The maximum interference input signal is limited to the value presented in Table I due to the saturation of the spaceborne receiver. In the Seasat SAR, the received signal was amplified and frequency converted for transmission to an earth station — the range and azimuth processing took place on the ground. The functional requirements for the Seasat SAR receiver called for the receiver to have a variable gain of 77 to 99 dB and to hard-limit at +13 dBm. Since the minimum receiver gain was specified to be 77 dB, an interfering signal with −64 dBm of peak power would have saturated the Seasat receiver. Of course, if the Seasat receiver were in its highest gain mode (98 dB), a signal of −85 dBm could saturate the receiver. In either situation, interfering pulse powers into the range and azimuth processors would be peak-limited, and the resulting interference would vary in an oscillatory pattern from 1 to 10 dB above noise, as shown in Table I.

Table II presents the saturation interference times expected to be experienced by the SAR as the terrestrial radar swept past the SAR. Locations of interference refer to the terrestrial radar site.
Interference time per terrestrial radar sweep decreases as the spacecraft moves higher in elevation in relation to the terrestrial radar — the exception being when the SAR main beam traverses the terrestrial radar site (near-overhead pass).

For saturation times less than the SAR integration time (2.49 s), the processed interference video waveform will have oscillations of less than 1 to 10 dB above the system noise. For example, for 0.86 s of saturation the oscillations would vary between 1 to 3 dB above system noise, since only two interference pulses (out of six in Fig. 4) could add during the azimuth processing of any 4 μs range group.

FIGURE 4 — Interference output from SAR azimuth processor

(a) to (f): successive scans
(g): cumulative
TABLE I - Input/output system comparisons

<table>
<thead>
<tr>
<th>Signal type</th>
<th>Input power (dBm)</th>
<th>Range processing (filter gain) (dB)</th>
<th>Azimuth processing (processing gain) (dB)</th>
<th>Output(1) power (dBm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Noise</td>
<td>-98.5(2)</td>
<td>0</td>
<td>35.6</td>
<td>-62.9</td>
</tr>
<tr>
<td>Minimum desired signal</td>
<td>-162.1</td>
<td>28</td>
<td>71.2</td>
<td>-62.9</td>
</tr>
<tr>
<td>Maximum desired signal</td>
<td>-134.6</td>
<td>28</td>
<td>71.2</td>
<td>-35.4</td>
</tr>
<tr>
<td>Maximum interfering signal(3)</td>
<td>-64</td>
<td>2.3</td>
<td>0 to 9.5(4)</td>
<td>-61.7 to -52.2</td>
</tr>
</tbody>
</table>

(1) Gains and losses not dependent on signal waveform, such as the receiver gain setting or space-to-Earth transmission losses, for ease of presentation, have not been included in this Table.
(2) Antenna temperature 290 K, receiver noise temperature 550 K and bandwidth of 19 MHz.
(3) At lowest receiver gain setting.
(4) Based on equal pulse powers being processed.

TABLE II - Interference times per terrestrial radar sweep

<table>
<thead>
<tr>
<th>Input interference level</th>
<th>Low gain mode -64 dBm</th>
<th>High gain mode -85 dBm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interference times (s)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>At the horizon</td>
<td>0.86</td>
<td>All the time</td>
</tr>
<tr>
<td>At 50° elevation</td>
<td>0.11</td>
<td>0.77</td>
</tr>
<tr>
<td>Near-overhead</td>
<td>1.27</td>
<td>All the time</td>
</tr>
</tbody>
</table>

Previous experience has indicated that actual scenes tend to “break-up” small magnitude interference patterns. Thus, when the SAR is in the low gain mode (maximum interference varying between 1 and 3 dB above noise for very short times) no harmful interference is expected. Also, from the operational viewpoint, the terrestrial radar will not be likely to sweep past the satellite SAR at the same azimuth heading on every pass. Consequently, “wood grain” interference would not occur in the same image-frame and, hence, multiple passes will obtain uncontaminated images.

The high gain mode, though, may provide somewhat more of a problem, since interference varies between 1 to 10 dB for long durations at the horizon and around the terrestrial radar site. However, regardless of gain mode, the spaceborne SAR could be designed to eliminate terrestrial radar interference by further receiver limiting to a level of +3 dBm. Such limiting will reduce SAR dynamic range by at least 3 dB and possibly more, depending upon linearity design constraints on the SAR receiver [NASA, 1977].
6. Summary and conclusions

The analysis of potential up-link interference to a spaceborne SAR, from a terrestrial radar, can be summarized as follows:

- The SAR is a state-of-the-art radar and is representative of a broad range of radars expected to be utilized in space.
- In the SAR low-gain mode, no harmful interference is expected.
- In the SAR high-gain mode, perceptible interference may occur; however, the nature of such interference would be similar to that encountered by airborne mapping radars currently operating in the radiolocation service.
- Interference-free SAR operation could be achieved through use of lower power saturation levels in the SAR receiver although at the cost of reduced dynamic range.

The analysis of potential down-link interference to a terrestrial radar from a spaceborne SAR, can be summarized as follows:

- The ARSR, on which the generic terrestrial radar model is based, is representative of a broad class of modern, high utilization radars.
- In the digital processing mode, the most common mode of terrestrial radar operation, and the integrated mode, the SAR emissions should not cause discernible interference due to processor discrimination, provided that the SAR pulse repetition rate is not at a harmonically related multiple of the terrestrial radar pulse repetition rate.
- In the normal and MTI modes, interference could be perceptible, and be of a nature such as that caused by other airborne and terrestrial radars. Perceptible interference will occur only for a very small percentage of the time — less than 0.094% from the Seasat type of SAR. The short term interference is a complicated function of elevation angle between the spaceborne radar and terrestrial radar. For a worst-case geometry, interference could occur over a 12 min period. In this case, interference time is 0.1 s per sweep for a total of 7.2 s over the 12 min period. The nature of the interference would be the appearance of “running rabbits” over 1% of the area of a PPI display.
- The analysis utilized a 800 km orbit for the spaceborne SAR, which is typical of the type foreseeable for Earth exploration satellites. Also, the gain patterns of typical Earth exploration satellite active microwave sensor antennas are likely to be of the form, \((\sin^2 X)/X^2 (\sin^2 Y)/Y^2\) which was used in the analysis. Consequently, the \(gs/R^2\) curve derived in the analysis is representative for this type of service. The analysis showed that even utilizing powers as great as 2.4 kW, (three times greater than the power used in the analyses and the most powerful active sensor launched by NASA to date) the interference time would be less than 0.15% of the time. Or conversely, the terrestrial service would be interference free 99.85% of the time.
- The percentages of time given for perceptible interference apply specifically for 360° scanning terrestrial radars; however, they are approximately the same for the case of tracking and sector scan radars.

The \(gs/R^2\) curve is strictly dependent on gain and range coupling geometries. Figure 1 is based on the particular terrestrial and spaceborne radars analyzed. Location of a point on the \(gs/R^2\) curve (long term percentage of interference) is determined by the interferer transmitter power, receiver minimum detectable signal, frequency of operation and the modulation transfer function.

The conclusion to be drawn from these analyses is that sharing between spaceborne radars and systems in the radiolocation service is technically feasible. Although an aeronautical radionavigation radar was used to derive the generic terrestrial radar model, sharing between spaceborne radars and systems in the aeronautical radionavigation service, where safety of life is of paramount concern, was not considered as perceptible interference may occur in certain operating modes.

REFERENCES


1. Introduction

The Radio Regulations define the meteorological satellite service as an Earth exploration-satellite service for meteorological purposes. Many techniques of observation and data transmission are common to both meteorology and the study of Earth resources. The objectives of meteorological satellites differ from other Earth exploration satellites and apart from some sensing functions, which are conducted within the EES service allocations, operate in bands specifically allocated for the service.

This Report concerns the radio-frequency requirements of the present operational system of low orbit and geostationary spacecraft utilizing passive sensors in the infra-red and microwave (millimetre wavelength) portions of the electromagnetic spectrum. Sensing bands in use are those selected for optimum measurement of surface and cloud-top temperatures, for calculation of the vertical temperature and moisture profiles (soundings) of the atmosphere, and for estimation of winds at several altitudes. Reference is made also to frequencies needed for the use of active sensors for the parameters already noted, and for sea state, winds at multiple heights, and above all, for more detailed and accurate world-wide profiles of temperature and moisture throughout the atmosphere, and over shorter time intervals.

2. Meteorological satellite systems

Operational meteorological satellites constitute an integral part of the World Meteorological Organization (WMO) observational programme called the world weather watch (WWW) [WMO Report 617, 1983]. Operation of the WWW spacecraft is described in [WMO Publication 411, 1975]. Within the framework of the WMO, coordination and planning for future satellites, including both sensor standardization and frequency utilization, is carried out, both for geostationary and low-orbit satellites. An Ad Hoc Group of all geostationary meteorological satellite operators has met annually since 1972 as a body called Coordination of Geostationary Meteorological Satellites (CGMS) [CGMS, 1984]. Other bodies exist to coordinate the requirements of low-orbit satellites, for example, the International Polar Orbiting Meteorological Satellite Group (IPOMS).

2.1 Low-orbit spacecraft

Low-orbit meteorological spacecraft, usually placed in Sun-synchronous orbits, are operated by the United States of America and the USSR [USSR, 1981]. Sensors include 1 km instantaneous field-of-view (IFOV), multi-spectral imagers, and an atmospheric temperature and moisture profiler using up to 23 infra-red channels, and five microwave channels, for tropospheric and stratospheric structure determination.

Table I lists characteristics of the present low-orbit meteorological satellites.
2.2 Geostationary spacecraft

Because geostationary satellites view their earth sectors continuously, they have grown in importance as sensor and data relay platforms for many suddenly-occurring life-threatening natural hazards: hurricanes, tornadoes, severe thunderstorms and frontal disturbances, flash floods, earthquakes, and tsunamis.

Operational geostationary satellites have multi-channel imagers, and in the case of the United States of America spacecraft, additional channels for experimental soundings. Tests indicate that soundings from geostationary satellites can have a quality equal to those from low-orbit spacecraft. However, sensors to provide soundings from geostationary satellites as rapidly as images are scanned, have not yet been developed [Johnson, 1984].

Table II lists present and planned geostationary spacecraft.

TABLE II — Geostationary meteorological satellites

<table>
<thead>
<tr>
<th>Operator</th>
<th>Name</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>ESA</td>
<td>METEOSAT</td>
<td>0° E</td>
</tr>
<tr>
<td>India</td>
<td>INSAT</td>
<td>74° E</td>
</tr>
<tr>
<td>Japan</td>
<td>GMS</td>
<td>140° E</td>
</tr>
<tr>
<td>United States of America</td>
<td>GOES-West</td>
<td>135° W</td>
</tr>
<tr>
<td>United States of America</td>
<td>GOES-East</td>
<td>75° W</td>
</tr>
<tr>
<td>USSR (planned)</td>
<td>GOES-Central (WEFAX only)</td>
<td>107° W</td>
</tr>
<tr>
<td>USSR (planned)</td>
<td>GOMS</td>
<td>76° E</td>
</tr>
<tr>
<td>USSR (planned)</td>
<td>GOMS-1</td>
<td>14° W</td>
</tr>
<tr>
<td>USSR (planned)</td>
<td>GOMS-2</td>
<td>166° E</td>
</tr>
</tbody>
</table>
3. Telecommunications requirements for meteorological satellites

Space telecommunications for meteorological satellites are required for several distinct functions, namely:
- for direct transmission of sensor data from spacecraft to earth stations;
- for active and passive sensing of the atmosphere, in the infra-red, in the visible, and in the microwave bands from 1-200 GHz;
- for data relay from remote earth-located sensors (i.e. data collection platforms) to central data processing facilities (see Report 538); for distribution of processed sensor and DCP data, analysed weather data and other data products from central processing facilities to distant users on land, at sea, or airborne; and
- for satellite control, sensor switching, and for multiple housekeeping functions.

3.1 Measurement frequencies and bandwidths

3.1.1 Passive measurements

The selection of spectral bands for passive sensing of the atmosphere is determined by the character of atmospheric transmission of electromagnetic radiation. These bands total in bandwidth from a few micrometres in the infra-red to a few megahertz in the microwave region (see Report 693 and Recommendation 515).

In both the infra-red and microwave regions of the spectrum, the frequency bands of value for atmospheric sounding and surface sensing are those at which either marked interaction, or a minimum interaction, occurs between atmospheric constituents and the passage of radiant energy. Frequencies are selected for the reactions that occur:
- with ozone (O$_3$) for determinations of temperatures and winds in the stratosphere;
- between radiation and water vapour and carbon dioxide for tropospheric sensing; and
- within atmospheric "window" channels for sensing surface temperatures and characteristics.

Microwave bands already used in experimental and operational satellites include: 1.27, 1.4, 3.5, 6.6, 8.8, 10.7, 13.5, 13.9, 14.6, 19.35, 22, 31, 33, 37 and 50-60 GHz, for atmospheric temperature and moisture profiles, and for sea surface temperature, surface roughness, and sea ice. Bands at 104, 118 and 140 are regions with windows and absorption bands suitable for atmospheric temperature profiles occur at 118 and 183 GHz (see Fig. 1, Report 852). Bands now planned for use in the advance microwave sounding unit (AMSU), for launch aboard NOAA-series spacecraft beginning in 1989, are listed in Table III (see also Report 693).
TABLE III — AMSU channels

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>Bandwidth (MHz)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>23.8</td>
<td>270</td>
<td>Total precipitable water over oceans</td>
</tr>
<tr>
<td>31.4</td>
<td>200</td>
<td>Window, for clouds and precipitation</td>
</tr>
<tr>
<td>50.3</td>
<td>200</td>
<td>Temperature profiles (O₂)</td>
</tr>
<tr>
<td>52.8</td>
<td>400</td>
<td>Temperature profiles (O₂)</td>
</tr>
<tr>
<td>53.3</td>
<td>400</td>
<td>Temperature profiles (O₂)</td>
</tr>
<tr>
<td>54.4</td>
<td>400</td>
<td>Temperature profiles (O₂)</td>
</tr>
<tr>
<td>54.9</td>
<td>400</td>
<td>Temperature profiles (O₂)</td>
</tr>
<tr>
<td>55.5</td>
<td>400</td>
<td>Temperature profiles (O₂)</td>
</tr>
<tr>
<td>57.3 (6 channels)</td>
<td>330</td>
<td>Temperature profiles (O₂)</td>
</tr>
<tr>
<td>89</td>
<td>6000</td>
<td>High-resolution detection of precipitation, sea ice, snow, land features</td>
</tr>
<tr>
<td>166 (3 channels)</td>
<td>4000</td>
<td>Water vapour profiles (H₂O)</td>
</tr>
<tr>
<td>183.3</td>
<td>4000</td>
<td>Water vapour profiles (H₂O)</td>
</tr>
</tbody>
</table>

3.1.2 Active measurements

Report 693 describes the bandwidths and preferred frequency bands for active microwave sensors. The use of spaceborne active sensors in meteorology continues to be developed. The observations of surface winds over the oceans by scatterometers planned for future Earth exploration satellites (see Report 535) may also be undertaken by future meteorological satellites. Bandwidths of 1 MHz near 15 GHz are required for these sensors. Pulsed lasers (LIDARs) are planned to operate in the infra-red wavelengths in order to measure the motions of aerosols and clouds. These LIDAR measurements are for deriving profiles of atmospheric winds [Johnson, 1982; Miller and Sparkman, 1984].

3.2 Data communications frequencies and bandwidths

Both low-orbit and geostationary meteorological satellites require appropriate wide bandwidths for data up and down links, for read-out of raw image and sounding data, and for direct dissemination of derived meteorological information. Additional transponder bandwidth is required for data relay from remotely located data collection platforms (including ships, aircraft and buoys) to central processing facilities.

3.2.1 Low-orbit spacecraft

Multi-spectral imaging in the visible and infra-red from low orbit requires a bandwidth of about 2.8 MHz for down-link data from sensors with instantaneous fields-of-view (IFOV) of 1 km (visible and infra-red). Future addition of spectral channels and reduction of IFOVs to 500 m will probably double this mission data rate by the end of this century. Bandwidths of up to 100 MHz may be required for transmission of LIDAR or other active sensor data.

It appears unlikely that an enhanced capacity for on-board data processing in space will reduce the requirements for image data flow. At present, there is little justification for on-board data processing as the current requirement for ground station processing of image data results in an increase of the data flow, because the raw data channels can be combined in various ways to provide different outputs, e.g. sea surface temperature, vegetation index, etc. [Dismacheck et al., 1980].

Low orbit sounding data, although involving many channels (approximately 30, since TIROS-N, 1978), have large IFOVs and a correspondingly low data rate, i.e. 3680 bit/s. This is not likely to increase by more than a factor of 2-4 in the foreseeable future.

Bandwidths for increased imaging data rates are not available in the currently assigned frequency bands. It appears likely that a shift to higher frequencies will be required for mission data down links.

Table IV lists the frequencies now used by the low-orbit meteorological satellites. Figure 1 illustrates a typical low-orbit satellite telecommunications system.
TABLE IV — Low-orbit meteorological satellite frequencies

### a) United States NOAA series

<table>
<thead>
<tr>
<th>Link</th>
<th>Carrier frequency (MHz)</th>
<th>Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Beacon</td>
<td>137.77</td>
<td>S-E</td>
</tr>
<tr>
<td></td>
<td>136.77 (*)</td>
<td></td>
</tr>
<tr>
<td>2. Real time APT</td>
<td>137.50</td>
<td>S-E</td>
</tr>
<tr>
<td></td>
<td>137.62</td>
<td></td>
</tr>
<tr>
<td>3. Real time HRPT</td>
<td>1698.0</td>
<td>S-E</td>
</tr>
<tr>
<td></td>
<td>1702.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1707.0</td>
<td></td>
</tr>
<tr>
<td>4. Mission data to CDAs</td>
<td>1698.0</td>
<td>S-E</td>
</tr>
<tr>
<td></td>
<td>1702.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1707.0</td>
<td></td>
</tr>
<tr>
<td>5. Data collection system</td>
<td>401.65</td>
<td>E-S</td>
</tr>
<tr>
<td>6. Command</td>
<td>148.56</td>
<td>E-S</td>
</tr>
<tr>
<td>7. Search and rescue</td>
<td>121.5</td>
<td>E-S</td>
</tr>
<tr>
<td></td>
<td>243.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>406.05</td>
<td></td>
</tr>
<tr>
<td>8. Search and rescue</td>
<td>1544.0</td>
<td>S-E</td>
</tr>
</tbody>
</table>

(*) Allocation status of this frequency becomes secondary in 1990 (WARC-79).

**APT:** automatic picture transmission  
**HRPT:** high resolution picture transmission  
**CDA:** command and data acquisition  
**S:** space  
**E:** Earth

### b) USSR METEOR series

<table>
<thead>
<tr>
<th>Link</th>
<th>Carrier frequency (MHz)</th>
<th>Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Real time APT</td>
<td>137.15</td>
<td>S-E</td>
</tr>
<tr>
<td></td>
<td>137.30</td>
<td></td>
</tr>
<tr>
<td></td>
<td>137.40</td>
<td></td>
</tr>
<tr>
<td></td>
<td>137.50</td>
<td></td>
</tr>
<tr>
<td>2. Mission data read-out</td>
<td>466.50</td>
<td>S-E</td>
</tr>
<tr>
<td>3. Search and rescue</td>
<td>121.5</td>
<td>E-S</td>
</tr>
<tr>
<td></td>
<td>243.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>406.05</td>
<td></td>
</tr>
<tr>
<td>4. Search and rescue</td>
<td>1544.0</td>
<td>S-E</td>
</tr>
</tbody>
</table>
SEM measurements

- Visible, infra-red, microwave and solar particle passive sensors

- Low-orbit meteorological satellite

- Command and data acquisition station

- Aircraft ships

- WMO global telecommunication system

- S and R local earth receiving station

- Rescue coordination centre

- APT earth receiving stations

- HRPT earth receiving stations

- HRPT, SEM, DCS and sounder data user station

Visible and infra-red imaging
Atmospheric temperature and moisture profile
Tropospheric and stratospheric structure
Surface temperature
Storm observations

Command and data collection platforms (random)

DCS and space environment data

DCS data

Search and rescue data

S and R data

Direct APT data

Direct HRPT data

S and R data: search and rescue data

APT: automatic picture transmission

HRPT: high resolution picture transmission

WMO: World Meteorological Organization

DCS: data collection system

SEM: solar environmental monitor

FIGURE 1 - A typical low-orbit meteorological satellite system
### TABLE V — Geostationary meteorological satellite frequencies

(All frequencies are in MHz except INSAT and indicate the centre frequency of the respective channel)

<table>
<thead>
<tr>
<th></th>
<th>METEOSAT</th>
<th>GOES</th>
<th>GMS</th>
<th>GOMS</th>
<th>INSAT</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Launch, TM</strong></td>
<td>137.08</td>
<td>2214</td>
<td>2280.72</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Operating, TM</strong></td>
<td>1675.929</td>
<td>1694</td>
<td>1694</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Launch, TC</strong></td>
<td>149.34</td>
<td></td>
<td>2100.16</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Operating, TC</strong></td>
<td>2098</td>
<td>2034.2</td>
<td>2034.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>No. of DCP channels</strong></td>
<td>66</td>
<td>66</td>
<td>133 (2)</td>
<td>66</td>
<td>33</td>
</tr>
<tr>
<td><strong>DCP report E-S</strong></td>
<td>402.1</td>
<td>401.9</td>
<td>402.2</td>
<td>401.9</td>
<td>402.75</td>
</tr>
<tr>
<td><strong>DCP report S-E</strong></td>
<td>1675.281</td>
<td>1694.5</td>
<td>1694.5</td>
<td>1696.9</td>
<td>4 GHz</td>
</tr>
<tr>
<td><strong>DCP interrogation E-S</strong></td>
<td>2098</td>
<td>2034.9</td>
<td>2034.9</td>
<td>2118.85</td>
<td></td>
</tr>
<tr>
<td><strong>DCP interrogation S-E</strong></td>
<td>468.9</td>
<td>468.825</td>
<td>468.8</td>
<td>468.85</td>
<td></td>
</tr>
<tr>
<td><strong>Raw image bit rate</strong></td>
<td>166 kbit/s (7.7 Mbit/s) (')</td>
<td>28 Mbit/s</td>
<td>14 Mbit/s</td>
<td>1.5 Mbit/s</td>
<td>400 kbit/s</td>
</tr>
<tr>
<td><strong>Raw image</strong></td>
<td>1686.833</td>
<td>1681.6</td>
<td>1681.6</td>
<td>1685</td>
<td>4 GHz</td>
</tr>
<tr>
<td><strong>Dissemination channel I (E-S)</strong></td>
<td>2101.5</td>
<td>2032.1 (WEFAX only)</td>
<td>2033 (WEFAX only)</td>
<td>2116 (WEFAX only)</td>
<td></td>
</tr>
<tr>
<td><strong>Dissemination channel I (S-E)</strong></td>
<td>1691</td>
<td>1691 (WEFAX only)</td>
<td>1691 (WEFAX only)</td>
<td>1691 (WEFAX only)</td>
<td></td>
</tr>
<tr>
<td><strong>Dissemination channel II (E-S)</strong></td>
<td>2105</td>
<td>2029.1</td>
<td>2029.1</td>
<td>2117 (WEFAX only)</td>
<td></td>
</tr>
<tr>
<td><strong>Dissemination channel II (S-E)</strong></td>
<td>1694.5</td>
<td>1687.1</td>
<td>1687.1</td>
<td>1692 (WEFAX only)</td>
<td></td>
</tr>
<tr>
<td><strong>High-accuracy ranging E-S</strong></td>
<td>2101.5</td>
<td>2026</td>
<td>2026</td>
<td>2026</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2105</td>
<td>2030.2</td>
<td>2030.2</td>
<td>2032.2</td>
<td></td>
</tr>
<tr>
<td><strong>High-accuracy ranging S-E</strong></td>
<td>1691</td>
<td>1684</td>
<td>1684</td>
<td>1684</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1694.5</td>
<td>1688.2</td>
<td>1688.2</td>
<td>1690.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1690.2</td>
<td>1690.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2209.086</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(') Back-up mode

(2') International 33ch, domestic 100ch

**DCP:** data collection platform
**TC:** telecommand
**TM:** telemetry
**WEFAX:** weather facsimile
**E:** Earth
**S:** space
Geostationary meteorological satellite

Visible, infra-red, microwave and solar particle passive sensors

Solar environmental measurements

Cloud cover imagery
Cloud top temperatures
Ground and sea surface temperatures
Atmospheric soundings
Water vapour imagery
Storm observations

Command and data acquisition station

Data collection

Data collection platforms (timed, interrogated, random)

Remote sites

WMO Global Telecommunication System

FIGURE 2 – A typical geostationary meteorological satellite system

Space links
Terrestrial links
WEFAX: Weather facsimile
3.2.2 Geostationary spacecraft

Use of a spinning platform for Earth observation from geostationary satellites levies a heavy penalty on sensor design and data flow rates. Sensors on spinning platforms for imaging and sounding view the Earth for only 1/18th of each platform revolution. Data rates during this brief Earth observation period reach 28 Mbit/s. When "stretched" by a ground station to fill in the remaining 17/18ths of each turn, the re-broadcast data transmission reduces to 1.75 Mbit/s.

Progress in spacecraft stabilizing techniques may permit the use of a non-spinning sensor platform, thus reducing the maximum data rates towards the 2 Mbit/s level. The success of INSAT as a three-axis-stabilized multi-purpose geostationary satellite with an imaging sensor has shown that a body-stabilized, imaging platform is feasible.

Table V lists the frequencies now used by the geostationary meteorological satellites. Figure 2 illustrates a typical geostationary meteorological satellite telecommunication system.

REFERENCES


REPORT 541-3

FEASIBILITY OF FREQUENCY SHARING BETWEEN A GEOSTATIONARY METEOROLOGICAL SATELLITE SYSTEM AND THE METEOROLOGICAL AIDS SERVICE IN THE REGION OF 400 MHz AND IN THE UPPER PART OF BAND 9 (1 TO 3 GHz)

(Study Programme 12C/2)


1. Introduction

This Report describes typical meteorological aids and satellite systems that may share frequency bands in the region of 400 MHz and in the upper part of band 9 (1 to 3 GHz), and presents sharing criteria that will ensure that neither system suffers nor causes harmful interference.

1.1 Meteorological satellite system characteristics

The meteorological satellite systems considered in this Report are at present in operation; these are the Geostationary Operational Environmental Satellite (GOES) system which has been developed by the United States, and the METEOSAT system, developed by the European Space Agency and the Geostationary Meteorological Satellite (GMS) system developed by Japan. These systems have communication links in the region of 400 MHz and in the upper part of band 9. Typical system transmitter, receiver and antenna characteristics that are relevant to an interference analysis for band 9 are shown in Tables I, II, III, IV, V and VI.

The systems use frequencies in the region of 400 MHz for reporting to the satellite from land-based data collection platforms (DCP's) and ocean buoys. Technical information on the DCP's is given in Table VIIa. Reports may be made by the platforms either in response to interrogations from the satellite or automatically on a regular basis controlled by an internal clock. Characteristics of the satellite receiver used in this link are given in Table VIIb.
TABLE I — Characteristics of GOES satellite system which are pertinent to frequency sharing in the upper portion of band 9 — Transmitters

<table>
<thead>
<tr>
<th>Transmitters</th>
<th>e.i.r.p. (dBW)</th>
<th>$G_t$ (dB)</th>
<th>Emission</th>
<th>Flux density at the surface of the earth for a bandwidth of 1.5 MHz (dB(W/m²))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Synchronous meteorological satellite</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>to CDA (1) (meteorological data)</td>
<td>27-9</td>
<td>15-7</td>
<td>M25F9</td>
<td>-146-3</td>
</tr>
<tr>
<td>to CDA/TARS (2) (ranging data)</td>
<td>27-9</td>
<td>15-7</td>
<td>M1F9</td>
<td>-134-1</td>
</tr>
<tr>
<td>to DRGS (3) (stretched data)</td>
<td>27-9</td>
<td>15-7</td>
<td>M3-5F9</td>
<td>-137-7</td>
</tr>
<tr>
<td>to FC (4) (facsimile data)</td>
<td>7-0</td>
<td>15-7</td>
<td>26F4</td>
<td>-134-1</td>
</tr>
<tr>
<td>to CDA (DCP (5) data)</td>
<td>14-0</td>
<td>12-7</td>
<td>400F9</td>
<td>-155-0</td>
</tr>
<tr>
<td>Meteorological satellite earth stations</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CDA (stretched data)</td>
<td>73-4</td>
<td>46-4</td>
<td>M3-5F9</td>
<td></td>
</tr>
<tr>
<td>CDA (facsimile data)</td>
<td>73-4</td>
<td>46-4</td>
<td>26F4</td>
<td></td>
</tr>
<tr>
<td>CDA (command link)</td>
<td>56-4</td>
<td>46-4</td>
<td>30F9</td>
<td></td>
</tr>
<tr>
<td>CDA (DCP interrogation)</td>
<td>56-4</td>
<td>46-4</td>
<td>0-1F9</td>
<td></td>
</tr>
<tr>
<td>CDA (ranging data)</td>
<td>64-4</td>
<td>46-4</td>
<td>M1F9</td>
<td></td>
</tr>
<tr>
<td>TARS (ranging data)</td>
<td>45-0</td>
<td>30-1</td>
<td>M1F9</td>
<td></td>
</tr>
</tbody>
</table>

(1) CDA: Command and data acquisition station.
(2) TARS: Turn-around ranging station; this system transmits a CW unmodulated signal on 1684.0, 1688.2 and 1699.2 MHz during the 10 s acquisition mode.
(3) DRGS: Direct readout ground station.
(4) FC: Forecast centre station.
(5) DCP: Data collection platform.

TABLE II — Characteristics of GOES satellite system which are pertinent to frequency sharing in the upper portion of band 9 — Receivers

<table>
<thead>
<tr>
<th>Receivers</th>
<th>$G_r$ (dB)</th>
<th>$T_r$ (K)</th>
<th>Noise bandwidth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meteorological satellite</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Data)</td>
<td>9-2</td>
<td>1630</td>
<td>8-2 MHz</td>
</tr>
<tr>
<td>(Command)</td>
<td></td>
<td>60 kHz</td>
<td></td>
</tr>
<tr>
<td>(DCP interrogation)</td>
<td></td>
<td>150 kHz</td>
<td></td>
</tr>
<tr>
<td>CDA (1)</td>
<td>47-6</td>
<td>100</td>
<td>25 MHz</td>
</tr>
<tr>
<td>(Telemetry)</td>
<td></td>
<td>200 kHz</td>
<td></td>
</tr>
<tr>
<td>(DCP reports)</td>
<td></td>
<td>400 kHz</td>
<td></td>
</tr>
<tr>
<td>DRGS (1)</td>
<td>37-5</td>
<td>300</td>
<td>3-5 MHz</td>
</tr>
<tr>
<td>FC (1)</td>
<td>30-0</td>
<td>1500</td>
<td>50 kHz</td>
</tr>
</tbody>
</table>

(1) See Table I.
TABLE III — Characteristics of METEOSAT satellite system which are pertinent to frequency sharing in the upper portion of band 9 — Transmitters

<table>
<thead>
<tr>
<th>Transmitter</th>
<th>Max. e.i.r.p. (dBW)</th>
<th>Max. $G_t$ (dB)</th>
<th>Emission</th>
<th>Maximum power-flux density at the surface of the Earth (sub-satellite point) (dB(W/m$^2$))</th>
</tr>
</thead>
<tbody>
<tr>
<td>METEOSAT satellite</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>to DATTS(1) (raw image data)</td>
<td>6.5</td>
<td>14</td>
<td>660F9</td>
<td>-155.6</td>
</tr>
<tr>
<td>to DATTS/LBT(2) (ranging data)</td>
<td>21.3</td>
<td>14</td>
<td>660F9</td>
<td>-140.8</td>
</tr>
<tr>
<td>to DATTS/PDUS(3) (high resolution pictures)</td>
<td>21.3</td>
<td>14</td>
<td>660F9</td>
<td>-140.8</td>
</tr>
<tr>
<td>to DATTS/SDUS(4) (facsimile data)</td>
<td>21.3</td>
<td>14</td>
<td>26F4</td>
<td>-140.8</td>
</tr>
<tr>
<td>to DATTS (DCP reports)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>normal</td>
<td>3.2</td>
<td>14</td>
<td>200F9</td>
<td>-158.9</td>
</tr>
<tr>
<td>eclipse</td>
<td>-9.2</td>
<td>3</td>
<td>200F9</td>
<td>-171.3</td>
</tr>
<tr>
<td>to DATTS (HK telemetry)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>normal</td>
<td>-5</td>
<td>14</td>
<td>30F9</td>
<td>-167.1</td>
</tr>
<tr>
<td>eclipse</td>
<td>-16.2</td>
<td>3</td>
<td>30F9</td>
<td>-178.3</td>
</tr>
</tbody>
</table>

Meteorological satellite earth station

| from DATTS (high resolution pictures) | 64 | 47 | 660F9 |
| from DATTS (facsimile data) | 64 | 47 | 26F4 |
| from DATTS (DCP interrogation) | 57 | 47 | 7F9 |
| from DATTS (HK telecommand) | 57 | 47 | 30F9 |
| from DATTS (DCP reports) |          |                |          |                                                  |
| PDUS | 35 | 250 | 660F9 |
| LBT | 30 | 560 | 250 |

(1) DATTS: Data acquisition telecommand and tracking station.
(2) LBT: Land-based transponder for ranging operations.
(3) PDUS: Primary data user station.
(4) SDUS: Secondary data user station.

TABLE IV — Characteristics of METEOSAT satellite system which are pertinent to frequency sharing in the upper portion of band 9 — Receivers

<table>
<thead>
<tr>
<th>Receivers</th>
<th>$G_r$ (dB)</th>
<th>$T_r$ (K)</th>
<th>Noise bandwidth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meteorological satellite</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Disseminated and ranging data)</td>
<td>3</td>
<td>750</td>
<td>1000 kHz</td>
</tr>
<tr>
<td>(HK telecommand)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(DCP interrogation)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DATTS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Picture data)</td>
<td>45</td>
<td>115</td>
<td>25 kHz</td>
</tr>
<tr>
<td>(DCP reports)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(HK telemetry)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Ranging data)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PDUS</td>
<td>35</td>
<td>250</td>
<td>1000 kHz</td>
</tr>
<tr>
<td>SDUS</td>
<td>30</td>
<td>560</td>
<td>50 kHz</td>
</tr>
<tr>
<td>LBT</td>
<td>30</td>
<td>250</td>
<td>1000 kHz</td>
</tr>
</tbody>
</table>
### TABLE V — Characteristics of GMS system transmitters which are pertinent to frequency sharing in the upper portion of band 9

<table>
<thead>
<tr>
<th>Transmitter</th>
<th>Maximum e.i.r.p. (dBW)</th>
<th>Maximum $G_r$ (dB)</th>
<th>Emission</th>
<th>Maximum power flux-density at the surface of the Earth for a bandwidth of 1.5 MHz (dB(W/m²))</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>GMS satellite</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>to CDAS (') (VISSR data)</td>
<td>29</td>
<td>18</td>
<td>2000G1D</td>
<td>- 133</td>
</tr>
<tr>
<td>to CDAS/TARS (') (ranging data)</td>
<td>17</td>
<td>18</td>
<td>1000G3D</td>
<td>- 145</td>
</tr>
<tr>
<td>to CDAS/MDUS (') (high resolution pictures)</td>
<td>29</td>
<td>18</td>
<td>1000F3C</td>
<td>- 133</td>
</tr>
<tr>
<td>to CDAS/SDUS (') (low resolution pictures)</td>
<td>29</td>
<td>18</td>
<td>260K3C</td>
<td>- 133</td>
</tr>
<tr>
<td>to CDAS (DCP report)</td>
<td>6.3</td>
<td>18</td>
<td>2000G1D</td>
<td>- 157.6</td>
</tr>
<tr>
<td>to CDAS (1K telemetry)</td>
<td>15.6</td>
<td>18</td>
<td>400K9D</td>
<td>- 147</td>
</tr>
<tr>
<td><strong>Meteorological satellite earth station</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>from CDAS (high resolution pictures)</td>
<td>77</td>
<td>50</td>
<td>1000F3C</td>
<td></td>
</tr>
<tr>
<td>from CDAS (low resolution pictures)</td>
<td>70</td>
<td>50</td>
<td>260K3C</td>
<td></td>
</tr>
<tr>
<td>from CDAS (DCP interrogation)</td>
<td>54</td>
<td>50</td>
<td>6000G1D</td>
<td></td>
</tr>
<tr>
<td>from CDAS (command)</td>
<td>54</td>
<td>50</td>
<td>3500G2D</td>
<td></td>
</tr>
<tr>
<td>from CDAS (ranging data)</td>
<td>67</td>
<td>50</td>
<td>1000G3D</td>
<td></td>
</tr>
<tr>
<td>from TARS (ranging data)</td>
<td>52</td>
<td>33</td>
<td>1000G3D</td>
<td></td>
</tr>
</tbody>
</table>

(') Command and data acquisition station.
(') Turn around ranging station.
(') Medium scale data utilization station.
(') Small scale data utilization station.

### TABLE VI — Characteristics of GMS system which are pertinent to frequency sharing in the upper portion of band 9 — Receivers

<table>
<thead>
<tr>
<th>Receivers</th>
<th>$G_r$ (dB)</th>
<th>$T_r$ (K)</th>
<th>Noise bandwidth</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Meteorological satellite</strong> (Disseminated data and ranging data)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Command)</td>
<td>18</td>
<td>1540</td>
<td>8.2 MHz</td>
</tr>
<tr>
<td>(DCP interrogation)</td>
<td></td>
<td></td>
<td>60 kHz</td>
</tr>
<tr>
<td><strong>CDAS</strong> (VISSR data)</td>
<td></td>
<td></td>
<td>200 kHz</td>
</tr>
<tr>
<td>(DCP reports)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(1K telemetry) (Ranging data)</td>
<td></td>
<td></td>
<td>20 MHz</td>
</tr>
<tr>
<td><strong>MDUS</strong></td>
<td>35</td>
<td>300</td>
<td>1 MHz</td>
</tr>
<tr>
<td><strong>SDUS</strong></td>
<td>30</td>
<td>500</td>
<td>260 kHz</td>
</tr>
<tr>
<td><strong>TARS</strong></td>
<td>32</td>
<td>600</td>
<td>1 MHz</td>
</tr>
</tbody>
</table>
### TABLE VII
**Characteristics of meteorological satellite systems in the region of 400 MHz**

<table>
<thead>
<tr>
<th>Data collection platform (land-based) characteristics (for satellite elevation angles &lt;45°)</th>
<th>GOES (Typical)</th>
<th>Meteosat (Typical)</th>
<th>GMS (Typical)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmitter power (dBW)</td>
<td>7</td>
<td>7</td>
<td>10/13</td>
</tr>
<tr>
<td>Feed loss (dB)</td>
<td>0.5</td>
<td>0.5</td>
<td>6</td>
</tr>
<tr>
<td>Antenna gain (dB)</td>
<td>10</td>
<td>10</td>
<td>9</td>
</tr>
<tr>
<td>Path loss (free space) (dB)</td>
<td>177</td>
<td>177</td>
<td>177</td>
</tr>
<tr>
<td>Polarization loss (dB)</td>
<td>0.2</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Satellite antenna gain (dB)</td>
<td>7.3</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>Feed loss (dB)</td>
<td>2.9</td>
<td>1.4</td>
<td></td>
</tr>
<tr>
<td>Receiver power (dBW)</td>
<td>-136.3</td>
<td>-162.4</td>
<td>-152/-169</td>
</tr>
</tbody>
</table>

### TABLE VIIb
**Satellite receiver characteristics**

<table>
<thead>
<tr>
<th>Satellite receiver characteristics</th>
<th>GOES</th>
<th>Meteosat</th>
<th>GMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centre frequency (MHz)</td>
<td>401.9</td>
<td>402.1</td>
<td>402.1</td>
</tr>
<tr>
<td>Bandwidth (kHz)</td>
<td>400</td>
<td>200</td>
<td>400</td>
</tr>
<tr>
<td>Antenna gain (dB) (including feed losses)</td>
<td>4.4</td>
<td>0</td>
<td>8</td>
</tr>
<tr>
<td>Noise temperature (K)</td>
<td>383</td>
<td>600</td>
<td>710</td>
</tr>
</tbody>
</table>

1.2 **Meteorological aid system characteristics**

The meteorological aids system characteristics used in this analysis are those of a typical radiotheodolite/radiosonde system used for gathering weather information. Meteorological aids (radiosondes) are launched from weather service sites up to four times a day. These launches are coordinated and usually occur near 0000, 0600, 1200 and 1800 UTC. The balloon-borne radiosondes transmit temperature, pressure and humidity data to ground-based radiotheodolites as they rise to a maximum altitude of about 30 km. Typical lifetimes range from one to one and a half hours and are limited by the bursting of the balloon and the operating life of the water-activated battery.

In the 400.15 MHz to 406 MHz band, there are two types of radiosonde transmitters in use; one type provides a maximum of 1 W of transmitter power when launched and has an unstabilized oscillator. The other type uses a crystal controlled 0.5 W transmitter and, in addition to the atmospheric data, rebroadcasts either Omega or Loran C transmissions for aid in position determination. Experience has shown a degradation in transmitter output with altitude, probably caused by the weakening of the battery. The degradation in output power is about 3 dB when the radiosonde is at its maximum altitude.

The radiosonde antenna is a quarter-wave monopole, providing up to 2 dB of gain over an isotropic antenna and emitting a signal which is, nominally, vertically polarized. The maximum range of a radiosonde from its launch point and receiving station is usually taken to be 200 km. The radiosonde transmitter uses amplitude modulation but, due to its design, a large amount of frequency modulation also occurs.
Radiosonde receiving stations use a dipole array that provides a gain of approximately 9 dB. Receivers may be sensitive enough to receive signals as low as —145 dBW, but nevertheless some may require signal levels as high as —130 dBW. The minimum radiosonde signal at the receiver is usually at least —127 dBW (assuming free-space loss) which provides some margin. In this condition, the minimum carrier-to-interference ratio for successful operation could not be less than about 6 dB. Since the radiosondes transmit continuously throughout their lifetime, and since the parameters being measured change only slowly, short periods of interference are not particularly harmful. Missed data can often be estimated by interpolating between the values received. The reporting period for each meteorological parameter ranges from 10 s to 1 min. To date, the United States has had no known cases of interference to reception of radiosonde transmission. Table VIII summarizes the meteorological aids system characteristics in the region of 400 MHz.

Meteorological aids systems transmitting in the upper part of band 9 have characteristics (Table IX) somewhat different from those in Table VIII although the operation and purpose of these systems are similar.

2. **Interference analysis**

Six possible interference cases exist between meteorological aids and meteorological satellite systems:

- radiotheodolite transmissions interfering with reception by the meteorological satellite receiver in the region of 400 MHz;
- radiosonde transmissions interfering with reception by the meteorological satellite in the region of 400 MHz;
- radiosonde transmissions interfering with reception by the meteorological satellite earth station in the upper part of band 9;
- meteorological satellite terrestrial station (data collection platforms) transmissions interfering with radiotheodolite receivers in the region of 400 MHz;
- meteorological satellite terrestrial station (data collection platforms) transmissions interfering with radiosonde receivers in the region of 400 MHz;
- meteorological satellite transmissions interfering with radiotheodolite reception in the upper part of band 9.

These possible interference cases are considered separately in the sub-section which follows.

### Table VIII

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Maximum</th>
<th>Minimum</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1. Radiosonde balloon transmissions</strong> (down-link)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transmitter power (dBW)</td>
<td>0</td>
<td>—6</td>
</tr>
<tr>
<td>Transmitter antenna gain (dB)</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>e.i.r.p. (dBW)</td>
<td>2</td>
<td>—6</td>
</tr>
<tr>
<td>Free-space path loss (at 200 km) (dB)</td>
<td>130</td>
<td>130</td>
</tr>
<tr>
<td>Receiver antenna gain (dB)</td>
<td>9</td>
<td>8</td>
</tr>
<tr>
<td>Minimum received signal (dBW)</td>
<td>—119</td>
<td>—128</td>
</tr>
<tr>
<td><strong>2. Radiotheodolite ground transmissions</strong> (up-link)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transmitter power (dBW)</td>
<td>14.8</td>
<td></td>
</tr>
<tr>
<td>Transmitter antenna gain (dB)</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>e.i.r.p. (dBW)</td>
<td>20.8</td>
<td></td>
</tr>
<tr>
<td>Free-space path loss (at 200 km) (dB)</td>
<td>130</td>
<td></td>
</tr>
<tr>
<td>Radiosonde antenna gain (dB)</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Power level at radiosonde (dBW)</td>
<td>—109.2</td>
<td></td>
</tr>
<tr>
<td>Receiver minimum sensitivity (dBW)</td>
<td>—125</td>
<td></td>
</tr>
</tbody>
</table>
TABLE IX — Characteristics of meteorological aids systems pertinent to frequency sharing in the upper part of band 9

<table>
<thead>
<tr>
<th>System</th>
<th>e.i.r.p. (dBW)</th>
<th>$G_t$ (dB)</th>
<th>Emission</th>
<th>$G_r$ (dB)</th>
<th>$T_r$ (K)</th>
<th>Noise bandwidth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiosonde transmitter:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>— non-ranging</td>
<td>-6</td>
<td>0</td>
<td>15F2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>— ranging</td>
<td>-6</td>
<td>0</td>
<td>400F9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radiotheodolite receiver</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>28</td>
<td>2900</td>
<td>1.5 MHz</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2.1 Radiotheodolite transmission interfering with reception by the meteorological satellite in the region of 400 MHz

The radiotheodolite transmitter has a higher e.i.r.p. than does the radiosonde transmitter (for this analysis, the worst case of intersection with the geostationary-satellite orbit is assumed). System parameters and hence the interfering power at the satellite are listed in Table X. The levels of interfering (theodolite) signal are significantly more than the typical signal levels from a DCP (see Table VIIa).

The theodolite transmissions are frequency modulated with a 75 kHz bandwidth and the DCP and the buoy, using PSK would be received at the meteorological satellite in a 400 kHz bandwidth. Thus, if the meteorological satellites and the theodolite operate on the same frequency, the entire interfering signal would be received by the satellites.

It is concluded that coordination of frequency assignments may be necessary in operational systems within a shared band.

TABLE X — Interference at the satellite from a theodolite (400 MHz)

<table>
<thead>
<tr>
<th>System</th>
<th>GOES</th>
<th>METEOSAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theodolite e.i.r.p. (dBW)</td>
<td>+20.8</td>
<td>+20.8</td>
</tr>
<tr>
<td>Path loss (dB)</td>
<td>177.0</td>
<td>177.0</td>
</tr>
<tr>
<td>Polarization loss (dB)</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Receiver antenna gain (dB)</td>
<td>7.3</td>
<td>0.5</td>
</tr>
<tr>
<td>Feed loss (dB)</td>
<td>2.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Interfering power (dBW)</td>
<td>-154.4</td>
<td>-159.2</td>
</tr>
</tbody>
</table>

2.2 Radiosonde transmissions interfering with reception at the meteorological satellite in the region of 400 MHz

The radiosonde transmitters in this band radiate a maximum power of 0 dBW, which is approximately 16 dB less than the minimum power from the proposed data collection platforms. Taking into account polarization discrimination and the relative bandwidths of the wanted and interfering signals at the spacecraft receiver, the interfering effect of the radiosonde transmissions is insignificant.
2.3 Radiosonde transmissions interfering with reception at the meteorological satellite earth station in the upper part of band 9

Interference from the meteorological aids service to meteorological satellite earth station receivers is influenced by the fact that the meteorological aids transmitter (radiosonde) is not fixed and could be within line-of-sight of a meteorological satellite earth station to a distance of approximately 700 km. The meteorological aids service transmitters in band 9 (radiosondes) are typically launched from a given site at 6 h intervals. The radiosonde ascends at a rate of approximately 500 m/min to an altitude of 30 km before the balloon bursts.

Assuming an allowable carrier-to-interference ratio of 10 dB, the maximum values of the undesired signal, $P_r$, for the GOES meteorological satellite earth stations are:

- **GOES**: Command and data acquisition station (CDA) (25 MHz noise bandwidth): $-144.6$ dBW
- **Direct read-out ground station (DRGS)** (3.5 MHz bandwidth): $-148.4$ dBW
- **Forecast centre station (FC)** (50 kHz noise bandwidth): $-159.9$ dBW

If a specific modulation technique and type of interfering signal are postulated, a different value of $P_r$ might be obtained. For example, assuming the satellite-to-CDA link to be a quadriphase shift-keyed, coherently detected signal and the interference a narrow-band signal, the required protection ratio (carrier/interference) for a $10^{-6}$ symbol error probability would be 10 dB, if the link were designed for a carrier-to-noise ratio of 18 dB. However, if the link were designed for a carrier-to-noise ratio of 14 dB, then the required protection ratio for the same error probability would increase to 30 dB [Rosenbaum, 1969]. Using the various proposed satellite power levels and the above protection ratios, $P_r$ could range from $-125.5$ dBW to $-145.5$ dBW. These values would only apply to the specific modulation technique and the interfering signal described above, but they demonstrate the sensitivity of the value of $P_r$ to the assumptions made. A reasonable compromise in a situation where the system is not completely defined is to compute as above the thermal noise level of the receiver and limit the interference to some percentage of this level. This approach is especially applicable to power-limited down links.

The case of the METEOSAT system is treated in Annex I, and that of the GMS system in Annex II.

Assuming, as a worst case, free-space propagation, the power flux-density at the meteorological satellite earth station could be as high as $-130$ dB(W/m²) from a radiosonde at a slant range of 700 km.

If the radiosonde were within the earth station antenna main beam with an emission bandwidth of 1 MHz, the interference signal levels within the receiver bandwidth of the earth stations would be as shown in Table XI. (Although it is a gross assumption, the power is assumed to be equally distributed across the 1 MHz band.) The negative margins shown are pessimistic in that they consider neither:

- **(a)** radiation pattern discrimination of the meteorological satellite earth station antenna; nor
- **(b)** the time duration of the interference; nor
- **(c)** the time between periods of interference.

Regarding **(a)**, for earth station antennas such that the ratio of antenna diameter to the wavelength exceeds 100, the CCIR reference pattern (see Report 391) provides a measure of the out-of-beam discrimination available. For example, based upon the CCIR reference pattern, a 12 m parabolic antenna at 1680 MHz could provide sufficient discrimination against radiosondes more than about 7° off the main beam and approximately 700 km distant. For ranges less than 700 km, say 150 km, the antenna could provide the needed discrimination against radiosondes more than about 20° off the main beam.

Regarding **(b)** and **(c)**, the time duration and time interval between periods of interference are important considerations, since as has been previously pointed out, radiosondes have limited operating lifetimes. Although it is not possible to make a quantitative assessment of the time factor, this fact does seem to reduce the importance of radiosonde interference on the earth station, since it provides a possible sharing alternative.
TABLE XI — Interference to GOES satellite earth stations in the upper portion of band 9

<table>
<thead>
<tr>
<th>Type of station</th>
<th>Bandwidth</th>
<th>Maximum permissible $P_r$ (dBW)</th>
<th>Interference level from radiosonde in antenna main beam (dBW)</th>
<th>Margin of protection (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Command and data acquisition</td>
<td>25 MHz</td>
<td>−144-6</td>
<td>−108-4</td>
<td>−36-2</td>
</tr>
<tr>
<td>Direct readout</td>
<td>3.5 MHz</td>
<td>−148-4</td>
<td>−118-5</td>
<td>−29-9</td>
</tr>
<tr>
<td>Forecast centre</td>
<td>50 kHz</td>
<td>−159-9</td>
<td>−139-0</td>
<td>−20-9</td>
</tr>
</tbody>
</table>

2.4 Meteorological satellite terrestrial station (data collection platforms) transmissions interfering with radiotheodolite receivers in the region of 400 MHz

Remote platforms (DCP) operating on land would emit about 16.5 dBW e.i.r.p. and have a fairly directive antenna. To interfere with reception of radiosonde signals at a radiotheodolite receiving ground station, the e.i.r.p. of the DCP in the direction of the ground station would have to be such as to produce a signal of at least −6 dB with respect to the radiosonde signal. The interference would be a function of the distance between the DCP and the receiver, and the signal would depend on the distance between the radiosonde and the receiver.

Buoys would be placed on bodies of water, generally at sea. At such locations, they would usually be out of the line-of-sight of radiotheodolite receivers and would not cause interference to them.

Both DCP and buoy transmitters could produce interference to a radiotheodolite receiver within line-of-sight range. Interference may be avoided by constraining the DCP or buoy antenna gain in the pertinent direction. However, this would be required on an individual case-by-case basis and would include side-lobe gain determination. To avoid the possibility of interference, DCPs and buoys should not be located within the line-of-sight of the radiotheodolite receivers.

2.5 Meteorological satellite terrestrial station (data collection platforms) transmissions interfering with radiosonde receivers in the region of 400 MHz

Interference can occur only when the balloon drifts through the main beam of either the DCP or buoy transmitters, which emit 15 to 16 dBW e.i.r.p. in the main beam for approximately 10 s during any period of 6 h. If the balloon drifts through the DCP main beam during this single 10 s period, interference could occur as the balloon may be closer to the DCP than is the theodolite transmitter. However, it is concluded that the possibility of interference caused by DCPs and buoys to radiosonde operation will be operationally insignificant.

2.6 Meteorological satellite transmissions interfering with radiotheodolite reception in the upper part of band 9

The power flux-density limit adopted for sharing between meteorological satellites and terrestrial fixed services does not apply to meteorological satellites sharing the same frequency bands with the meteorological aids service. A power flux-density limitation is therefore developed here specifically for a geostationary meteorological satellite sharing a common band with a meteorological aids (radiotheodolite/radiosonde) system.
2.6.1 Maximum allowable interference for the meteorological aids operations

Table XII presents the computed maximum allowable interfering signal level for meteorological aids operation, using the minimum desired signal level approach. It is assumed that the interfering signal could be equal to the total noise at the input to a meteorological aids (radiotheodolite) receiver. The protection ratio is based upon empirical data obtained from a series of tests on a radiotheodolite system, and an analytical study of the interference susceptibility of conical scan tracking radar. The minimum level of the desired radiosonde signal applies only for the maximum range of 200 km. A radiotheodolite system tracks a radiosonde during a typical mission over a range from zero to 200 km, and for only a very small proportion of the mission would the desired signal level be as low as $-133 \text{ dBW}$. 

<table>
<thead>
<tr>
<th><strong>Table XII</strong> — Maximum allowable interference in a radiotheodolite receiver (limited by minimum value of desired signal)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Radiosonde e.i.r.p. (250 mW, 0 dB antenna gain) (dBW)</strong></td>
</tr>
<tr>
<td><strong>Free-space loss (200 km at 1680 MHz) (dB)</strong></td>
</tr>
<tr>
<td><strong>Radiotheodolite antenna gain (normal) (dB)</strong></td>
</tr>
<tr>
<td><strong>Losses (dB)</strong></td>
</tr>
<tr>
<td><strong>Minimum radiosonde signal level at receiver input (no fading) (dBW)</strong></td>
</tr>
<tr>
<td><strong>Protection ratio required (dB)</strong></td>
</tr>
<tr>
<td><strong>Permissible interference level at receiver input in 1.5 MHz bandwidth (dBW)</strong></td>
</tr>
</tbody>
</table>

2.6.2 Probability of interference between the two systems

The probability that the flux-density from a geostationary meteorological satellite would exceed the interference threshold has been analyzed and summarized in Fig. 1. The analysis was based upon the assumption that the probability of the radiotheodolite antenna traversing the satellite would be proportional to the solid angle defined by the effective radiotheodolite antenna beamwidth. The amount of time the interference from the satellite would exceed the maximum allowable interference would then be a function of the flux-density from the satellite, the effective radiotheodolite antenna beamwidth and the scan rate of the radiotheodolite antenna.

The highest power flux-density at the surface of the Earth from the proposed geostationary meteorological satellite would be $-134.1 \text{ dB(W/m}^2\text{)}$ in a 1.5 MHz bandwidth. Figure 1 shows that, with a probability of 98%, the interference to the radiotheodolite would not exceed the allowable value of $-133 \text{ dB(W/(m}^2\text{ · 1.5 MHz)})$ for longer than one minute; with a probability of 99.9%, the interference level would not be exceeded for longer than four minutes.

The basic unit of bandwidth used in quoting power flux-density values has been 1.5 MHz instead of the 4 kHz that is commonly used in flux-density limits for sharing with radio-relay systems. A radiotheodolite receiver operating in this band has a nominal 1.5 MHz bandwidth and, therefore, this is the proper basic unit of bandwidth for use in establishing limits of power flux-density from satellites sharing with the meteorological aids service. Limiting the interference to $-133 \text{ dBW}$ in a 1.5 MHz bandwidth would, in effect, allow the satellite to transmit a signal with a total power so that the power in a bandwidth wider than 1.5 MHz could be greater than $-133 \text{ dBW}$, as long as the total power within any 1.5 MHz bandwidth would not exceed $-133 \text{ dBW}$; and would also allow the interference power to be equal to $-133 \text{ dBW}$ in any bandwidth narrower than 1.5 MHz, as long as the total power within any 1.5 MHz bandwidth would not exceed $-133 \text{ dBW}$. 

FIGURE 1 - Probability that interference at the radiotheodolite receiver does not equal or exceed the maximum allowable interference for $\geq t$ minutes

Assumptions:
Maximum allowable interference: $-133$ dBW in a bandwidth of 1.5 MHz,
Radiotheodolite antenna: 3 m parabolic,
Gain: 32 dB,
Half-power beamwidth: 4°,
Radiation pattern of a 3 m plane polarized antenna,
Scanning rate: 1°/min

Values of $P_R$ (dB (W/(m° in 1.5 MHz)):

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>-108</td>
</tr>
<tr>
<td>B</td>
<td>-112</td>
</tr>
<tr>
<td>C</td>
<td>-118</td>
</tr>
<tr>
<td>D</td>
<td>-122</td>
</tr>
<tr>
<td>E</td>
<td>-132</td>
</tr>
<tr>
<td>F</td>
<td>-139</td>
</tr>
</tbody>
</table>

3. Summary

It is concluded that sharing in the region of 400 MHz between meteorological aids and meteorological satellite systems is technically and operationally feasible provided that the use of the following techniques is considered:
- coordination of frequency assignments;
- geographical separation.

It is noted that both systems would be operated by meteorological organizations and that operational time sharing may also be used to advantage.

It is also concluded that sharing in the upper part of band 9 is technically and operationally feasible.

Interference may occur from transmitters in the space-to-Earth links of geostationary meteorological satellites to receivers in the meteorological aids service. If the power flux-density at the surface of the Earth from the satellite transmission is limited to $-133$ dB(W/m²) in any 1.5 MHz bandwidth, the probability of interference will be low.
There is a potential problem as regards interference from radiosondes at the satellite earth station. The possible alternatives available for sharing, considering the different types of earth stations involved are:

- coordination of frequency assignments between radiosondes and specific satellite down links;
- time sharing of satellite transmissions with radiosonde operations within a given radius of an earth station. The radius of coordination with radiosonde operations will depend upon the type of earth station and antenna discrimination available;
- coordination on the distance between radiosonde operations and satellite earth stations (the actual coordination distance will depend upon the type of earth station and antenna discrimination available).

REFERENCES


ANNEX 1

FREQUENCY SHARING OF THE UPPER PART OF BAND 9 BETWEEN RADIOSONDES AND THE METEOSAT DOWN-LINK TRANSMISSIONS

1. Introduction

After more detailed studies, and in the light of the advanced systems definition of the Meteosat meteorological satellite (the METEOSAT system is described in Report 395), it has been found that the conclusions of this Report concerning the METEOSAT system need to be reviewed.

The present Annex supplies guidance to meteorological authorities located in the European coverage zone of Meteosat, regarding the sharing problems between the operation of radiosondes and METEOSAT in the vicinity of the DATTS and/or PDUS and SDUS installations*. The situation in other parts of the coverage zone will be different depending upon the geographical location of the meteorological data user stations.

The indicative values furnished in this Annex apply to the METEOSAT system only and may well be different for other meteorological satellites.

2. Summary of relevant parameters of DATTS and radiosondes

2.1 DATTS characteristics

The DATTS (data acquisition telecommand and tracking station) is the earth station that ensures the Earth-to-space and space-to-Earth links with Meteosat, in the upper part of band 9. The DATTS is located in the Odenwald, Federal Republic of Germany (08° 50' E, 49° 40' N). Besides its Earth-to-space transmission functions, which are not considered in the present Annex, DATTS receives on a 24 hours per day basis, the following signals transmitted or relayed by Meteosat:
- raw-image telemetry;
- ranging data and/or disseminated meteorological data;
- housekeeping telemetry.

It is of paramount importance for the safety of operations, and thus the success of the METEOSAT mission, that these links operate continuously and free from harmful interference.

DATTS receiving equipment performance

Antenna gain: 45 dBi
System noise temperature: 115 K
Saturation level: -80 dBW (at preamplifier input, within the band 1655 to 1715 MHz)
Antenna beamwidth: 0.8° at -3 dB

Discrimination due to antenna pattern (referred to gain of main beam):
- 50 dB for directions within the sector 15° to 30° off the main beam axis;
- 55 dB for directions within the sector 30° to 90° off the main beam axis;
- 70 dB for directions >90° off the main beam axis.

* DATTS: data acquisition, telecommand and tracking station
PDUS: primary data user station
SDUS: secondary data user station.
The nominal received signals, carrier frequencies and power flux-densities are summarized in Table XIII.

<table>
<thead>
<tr>
<th>Nominal signal received at DATTS</th>
<th>Frequency (MHz)</th>
<th>Signal bandwidth (kHz)</th>
<th>Nominal pfd at the DATTS (dB(W/m²))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw image - nominal mode</td>
<td>1686.833</td>
<td>660</td>
<td>-156.6</td>
</tr>
<tr>
<td>Raw image - real-time mode</td>
<td>1686.833</td>
<td>5400</td>
<td>-142.8</td>
</tr>
<tr>
<td>Dissemination channel 1</td>
<td>1691.000</td>
<td>660</td>
<td>-141.8</td>
</tr>
<tr>
<td>Dissemination channel 2</td>
<td>1694.500</td>
<td>660</td>
<td>-141.8</td>
</tr>
<tr>
<td>Data collection reports</td>
<td>1675.281</td>
<td>200</td>
<td>-190.5(1)</td>
</tr>
<tr>
<td>Housekeeping telemetry</td>
<td>1675.929</td>
<td>30</td>
<td>-179.3</td>
</tr>
</tbody>
</table>

(1) Pfd per channel, 66 adjacent channels.

2.2 Radiosondes in the meteorological aids service

For the purpose of this analysis only three characteristics of a meteorological radiosonde are relevant:
- RF transmission system parameters;
- trajectory and lifetime;
- typical launch schedule.

Typical transmission system parameters are given in Table XIV.

<table>
<thead>
<tr>
<th>Type of sonde</th>
<th>Transmitter output power (W)</th>
<th>Antenna gain (dB)</th>
<th>Emission</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-ranging</td>
<td>0.25 to 1</td>
<td>0</td>
<td>15K0G7DXN</td>
</tr>
<tr>
<td>Ranging</td>
<td>0.25 to 1</td>
<td>0</td>
<td>400KG7DXN to 1M00G7DXN</td>
</tr>
</tbody>
</table>

Radiosonde transmitters, which are used in great quantities by meteorological authorities, generally use relatively simple technologies, in respect to the design of the modulation system, the temperature compensation of frequency determining components and the initial RF carrier setting. These factors can considerably increase the bandwidth occupied by a series of radiosondes. In fact, the bandwidth within which radiosonde transmissions from a particular series of radiosondes can cause harmful interference may be a multiple of the useful signal bandwidth.

Radiosondes, being in principle balloon-suspended sensors with an RF transmitting system, rise at a rate of 500 metres per minute to a maximum altitude not exceeding 40 km. Their lifetime varies between 1 hour and 2 hours. The distance travelled by a radiosonde during that time can be well in excess of 100 km, depending upon the wind speeds encountered. The direction of its trajectory is a function of prevailing wind directions. Generally four launches are carried out per day, at intervals of 6 hours: 0000, 0600, 1200 and 1800 UTC.
3. Coordination requirements

The basic criteria for the interference study is a bit error ratio in the received METEOSAT signal not exceeding 5 times its nominal value in an interference-free environment. This criterion permits determining the maximum tolerable power flux-densities of the interfering signal at the ground reception station (DATTS or PDUS/SDUS) within the frequency band occupied by the METEOSAT space-to-Earth transmissions.

A simplified presentation of the geometry of the interference problem for the particular case of the DATTS is given in Fig. 2. The trajectory of the radiosondes, the receiving antenna pattern and its main beam azimuth and elevation, result in the definition of areas within which maximum interference levels are applicable. In the definition of the areas the effects of high wind velocities have not been included. Consequently, in the presence of heavy winds blowing from the radiosonde launch station in the direction of the DATTS an allowance has to be made for the distance likely to be travelled by the radiosonde; this can considerably increase the site of the area affected.

![Coordination areas for METEOSAT DATTS](image)

**FIGURE 2 — Coordination areas for METEOSAT DATTS**

Area 1
- In this area radiosonde operations in the 1670 to 1700 MHz band will cause harmful interference, as the receiving antenna pattern does not provide sufficient protection of the useful signal from interfering sources.

Area 2
- Within this area radiosonde operations are possible with certain limitations, which are defined in Fig. 4. It can be seen that, when limiting the e.i.r.p. of a radiosonde transmitter to 0 dBW, three gaps for radiosonde operations are available in the frequency band; from 1670 to 1673 MHz, from 1678 to 1684 MHz, and from 1696 to 1700 MHz.
Area 3 — The same applies as in the case of Area 2, except that the maximum e.i.r.p. has been increased by 10 dB (see dotted curve in Fig. 4).

Beyond Area 3 — No interference caused.

Attention is drawn to the fact that other low-orbiting meteorological satellites may operate in these bands and their reception by interested meteorological services may be subject to interference from the radiosonde transmissions.

The interference situation at the PDUS and SDUS is largely dependent upon the geographical position of the installation (particularly the elevation angle of its antenna beam) and its technical characteristics. Generally, it can be said that the feasibility of sharing the frequency band is somewhat better than for the case of the DATTS. An example of a PDUS and SDUS coordination requirement is given in Fig. 5. It is pointed out, however, that the interference problem should be studied for each installation, on a case by case basis.

FIGURE 3 — Coordination areas for METEOSAT DATTS (08°50'E, 49°40'N)
FIGURE 4 - Maximum radiosonde e.i.r.p. towards DATTS

Assumptions:
- CCIR standard antenna diagram following Recommendation 465
- Radiosonde outside main antenna beam
- Distance greater than 150 km

A: PDUS Protection
B: SDUS Protection
4. Conclusion

The above interference study leads to the conclusion that sharing of the upper part of band 9 between the "meteorological aids service" and the "meteorological satellites service" is feasible provided that:

- close frequency coordination is effected between the two services;
- radiosonde e.i.r.p. is limited in coordination areas around satellite reception installations;
- efforts are made by radiosonde operators to control the bandwidth occupied by the radiosondes as well as their initial RF carrier setting.

Sharing between the two services can be achieved through an appropriate technical and operational coordination either directly between the authorities responsible for the operations of the satellite(s) and those responsible for the operations of the radiosonde station(s) or through World Meteorological Organization (WMO).

ANNEX II
FREQUENCY SHARING OF THE UPPER PART OF BAND 9 BETWEEN RADIOSONDES AND THE GEOSTATIONARY METEOROLOGICAL SATELLITE (GMS) DOWN-LINK TRANSMISSIONS

1. Introduction

In choosing the site for the command and data acquisition station (CDAS), operating to the Geostationary Meteorological Satellite (GMS (described in Report 395)), it was necessary to undertake a study of the possible interference conditions resulting from frequency sharing of the upper portion of band 9 between the GMS down-link transmission and radiosondes in the meteorological aids service.

This Annex describes the results of experimental investigations of interference levels and consequent bit error ratios in band 9. It also presents the results of the survey of the radiosonde drop points (i.e. balloon burst points) around the CDAS. As a result, frequency sharing between the two services proved to be feasible since radiosondes may drift into the CDAS antenna main beam volume with a very low probability.

2. Summary of relevant characteristics of CDAS and radiosondes

2.1 CDAS characteristics

The CDAS is located in Hatoyamamura, Saitama prefecture (35°58' N, 139°19' E) which is about 50 km northwest of Tokyo. The station provides the Earth-to-space and space-to-Earth telecommunication links for the GMS. The CDAS is operated for 24 hours a day and performs the following missions:

- VISSR data reception,
- facsimile data dissemination,
- trilateration ranging,
- meteorological data collection,
- telemetry data reception and command data transmission.

Characteristics of the CDAS antenna and each channel are listed in Tables XV and XVI respectively as a reference in the consideration of the interference with the down-link channels.

<table>
<thead>
<tr>
<th>TABLE XV — Characteristics of 18 m diameter antenna</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (MHz)</td>
</tr>
<tr>
<td>Gain (dB)</td>
</tr>
<tr>
<td>Noise temperature (K)</td>
</tr>
<tr>
<td>Voltage standing wave ratio</td>
</tr>
<tr>
<td>Beamwidth</td>
</tr>
</tbody>
</table>
**TABLE XVI — GMS telecommunication system of down link**

<table>
<thead>
<tr>
<th>Function</th>
<th>Centre frequency (MHz)</th>
<th>RF bandwidth (MHz)</th>
<th>Transmitter power (W)</th>
<th>Modulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>DCP interrogation</td>
<td>468.8</td>
<td>0.2</td>
<td>3</td>
<td>PCM-PSK</td>
</tr>
<tr>
<td>VISSR data transmission</td>
<td>1681.6</td>
<td>20</td>
<td>10</td>
<td>PCM-4Φ PSK</td>
</tr>
<tr>
<td>Facsimile</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>high resolution</td>
<td>1687.1</td>
<td>1</td>
<td>10</td>
<td>FM-FM</td>
</tr>
<tr>
<td>low resolution</td>
<td>1691.0</td>
<td>0.032 or 0.26</td>
<td>1 or 10</td>
<td>AM-FM</td>
</tr>
<tr>
<td>Ranging</td>
<td>1684.0</td>
<td>1</td>
<td>1</td>
<td>AM-PM</td>
</tr>
<tr>
<td>Ranging</td>
<td>1688.2</td>
<td>1</td>
<td>0.01</td>
<td>AM-PM</td>
</tr>
<tr>
<td>DCP report</td>
<td>1694.3</td>
<td>0.4 (¹)</td>
<td>0.05 (²)</td>
<td>PCM-PSK</td>
</tr>
<tr>
<td>Telemetry</td>
<td>1694.0</td>
<td>0.4</td>
<td>0.5</td>
<td>PCM-PSK/FM-PM</td>
</tr>
<tr>
<td>Telemetry/ranging</td>
<td>2280.72</td>
<td>0.3/1</td>
<td>3</td>
<td>PCM-PSK/FM-PM</td>
</tr>
</tbody>
</table>

(¹) 133 channels.
(²) Power per one channel

2.2 **Radiosondes characteristics**

The characteristics of Japanese radiosondes are listed in Table XVII. Figure 6 shows the location of the radiosonde launching sites (observatories) and the CDAS.

**TABLE XVII — Characteristics of radiosonde RS2 56A which were used for the experiment**

<table>
<thead>
<tr>
<th>Centre frequency of transmitter</th>
<th>1682.4 MHz (¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmitting power</td>
<td>0.4 W (²)</td>
</tr>
<tr>
<td>Type of emission</td>
<td>A2B</td>
</tr>
<tr>
<td>Modulation frequency</td>
<td></td>
</tr>
<tr>
<td>Space time</td>
<td>750 Hz + 20 %</td>
</tr>
<tr>
<td>Mark time</td>
<td>375 Hz + 20 %</td>
</tr>
<tr>
<td>Pulse time</td>
<td>100 µs-450 µs</td>
</tr>
<tr>
<td>Modulation Index</td>
<td>100 %</td>
</tr>
</tbody>
</table>

(¹) 1680 ± 4 MHz in specification.
(²) Antenna gain : 0 dB.

3. **The interference simulation experiment and the survey of radiosonde drop points**

3.1 **Interference simulation experiment**

The following experiment was conducted with the VISSR channel in order to determine the relationship between interference from radiosondes to the GMS telecommunication channels.
3.1.1 Experimental method

The experiment was performed by placing a radiosonde with the characteristics shown in Table XVII at a distance of 6.8 km from the CDAS and measuring the effects on the receiving channel. The interfering signal level from the radiosonde was varied by controlling the CDAS antenna azimuth direction and Fig. 7 shows the block diagram of the CDAS configuration.

The interfering signal level from the radiosonde was measured with a spectrum analyzer, and the degradation of the VISSR channel bit error ratio (BER) was obtained from outputs of the synchronizer and data buffer. The influence on the VISSR image quality was noted from the display on the image monitor quick-look facility.

3.1.2 Results

Table XVIII presents a summary of the relationship of the interfering signal input level from the radiosonde and the BER, qualitative statement of the effect to the VISSR image quality is also shown. $E_b/N_0$ in Table XVIII is calculated from:

$$
\frac{E_b}{N_0} = \frac{S}{N} \cdot \frac{B}{M}
$$

(1)

where:

- $S$: VISSR test pattern signal input level to the quadriphase demodulator/demultiplexer (QPDD),
- $N$: total noise (interference) input level to the QPDD,
- $B$: QPDD input band pass filter band width (22.5 MHz),
- $M$: VISSR data bit rate (14 Mbit/s),
- $E_b$: signal energy per bit,
- $N_0$: noise power per Hz.
Command and data acquisition station

Position of radiosonde:
distance: 6.8 km
direction: 80.1°

FIGURE 7 — Block diagram of interference test
See Fig. 8 for the relation of the $E_b/N_0$ to BER.

This experiment indicates that the VISSR channel will not be harmfully degraded when the level of the interference entering the CDAS antenna output is below $-106.9$ dBm.

**TABLE XVIII — The results of the experiment**

<table>
<thead>
<tr>
<th>Radiosonde signal power entering 18 m antenna (dBm)</th>
<th>4 $\Phi$ DEM/DEM$\times$ input level (dBm)</th>
<th>$E_b/N_0$ (dB)</th>
<th>BER</th>
<th>Degree of interference on the VISSR image</th>
</tr>
</thead>
<tbody>
<tr>
<td>- 106.9</td>
<td>- 18.9</td>
<td>13.5</td>
<td>&lt; $1 \times 10^{-6}$</td>
<td>None</td>
</tr>
<tr>
<td>- 105.9</td>
<td>- 17.9</td>
<td>12.5</td>
<td>$1 \times 10^{-6}$</td>
<td>Noise as recognized</td>
</tr>
<tr>
<td>- 104.9</td>
<td>- 16.9</td>
<td>11.5</td>
<td>$1 \times 10^{-5}$</td>
<td>on the image</td>
</tr>
<tr>
<td>- 102.5</td>
<td>- 14.5</td>
<td>9.1</td>
<td>$1 \times 10^{-3}$</td>
<td></td>
</tr>
<tr>
<td>- 100.0</td>
<td>- 12.0</td>
<td>6.6</td>
<td>1</td>
<td>It was impossible</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>to receive the image</td>
</tr>
</tbody>
</table>

**FIGURE 8 — Relation between the BER and the $E_b/N_0$**
3.2 Survey of drop points of radiosondes

Drop points of radiosondes were surveyed for a year during 1975 in order to quantify the effect on practical radiosonde operations on the GMS-CDAS telecommunication channels. These radiosondes were launched at Tateno, about 74 km distant to the east-northeast of the CDAS, and at Hamamatsu, about 170 km distant to the southeast of the CDAS. Their drop points around the GMS CDAS are plotted in Fig. 9. The area of the pattern marked “interference area” is bounded by the locus of power flux level which will not result in interference to the VISSR imaging (i.e. $-106.9 \text{ dBm} + 47.9 \text{ dB} = -59 \text{ dBm}$) and determined by the following equations. The slant range from a radiosonde to the CDAS antenna $d$ is:

$$d = \left( \frac{P_r}{G_s \cdot P_i} \right)^{1/2} \frac{\lambda}{4\pi} \tag{2}$$

![Figure 9](image_url)

**FIGURE 9** — The relation between the interference area and the radiosonde drop points

- The drop points of Hamamatsu radiosonde
- The drop points of Tateno radiosonde

A: to GMS ($140^\circ$ E)
B: interference area

*Note 1.* — Within the interference area, the radiosonde signal power entering the 18 m diameter antenna is greater than $-106.9 \text{ dBm}$.

*Note 2.* — The drop points were surveyed during 1975.

*Note 3.* — The drop point is the balloon burst point.
and the distance from the radiosonde sub-point (plumb projection of the radiosonde to the Earth) to the CDAS antenna \( r \) is:

\[
r = R \cos^{-1} \left( \frac{R^3 + (R + H)^2 - d^2}{2R(R + H)} \right)
\]

where:

\[
H = H_0 + 1000 d \sin \theta + 0.0589 d^2 \cos^2 \theta
\]

- \( P_r \): radiosonde e.i.r.p.,
- \( P_r \): antenna output power,
- \( G_a \): antenna gain at a degrees off from the centre axis,
- \( \lambda \): wave length,
- \( R \): radius of the Earth,
- \( H \): radiosonde height which includes the coefficient of effective radius of the Earth,
- \( H_0 \): antenna height from the sea level,
- \( \theta \): antenna elevation.

4. Conclusions

The results of the interference experiment and survey described above lead to the conclusion that sharing of the upper part of band 9 between the meteorological aids service and the meteorological satellite service is feasible. The basis of this conclusion is the low probability that radiosonde trajectories will pass through the main beam of the 18 m diameter CDAS antenna as a result of careful location of the CDAS site.

In the case of the facsimile data receiving stations (DUS = data utilization station) interference can be minimized by carefully selecting the locations of these stations with respect to the radiosonde launching sites (observatories) and taking into account their trajectories.
REPORT 851-1*

POWER FLUX-DENSITY LIMITATION IN THE BAND 1 670 - 1 710 MHz
FOR DISSEMINATION OF METEOROLOGICAL INFORMATION
TO SMALL EARTH TERMINALS
(Study Programme 12C/2)

(1982-1990)

1. Introduction

The problem of data dissemination is a critical aspect of meteorological satellite systems. Various kinds of data generated by these systems are of very high and direct interest to a wide community of individual users.

Processed or raw data can be disseminated to the users by the meteorological satellites themselves which generated them, in the frequency band allocated to the meteorological-satellite service (1 670 - 1 710 MHz). This capability has been successfully illustrated for several years by the geostationary and low orbit systems in operation, which implement the meteorological data dissemination mission in a cost effective way, as an integral part of their data generation/processing and transmission facilities. Many users have now procured the appropriate terminals enabling them to acquire the data disseminated and there is an increasing demand from the user's community towards improvement and extension of this service. This demand originates particularly from users for which the service proposed is an important means - if not the only one - for obtaining meteorological data. Potential users include those who cannot afford costly receiving equipment, and those who often experience severe operational conditions (e.g. ships, offshore installations) and who might use this facility as a warning tool.

2. Improvements of services

Two major areas of improvement are needed in METSAT systems:
- reduction of cost of the user's terminals which acquire the disseminated data;
- reduction of their operational complexity, particularly in view of shipborne or offshore utilization.

In these respects, one parameter of primary importance is the factor of merit of the terminal (antenna dimension and gain, receiver noise figure). For the terminals presently in operation with the METEOSAT geostationary satellite, the minimum G/T figure compatible with acceptable performance is +2.5 dB(K-1) (corresponding roughly to a 2.0 m dish associated with a transistorized preamplifier) due to:
- limitation of the e.i.r.p. of the satellite;
- pfd limits on the Earth's surface (see No. 2557 of the Radio Regulations).

* This Report should be brought to the attention of Study Group 9.
Similarly, in current METSAT systems using satellites in low Earth orbits, the G/T figure compatible with acceptable performance at low elevation angles is $+7.2 \text{ dB}(K^{-1})$ as a result of the above limitations. However, the G/T figures of stations that have been found to be affordable vary from about $6 \text{ dB } (K^{-1})$ to $4.1 \text{ (K^{-1})}$ as the antenna elevation angle decreases from about 8 to 0 degrees (Report AC/2, Table II). These stations may not meet applicable performance objectives (i.e., bit error ratio of no more that $10^{-6}$ for 0.1% of the time). Moreover, future systems may operate with increased data rates that may require higher downlink power densities for acceptable service to these existing ground stations.

Technological progress in the area will easily allow an increase in the e.i.r.p. of the future satellites, but this can only be done if the currently valid power flux-density (pfd) limitation is relaxed (see RR 2557); the subsequent paragraph proposes such relaxations for geostationary METSATS and those in low-Earth orbits. These increased pfd levels which should be applicable to an appropriate portion of the band 1 670 to 1 710 MHz. With a view to protecting the radioastronomy service in the band 1 660 to 1 670 MHz, the pfd in this band should not exceed $-237 \text{ dBW/m}^2 \cdot \text{Hz} \cdot 4 \text{ kHz}$. Protection for radioastronomy in the band 1 718.8 - 1 722.2 MHz shall be maintained (see RR Footnote 744).

3. **Required relaxation of pfd limitation for geostationary systems**

The objective is to decrease the $G/T$ figure of the terminal to a value of $-4 \text{ dB}(K^{-1})$, while keeping the bandwidth occupied by the meteorological data signal to its standard value. This would have the following main advantages:

- decrease the dimension of the antenna to a diameter of less than 1 m, with the corresponding significant reduction of procurement cost as well as a reduction in the complexity of installation, maintenance, etc.;
- render possible the compatibility of meteorological data dissemination with small ship terminals which are under development in the framework of INMARSAT; (these small terminals are working in the 1540 to 1660 MHz band and typically have a $G/T$ figure of $-4 \text{ dB}(K^{-1})$ at 1540 MHz).

The bandwidth of image data analogue signals which are currently being disseminated by the present systems can be assumed to be 30 kHz. A typical spectrum of this signal is given in Fig. 1, and shows that the maximum power density within a 4 kHz slot is 3.6 dB below the level of the unmodulated carrier.
3.1 Characteristics of terminal

\[ G/T = -4 \text{ dB}(K^{-1}) \], which corresponds to a dish diameter of 0.9 m, with a system noise temperature of 400 K.

3.2 Minimum performance

\[ S/N \geq 12 \text{ dB} \] in 30 kHz

Received signal \[ S = pfd \times G \times \frac{\lambda^2}{4\pi} \]

Noise signal \[ N = kTB \]

\[ \frac{S}{N} = pfd \times G \times \frac{\lambda^2}{4\pi \times \frac{1}{kB}} \geq 12 \text{ dB} \]

3.3 Power flux-density

Total minimum \[ pfd = -141.7 \text{ dB(W/m}^2\text{)} \]

\[ pfd/4 \text{ kHz} = -141.7 \text{ dB(W/m}^2\text{)} - 3.6 \text{ dB} = -145.3 \text{ dB(W/(m}^2\cdot4 \text{ kHz})} \] (see Fig. 1)

This is applicable for all elevation angles.
4. Required relaxation of pfd limitations for satellites in low Earth orbits

The objective is to accommodate data rates of up to about 4 Mbps for advanced High Resolution Picture Transmission (HRPT) to earth stations having G/T figures of 4.1 dB(K⁻¹) and 6 dB(K⁻¹) at elevation angles of 0° and 8°, respectively. A form of QPSK modulation may be used, which would require carrier-to-thermal noise power ratio (C/N) levels at the receiving antenna output of 14.4 dB and 18.6 dB for 0° and 8° antenna elevation angles, respectively (see Annex I to Report AC/2). By the above equations (and with 3 dB allowance for earth station antenna pointing error and other degradations), the minimum required pfd level is about -151 dB (W/m²·4 kHz) at low elevation angles, which is somewhat less than the pfd needed for the geostationary systems.

At higher elevation angles, the pfd levels are necessarily higher than those at low elevation angles due to limitations in capabilities for shaping spacecraft antenna gain at off-axis angles to compensate for associated changes in slant-path range and propagation losses. The gain shaping of some current spacecraft antennas results in pfd levels at 25°, 40° and 90° angles of arrival that are 6 dB, 7.5 dB and 5 dB higher, respectively, than those occurring at a 0° angle of arrival. Thus, the pfd limits for higher angles of arrival should be similarly relaxed with respect to the -151 dB (W/m²·4 kHz) level required for low elevation angles.

5. Conclusion

Requirements for downlinks from meteorological satellites in geostationary orbit can be met with a pfd level of -144 dB (W/m²·4 kHz) at all angles of arrival. For meteorological satellites in low Earth orbits, a pfd level of -151 dB (W/m²·4 kHz) would be satisfactory at low elevation angles and pfd levels about 8 dB higher would occur at angles of arrival of 40° or more due to spacecraft antenna gain patterns. Consistent with typical frequency plans for these systems, it may be practical to separately accommodate the pfd requirements for geostationary and low-Earth-orbit satellites in lower and upper portions of the 1670 - 1710 MHz band respectively. Further study is required of the effects of these pfd levels on terrestrial services.
REPORT 1121*

PERFORMANCE, INTERFERENCE AND SHARING CRITERIA FOR RECEIVING
EARTH STATIONS IN THE METEOROLOGICAL-SATELLITE SERVICE
OPERATING IN THE 1 670 - 1 710 MHz BAND
WITH SATELLITES IN LOW EARTH ORBIT

(Question 12/2 and Study Programme 12/2)

1. Introduction

The methods in Reports 1120, 1122 and 1123 are applied in this report to develop performance, interference and sharing criteria. The meteorological-satellite (METSAT) systems are assumed to utilize satellites in low earth orbits (e.g., 600 - 1,000 km altitude) and operate in the band 1 670 - 1 710 MHz.

Earth stations for reception in the meteorological-satellite (METSAT) service share portions of the 1 670 - 1 710 MHz band with transmitters in the terrestrial fixed, meteorological aids and mobile services and spacecraft in the earth exploration-satellite service. Sharing criteria are needed for METSAT earth stations with respect to terrestrial and space station transmitters for use in analyses of interference situations that are potentially unacceptable. Performance criteria and selected characteristics of two example systems are presented in section 2. Interference criteria for selected earth stations operating in the 1 670 - 1 710 MHz band are developed in section 3. These criteria are shown in Annex I to be applicable to prospective future systems operating at 1 670 - 1 710 MHz. Sharing criteria are then derived in section 4 from the interference criteria.

2. Performance objectives and characteristics

Transmissions of sensor data from the United States NOAA satellites in the 1 670 - 1 710 MHz band are received by a wide variety of earth stations. The earth stations can be broadly characterized as: 1) large aperture (diameter of 25.9 m) earth stations, which receive real time and recorded data, and 2) small aperture (diameter of 2.44 m) earth stations for reception of real time data. The generalized characteristics of these satellites and earth stations may

* This report should be brought to the attention of Study Groups 1, 8 and 9
be assumed to correspond to representative METSAT systems operating in the 1670 - 1710 MHz band. These are described in the sub-sections below, where performance objectives are specified and achievable performance is analysed in accordance with the methods described in Report [1120].

2.1 Performance objectives

The representative systems employ digital modulation for the downlinks, with the output data from many satellite sensors being multiplexed prior to transmission. A performance objective based on an acceptable Bit Error Ratio (BER) is appropriate, where a specified BER is not to be exceeded for more than a specified percentage of time. As the BER is increased, the measurement uncertainty is generally increased such that overall system performance could be dominated by the down-link performance. Further increases in the BER could cause loss of data frame synchronization, which makes demultiplexing impossible and prevents data recovery. The METSAT performance objectives relate to acceptable increases in measurement uncertainty. These objectives will assure that the satellite carrier signal is initially acquired and that bit and data frame synchronization is achieved and maintained throughout each satellite pass.

The process of quantizing the analogue signals from sensors places an upper bound on the average signal-to-noise power ratio (S/N) which can be achieved in the recovered analogue signal. The analogue-to-digital converters are typically designed to preserve the sensor output signal quality, and will therefore have a higher S/N than that of the sensor output. Accordingly, the BER on the down link should not reduce the S/N of the recoverable signal by much more than the quantization process in order to preserve the system performance. A BER of $10^{-6}$ is considered to generally meet this criterion for typical METSAT quantization hardware. For example, if the sensor output is quantized into 8-bit symbols with all quantization levels being equally likely, a BER of $10^{-6}$ reduces the average S/N of quantization of 48 dB by 1 dB. For 10-bit symbols, a BER of $10^{-6}$ reduces the 60 dB average S/N of quantization by about 7 dB. A performance threshold of $10^{-6}$ BER for the down link is consequently taken to correspond with a threshold of acceptable measurement uncertainty. Future meteorological satellites may use block coding and convolution coding techniques to preserve the high S/N associated with quantization using more bits (e.g., 10-bit symbols).

The large and small earth stations that are analysed as representative systems both require reliable data for the entire time of reception. Hence, the BER of $10^{-6}$ cannot be exceeded for more than a small percentage of the reception time. Furthermore, in order to initially acquire the satellite signal and establish synchronization of the data frame, the down-link BER must be less than about $10^{-3}$. Such degraded performance should not occur for more than a negligibly small percentage of the time. The following performance objective would appear to satisfy all performance requirements and assure that the long-term down-link performance is significantly better than $10^{-6}$ BER.

METSAT Performance Objective: The total BER at an earth station should be less that $1 \times 10^{-6}$ for all but 0.1% of the reception time due to all causes during an average year.
2.2 Performance analysis for the selected representative systems

Tables I and II show performance analyses for the representative systems based on large and small earth stations, respectively. The columns labelled "short-term performance analysis" list parameter values assumed to correspond with BERs which are exceeded for no more than 0.1% of the time. The columns labelled "long-term performance analysis" list parameter values assumed to correspond with BERs which are exceeded for no more than 20% of the time.

**TABLE I**

Performance analysis for representative large METSAT receiving earth station

(1 700 MHz)

<table>
<thead>
<tr>
<th>Performance Factor</th>
<th>Short Term Performance Analysis (p = 0.1%)</th>
<th>Long Term Performance Analysis (p = 20%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Satellite transmitter output power (dBW)</td>
<td>8.0</td>
<td>8.0</td>
</tr>
<tr>
<td>2. Filter/cable losses (dB)</td>
<td>1.7</td>
<td>1.7</td>
</tr>
<tr>
<td>3. Impedance mismatch losses (dB)</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>4. Satellite antenna gain (dBi)</td>
<td>-</td>
<td>2.0</td>
</tr>
<tr>
<td>a. 59° off-nadir (13° elevation)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>b. 61° off-nadir (5° elevation)</td>
<td>2.1</td>
<td>-</td>
</tr>
<tr>
<td>5. Satellite e.i.r.p. (dBW)</td>
<td>8.2</td>
<td>8.1</td>
</tr>
<tr>
<td>6. Free space loss (dB)</td>
<td>-</td>
<td>164.0</td>
</tr>
<tr>
<td>a. 13° elevation (2217 km)</td>
<td>166.3</td>
<td>-</td>
</tr>
<tr>
<td>b. 5° elevation (2873 km)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>7. Excess path loss (dB)</td>
<td>0.2</td>
<td>0.0</td>
</tr>
<tr>
<td>8. Earth station antenna gain (dBi)</td>
<td>46.8</td>
<td>46.8</td>
</tr>
<tr>
<td>9. Antenna pointing error (dB)</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>10. Polarization mismatch loss (dB)</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>11. Residual carrier loss (dB)</td>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
<td>12. Demodulator implementation loss (dB)</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>13. Received signal power (dBW)</td>
<td>-114.9</td>
<td>-112.5</td>
</tr>
<tr>
<td>14. Data rate (dB bit/second)</td>
<td>64.2</td>
<td>64.2</td>
</tr>
<tr>
<td>15. Received energy/bit, $E_b$ (dBW/Hz)</td>
<td>-179.1</td>
<td>-176.7</td>
</tr>
<tr>
<td>16. Receiver system noise temperature (K)</td>
<td>320</td>
<td>210</td>
</tr>
<tr>
<td>17. Receiver noise power density (dBW/Hz)</td>
<td>-203.5</td>
<td>-205.4</td>
</tr>
<tr>
<td>18. Adjacent channel interference power (dBW/Hz)</td>
<td>-202.4</td>
<td>-202.4</td>
</tr>
<tr>
<td>19. Intra-system noise power density, $N_0$ (dBW/Hz)</td>
<td>-199.9</td>
<td>-200.6</td>
</tr>
<tr>
<td>20. $E_b/N_0$ (dB)</td>
<td>20.8</td>
<td>23.9</td>
</tr>
<tr>
<td>21. Link bit error ratio, coherent BPSK</td>
<td>$10^{-12}$</td>
<td>$10^{-12}$</td>
</tr>
<tr>
<td>22. Satellite data storage/handling error ratio</td>
<td>$5 \times 10^{-7}$</td>
<td>$5 \times 10^{-7}$</td>
</tr>
<tr>
<td>23. Total bit error ratio</td>
<td>$5 \times 10^{-7}$</td>
<td>$5 \times 10^{-7}$</td>
</tr>
</tbody>
</table>
TABLE II

Performance analysis for representative small
METSAT receiving earth station
(1 700 MHz)

<table>
<thead>
<tr>
<th>Performance Factor</th>
<th>Short Term Performance Analysis (p = 0.1%)</th>
<th>Long Term Performance Analysis (p = 20%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Satellite transmitter output power (dBW)</td>
<td>8.0</td>
<td>8.0</td>
</tr>
<tr>
<td>2. Filter/cable losses (dB)</td>
<td>1.7</td>
<td>1.7</td>
</tr>
<tr>
<td>3. Impedance mismatch losses (dB)</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>4. Satellite antenna gain (dBi)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. 61° off-nadir (8° elevation)</td>
<td>-</td>
<td>2.1</td>
</tr>
<tr>
<td>b. 62° off-nadir (0° elevation)</td>
<td>2.1</td>
<td>-</td>
</tr>
<tr>
<td>5. Satellite e.i.r.p. (dBW)</td>
<td>8.2</td>
<td>8.2</td>
</tr>
<tr>
<td>6. Free space loss (dB)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. 8° elevation (2586 km)</td>
<td>-</td>
<td>165.3</td>
</tr>
<tr>
<td>b. 0° elevation (3362 km)</td>
<td>167.6</td>
<td>-</td>
</tr>
<tr>
<td>7. Excess path loss (dB)</td>
<td>0.4</td>
<td>0.0</td>
</tr>
<tr>
<td>8. Earth station antenna gain (dBi)</td>
<td>29.8</td>
<td>29.8</td>
</tr>
<tr>
<td>9. Antenna pointing error (dB)</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>10. Polarization mismatch loss (dB)</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>11. Residual carrier loss (dB)</td>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
<td>12. Demodulator implementation loss (dB)</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>13. Received signal power (dBW)</td>
<td>-133.7</td>
<td>-131.0</td>
</tr>
<tr>
<td>14. Data rate (dB bit/second)</td>
<td>58.2</td>
<td>58.2</td>
</tr>
<tr>
<td>15. Received energy/bit, $E_b$ (dBW/Hz)</td>
<td>-191.9</td>
<td>-189.2</td>
</tr>
<tr>
<td>16. Receiver system noise temperature (k)</td>
<td>370</td>
<td>240</td>
</tr>
<tr>
<td>17. Receiver noise power density (dBW/Hz)</td>
<td>-202.9</td>
<td>-204.8</td>
</tr>
<tr>
<td>18. Adjacent channel interference power (dBW/Hz)</td>
<td>-204.2</td>
<td>-204.2</td>
</tr>
<tr>
<td>19. Intra-system noise power density, $N_0$ (dBW/Hz)</td>
<td>-200.5</td>
<td>-201.5</td>
</tr>
<tr>
<td>20. $E_b/N_0$ (dB)</td>
<td>8.6</td>
<td>12.3</td>
</tr>
<tr>
<td>21. Link bit error ratio, coherent BPSK</td>
<td>$1.3 \times 10^{-6}$</td>
<td>$6.7 \times 10^{-9}$</td>
</tr>
<tr>
<td>22. Satellite data storage/handling error ratio</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>23. Total link bit error ratio</td>
<td>$1.3 \times 10^{-6}$</td>
<td>$6.7 \times 10^{-9}$</td>
</tr>
</tbody>
</table>

Both representative systems are assumed to receive transmissions from the same satellite, which employs a circularly polarized beam-shaped antenna that partially offsets the increased propagation losses toward the Earth limb as compared to nadir (item 4, Tables I and II). The large station has a 5° minimum elevation angle, because this visibility is adequate for the transmission of all stored data (item 4b). The small station requires reception during the entire period of visibility, from horizon to horizon, since valuable and extensive data are available at low elevation angles. It should be noted that a 3° minimum elevation angle is presently to be assumed for coordination purposes when sharing is on an equal-rights basis (RR 2550). The small earth station antennas are pointed near or below the 3° elevation angle for 0.1% of the time of reception; this analysis assumes it to be pointed at the horizon for 0.1% of the time. The antenna elevation angles that are exceeded for all but 20% of the time...
of reception are assumed to be 13° and 8° for the large and small earth station, respectively (items 4a and 6a). These are conservatively low values based on the antenna pointing probabilities for these stations.

The long-term propagation losses in excess of the free space level are negligible. However, the short-term path losses in excess of the free space level (item 7) are significant. These losses are primarily due to multipath (rain attenuation is generally less than 0.1 dB at these frequencies in all rain climates). The large station is assumed to have a 25.9 metre antenna with a pointing tolerance which can lead to a gain loss of 0.5 dB. The small station is assumed to have a 2.44 metre antenna with a pointing tolerance which leads to a gain loss of 0.5 dB. The polarization axial ratio of the large station antenna is somewhat better than that for the small station (item 10).

The deviation of the satellite's transmitter in BPSK phase is assumed to be about 67° which results in a residual carrier to permit signal acquisition and coherent demodulation. This slightly reduces the data signal power (item 11). Satellite transmitter noise is assumed to be negligible. The demodulator implementation loss (item 12) can be viewed as a signal loss or noise increase which is the result of several factors such as instability in the carrier frequency and non-symmetry in the transmitted symbols. A 3 dB value is given in Report 455 for FDMA systems in the fixed-satellite service, but the 2 dB value is achievable in the METSAT receivers. The large earth station receives stored data at a rate of 2.667 Mbps, whereas the small earth station receives only real time data at 0.667 Mbps (item 14).

The large earth station has a lower thermal noise temperature in the receiver than the small earth station (item 16), as referenced to the antenna output. The level of thermal noise in the short term exceeds that of the long term because of increased noise contributions from terrain at the lower elevation angles and because of increased noise contributed by rain. The transmissions of the stored data and real time data are assumed to be made at the same time on separate carriers, which gives rise to adjacent channel interference (item 18). This noise level is higher for the large earth station because of its relatively large bandwidth. However, as new receivers have better adjacent channel rejection this noise could be considerably reduced in the future. The satellite's on-board storage introduces random errors (item 22) which must be considered for the large earth station. This error source can be seen to dominate the Bit Error Ratio (BER) performance of the large earth station.

The reference bandwidths for the earth station receivers can be taken to be the bandwidth between the first nulls of the received PSK signal spectral power density. For the large earth station, a 2.667 Mbps data rate and NRZ coding are assumed, which give a reference bandwidth of 5.334 MHz. For the small earth station, a 0.667 Mbps data rate and split-phase coding are assumed, which give a reference bandwidth of 2.668 MHz.

3. Derivation of interference criteria

3.1 Criteria for the representative stations

The short-term and long-term BER performance levels shown in Tables I and II can be seen to meet the performance objectives in the absence of inter-system interference, except for the small earth station for short-term operating conditions. The long-term performance level is used to determine the permissible short-term enhanced interference level. The system designer has good control over the short-term performance if the percentage of time that interference
Increases the BER to $10^{-6}$ is one-fourth the total time percentage that a $10^{-6}$ BER can be tolerated. Thus, the long-term noise can be increased by short-term interference to cause a $10^{-6}$ BER for 0.025% of the time. For this small percentage of time, the intra-system degradations are assumed to be at their long-term levels and interference can be allowed to degrade the BER to $10^{-6}$. However, for some time percentage less than 0.025%, simultaneous desired signal fading and enhanced short-term interference can lead to BERs greater than $10^{-6}$.

The long-term interference power level (exceeded for no more than 20% of the time) should constitute no more than 25% of the total short-term noise power that gives rise to a $10^{-6}$ BER. This insures that the system designer has good control over both short- and long-term performance (e.g., through selection of earth station antenna size). The short-term performance of the large earth station is sufficient to permit the long-term interference power to be the full 25% of the total noise power that results in a total BER of $10^{-6}$. This interference power has a negligible effect on the long-term performance of the large earth station. However, the small earth station does not meet the performance objective in the absence of inter-system interference. (Note that the $E_b/N_0$ is degraded by 2.4 dB from the noise due to adjacent channel interference, which occurs in the NOAA system only when the recorded data is being transmitted by the same satellite to a large earth station. In the absence of this intra-system degradation, the performance objective would be met by the small earth station during short-term operating conditions.) Allowing the long-term interference power to equal 25% of the total noise giving $10^{-6}$ BER results in acceptable reductions of performance of the small earth station. Table III summarizes the resulting interference criteria.

**TABLE III**

Interference criteria for representative METSAT earth station receivers

(Interference power at antenna output port)

<table>
<thead>
<tr>
<th></th>
<th>Large Earth Station (46.8 dBi gain)</th>
<th>Small Earth Station (29.8 dBi gain)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total Interference</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power Density, To Be</td>
<td>-132 dBW per 5.334 MHz</td>
<td>-150 dBW per 2.668 MHz</td>
</tr>
<tr>
<td>Exceeded for No More</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Than 20% of the Time</td>
<td></td>
<td></td>
</tr>
<tr>
<td>During Reception</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total Interference</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power Density, To Be</td>
<td>-124 dBW per 5.334 MHz</td>
<td>-147 dBW per 2.668 MHz</td>
</tr>
<tr>
<td>Exceeded for No More</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Than 0.025% of the Time</td>
<td></td>
<td></td>
</tr>
<tr>
<td>During Reception</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
3.2 Generalized interference criteria

METSAT systems may have characteristics different from those used for the representative systems analysed in Tables I and II. Because permissible levels of interference are highly dependent on the gain of the earth station antenna, and the earth stations must be coordinated with transmitting terrestrial stations on a case-by-case basis, it is reasonable to adjust interference and sharing criteria in accordance with the actual antenna gain of an earth station. The method for making these adjustments is presented in Annex I of [Report 1123].

4. Derivation of sharing criteria and coordination thresholds

Interference to METSAT earth stations could arise from space stations in other systems, but would occur most of the time through far side-lobes of the earth station antenna. Terrestrial radio-relay stations could be expected to present a much higher level of interference, albeit through the far side-lobes of the earth station antenna for most of the time, because of higher e.i.r.p. and perhaps smaller propagation losses on the interfering signal paths. Transmitters in the meteorological aids service typically use frequencies that are, by agreement among the operations agencies, offset from the METSAT frequency assignments to limit their interference contributions. It would appear to be reasonable to assume that 10% of the long-term interference I(20) should be budgeted to space services (I_s(20)) and the remaining 90% to terrestrial services (I_t(20)). For small percentages of time, spacecraft and terrestrial station interfering signals might enter the earth station antenna through the near side-lobes or mainbeam. It would be appropriate to assume equal time percentage allowances for short-term interference from space (I_s(p_s)) and terrestrial (I_t(p_t)) systems. Using the interference criteria (Table III) derived with the methods of Report 1122, the total interference allowances given in Table IV are for space and terrestrial services. The reference bandwidths are the same as those given for the interference criteria and the time percentages refer to time of reception during the average year.

<table>
<thead>
<tr>
<th>Receiving Earth Station</th>
<th>Long Term Allowances</th>
<th>Short Term Allowances</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>I_s(20)</td>
<td>I_t(20)</td>
</tr>
<tr>
<td>Large</td>
<td>-142 dBW</td>
<td>-133 dBW</td>
</tr>
<tr>
<td>Small</td>
<td>-160 dBW</td>
<td>-151 dBW</td>
</tr>
<tr>
<td></td>
<td></td>
<td>I_s(p_s)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.125</td>
</tr>
<tr>
<td></td>
<td></td>
<td>I_t(p_t)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.125</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

It would be reasonable to assume that there are two interfering satellites simultaneously present most of the time, which together with spurious emissions from other space systems generate a long-term aggregate-to-single entry interference power ratio of 2. An allowance of 5% of the total long-term interference that can be permitted from space services is assumed for spurious
emissions from space systems operating in the 806 - 890 MHz band (RR Footnote 700) and the 335.4 - 399.9 MHz band (RR Footnote 641). It can be assumed that several space stations will occasionally introduce a relatively high level of interference for small time percentages; it is assumed in this analysis that their effect is equivalent to two equal-level entries of interference occurring for equal percentages of time.

For terrestrial services, it is again reasonable to assume that there are two significant in-band interferers simultaneously present most of the time and that spurious emissions constitute about 5% of the long-term total interference from terrestrial stations. The significant terrestrial systems are assumed to be line-of-sight or troposcatter radio-relay systems. Meteorological aids systems would also contribute significant interference in the absence of the frequency offsets that are typically employed. Two terrestrial stations might generate relatively high interference levels for small percentage of the time. Each of these terrestrial stations can be allowed to generate the interference level \( I_L(p_T) \) for as much as \( p_T/2 \) of the reception time.

Table V presents the single entry interference allowances using the aggregate-to-single entry interference power ratios described above. It should be noted that there is no procedure established in the Radio Regulations (RR) for predicting when coordination is needed for non-geostationary satellites. (RR Appendix 29 does provide such a procedure for interactions between geostationary satellite systems.) Nevertheless, RR Article 11 requires that coordination be conducted when it is anticipated that unacceptable interference might occur between an Advance Published satellite system and other satellite systems. The space service single entry allowances in Table V define the permissible levels of interference from another satellite system, and can therefore be used to determine when coordination with other satellite systems is warranted. In cases where the criteria for sharing with another space system are not met on the basis of co-channel operations, it may be possible to arrange frequency plans or transmission schedules to reduce interference, or a higher level of interference may be accepted (e.g., the affected earth station(s) may be located far from any co-channel terrestrial stations, thus allowing a greater portion of the overall interference budget to be consumed by the space system undergoing consideration).

It should be noted that Report 1122 develops an alternative to the RR Appendix 28 method for treatment of tracking earth stations in the determination of coordination area. This alternative method specifically accounts for the joint statistics of antenna pointing and the propagation of interfering signals. Because of the large difference in the permissible short-term single entry interference levels for the large and small earth stations, the size of their coordination areas will differ dramatically.
TABLE V

Single entry interference allowances (sharing criteria)
for example METSAT systems

<table>
<thead>
<tr>
<th>Receiving Earth Station</th>
<th>Long Term Allowances</th>
<th>Short Term Allowances</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Space</td>
<td>Terrestrial</td>
</tr>
<tr>
<td>I_s(20)</td>
<td>I_t(20)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Large</td>
<td>-145 dBW</td>
<td>-125 dBW</td>
</tr>
<tr>
<td>Small</td>
<td>-163 dBW</td>
<td>-148 dBW</td>
</tr>
</tbody>
</table>

The single entry interference allowances given in Table V, for representative earth stations (46.8 dBi and 29.8 dBi), may be scaled in accordance with Annex I of Report [1123] as indicated below for earth stations having other antenna gain values. Appropriate coordination thresholds for the determination of coordination areas are as follows (see Report 382 or RR Appendix 28 for parameter definitions):

- for large earth stations receiving stored data with an antenna gain of 46.8 dBi:

  \[ P_r(p) = -124 \text{ dBW}^*, B = 5.334 \times 10^6 \text{ Hz}, P_0 = 0.012, \]
  \[ \text{and } p = 0.006. \]

  * This value applies for earth stations with an antenna gain of 46.8 dBi. For earth stations receiving stored data with antennas having other gain values \( G \) (39 dBi < \( G \) < 46.8 dBi), the appropriate values for \( P_r(p) \) are as follows:

  \[ P_r(p) = G - 170.8 \text{ dBW}; \]

- for small earth stations receiving real-time data with an antenna gain of 29.8 dBi:

  \[ P_r(p) = -147 \text{ dBW}^*, B = 2.668 \times 10^6 \text{ Hz}, P_0 = 0.012, \]
  \[ \text{and } p = 0.006. \]

  * This value applies for earth stations with an antenna gain of 29.8 dBi. For earth stations receiving real-time data with antennas having other gain values \( G \) (\( G \) < 38 dBi), the appropriate values for \( P_r(p) \) are as follows:

  \[ P_r(p) = -147 \text{ dBW}, \text{ for } G \leq 30 \text{ dBi} \]
  \[ P_r(p) = 2(G - 30) - 147 \text{ dBW}, \text{ for } 30 \text{ dBi} < G \leq 34 \text{ dBi} \]
  \[ P_r(p) = G - 173 \text{ dBW}, \text{ for } 34 \text{ dBi} < G < 38 \text{ dBi} \]
5. **Summary and conclusions**

Two examples of earth stations receiving data from a particular low-earth-orbit METSAT system operating in the 1 670 - 1 700 MHz band have been analysed to determine expected performance levels. On the basis of system performance objectives which are specified, appropriate interference criteria were developed for the example systems. These criteria were further budgeted among interferers in the space and terrestrial services to determine sharing criteria in the form of permissible single entry interference levels. A method for scaling these criteria according to the earth station antenna gain is presented in Annex I of Report [1123].

Coordination thresholds were determined for interference from terrestrial radio-relay stations. In applying these thresholds, it should be noted that Report 1122 suggests an alternative to the RR Appendix 28 method for determining coordination areas for earth stations tracking low-earth-orbit satellites.

Based on the analysis of the system characteristics of the example systems, as well as those of potential future systems (Annex I), it may be concluded that the interference and sharing criteria presented herein should be used for all METSAT systems operating in the 1 670 - 1 710 MHz band.

It is further concluded that coordination should be conducted, to prevent unacceptable interference, to a METSAT system from other satellite systems operating in the 1 670 - 1 710 MHz, when it is anticipated that the applicable sharing criteria might not be met. Coordinated transmission schedules and/or frequency plans can preclude harmful interference in such cases.
ANNEX I

CONSIDERATIONS FOR POTENTIAL FUTURE METSAT SYSTEMS OPERATING NEAR 1700 MHZ WITH SATELLITES IN LOW EARTH ORBIT

1. Introduction

Future METSAT systems using satellites in low Earth orbits are expected to operate with new and improved sensors and, consequently, higher data rates on downlinks carrying real-time data. Data rates of about 3.5 Mbps are envisaged for real-time data. Presently, many METSAT systems with satellites in low Earth orbit utilize the upper part of the 1670-1710 MHz band, whereas METSAT systems using geostationary satellites operate in the lower part of that band. In order to minimize the future equipment modifications needed for the many small earth stations receiving real-time data and to confine downlinks from low orbit satellites to the upper part of the 1670-1710 MHz band, the following measures are planned:

• Use of QPSK modulation for down links carrying real-time data at data rates of about 3.5 Mbps.

• Use a frequency plan with two channels for real-time data transmission, sufficiently separated in frequency so as to allow each of two satellites to use a separate channel without causing significant mutual interference. This frequency plan would also be compatible with current frequency plans, as far as practicable.

• Accommodation of downlinks to large earth stations in the band 7450-7550 MHz for transmission of stored data.

This annex shows that future METSAT systems could be designed to operate with the interference and sharing criteria and coordination thresholds developed in this Report.

2. Performance of future systems

Table VI presents an analysis of the performance of the potential future METSAT system described above. The analysis is similar to that presented in Table II for small earth stations, with the exception that the interference allowances from Table III are encompassed. Comparisons of the short-term and long-term levels of $E_b/N_0$ in Table VI and Table II show that the performance of the prospective future system in the presence of interference exceeds that achieved by the current representative system in the absence of interference. This is mainly because adjacent channel interference would no longer occur from downlink transmissions of stored data from the same satellite.
TABLE VI
PERFORMANCE ANALYSIS OF POTENTIAL FUTURE METSAT SMALL EARTH STATION RECEIVING REAL TIME DATA IN THE PRESENCE OF INTERFERENCE (1 700 MHz)

<table>
<thead>
<tr>
<th>Performance Factor</th>
<th>Short Term Analysis</th>
<th>Long Term Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Satellite transmitter output power (dBW)</td>
<td>14.5</td>
<td>14.5</td>
</tr>
<tr>
<td>2. Filter/cable losses (dB)</td>
<td>1.7</td>
<td>1.7</td>
</tr>
<tr>
<td>3. Impedance mismatch losses (dB)</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>4. Satellite antenna gain (dBi)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. 61° off-nadir (8° elevation)</td>
<td>-</td>
<td>2.1</td>
</tr>
<tr>
<td>b. 62° off-nadir (0° elevation)</td>
<td>2.1</td>
<td>-</td>
</tr>
<tr>
<td>5. Satellite e.i.r.p. (dBW)</td>
<td>14.7</td>
<td>14.7</td>
</tr>
<tr>
<td>6. Free space loss (dB)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. 8° elevation</td>
<td>-</td>
<td>165.3</td>
</tr>
<tr>
<td>b. 0° elevation</td>
<td>167.6</td>
<td>-</td>
</tr>
<tr>
<td>7. Excess path loss (dB)</td>
<td>0.4</td>
<td>0.0</td>
</tr>
<tr>
<td>8. Earth station antenna gain (dBi)</td>
<td>29.8</td>
<td>29.8</td>
</tr>
<tr>
<td>9. Antenna pointing error (dB)</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>10. Polarization mismatch loss (dB)</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>11. Residual carrier loss (dB)</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>12. Demodulator implementation loss (dB)</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>13. Received signal power (dB)</td>
<td>-126.5</td>
<td>-123.8</td>
</tr>
<tr>
<td>14. Data rate, 3.5 Mbps (dB bits/second)</td>
<td>65.4</td>
<td>65.4</td>
</tr>
<tr>
<td>15. Received energy-per-bit, E_b (dBW/Hz)</td>
<td>-191.9</td>
<td>-189.2</td>
</tr>
<tr>
<td>16. Receiver system noise temperature (K)</td>
<td>370.0</td>
<td>240.0</td>
</tr>
<tr>
<td>17. Receiver noise power density (dBW/Hz)</td>
<td>-202.9</td>
<td>-204.8</td>
</tr>
<tr>
<td>18. Adjacent channel interference (dBW/Hz)</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>19. Noise power density</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. Intra-system (dBW/Hz)</td>
<td>-202.9</td>
<td>-204.8</td>
</tr>
<tr>
<td>b. Inter-system (dBW/2.668 MHz)</td>
<td>-150.0</td>
<td>-147.0</td>
</tr>
<tr>
<td>c. Inter-system (dBW/Hz)</td>
<td>-214.3</td>
<td>-211.3</td>
</tr>
<tr>
<td>d. Total, N_0 (dBW/Hz)</td>
<td>-202.6</td>
<td>-203.9</td>
</tr>
<tr>
<td>20. E_b/N_0 (dB) (including interference)</td>
<td>10.7</td>
<td>14.7</td>
</tr>
<tr>
<td>21. Link bit error ratio, coherent QPSK</td>
<td>1 x 10^{-6}</td>
<td>8 x 10^{-8}</td>
</tr>
<tr>
<td>22. Satellite bit error ratio</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>23. Total link bit error ratio</td>
<td>1 x 10^{-6}</td>
<td>8 x 10^{-8}</td>
</tr>
</tbody>
</table>
REPORT 1124*

PERFORMANCE, INTERFERENCE AND SHARING CRITERIA FOR RECEIVING EARTH STATIONS IN THE METEOROLOGICAL-SATELLITE SERVICE OPERATING IN THE 7 450 - 7 550 MHz BAND WITH SATELLITES IN LOW EARTH ORBIT

(Question 12/2 and Study Programme 12C/2)

1. Introduction

The bandwidth available in the 1 670 - 1 710 MHz band for meteorological satellite (METSAT) systems is not sufficient to accommodate down links operating at very high data rates (i.e., upwards of 20 Mbps). However, it is expected that successors to some METSAT systems presently operating in the upper part of the 1 670 - 1 710 MHz band with satellites in low earth orbit will require down links with very high data rates for the transmission of stored data. These down links can be operated in the band 7 450 - 7 550 MHz, which is shared with the fixed-satellite (space-to-Earth), fixed and mobile (except aeronautical mobile) services as well as with geostationary systems in the meteorological-satellite service. Article 28 of the Radio Regulations specifies limits on the power-flux densities from METSAT spacecraft to protect the fixed and mobile services. This report applies performance objectives and the methods of Reports AE/2 and AD/2 to establish interference and sharing criteria for METSAT systems using the 7 450 - 7 550 MHz band with satellites in low earth orbit (i.e., circular orbit of 600 - 1 000 km altitude).

2. Performance objectives

The performance objectives for METSAT down links operating near 7500 MHz are assumed to be the same as for down links operating near 1700 MHz. These are given in Report AC/2 as:

The total Bit Error Ratio (BER) at an earth station should be less than $1 \times 10^{-6}$ for all but 0.1% of the reception time due to all causes during an average year.

3. Performance analysis

Table I presents a performance analysis for a representative METSAT system operating a down link near 7500 MHz. The column

* This report should be brought to the attention of Study Groups 4, 8 and 9.
labelled "short term performance analysis" lists parameter values assumed to correspond with BERs which are exceeded for no more than 0.1% of the time. The column labelled "long term performance analysis" lists parameter values assumed to correspond with BERs which are exceeded for no more than 20% of the time.

### TABLE I

PERFORMANCE ANALYSIS OF POTENTIAL FUTURE METSAT EARTH STATION RECEIVING STORED DATA NEAR 7500 MHz

<table>
<thead>
<tr>
<th>Performance Factor</th>
<th>Short Term Analysis</th>
<th>Long Term Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Satellite transmitter output power (dBW)</td>
<td>16.0</td>
<td>16.0</td>
</tr>
<tr>
<td>2. Filter/cable losses (dB)</td>
<td>1.7</td>
<td>1.7</td>
</tr>
<tr>
<td>3. Impedance mismatch losses (dB)</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>4. Satellite antenna gain (dBi)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. 61' off-nadir (8' elevation)</td>
<td>-</td>
<td>2.0</td>
</tr>
<tr>
<td>b. 62' off-nadir (0' elevation)</td>
<td>2.1</td>
<td>-</td>
</tr>
<tr>
<td>5. Satellite e.i.r.p. (dBW)</td>
<td>16.2</td>
<td>16.1</td>
</tr>
<tr>
<td>6. Free space loss (dB)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. 8' elevation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>b. 0' elevation</td>
<td>179.1</td>
<td>-</td>
</tr>
<tr>
<td>7. Excess path loss (dB)</td>
<td>3.7</td>
<td>0.5</td>
</tr>
<tr>
<td>8. Earth station antenna gain (dBi)</td>
<td>54.0</td>
<td>54.0</td>
</tr>
<tr>
<td>9. Antenna pointing error (dB)</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>10. Polarization mismatch loss (dB)</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>11. Residual carrier loss (dB)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>12. Demodulator implementation loss (dB)</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>13. Received signal power (dBW)</td>
<td>-115.3</td>
<td>-110.0</td>
</tr>
<tr>
<td>14. Data rate, 50 Mbps (dB bits/second)</td>
<td>77.0</td>
<td>77.0</td>
</tr>
<tr>
<td>15. Received energy-per-bit, E_b (dBW/Hz)</td>
<td>-192.3</td>
<td>-187.0</td>
</tr>
<tr>
<td>16. Receiver system noise temperature (K)</td>
<td>320.0</td>
<td>210.0</td>
</tr>
<tr>
<td>17. Receiver noise power density (dBW/Hz)</td>
<td>-203.5</td>
<td>-205.4</td>
</tr>
<tr>
<td>18. Adjacent channel interference (dBW/Hz)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>19. Intra-system noise power density, E_b (dBW/Hz)</td>
<td>-203.5</td>
<td>-205.4</td>
</tr>
<tr>
<td>20. E_b/N_0 (dB)</td>
<td>11.2</td>
<td>18.4</td>
</tr>
<tr>
<td>21. Link BER, coherent BPSK</td>
<td>5x10^-7</td>
<td>&lt;10^-12</td>
</tr>
<tr>
<td>22. Satellite data storage/handling error ratio</td>
<td>5x10^-7</td>
<td>5x10^-7</td>
</tr>
<tr>
<td>23. Total link bit error ratio</td>
<td>1x10^-6</td>
<td>5x10^-7</td>
</tr>
</tbody>
</table>
The satellite characterized in Table I is assumed to be designed with sufficient end-of-life power and e.i.r.p. to just meet the performance objective during relatively degraded operating conditions that occur for small percentages of time. The satellite antenna is assumed to have a shaped gain pattern which partially offsets the increase in free space loss on signal paths from the satellite at increasing off-nadir angles. As with large earth stations operating near 1700 MHz (Report 1121), the minimum operational elevation angle of the earth station (Item 4b) is taken to be five degrees and is assumed to be the elevation angle occurring for 0.1% of the time.

The short term path loss in excess of free space is the rain fade depth predicted for rain zone K (Report 763) for 0.1% of the time using the model of Report 564. The long term value for this parameter is based on expected gaseous attenuation. The earth station is assumed to have an antenna with 12.2m diameter, which is the smallest antenna anticipated for routine reception of the stored data. The assumed modulation is BPSK, although the results are also applicable for QPSK and variants thereof. The bandwidth for the assumed receiver is nominally 100 MHz.

4. Derivation of interference criteria

4.1 Criteria for the representative system

The long term BER performance level shown in Table I surpasses the performance objective by a large margin in the absence of interference (7.2 dB excess $E_b/N_0$ for a radio link BER of $5 \times 10^{-7}$ needed to achieve an overall BER of $10^{-6}$). For a small percentage of time $p$, interference can be allowed to reduce the $E_b/N_0$ by 7.2 dB because interference is uncorrelated with short term intra-system degradations. The percentage of time $p$ associated with this interference should be one-fourth the total time percentage that a $10^{-6}$ BER can be tolerated, specifically $p = 0.025\%$ of time, in order to allow good control over short term performance in the system design process. The resulting total level of short term interfering signal power that is permissible within a receiver bandwidth of 100 MHz, to be exceeded for no more than 0.025% of the time, is -122 dBW.

The short term BER performance level shown in Table I for the representative system just meets the BER performance objective in the absence of interference. However, the long term interference power level (exceeded for no more than 20% of the time) should be permitted to equal 25% of the total noise which would cause the performance achieved to equal the performance objective. The resulting total level of long term interfering signal power that is permissible within a receiver bandwidth of 100 MHz, to be exceeded for no more than 20% of the time, is -133 dBW.
4.2 Generalized interference criteria

The earth station antenna assumed in Table I (nominally 12.2m diameter) is the smallest antenna expected to be routinely used in systems operating near 7500 MHz. However, larger antennas having larger gain values are anticipated for some earth stations. A method for scaling interference (and sharing) criteria is presented in Annex I of Report 1123.

5. Derivation of sharing criteria

Interference to METSAT earth stations operating near 7500 MHz could arise from other satellites operating in the same service or in the Fixed-Satellite service, but would occur most of the time through the far sidelobes of the earth station antenna. Terrestrial fixed and mobile transmitters could be expected to cause higher levels of interference in many cases. Each of these interfering systems, other than METSAT systems, will usually operate more than one channel within the wide-bandwidth channel (100 MHz) used in the METSAT downlinks. A three step approach is used here for budgeting interference among interfering systems: (1) establish general allowances for total interference from space and terrestrial services; (2) if appropriate, determine reference bandwidths (smaller than 100 MHz) for application with adjusted interference criteria for space and terrestrial services; and (3) establish single entry interference criteria. Interference thresholds for use in determining coordination areas are based on the single entry interference criteria.

5.1 Allowances for space and terrestrial interferers

The long term interference from terrestrial transmitters operating near receiving METSAT earth stations could easily exceed that from satellite systems as a result of inherent differences in the associated average power flux densities arriving at the METSAT earth station. Accordingly, 90% of the long term allowance for total interference is budgeted for terrestrial systems and 10% is budgeted for space services.

For small percentages of time, interfering signals from satellites could enter the METSAT earth station mainbeam, whereas interference from terrestrial stations could arrive at off-axis angles of no less than about five degrees (i.e., the assumed minimum earth station antenna elevation angle), thus tending to equalize the highest levels of interference received from space and terrestrial services. However, insofar as the METSAT earth station mainbeam will intersect the geostationary orbit on almost every METSAT satellite pass, and while its mainbeam azimuth will less frequently be directed towards terrestrial transmitters, it would
be reasonable to budget one-fourth of the time percentage associated with short term interference to terrestrial services. Table II lists the resulting interference allowances for space and terrestrial services, which may be scaled as described in Annex I of Report [1123] for METSAT earth stations having antenna gains greater than 54 dBi.

TABLE II - Interference allowances for space and terrestrial services

<table>
<thead>
<tr>
<th>Total Interfering Signal Power per 100 MHz, to be Exceeded for No More Than 20% of the Time</th>
<th>Space Services</th>
<th>Terrestrial Services</th>
</tr>
</thead>
<tbody>
<tr>
<td>-143 dBW</td>
<td>-134 dBW</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total Interfering Signal Power per 100 MHz, to be Exceeded for No More Than ( p% ) of the Time</th>
<th>( P_s = 0.0188% )</th>
<th>( P_t = 0.0062% )</th>
</tr>
</thead>
<tbody>
<tr>
<td>-122 dBW</td>
<td>-122 dBW</td>
<td></td>
</tr>
</tbody>
</table>

5.2 Reference bandwidth for sharing criteria

Interfering satellites may operate varying numbers of carriers with varying power levels and bandwidths within the 100 MHz bandwidth assumed for the METSAT receiver, and these operations may differ significantly from satellite to satellite. Likewise, the relevant number of channels and associated power levels and bandwidths of interfering terrestrial stations may vary widely from system to system. It is possible to arrive at sharing criteria for a reference bandwidth smaller than the 100 MHz associated with the METSAT receiver bandwidth. However, this would require assumptions for the above factors that would necessarily have to be conservative in nature, thus possibly resulting in sharing criteria that are overly conservative. Further study is needed to determine appropriate criteria for smaller reference bandwidths (e.g., one MHz).

5.3 Single entry interference criteria

In light of the numerous satellites operating near 7500 MHz which may simultaneously interfere with a METSAT earth station through its antenna sidelobes, and the potential variations in the total power level of interfering signals from each satellite in the 100 MHz reference bandwidth, a value of four is assumed for the ratio of long term interfering signal power from all satellites to that generated by one satellite. In effect, more than four satellites are accommodated in this budgeting of the long term criteria, but their total interfering signal power within the reference bandwidth is assumed to be four times that of the worst long term interferer. Similar considerations for the
short term interference allowance for space services justifies an assumption of five equal-level interference entries for the purpose of subdividing the short term percentage of time criterion. Only one of these interference entries is assumed to be enhanced at the same time \( y = 1/5 \), in equation 6 of Report 1122. More than five satellites are accommodated in this budget, but the total percentage of time during which the short term interference power criterion is exceeded is assumed to be five times that of the worst short term interferer. A long term allowance of 5% of the permissible interference is made for spurious emissions from space systems prior to the above budgeting. Table III presents the resulting single entry interference criteria to be applied for transmitters in the space services.

For terrestrial services, it is reasonable to assume that there are two significant interference entries present in the long term and that spurious emissions from terrestrial stations should be allowed 5% of the budget for interference from terrestrial services. Two terrestrial interferers are also assumed to be significant for small percentages of time, one of which is enhanced at any given time. The actual numbers of interferers that influence the long term and short term interference levels may be greater than two, but their combined effects are assumed to be no worse than twice that of the worst interferer. Table III presents the resulting single entry interference criteria to be applied for transmitters in the terrestrial services.

**TABLE III - Single entry interference criteria to be applied against individual transmitting stations**

<table>
<thead>
<tr>
<th></th>
<th>Space Services</th>
<th>Terrestrial Services</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Interfering Signal Power per 100 MHz, to be Exceeded for No More Than 20% of the Time</td>
<td>-149 dBW</td>
<td>-137 dBW</td>
</tr>
<tr>
<td>Total Interfering Signal Power per 100 MHz, to be Exceeded for No More Than p% of the Time</td>
<td>-122 dBW</td>
<td>-122 dBW</td>
</tr>
<tr>
<td>p = 0.0038%</td>
<td>p_t = 0.0031%</td>
<td></td>
</tr>
</tbody>
</table>

The permissible levels for single entry interference given in Table III may be adjusted for earth stations with antenna gains above the assumed 54 dBi value using the method of Report AE/2.
The following criteria should be used in Appendix 28 of the Radio Regulations when considering coordination between a receiving METSAT earth station and terrestrial stations. For earth stations having gain values other than the assumed value of 54 dBi, the method of Annex I of Report [1123] may be used to adjust the interference threshold.

\[ P_r(p) = -122 \text{ dBW}, \quad B = 100 \times 10^6 \text{ Hz}, \quad P_0 = 0.006, \]
\[ n = 2, \quad p = 0.003 \]

6. Summary

The methods of Reports 1123 and 1122—have been applied to determine interference and sharing criteria for METSAT systems operating near 7500 MHz with satellites in low Earth orbit. The criteria for the total permissible level of interference presented in Table II should be taken into account in the design of METSAT systems. The single entry interference criteria presented in Table III define applicable sharing criteria. Parameters for calculating coordination areas have also been presented.
REPORT 1125*

FREQUENCY SHARING BETWEEN SYSTEMS IN THE FIXED-SATELLITE
SERVICE AND THE METEOROLOGICAL-SATELLITE SERVICE
OPERATING WITH SATELLITES IN LOW EARTH ORBIT
IN THE BAND 7 450 - 7 550 MHz

(Question 12-2/2) (1990)

1. Introduction

Systems in the meteorological-satellite service will make increasing
use of the 7 450 - 7 550 MHz band as the data rates required for down links
escalate, particularly for dumping stored data in systems using satellites in
low earth orbit. This frequency band is utilized by the fixed-satellite
service (FSS) and by the meteorological-satellite service for systems using
geosationary satellites. These geostationary systems could cause or suffer
interference with respect to meteorological satellite (METSAT) systems using
satellites in low earth orbit. This band is also used by the fixed and mobile
services which are protected from harmful interference by power flux-density
limits specified in Article 28 of the Radio Regulations. This report establishes
a method for identifying METSAT (low orbit) and FSS systems that may be affected
by the sharing and analyzes the sharing situation. It does not consider problems
of interference within the METSAT service, i.e. interference from METSATS in low
earth orbit to earth stations receiving signals from geostationary METSATS. The
sharing criteria developed in Report 1124 for the METSAT systems (low orbit) are
applied.

2. Identification of systems that may be affected

Data that is stored on board a METSAT satellite in low-
Earth-orbit are transmitted upon command from a METSAT receiving
earth station (i.e., a Command Data Acquisition (CDA) earth
station). These stations are generally located at latitudes at
least 35 degrees from the equator because the satellite
(generally at altitudes of 600-1000 km) is more frequently in
view from higher latitudes. Two or three such stations are
adequate to retrieve all data that are collected and stored on all
satellite orbits. The CDA station location serves as a convenient
reference point for identifying potentially affected FSS earth
stations and their associated satellites since the transmitter on
board the Metsat satellite is only activated when in view of the
CDA station at elevation angles greater than a certain minimum
value. (Minimum elevation angle constraints are established by

* This Report should be brought to the attention of Study Group 4.
the physical constraints imposed by pointing large, heavy CDA antennas and the intra-system degradations suffered on the relatively long paths to the satellite at low elevation angles.)

2.1 Geostationary orbital locations of FSS satellites that could potentially affect a METSAT earth station

The identification of FSS satellites in geostationary orbit that could cause interference to a METSAT earth station is accomplished by determining the portion of the geostationary orbit visible from the METSAT earth station above a specified minimum elevation angle. The IFRB Advanced Publications and Notifications can then be reviewed to identify the particular satellites that are situated in the calculated arc. This arc is extends a certain angle $\beta$ from the longitude of the METSAT earth station and may be calculated as follows:

$$\beta = \arccos \left[ \frac{(1 - (D/42,644))^2}{0.2954 \cdot \cos \Gamma} \right]$$  \hspace{1cm} (1)

$$D = (R_e+h) \left[ \frac{\sin(90-E-\arcsin(\frac{Re}{Re+h}\cos E))}{\cos E} \right]$$ \hspace{1cm} \text{km} \hspace{1cm} (2)

where:

$\beta = $ maximum difference in longitude between a visible FSS satellite and the METSAT earth station;

$\Gamma = $ latitude of the METSAT earth station;

$D = $ slant range (km) between the FSS satellite and METSAT earth station;

$R_e = $ radius of earth (km), (6378 km);

$h = $ altitude (km) of the FSS satellite (35,788 km);

$E = $ elevation angle (degrees) measured at the METSAT earth station towards the most easterly or westerly positions in the visible portion of the geostationary orbit (i.e., the elevation angle of the terrain in that direction).

Using the example of a CDA station located at 75.5° longitude and 37.95° latitude, with physical horizon angles of 0° towards the most easterly and westerly visible points in the geostationary orbit (i.e., $E = 0$), the arc can be determined as follows (using Equation 2):

$$D = (6378 + 35788) \sin (90 - \arcsin[6378/(6378 + 35788)])$$

$$D = 41680 \text{ km}$$

Therefore, Equation 1 gives $\beta = 72.6^\circ$ to both the east and west and the geostationary orbit arc containing FSS satellites that could affect the example CDA station extends over $2\beta$ or $145.2^\circ$, at longitudes from 148.1° W to 2.9° W.
2.2 Locations of FSS earth stations that might be affected

The area within a circle centered on the METS SAT earth station may be used to define the locations where interference to FSS earth stations might be caused by emissions from METS SAT satellites. The radius of this circle is determined by the distance between the CDA station and any FSS earth station that may be visible to the METS SAT spacecraft while it is transmitting to the CDA earth station. The radius $S$ of the circle containing all potentially affected FSS earth stations is determined from the following equations:

$$S = S_{\text{MET}} + S_{\text{FSS}}$$

where:

$S =$ maximum surface distance (km) between a CDA earth station and an FSS earth station which could receive interference;

$S_{\text{MET}} =$ maximum surface (km) distance from the subsatellite point to a CDA earth station receiving transmissions from the METS AT spacecraft (km);

$S_{\text{FSS}} =$ maximum surface distance (km) from the sub-satellite point to a point at which an FSS earth station could be visible to a METS AT spacecraft.

with:

$$S_{\text{MET}} \text{ or } S_{\text{FSS}} = 2\pi \cdot R_e \cdot [(90 - E + \phi) / 360]$$

$$\phi = \arcsin \left[ \frac{R_e \cdot \sin(90 + E)}{h + R_e} \right]$$

where:

$\phi =$ exocentric angle (degrees) at the METS AT satellite from nadir to the Earth horizon;

$R_e =$ radius of the Earth (6378 km);

$E =$ elevation angle (degrees) towards the METS AT satellite;

$h =$ altitude (km) of the METS AT satellite.

For example, assuming a minimum operational elevation angle of 5° for the METS AT earth station antenna and an 825 km orbital altitude for the METS AT satellite, then the distance between the earth station and the farthest subsatellite point during transmission is:

$$\phi = \arcsin \left[ \frac{6378 \cdot \sin(90 + 5)}{(825 + 6378)} \right] = 61.9°$$

$$S_{\text{MET}} = 2\pi(6378)[23.1/360] = 2572 \text{ km}$$

An elevation angle of 0° at the FSS earth station towards the METS AT satellite at the above position similarly determines a distance of 3158 km between the FSS earth station and the subsatellite point. Thus, FSS earth stations located within an area of $(2572 \text{ km} + 3158 \text{ km} = 5730 \text{ km})$ radius centered on the CDA earth station could be affected by METS AT downlink transmissions.
3. Analysis of the general sharing situation

An analysis was conducted of the interference between example METSAT and FSS systems to determine the statistics of interference. This section describes the assumed sharing scenarios and the analytical approach, and discusses the analysis results.

3.1 Assumed sharing scenarios

Advance Publications and Notifications (as of November 1988) for FSS systems that may be operating downlinks in the band 7450-7550 MHz were reviewed to determine representative FSS system characteristics. About 50 satellites were identified, with an average deployment density of about one satellite per seven degrees of orbital arc and a peak density within a forty degree arc of about one satellite per 3.5°. It was assumed for the analysis of FSS satellite constellations that satellites are uniformly spaced by three degrees in order to account for potential future growth. Table I presents a summary of other relevant characteristics for FSS systems using small earth station antennas and the satellite e.i.r.p. levels assumed in the analysis. The FSS earth station antennas are assumed to have the radiation pattern given in Appendix 29 to the Radio Regulations.

<table>
<thead>
<tr>
<th>Earth Station Antenna Diameter (meters)</th>
<th>Satellite Parameters</th>
<th>Earth Station Antenna Diameter (meters)</th>
<th>Satellite Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Minimum e.i.r.p. (dBW/Hz)</td>
<td>Maximum e.i.r.p. (dBW/Hz)</td>
<td>Assumed e.i.r.p. (dBW/Hz)</td>
</tr>
<tr>
<td>1.00</td>
<td>-30</td>
<td>-25</td>
<td>-27</td>
</tr>
<tr>
<td>2.44</td>
<td>-38</td>
<td>-26</td>
<td>-32</td>
</tr>
<tr>
<td>6.09</td>
<td>-38</td>
<td>-24</td>
<td>-31</td>
</tr>
</tbody>
</table>

The parameters assumed for the METSAT system are based on the system described in Report AF/2 and are listed below.

- METSAT Earth Station
  - Latitudes: 35°N, 50°N, 65°N.
  - Frequency: 7500 MHz.
  - Antenna diameter: 25.9 meters; gain of 64.8 dBi; antenna off-axis gain pattern of Appendix 29 of the Radio Regulations.
  - Minimum elevation angle for METSAT transmission and reception: 5 degrees above smooth Earth horizon.
- Minimum satellite visibility time (above 5 degree elevation angle) for which data retrieval is attempted: 0 seconds (worst-case assumption regarding transmission scheduling).

o METSAT Satellite
- Sun synchronous, circular orbit.
- Orbital height: 825 kilometers above earth surface.
- Orbital inclination: 98.89 degrees.
- Satellite antenna input power: 16 dBW/100 MHz, (power density of -62 dBW/Hz).
- Satellite antenna gain: 2.1 dBi towards Earth limb, decreasing to -4.5 dBi at nadir.
- Satellite transmits only when commanded by a METSAT earth station.

The deployment scenarios and other factors were assumed to be as follows:

o FSS satellite location(s), three variations
  (1) A single satellite located as far east as visible at the five degree minimum operational elevation angle of the CDA station. (See Table II, which summarizes the relative positions of the METSAT earth station, the FSS earth station, and the FSS satellite.)
  (2) A single satellite located at the same longitude as the METSAT earth station.
  (3) A constellation of FSS satellites spaced every 3 degrees (used only with the METSAT earth station as the victim receiver).

o FSS satellite antenna gain: no allowance for off-axis discrimination towards the victim METSAT earth station.

o FSS Earth Station Location: Worst case (i.e., positioned for maximum cumulative time of visibility to the METSAT satellite). Positioned 512 km (4.6 degrees of spherical arc distance) to the north-west of the METSAT earth station, in the plane defined by the Earth center and the position of the FSS satellite whose transmissions are being received and the METSAT earth station. The relative positions of the METSAT and FSS earth stations and the FSS satellite are summarized in Table II. (It should be noted that at other locations, FSS earth stations would receive significantly lower levels of interference with a given probability).
TABLE II. Geometrical Parameters Used in Analysis

<table>
<thead>
<tr>
<th>METSAT EARTH STATION LAT. (deg.)</th>
<th>FSS SAT. LAT. (deg.)</th>
<th>FSS SAT. WITH RESPECT TO METSAT EARTH STATION LAT. (deg.) and LONG. (deg.)</th>
<th>FSS EARTH STATION LOCATION LAT. (deg.) and LONG. (deg.)</th>
<th>FSS SAT. WITH RESPECT TO FSS EARTH STATION ELEV AZIMUTH (deg.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>35N</td>
<td>073.2E</td>
<td>05.0 100</td>
<td>35.7N 005.6W</td>
<td>00.4 107</td>
</tr>
<tr>
<td>50N</td>
<td>068.4E</td>
<td>05.0 107</td>
<td>51.1N 007.0W</td>
<td>00.4 112</td>
</tr>
<tr>
<td>65N</td>
<td>056.0E</td>
<td>05.0 121</td>
<td>67.1N 010.1W</td>
<td>00.4 112</td>
</tr>
<tr>
<td>35N</td>
<td>000.0E</td>
<td>49.3 180</td>
<td>39.6N 000.0E</td>
<td>44.2 180</td>
</tr>
<tr>
<td>50N</td>
<td>000.0E</td>
<td>32.7 180</td>
<td>54.6N 000.0E</td>
<td>27.7 180</td>
</tr>
<tr>
<td>65N</td>
<td>000.0E</td>
<td>16.7 180</td>
<td>69.6N 000.0E</td>
<td>11.9 180</td>
</tr>
</tbody>
</table>

3.2 Analytical approach

The carrier-to-interference power density ratio $C_0/I_0$ was computed and recorded for the FSS and METSAT earth stations in a simulation program as the METSAT satellite orbited the Earth. The simulations were terminated when the statistics of the $C_0/I_0$ stabilized and reached asymptotic values. The $C_0/I_0$ approach was used because it yields worst-case results which could later be adjusted to estimate $C/I$ values the basis of emission bandwidths, modulation types, and the number FSS carriers within the 100 MHz reference bandwidth of the METSAT receiver.

3.3 Discussion of results

Figure 1 presents the results of the analysis of interference to the METSAT earth station from a single FSS satellite and from the constellation of FSS satellites. Figure 2 present the results for interference to FSS earth stations located at sites experiencing the highest levels of interference. Comparisons of the results for the METSAT and FSS systems show that the METSAT system will generally experience significantly lower $C_0/I_0$ values than the FSS systems.

3.3.1 Interference at METSAT earth stations

Figure 1 shows that the an FSS satellite could cause $C_0/I_0$ values of about 5 dB at a METSAT earth station for percentages of time of the order of 0.003% and about 57 dB for percentages of time of the order of 20%. The applicable single-entry sharing criteria given in Report 1124 for the assumed METSAT system are single entry $C/1s$ of 12 dB and 33.7 dB for 0.0038% and 20% of the time, respectively. The actual $C/I$ at the METSAT receiver will be significantly greater than the $C_0/I_0$ values shown in Figure 1, because there are guardbands between the FSS carriers and the assumed FSS satellite power densities values are greater than those used in many FSS carriers. Thus, there is not likely to be a need to schedule METSAT transmissions for the protection of the METSAT receiver from the emissions of individual FSS satellites.
Figure 1 also shows that the aggregate interference from a constellation of FSS satellites is more than 10 dB higher than that from an individual FSS satellite. The permissible aggregate interference from all satellites (Report 1124) corresponds with C/Is of 12 dB and 27.3 dB for 0.01875% and 20% of the time, respectively. The short-term interference criteria are not met for the example systems, assuming that C/Is and C0/I0s are equal. However, the C/I values could be expected to be much higher than the C0/I0 values, such that unacceptable interference would not be expected at METSAT earth stations in the absence of METSAT transmission scheduling, even with the high assumed density of FSS satellites operating near 7500 MHz.

3.3.2 Interference at FSS earth stations

Figure 2 shows the C0/I0 levels computed for FSS earth stations at worst-case sites near METSAT earth stations at latitudes of 35°N, 50°N and 65°N. The sharing criteria given in Recommendations 466-2, 483-1 and 523-2 of volume IV indicate that for single-entry interference, C0/I0 values of the order of 28 dB and 21 dB may be generally acceptable for 20% and 0.03% of the worst month, respectively. Note that interference is not possible for more than about 8.5% of the time at any latitude because of the statistics of METSAT satellite visibility; however, values of C0/I0 interpolated between the 20% and 0.03% criteria can be compared with the computed values for the intervening percentages of time. The computed C0/I0 values exceed these FSS C0/I0 sharing criteria for the assumed FSS earth stations in all cases by large margins. In fact, the margins are sufficient to protect FSS earth stations receiving the carriers having the lowest FSS satellite e.i.r.p. densities shown in Table I. Thus, on the basis of these findings, it can be seen that METSAT systems with the assumed satellite e.i.r.p. levels may not need to practice transmission scheduling in order to protect FSS earth stations operating with small antennas.

Figure 2 also illustrates that as the antenna diameter of the FSS receiving earth station is increased, and its satellite e.i.r.p. density is reduced to provide a constant received signal power level, two effects will occur: (1) the asymptotic minimum value of C0/I0 will decrease with the FSS satellite e.i.r.p., but (2) the C0/I0 value exceeded for 0.03% and greater percentages of the time will increase. The latter effect is a result of the reduction of earth station antenna beamwidth with increasing antenna diameter (and gain), which decreases the percentages of time during which the C0/I0 level is near the asymptotic minimum C0/I0 value. Thus, interference to FSS earth stations having larger antennas than those assumed in this analysis may also be at acceptable levels in the absence of METSAT transmission scheduling. Further analysis of typical FSS downlinks to large FSS earth stations is needed to confirm this deduction.
Figure 1. Carrier-to-interference power densities calculated for METSAT earth station receivers
Figure 2. Carrier-to-interference power densities calculated for FSS earth station receivers at the worst-case site with respect to a METSAT earth station.

Legend

- FSS earth station with 1.0 meter antenna
- FSS earth station with 2.44 meter antenna
- FSS earth station with 6.09 meter antenna

Scale A: METSAT earth station at 35°N latitude
Scale B: METSAT earth station at 50°N latitude
Scale C: METSAT earth station at 65°N latitude
4. Summary

Methods have been presented for identifying FSS systems that may affect or be affected by transmissions from METSAT satellites in low Earth orbit operating near 7500 MHz.

Analyses were conducted to determine the statistics of interference that may occur between FSS and METSAT systems in the absence of any measures to avoid interference through METSAT transmission scheduling. The interfering signal power levels predicted to occur in an example METSAT system were found to be close to the acceptable levels for small percentages of time and to be far less than the levels that are acceptable for 20% of the time. For receiving FSS earth stations with antenna diameters ranging from 1m to 6m, it was found that the ratios of carrier-to-interference power density would exceed minimum acceptable values by large margins. Computations were not performed for FSS downlinks to earth stations with larger antennas, but extrapolation of the results obtained for smaller FSS earth station antennas indicates that interference may be at acceptable levels for these cases.

On the basis of these results, it appears that transmissions from METSAT satellites do not generally need to be scheduled for the purpose of avoiding interference from FSS satellites. Further, insofar as the margins by which acceptable interference exceeds predicted interference are smaller for the METSAT receivers than for the FSS receivers, any requirements for METSAT transmission scheduling would likely be based on the need to reduce interference to METSAT receivers.
1. Principle and applications

The purpose of data collection satellite systems, is to provide a telecommunication network for users needing information from a variety of sources, which may be located anywhere in the world, including desert regions.

The concept of a data collection satellite system is the following:

- automatic, autonomous platforms installed on land or mounted on a support (boat, aircraft, balloon, anchored or drifting buoy, land vehicle) for the transmission of meteorological (pressure, temperature, humidity, etc.) or geophysical (tsunami warnings, seismic, oceanographic and geodetic data, etc.) parameters. These platforms should, as far as possible, be light and compact, use little power and be inexpensive;
- the information compiled and transmitted by the platforms is received on board a satellite and forwarded through one or more telemetry stations to a system management centre;
- once centralized, the information is carried to users by conventional means of telecommunication;
- if necessary, provision may also be made to distribute information from the management centre to the platforms.

It is obvious that such a system differs from conventional telecommunications in that it cannot be conceived without the use of satellites and is intended for a special category of customers whose needs cannot be met by other means. In general, it favours one direction of transmission and essentially serves to centralize information. It may, however, be backed up by a facility for the distribution of information to the collection platforms. If desired, the information may be retrieved automatically from the platforms. Finally, a requirement that is very important for many users, is that the data collection function may easily be coupled with a location system which determines the coordinates of the transmitting platforms.

A data collection system has many fields of application:

- meteorology;
- Earth resources;
- hydrography;
- seismic observation;
- vulcanology;
- geodesy and geodynamics;
- anchored or drifting oceanographic buoys;
- oil prospecting;
- wild-animal tracking.
2. Data collection systems design

Data collection systems may be classified according to:

- satellite orbital altitude;
- mode of operation of platforms;
- existence or absence of a location function.

2.1 Types of orbit

Two types of orbit may be used: the geostationary-satellite orbit or low orbits.

2.1.1 Geostationary satellites

The coverage area of a satellite is a spherical cap with a geocentric half-angle of approximately 75°.

| TABLE I |
|-----------------|-----------------|
| Advantages | Disadvantages |
| Continuous coverage within view of the satellite. The information is transmitted continually and reaches the user very rapidly | At least four satellites are required for world coverage, excluding the polar regions |
| | The platforms must be equipped with directional antennas and/or higher powered transmitters |
| | The location function is difficult to provide |

2.1.2 Low-orbit satellites

These are generally placed on circular orbit at altitudes of between 600 and 1800 km, with a period of revolution of approximately 2 h. The whole of the Earth (including the poles) can be scanned with a single satellite, but the number of passes is relatively low (about 3 or 4 per day over the equator). It may be increased by using several satellites e.g. a dozen passes per day over the equator may be obtained with three satellites. Passes are far more frequent near the poles.

| TABLE II |
|-----------------|-----------------|
| Advantages | Disadvantages |
| World coverage, including the poles | Coverage limited to the overpass of the low-orbit satellite |
| Simpler platforms | It is generally necessary to store information on board the satellite |
| Location function easier to provide |

2.1.3 Comparison

The choice of system will depend on the characteristics of the field of application. A geostationary-satellite system is essential where instantaneous transmission is required either continuously or at set times. A low-Earth satellite system provides global coverage including the polar regions and economically provides platform location.
2.2 Mode of operation of platform

Several types of platform are used.

2.2.1 Interrogated platforms

These platforms are used principally with geostationary data collection systems. Each platform contains both a transmitter and a receiver.

The system management centre transmits to the satellite a work programme containing the addresses of the platforms to be interrogated and the time at which this operation must be carried out.

The platforms cannot transmit unless they are interrogated. However, they can be designed to request interrogation, e.g. geophysical warning systems.

This mode of operation is very reliable and there is no risk of mutual interference. However, the platform must be equipped with a receiver which increases its cost.

2.2.2 Platforms operating in a random access mode

a) In geostationary satellite data collection systems, the platforms are used for transmitting warnings. The platform normally reports only when a fixed threshold of the phenomenon being measured is met or exceeded. An example is a platform which in monitoring seismic activity only reports if the seismic activity is greater than normal. In practice, separate channels in the allocated band are reserved for random-access platforms in order to reduce the probability of interference with the other types of platform.

b) In low-orbit satellite data collection systems, each platform repeats its message separately from the others and at given intervals. Interference may therefore occur between platforms which are in line-of-sight of the satellite at the same time.

Conversely, the satellite can work with only a limited number of platforms in line-of-sight at the same time.

2.2.3 Self-timed platforms

These platforms are used principally with geostationary data collection systems. Each platform transmits its message automatically within pre-set times. The reporting intervals are determined at pre-set times by a clock internal to the platform. Each platform is identified by its address and the frequency (assigned channel) on which it transmits its report. In practice, satellite operators manage the assignment of the time slots and the broadcast channels of the platforms.

2.3 Platform location

Mobile platforms (balloons, drifting buoys, wild animals, etc.) are used for a great many applications and their movements, which are unpredictable, need to be tracked in order to carry out the mission (wind determination, study of marine currents, study of migratory movements, etc.). In such cases, the location and collection functions are performed simultaneously.

Either the range or the range rate (Doppler effect), or both, may be measured. A number of measurements are taken and processed in order to locate the transmitting platform with an accuracy ranging from a few metres to a few kilometres. High-precision position determination to sub-metre accuracy is required for geodetic and geodynamic missions. Corresponding systems are described in Rapport 588.

The Doppler method of location is not applicable to geostationary satellites. Location from geostationary satellites may be achieved by interferometric data from a single satellite or by ranging within the overlap area of two satellites.

3. Examples of satellite data collection and location systems

Examples of a low-orbit satellite system are given in Annexes I and II. An example of a geostationary-satellite system is presented in Annex III. Annex IV describes the aircraft to satellite data relay (ASDAR) system. Annex V presents an example of a planned geostationary-satellite system in the radiodetermination satellite service for remote platform location and data collection.

Other systems, no longer operational or planned, are described in Report 538 (Geneva, 1982): they are OPLE, IRLS, LANDSAT-1 and 2, RAMS and GEOLE.
ANNEX I

PRINCIPLE AND CHARACTERISTICS OF THE ARGOS SYSTEM

1. Introduction

ARGOS is a data collection and location system designed and developed by CNES (France) in cooperation with NASA and NOAA (United States). It has been operated under the aegis of these three agencies since 1978 and is used by numerous countries. In 1985, the three agencies decided to keep the system in operation until at least 1995. The number of platforms is increasing on average by 15% per year. In 1988, 1,300 platforms were in routine operation (the actual number of platforms is in fact higher, but they are not in routine operation).

The ARGOS system uses low-orbit satellites and platforms operating in a random access mode. Location is determined by measuring the one-way Doppler shift.

2. Orbit of the satellites

The system comprises two satellites in orbit simultaneously. The nominal orbit characteristics are:

- **Inclination:** 98°
- **Altitude:** 830 km and 870 km
- **Period of revolution:** 102 minutes

The planes of the two orbits form an angle of 90°.

3. Platforms

Each platform emits sporadically. Each emission consists of two successive parts: during the first part, a pure carrier is emitted; during the second part, the signal is modulated by the message to be transmitted.

- **Unmodulated part:** duration of the order of 160 ms.
- **Modulated part:** includes 48 service bits followed by the data from the sensors. Depending on the number of sensors the total duration of the modulated part ranges between 200 ms and 760 ms.

- **Period of repetition:**
  - platforms to be located: chosen between 60 and 100 s,
  - platforms to be used only for data collection: chosen above 200 s.

**Bit rate:** 400 bit/s.

- **Encoding:** two-phase Manchester code.
- **Carrier:** 401.65 MHz ± 3.2 kHz.
- **Emitted power:** less than 3 W.
- **Frequency stability** (to obtain a location accuracy of better than 1 km):
  - short-term drift (20 min) not to exceed $0.5 \times 10^{-4}$/min,
  - jitter (120 ms): $10^{-6}$.

**Note.** The location accuracy depends to some extent on the stability of the platform oscillator; this specification may vary according to the objective sought.

4. Satellite receiver

- **Reception power of an individual signal:** between -131 and -108 dBm;
  (The system margin allows reception of an important proportion of signals down to -137 dBm.)
- **Noise power:** -171 dB(mW/Hz);
- **Analysis bandwidth:** 24 kHz (80 kHz from 1992 onwards);
- **Number of processing channels:** 4 (8 from 1992 onwards).
5. **Performance**

**Capacity:**

- for data collection with location (4 sensors):
  - 1087 platforms in the same circle of visibility (2825 from 1992 onwards);
- for data collection without location (16 sensors):
  - 2175 platforms in the same circle of visibility (5650 from 1992 onwards).

**Precision of location:**

- about 1 km for balloon-type mobile platforms, the altitude of which is known at ± 500 m:
- about 300 m for drifting-buoy type mobile platforms with slow and regular drift:
- different levels of precision (from some hundreds to some tens of metres) are attainable when the movement is at constant speed and when the stability of the platform’s oscillator is sufficiently high, the uncertainty of the satellite orbit parameters then becomes the main source of error.

**ANNEX II**

**Principle and characteristics of the MOS-DCS**

1. **Introduction**

Marine Observation Satellite-Data Collection System (MOS-DCS) is a data collection and location system designed and developed by NASDA (National Space Development Agency of Japan). It has been operating since 1987. The system is now used by several agencies within the service area of MOS-DCS, with a radius of about 2,600 km centred on the HATOLAMA Earth Observation Centre, and about 10 DCPs (Data Collection Platform) are experimentally operated.

The MOS-DCS uses low-orbit satellites and platforms operating in random access mode. Location is determined by measuring one way Doppler shift.

2. **Satellite orbit**

The system is operating on board the Japanese first marine observation satellite MOS-1. The characteristics of the orbit are as follows:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inclination</td>
<td>99°</td>
</tr>
<tr>
<td>Altitude</td>
<td>909 km</td>
</tr>
<tr>
<td>Period of revolution</td>
<td>103 min.</td>
</tr>
<tr>
<td>Local mean solar time at descending node</td>
<td>10:00 ~ 10:30</td>
</tr>
</tbody>
</table>
3. **Platform**

Each platform transmits signals sporadically. Each pulse is composed of two successive parts: during the first part a pure carrier is emitted; during the second part the signal is modulated by the message to be transmitted.

- **Unmodulated part**: duration of 160 msec
- **Modulated part**: includes 48 service bits followed by the data from the sensors. Depending on the number of sensors, the total duration of the modulated part ranges from 200 msec to 760 sec

- **Pulse repetition frequency**: less than 1/30 (sec⁻¹)
- **Bit rate**: 400 bps in modulation part
- **Modulation Characteristics**: PCM-PSK
- **Carrier frequency**: 401.47 MHz
- **Transmission Power**: 6.0 dBW

**Frequency Stability**

- **short term stability**: < 1.0 x 10⁻⁹ during 100 msec
- **medium term stability**: < 1.0 x 10⁻⁸ during 20 min
- **long term stability**: < 32 Hz

*Note*: The location accuracy depends mainly on the medium term stability, among stability terms mentioned above.

4. **Satellite**

DCST (Data Collection System Transponder), which is a satellite part of the MOS-DCS, plays the role as a transponder with frequency change and modulation of the DCP emitted pulses.

- **Minimum power level of an individual signal**: -145 dBW/m²
- **Maximum power level of an individual signal**: -120 dBW/m²
- **Reception bandpass filter**: 401.5 MHz ± 40kHz
- **Remodulation**: PM
- **Down link carrier frequency**: 1702.4848 MHz ± 20 kHz
5. **Ground based receiver**

- **Analysis bandwidth at reception**: 30 kHz
- **Number of processing channels**: 2
- **Signal analysis**: Digital processing based on FFT
- **Frequency measurement accuracy**: 0.4 Hz (1 σ)

6. **Performance**

**Data reception**

Within the service area around Japan, the probability of successful data acquisition under the circumstances of data collisions, which means existence of more than two DCP signals having nearly the same frequencies at the same time, is 80% for each message occurrence with a 4 W transmission power.

**Precision of location**

- better than 500 m for the ground fixed type DCP.

**ANNEX III**

**CHARACTERISTICS OF THE GEOSTATIONARY METEOROLOGICAL SATELLITE DATA COLLECTION SYSTEM**

1. **Introduction**

The international geostationary meteorological satellite data collection system (IGMSDCS) is comprised of data collection platforms (DCPs) and data relay transponders deployed aboard four geostationary meteorological satellites: METEOSAT, located at 0° W longitude operated by the European Space Agency (ESA); GOES-East (75° W) and GOES-West (135° W), operated by the United States of America; and the geostationary meteorological satellite (GMS) (140° E), operated by Japan. A fifth IGMSDCS satellite is projected for launch by the USSR for operation near 70° E.

Each of the satellites listed above has reserved one band of frequencies for operation of so-called international DCPs, that is, for data collection platforms which may move from the operational area of one satellite to that of another. Another band of frequencies is reserved for DCPs operating within the coverage area of each of the satellites.

Through coordination, satellite operators share domestic DCP frequencies: the United States of America and the USSR share one band (401.7-402.0 MHz) while ESA's METEOSAT and Japan's GMS share use of a second band (402.1-402.4 MHz). This coordination obviates the need for additional bandwidth for each satellite operator.

2. **Coverage areas**

The system design of the geostationary meteorological satellite data collection system permits the operation of low-cost, low-power platforms from locations anywhere within the geometric field of view of each spacecraft. For geostationary spacecraft, the geometric horizon is almost 83 great-circle degrees (i.e. 9000 km) from each satellite's sub-point. Since the participating satellites are separated by 75, 60, 85 and 140 great-circle degrees (measured along the equator), this results in large field-of-view overlaps, covering much of the Earth outside the polar regions.
3. Platforms

DCP reports are transmitted at 100 bit/s, and consist of:
- an unmodulated carrier,
- a bit preamble,
- a synchronization code,
- a platform address,
- environmental data,
- an end of transmission sequence.

The details of these transmissions vary between domestic and international services; in the United States system, the minimum required introductory transmissions are shorter for domestic transmissions but longer headers would not be rejected. The following information pertains to transmissions for the international system.

Report format: international platform reports include the following contiguous elements:
- unmodulated carrier for 5 s,
- a 250 bit alternate "0" and "1" preamble,
- a 15 bits maximal linear sequence (MLS) code synchronization word,
- the UCP address which is a 31 bits Bose-Chaudhuri-Hocquenghem (BCH) coded word,
- the environmental data which are a maximum of 649 words, each word being 8 bits long,
- the 31 bits end-of-transmission sequence.

Bit rate: 100 bit/s.

Encoding: non-return to zero (NRZ) split-phase Manchester encoding.

Carrier: the International DCS includes 33 channels filling the band from 402.0-402.1 MHz. GOES United States domestic channels lie between 401.7 and 402.0 MHz (200 channels). Transmissions are phase-shift modulated.

Platform power: approximately 10 W for a platform with a high-gain (helical) antenna; about 80 W for a semi-isotropic (full horizon to zenith) antenna. Antenna polarization is right-hand circular.

Frequency stability: \(1.5 \times 10^{-6}/\text{year}\), including temperature changes from \(-20^\circ\text{C}\) to \(+50^\circ\text{C}\). Phase jitter on an unmodulated carrier shall not exceed 3° r.m.s. when measured with a phase-lock loop two-sided noise bandwidth of 20 Hz within a 2 kHz band.

4. Satellite

Power level of an individual received signal: \(-145 \text{ dB(W/m}^2\) ± 5 dB

Signal/noise level: gain/temperature:

\[-18.5 \text{ dB(K}^{-1}\) \quad 6.5 dB

Data relay bandwidth: 0.4 MHz

Number of channels: 33 (international); 200 (GOES, domestic)

Estimated service life: 5 years

5. Performance

5.1 Capacity

Utilization of any one channel requires availability of the channel in the satellite's transponder, and availability of a demodulator (i.e. a narrow-band receiver) for that channel at the ground control station. The ultimate platform capacity is determined by the total number of channels, and by the total message length (including a guard band of time between messages). For platforms that need not report at regular intervals, but only when some environmental threshold is reached (such as river height, or rainfall rate), the total number of platforms served can be quite large.
5.2 Data availability

IGMSDCS reports include environmental data of general use, as well as of value to the platform operator. Most reports are processed and are made available to such users as regional and local centres for numerical weather prediction and short-term forecasting. However, platform operators are not limited to receipt of their data by way of central processing facilities. If they wish, they may install ground station facilities for receiving the channel(s) on which their platform reports are carried.

ANNEX IV

THE ASDAR DATA COLLECTION SYSTEM

1. Introduction

The aircraft to satellite data relay (ASDAR) system, first operational in 1979, is an international fixed-time data collection system (DCS) engineered for deployment aboard wide-bodied jet aircraft, for the collection of in-flight meteorological reports. Although engineered by a United States National Aeronautics and Space Administration (NASA) laboratory for use aboard commercial wide-bodied aircraft having digital navigation and flight-control data streams, the ASDAR package proved capable of modification for flight aboard other modern aircraft designs.

2. Operation

In operation, the ASDAR unit monitors the data streams within the host aircraft and, on schedule, selects values for altitude and location, wind speed and direction, and outside air temperature. Once an hour, eight timed ASDAR reports are transmitted (as a single batch message) for satellite relay. ASDAR messages, including preface and end-of-transmission signals, are about 50 s long. This allows each message to be assigned a two minute time-slot, with a 35 s guard band of time at each end. Data users include centres for large-scale numerical weather prediction, regional weather forecasters, aircraft in-flight controllers, and airline flight planners.

A single micro-processor oversees all ASDAR functions, including message formation, and command of the ASDAR 80 W transmitter. This design feature ensures that any malfunction of the message data-processor will also guarantee that no messages are transmitted. Other design features include fail-safe isolation between the ASDAR box and its sources of data, notably the aircraft's inertial navigation system and central air data computer. Additional circuits were installed to disable the transmitter permanently should any transmission take place after the time for a message broadcast.

3. Satellite considerations

Cooperation among operators of four geostationary meteorological satellites, who established a radio-frequency band for "international" data relay, permit ASDAR data relay from virtually any location on Earth. Where the fields of view of adjacent data relay satellites overlap, processing areas are delineated to reduce the number of redundant ASDAR reports which might originate from data processing centres in Europe and America, or America and Japan.

4. Quality control

An ASDAR message suffers considerable Doppler shift of its transmitter frequency as the host aircraft either approaches or departs from a satellite sub-point. For this reason, it is necessary to monitor closely the receipt of data from ASDAR packages, in order to assure transmitter stability. United States satellite operators spot-check ASDAR signal quality, and report their findings to the ASDAR control staff. Monitors observe the transmitter centre frequency, the signal strength, and the quality of signal modulation on the transmitter carrier. The demonstrated value of this overall quality monitoring has led United States satellite operators to implement fully automated quality monitoring of all DCPs, both in its domestic and international bands.

5. Future plans

A re-engineered ASDAR package is currently planned for future deployment. (A system called ACARS is also now in use, but involves direct radio transmission of data, sometimes including meteorological reports, from an aircraft in flight to a ground radio station.)
ANNEX V
GEOSTAR POSITIONING AND COMMUNICATIONS SYSTEM

1. Introduction

The GEOSTAR is a proposed radiodetermination satellite service system being developed for use in the United States of America for implementation in the 1987-1988 time-frame which will provide position information and message service to aeronautical, maritime and terrestrial users. The user transceivers utilized with the GEOSTAR are being designed to be low cost, light weight, physically small units. In addition to determining the position of the user transceiver to an accuracy of 2-7 m, the GEOSTAR will be capable of relaying short digital messages between user transceivers and the central control earth station.

2. Potential applications

A potential application of the GEOSTAR transceiver is for the automatic collection of environmental data. Using the GEOSTAR, remote measurements similar to those gathered by data collection platforms (DCPs) can be collected and distributed to any desired pre-determined earth location. As such, the GEOSTAR can support DCP functions and may be an attractive alternative for some DCP applications, particularly those in which knowledge of the location of moving data collection platforms is required.

In addition to relaying data, the GEOSTAR system has the potential to be used for generating wind velocity data. The true course of an aircraft can be determined by the GEOSTAR control centre by comparing its current position to its position at the previous request for position determination. If the aircraft transmits its true heading and air speed to the GEOSTAR satellite, which then relays these data to the central control earth station, the control centre computer can calculate the velocity and direction of winds aloft by comparing the true course of the aircraft to its true heading. This information, if obtained from a large number of aeronautical users, could be used to develop a detailed 3-dimensional data source for winds aloft. The data have the potential for producing large fuel savings in the airline industry as well as providing a real-time data source for meteorological studies.

3. Orbit of the satellites

The system will be comprised of three geostationary satellites at longitudes 70° W, 100° W, and 130° W.

4. Platforms

<table>
<thead>
<tr>
<th>Bit rate:</th>
<th>16 kbit/s</th>
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<td>Coding:</td>
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<td>Transmit carrier:</td>
<td>1618.25 MHz</td>
</tr>
<tr>
<td>Receive carrier:</td>
<td>2491.75 MHz</td>
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<tr>
<td>Emitted power:</td>
<td>40 or 80 W</td>
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<tr>
<td>Modulation:</td>
<td>spread spectrum, 2-PSK</td>
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<td>Chip rate:</td>
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<td>Chip period:</td>
<td>122.07 ns</td>
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<td>Signal format:</td>
<td>SS/TDMA</td>
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</table>

5. Satellite

<table>
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<tr>
<th>Received power level:</th>
<th>-170.7 or -167.7 dBW</th>
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</thead>
<tbody>
<tr>
<td>Thermal noise density:</td>
<td>-200.8 dB(W/Hz)</td>
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<tr>
<td>Bandwidth:</td>
<td>16.5 MHz</td>
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<tr>
<td>Number of beams:</td>
<td>8</td>
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<tr>
<td>Estimated service life:</td>
<td>10 years</td>
</tr>
</tbody>
</table>
6. Performance

6.1 Capacity

The system will be capable of processing an average of 10 simultaneous user accesses within each of the 8 beams.

6.2 Positioning

- Primary method: two satellites used with a digital terrain map or encoded altimeter readings
- Back-up positioning: tri-lateration of three satellites if no terrain map or altimeter reading is used
- Accuracy: 2-7 m (primary) 50-100 m (back-up).
REPORT 988-1

SATELLITE SYSTEMS FOR GEODESY AND GEODYNAMICS

(Question 12/2 and Study Programme 12/2)

(1986-1990)

1. Introduction

Space techniques, which enable more and better information to be obtained about the Earth (shape, motions, gravitational field and their temporal variations), have made a significant contribution to geodesy and geodynamics since the placing in orbit of the first artificial earth satellites. Since 1964, more than 20 dedicated geodetic satellites have been launched including Explorer-22, Explorer-27, GEOS-1, Pageos-1, GEOS-2, GEOS-3 and LAGEOS. A typical representative of that generation of geodetic satellites is GEOS-3. It was launched in 1975 and carried a radar transponder, a range and range-rate system, a laser retro-reflector, a radar altimeter, and a two-frequency Doppler beacon system. This combination of instruments was used for a variety of measurements related to geodesy and geodynamics. An inter-comparison of geodetic and geophysical measuring systems was also made and a satellite-to-satellite tracking experiment was carried out. More details of most of these satellites can be found in Annex III to Report 535 (Geneva, 1982).

New satellite systems for geodesy and geodynamics are under consideration by several countries and agencies for launch in the late 1980s or early 1990s. Some of them are described in Annexes I to III.

This Report concerns satellite systems in which one or more satellites are linked to earth stations and/or to each other by means of high-precision range and range-rate measurements, using radio waves.

There are other satellite systems which contribute to the advancement of geodesy and geodynamics. Examples are:

- ocean altimetry using satellite-borne radar (see Reports 535 and 693);
- range measurement by pulsed laser (see Report 680);
- microwave radiometry (see Report 693) for determining the composition of the troposphere and so correcting other measurements.

2. Telecommunication requirements for space geodesy and geodynamics

2.1 General

Space telecommunication systems for geodesy and geodynamics are generally required to perform three functions:

- high-precision orbit determination;
- high-precision positioning of points on the Earth's surface;
- rapid data distribution (preferably, this function is performed by the system itself).

The first and second functions are closely linked. In order to position points in a geocentric reference system, it must be possible to predict or restore the satellite orbit in that reference system with a degree of accuracy comparable to that required for the positioning. Consequently, the orbit determination system used for the tracking of geodetic satellites must have better accuracy than that which is generally required for application satellites. Such an orbit determination system typically uses a fairly large number of earth stations (e.g. 10-50) distributed geographically so as to ensure continuous tracking of the satellite(s) which should always be visible from two or more stations. This network may be used also for geodetic applications, i.e. to determine parameters relating to the Earth's rotation, the geocentric coordinates of stations and the base lines linking pairs of stations.
The second function (precise absolute and relative point positioning) is generally performed with transportable ground stations or networks to be established temporarily in areas of geographical interest, sometimes in clusters of more than 20 stations within a limited region. High precision positioning of points on the Earth's surface may also be performed using VLBI technique.

With respect to the third function, certain geodetic and satellite orbital parameters must be recovered within a relatively short time (approximately one day). It may also be necessary to distribute in situ data gathered locally and orbit prediction data generated at a central facility.

2.2 Types of telecommunication required

Two main types of telecommunication are required to perform the functions described above:

— measurement telecommunication (between the earth stations and satellites or between satellites);
— data communication.

These may be used in conjunction or separately.

2.2.1 Measurement telecommunication

Determination of the relative positions of earth stations and satellites or of their variation in relation to the movement of the spacecraft, using electromagnetic wave propagation, has thus far been based on the measurement of:

— range rate;
— range;
— range difference.

These values may be obtained by various methods, which may be classified as either one-way or two-way.

2.2.1.1 One-way measurements between earth stations and satellites

One-way measurements are used in the space-to-Earth direction as, for example, in the TRANSIT and GPS-NAVSTAR systems [Stansell, 1971; Milliken and Zoller, 1978]. The measurements are taken in this case on the ground, at each station. Such systems facilitate data distribution to a large number of users. They cannot be used directly for the determination of the base lines linking pairs of stations.

One-way measurements may also be used in the Earth-to-space direction as for example, in the planned DORIS system (see Annex I). This system offers the possibility to collect data at a central point. Whatever direction the one-way measurements are performed, they require very high frequency stability at both the transmitter and the receiver local oscillator. For example, a relative frequency shift of $\delta f/f = 10^{-11}$ introduces an error of $\delta v = 3 \text{ mm/s}$ in range-rate measurements. In one-way range measurements systems, such as GPS-NAVSTAR, where phase stability must also be maintained, when higher frequency stability is necessary.

On the other hand, one-way systems have the advantage of requiring only a transmitter at one end of the link and a receiver at the other.

2.2.1.2 Two-way measurements between earth stations and satellites

Systems employing two-way measurements have considerably lower requirements on the stability of their oscillators. Depending upon operational conditions, the measurement signal can either be generated on board a satellite or in the ground terminals with one of the link elements operating as a simple transponder. If suitable modulation schemes are used, these systems can serve several stations simultaneously permitting the precise determination of relative distances (base lines) between pairs of stations. The planned POPS AT system (see Annex II) and the Precise Range and Range-Rate Experiment PRARE (a payload of the European remote-sensing satellite ERS-1, see Annex V to Report 535) are two-way measurement systems.

2.2.1.3 Satellite-to-satellite tracking (SST)

Space techniques can provide the key to the determination of the short and medium wavelength components of the Earth's gravitational field. One particular method is the measurement of the relative velocity between two satellites. The principle of SST has been successfully demonstrated in a mission where a geostationary satellite (ATS-6) tracked a satellite in low orbit (GEOS-3). Another possibility is to perform satellite-to-satellite tracking with both satellites in the same low orbit, but separated by up to 300 km. The proposed Geopotential Research Mission (see Annex III) represents such a configuration.
2.2.2 Data telecommunications

The measurement systems described above provide their results at one end of the system. In the case where these data are not extracted at the point where they are needed for further processing or dissemination, they have to be transmitted back to the other end of the system. Furthermore, processing the raw data might entail the addition of auxiliary data available at the other end of the link, for example:

- data on propagation conditions measured in the vicinity of the earth stations (atmospheric pressure, temperature, humidity), and added to the up-link signal;
- ephemeris data of the satellites, information on the state of the ionosphere, etc. to be distributed to the earth stations.

Three types of information can be transferred within the system:

- measurement signals;
- measurement results;
- auxiliary data.

The latter two could be multiplexed with the measurement signal or use separate links for re-transmission.

3. Preferred frequency bands

3.1 RF spectrum constraints due to propagation characteristics

The usable frequency bands are limited by the characteristics of the media through which the signals pass.

- The troposphere causes both absorption loss and signal delay. Although tropospheric delay causes errors which exceed the accuracy goals of satellite geodesy and which have to be corrected in the parameter recovery process, it is not a criterion for the choice of preferred frequencies. Absorption loss significantly affects link budgets only above about 20 GHz.

- The ionosphere causes negligible absorption above about 100 MHz. The lower limit of usable frequencies is determined by the phase shift and group delay of the signals used for measurement.

Report 263 describes in detail the ionospheric effects on Earth-to-space and space-to-Earth propagation. A simplified description is given in § 3.1.1 of Report 845.

Range measurement errors due to the ionosphere depend on the total electron content (TEC), which generally varies according to latitude, time, season and solar activity within a range as broad as from \(1.4 \times 10^{16}\) to \(70 \times 10^{16}\) electrons/m\(^2\) and beyond that range in some regions. The direct correction of measurement errors by means of models is not very accurate owing to the great variability of the ionosphere.

In order to reduce measurement errors caused by inadequate knowledge of the ionosphere, it is necessary either to use fairly high frequencies or to merge the measurement data obtained simultaneously at a number of coherent frequencies. [Saint Etienne, 1981; Lassudrie-Duchesne et al., 1986].

For a mean TEC value of \(20 \times 10^{16}\) el/m\(^2\), the gross error and residual error after correction by the combination of dual-frequency measurements are given in Table I for a vertical path completely traversing the ionosphere.
TABLE I
Ionospheric error over a vertical path for
TEC = 20 x 10^4 el/m^2

<table>
<thead>
<tr>
<th>Frequencies</th>
<th>Path measurement error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main frequency</td>
<td>Auxiliary frequency</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>400 MHz</td>
<td>150 MHz</td>
</tr>
<tr>
<td>2 000 MHz</td>
<td>400 MHz</td>
</tr>
<tr>
<td>1 227 MHz</td>
<td>1 575 MHz</td>
</tr>
<tr>
<td>8 000 MHz</td>
<td>2 000 MHz</td>
</tr>
</tbody>
</table>

For an oblique path inclined at 30° in relation to the ground horizontal, the values in Table I should be multiplied by 1.8. At elevation angles less than 20° at 400 MHz or less than 10° at 2 000 MHz, the differential curve of the rays causes a rapid increase in residual errors.

As shown in Table I, the combination of dual-frequency measurements considerably reduces the ionospheric error. However, if in dual-frequency systems these frequencies are not sufficiently spaced in the radio spectrum, the non-ionospheric errors grow by a factor which is, for example, between 1.2 and 1.6 for the pair 150/400 MHz and attains 3.4 for the pair 1227/1575 MHz.

One major conclusion that can be drawn from the above considerations is that single-frequency measurement systems are generally inadequate for high-accuracy satellite geodesy and geodynamics missions. Measurement systems for such missions require at least two frequency bands sufficiently spaced in the radio spectrum.

3.2 Necessary bandwidth

3.2.1 Necessary bandwidth for Doppler effect measurements

Owing to the Doppler shift, the received frequency differs from the emitted frequency by a quantity +Δf or −Δf depending upon whether the slant range is decreasing or increasing.

\[ \Delta f = \frac{v}{\lambda} \] for one-way measurements,

\[ \Delta f = \frac{2v}{\lambda} \] for two-way measurements,

v being the range rate and \( \lambda \) the wavelength.
Table II gives the necessary bandwidth \(2\Delta f\) for \(v = 9 \text{ km/s}\).

<table>
<thead>
<tr>
<th>(f) (MHz)</th>
<th>150</th>
<th>400</th>
<th>2000</th>
<th>8000</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\lambda) (m)</td>
<td>2</td>
<td>0.75</td>
<td>0.15</td>
<td>0.0375</td>
</tr>
<tr>
<td>(2\Delta f) (kHz)</td>
<td>(9)</td>
<td>(24)</td>
<td>(120)</td>
<td>(480)</td>
</tr>
</tbody>
</table>

3.2.2 Necessary bandwidth for ranging

Radio ranging consists of measuring the propagation phase or group delay of signals between the spacecraft and the earth station. However, the measurement is generally not taken on the carrier because of the ambiguity of \(n\lambda\) (one-way) or \(n\lambda/2\) (two-way). In order to remove the ambiguity, measurements are taken on signals which modulate the carrier.

Two main types of modulation are used. In one case, the phase delay of several sinusoidal signals or tones, modulating the carrier simultaneously or sequentially, is measured. The lowest frequency tone is used to remove the ambiguity, while the highest determines the range resolution. Highest modulating frequencies are typically about 1-10 MHz. However, this technique has the disadvantage of concentrating RF energy on spectrum lines and therefore its use may be difficult in some of the bands shared with services requiring protection defined in terms of a spectral power-density limit.

In the other case, the group delay of a pseudo-noise code, modulated on the carrier, is measured. Here the energy is spread over a band of some 1-10 MHz.

In both cases, after modulation of the carrier, the RF bandwidth is between about 2-20 MHz. Larger bandwidths might be used in the future.

The Doppler frequency shift (see Table II) must be added to these values.

3.2.3 Necessary bandwidth for data communications

The data rate of the auxiliary data is in the region of some tens of bit/s. This information may be multiplexed with ranging signals.

3.3 Usable frequency bands

Telecommunication systems for satellite geodesy and geodynamics are relevant to the space research service and to the earth exploration-satellite service. Furthermore, some systems operated by the radionavigation-satellite service can also be exploited for geodesy or geodynamics. An example of combined use of a radionavigation satellite system and VLBI technique for geodetic purpose is given in Annex IV.
Table III shows some of the frequency bands currently used or envisaged for satellite geodesy and geodynamics applications.

**TABLE III**  Frequency bands currently used or envisaged in satellite telecommunication systems for geodesy and geodynamics

<table>
<thead>
<tr>
<th>Frequency band (MHz)</th>
<th>Direction</th>
<th>Allocation</th>
</tr>
</thead>
<tbody>
<tr>
<td>149.9-150.05</td>
<td>Not specified</td>
<td>Radionavigation satellite</td>
</tr>
<tr>
<td>399.9-400.05</td>
<td>Not specified</td>
<td>Radionavigation satellite</td>
</tr>
<tr>
<td>401-403</td>
<td>Earth-to-space</td>
<td>Earth exploration satellite</td>
</tr>
<tr>
<td>1215-1260</td>
<td>Space-to-Earth</td>
<td>Radionavigation satellite</td>
</tr>
<tr>
<td>1559-1610</td>
<td>Space-to-Earth</td>
<td>Radionavigation satellite</td>
</tr>
<tr>
<td>2025-2110</td>
<td>Earth-to-space</td>
<td>Space research and earth exploration satellite</td>
</tr>
<tr>
<td>2200-2290</td>
<td>Space-to-Earth</td>
<td>Space research and earth exploration satellite</td>
</tr>
<tr>
<td>7190-7235</td>
<td>Earth-to-space</td>
<td>Space research</td>
</tr>
<tr>
<td>8025-8400</td>
<td>Space-to-Earth</td>
<td>Earth exploration satellite</td>
</tr>
<tr>
<td>8450-8500</td>
<td>Space-to-Earth</td>
<td>Space research</td>
</tr>
</tbody>
</table>

*Note.* — For geodesy and geodynamics purposes the bands allocated to the radionavigation-satellite service should only be for reception.

**REFERENCES**


ANNEX I
DORIS SYSTEM OF FINE POSITIONING AND TRACKING

1. Introduction

The DORIS system of fine positioning and tracking is being developed in France. It is intended to be used mainly for geodynamics and, in conjunction with a radar altimeter, for physical oceanography missions. Its first application is planned on the SPOT-2 satellite (1989) and subsequently on the TOPEX-POSEIDON satellite in 1992.

2. Technique and objectives

2.1 Principal mission

The DORIS system offers a means of precisely determining the orbit to any number of user satellites. It will comprise about 50 tracking beacons distributed uniformly around the Earth. These beacons will all emit the same signals with very high frequency stability for measurement purposes. Each beacon will also emit specific auxiliary data.

Each user satellite will carry receiving and measuring equipment, driven by a local oscillator, with very high frequency stability. This equipment will permit one-way measurement of the Doppler effect and the reception of auxiliary data from which the orbit will be derived.

2.2 Secondary mission

It is planned to install additional, geophysical beacons for studies of the movements of the Earth’s crust. These beacons will be placed in active seismic zones for durations of a few weeks. Since the satellite orbit is determined in the context of the principal mission, the positions of the geophysical beacons can be deduced from the Doppler effect measurements.

3. Technical characteristics

3.1 Frequency stability

The signals emitted and the signal of the receiver local oscillator should have a frequency stability, \( \Delta f / f \), of \( 10^{-12} \) per 500 s and of \( 10^{-10} \) per 24 h.

3.2 Frequency bands used

- Main link: 2025-2110 MHz,
- Ionospheric correction link: 401-403 MHz.

3.3 Auxiliary data

These data include the identification number of the beacon and meteorological information collected in situ which are used to correct the tropospheric measurement error. The data will be transmitted continuously at a rate of 200 bit/s and with a format of 0.8 s duration which repeats every 10 s.

3.4 Occupied bandwidths

The bandwidth of the signals transmitted by the beacons is 1 kHz on each of two frequencies. Owing to the Doppler effect, the necessary bandwidth of the satellite receivers is much wider (see, for example, Table II).

3.5 Link performance

With a transmitting power of 7 dBW at 400 MHz and 10 dBW at 2 GHz, and using hemispheric radiation pattern antennas on board and on the ground, the error due to total noise (thermal and interference noise) will be about 0.15 mm/s after processing, for an integration time of 10 s and a satellite distance of 1600 km. Noise due to interference from terrestrial stations is assumed to exceed thermal noise by 4 dB at 400 MHz and 7 dB at 2 GHz.
3.6 Accuracy

The system is designed so that the overall error of satellite-beacon range-rate measurement due to the
instrument (including ultra-stable oscillators), to interference and to propagation does not exceed 0.4 mm/s.

Depending on the application and the data processing method, the relative satellite-beacon equivalent
range measurement precision should be between 2 and 10 cm.

ANNEX II

PRECISE ORBIT POSITIONING SATELLITE (POPSAT)

1. Introduction

An active geodetic satellite system named POPSAT is currently being investigated comprising all elements
of an operational system for continuously monitoring the absolute and relative positions of points on the Earth’s
surface, the spin-axis motion and the Earth’s rotation rate. The essential elements of the system are: all-day,
all-weather self-tracking capability, data collection/transmission capability, ionospheric path delay correction
capability, possibility to serve unattended automated user stations, simultaneously tracking to four ground
transponders in the two-way mode, and unlimited access to orbit ephemeris for real-time positioning in
receive-only mode.

POPSAT is being studied for a launch in the early 1990s. Its mission is expected to permit determination
develop kinematics parameters and the absolute position of points with sub-decimetre accuracy. For relative
positioning (baseline determination), the achievable precision will be in the 2-3 cm range.

2. System description

The POPSAT system is conceived to comprise:

- a single satellite orbiting at a nominal altitude of 7000 km with an inclination of 98.6°, and
- a network of about 10-20 fixed ground terminals.

The spacecraft will have a mass of between 500 and 700 kg, and its principal payload is a microwave
tracking system for precise range and range-rate measurements performed in the 8 GHz and 2 GHz frequency
bands.

The system offers unlimited access by the world-wide community of geodesists and geophysicists by means
of transportable transceiver stations or simpler receive-only user terminals.

In order to achieve the geodetic objective mentioned above, the system is conceived for range and
range-rate accuracies of 10-20 cm and 0.1 mm/s, respectively.

A special feature of the system is that it allows for data transmission from the user stations to a
co-ordination centre via the tracking link.

POPSAT will also be equipped with a retro-reflector array as a target for laser-tracking stations. Since the
orbit of POPSAT can be predicted to a high degree of accuracy with the use of its microwave payload, the
addition of such a supplementary payload offers the possibility of geodetic laser tracking operations and of
contributing to orbit determination.
3. Frequency bands used

The range measurement is performed electronically by digital code correlation techniques. The actual parameter observed is the time shift measured in the spacecraft between an emitted code sequence and its received replica after two-way transmission, where the ground terminal acts as a transponder.

The carrier frequencies will be assigned either in the 7/8 GHz bands or in the 13/15 GHz bands. The spectral characteristics of these links are dominated by a digital NRZ modulation with a pseudo-random ranging code at a chip rate of 10 MHz, modulated in PSK, to achieve spectrum spreading over a bandwidth of 20 MHz. An auxiliary down link modulated with a 1 MHz PN pseudo-noise ranging code is foreseen in the 2 GHz band for ionospheric delay correction. This link is coherent in carrier and modulation with the 8 GHz down link. With transmitter powers of 5 W and 20 W for the down and up links, respectively, the nominal signal-to-noise density ratio ($S/N_0$) is about 66 dB(Hz); the system thus operates at receiver input $S/N$ ratios of −7 to −10 dB.

Since the transponder is of the regenerative type, a data code can be modulated on the same carrier together with the PN ranging signal.

BIBLIOGRAPHY


ANNEX III

GEOPOTENTIAL RESEARCH MISSION (GRM)

1. Mission description

The geopotential research mission (GRM), formerly known as GRAVSAT/MAGSAT, is being studied for launch in the early 1990s. The objective of the GRM is to determine the Earth's gravity and magnetic fields to provide accurate mathematical models for studies of the structure, composition and movement of the solid Earth and oceans, resource exploration, orbit determination, and navigation. GRM is expected to permit determination of the gravity field to 2 milligal, the geoid to 10 cm, with a 100 km horizontal resolution. Determination of the magnetic field anomaly map to 1 nanotesla (nT) with a 100 km resolution is expected.

2. System description

The GRM will consist of two spacecraft orbiting at a 160 km altitude and separated in orbit by about 300 km. The two spacecraft differ in that one of them (A1) will carry the magnetometers and the star cameras (required for precise measurement of the orientation of the magnetometers). The two spacecraft are alike with respect to the gravity field detection system. An interesting feature of the gravity measurement system is that the spacecraft themselves serve as the detecting instruments. The supporting instrumentation, the Doppler tracking, and the disturbance compensation system (DISCOS) measure the spacecraft response to the variations of the Earth's gravity field.

3. Spectrum considerations

3.1 Doppler tracking instrument

The Doppler frequency shift due to changes in the relative velocity between the two spacecraft will be measured at two frequencies, near 95 GHz and near 40 GHz. A continuous wave signal is radiated by the A1 spacecraft to the A2 spacecraft which receives it and compares it to an on-board signal. At the same time, the A2 spacecraft is radiating an incrementally frequency-shifted signal to the A1 spacecraft where it is compared. The resultant continuous comparison of the signals serves to measure the velocity changes to a precision of $10^{-4}$ m/s.
Command, telemetry, and tracking will use the TDRS multiple-access system which operates in band 9 (see Report 848). In addition, a ground-based precision Doppler tracking system will provide spacecraft-to-ground tracking data which will be processed in conjunction with the spacecraft-to-spacecraft tracking data to determine the gravity field. The ground-based Doppler tracking system operates in band 9.

ANNEX IV
THE JOINT USE OF RADIONAVIGATION SATELLITES AND VERY LONG BASELINE INTERFEROMETRY IN GEODESY

1. Introduction

The development of an accurate system of geodetic positions has become important for global geodesy. Very precise positioning techniques using Very Long Baseline Interferometry (VLBI) and satellites in the Global Positioning System (GPS) are used jointly in this document.

The VLBI technique uses extra-galactic radio sources and large aperture radio telescopes. The length of the VLBI baseline may be from 100 km to 10,000 km. The GPS technique uses a cluster of satellites and very small and portable receivers. The length of the GPS baseline ranges from 10 km to 1,000 km. To take advantage of the merits of each technique, the combined utilization of VLBI and GPS is important.

2. Combined utilization of VLBI and GPS

GPS geodesy, combined with accurate radio reference points established by use of VLBI, is expected to replace conventional ground-survey methods, particularly for global and precise applications.

VLBI techniques provide absolute baseline measurements for lengths exceeding 10,000 km, and by means of geodetic VLBI measurements, positions of VLBI antennas can be determined very accurately.

Geodetic measurements using GPS are relative, and in order to make them absolute, co-located measurements using both VLBI and GPS are needed.

The errors resulting from GPS orbital uncertainties are reduced by the simultaneous observations at VLBI reference points where position errors can be reduced to less than a few centimeters in a global coordinate system.

To calibrate the differences between receivers, it is essential that each receiver located at a VLBI reference point observe GPS under the same conditions. Thus, a large number of GPS receivers and a small number of VLBI stations can be used effectively.
Most sources of error in VLBI and GPS measurements can be classified, thermal noise errors, position errors of radio sources and errors due to atmospheric phase delay and instability [Kawaguchi, 1985; Sugimoto et al., 1987].

3. Examples of observational measurements

3.1 VLBI measurements

The r.m.s. error of VLBI measurements between the Kashima station and other stations are summarized in Table IV [1984-1989].

TABLE IV
Examples of VLBI measurements

<table>
<thead>
<tr>
<th>No</th>
<th>other stations</th>
<th>Baseline lengths</th>
<th>r.m.s. error of length</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>KAUAI</td>
<td>5 709 km</td>
<td>12.4 mm</td>
<td>Jul. 1984 ~ Jan. 1988</td>
</tr>
<tr>
<td>2</td>
<td>KWAJAL 26</td>
<td>3 936 km</td>
<td>12.8 mm</td>
<td>Jul. 1984 ~ Jan. 1987</td>
</tr>
<tr>
<td>3</td>
<td>WETZELL</td>
<td>8 475 km</td>
<td>18.8 mm</td>
<td>Jul. 1984 ~ Jan. 1988</td>
</tr>
<tr>
<td>4</td>
<td>VANDENBERG</td>
<td>7 813 km</td>
<td>20.2 mm</td>
<td>Jan. 1985 ~ Jan. 1988</td>
</tr>
<tr>
<td>5</td>
<td>MOJAVE 12</td>
<td>8 019 km</td>
<td>22.9 mm</td>
<td>Jan. 1984 ~ Jan. 1988</td>
</tr>
</tbody>
</table>

3.2 Combined use of VLBI and GPS measurements

Comparisons of repeated measurements by GPS and VLBI of baselines from Vandenberg to Mojave (351 km) and Vandenberg to Palos Verdes (223 km) have been made. The r.m.s. errors measured for the baselines from Vandenberg to Mojave were 7.5 mm for GPS and 7.1 mm for VLBI, and for Vandenberg to Palos Verdes were 10 mm for GPS and 8 mm for VLBI [Thornton et al., 1989].
REFERENCES


3. [1984-1989] - Data base of joint United States-Japan VLBI experiment under the NASA crustal dynamics project.

A. CHARACTERISTICS OF THE RADIO ASTRONOMY SERVICE

1. Introduction

The science of astronomy is concerned with the study of the Universe. With a few exceptions - neutrinos, cosmic rays, meteorites, particles ejected from the Sun, space probes - all the available information is conveyed by electromagnetic waves.

Radio astronomy and the radio astronomy service are defined in Article 1, Nos. 14, 55 and 91 of the Radio Regulations as being astronomy based upon the reception of cosmic radio waves. These cosmic emissions constitute the "cosmic background noise" of communications engineering. Being a passive service, radio astronomy does not involve the transmission of radio waves within its allocated bands, and therefore use of these bands cannot cause harmful interference to any other service. On the other hand, the cosmic signals received are extremely weak, and are very susceptible to harmful interference by transmissions of other services. At present radio astronomy utilizes the electromagnetic spectrum at frequencies from 1 MHz to well beyond the 400 GHz currently allocated by the Radio Regulations. In terms of the availability of technology, however, it could now operate over the entire radio spectrum.

Compared with optical astronomy, radio astronomy is a very young science. It began only in 1932 when Karl Jansky discovered the existence of radio waves of extra-terrestrial origin [Jansky, 1935]. However, it is now firmly established as an important branch of astronomy. It has increased our knowledge of the Sun and the physical processes responsible for the emissions of plasmas, and also of the planets and interplanetary space. On a larger scale, multi-frequency studies of cosmic sources of radio emission have provided information about interstellar gas clouds and the star formation within them, interstellar magnetic fields, and of the structure and evolution of galaxies and of the Universe as a whole. Spectral line emissions of atoms at naturally-occurring frequencies have provided information about the composition, physical characteristics, and motions of interstellar gas clouds. Aside from astronomy, the science has assisted telecommunications through studies of atmospheric absorption at radio frequencies, and of the major disturbances in the solar atmosphere. Such disturbances are often the forerunners of interruptions to radio communication circuits and of radiation hazards to man in space. Indeed, much of the information obtained by radio astronomers is unique because it cannot be obtained at optical or other wavelengths.
In addition to providing new knowledge, radio astronomy benefits the communications industry through developments in the specialized technology that helped to bring it into being. The continuing development of low noise amplifier techniques, extending to progressively higher frequencies and wider bandwidths, has led to the production of receiver systems with ever increasing sensitivity. Significant contributions are being made to the design of feed systems and large steerable antennas. The techniques of very long baseline interferometry (VLBI) are becoming more important for geodetic measurements of global distances, and for the accurate tracking of spacecraft. The development of very large scale integration (VLSI) chips to process the data collected by radio astronomy arrays provide a technology that has applications in other areas of electronics. The sophisticated image processing techniques that have been developed have direct application in the medical and mining areas.

The cosmic radio emissions have low power flux-density levels at the Earth. Most show no modulation other than that similar to random noise; exceptions are the pulsed emission at extremely regular rates (as high as 660 times per second) from pulsars, interplanetary and ionospheric scintillations of small-diameter radio sources, irregular bursts from some stars (including the Sun), variations on the scale of months for some radio sources, and variations (both periodic and bursts) associated with the planet Jupiter. The best times for observation of radio sources are generally dictated by natural phenomena (the position of the source in the sky and the rotation of the Earth). The radio astronomer cannot change the character of the "signal" to be received - neither can the transmitter power be increased nor the transmitted signal be coded in order to increase the detectability. Moreover, some astrophysically important interstellar molecules give rise to discrete line emissions which have frequencies other than those currently allocated to radio astronomy, causing radio astronomers to be faced with interference situations over which they have little control.

In the study of cosmic radio sources, the radio astronomer observes and measures all the properties of electromagnetic radiation. These are intensity, frequency, polarization, direction (i.e. position in the sky), and temporal variations of these parameters.

An allied science, radar astronomy, is a quite different activity; it is covered in Question 6/2 and Report 226. It involves the transmission of a signal at a high power-level, and the detection of the associated signal reflected from celestial bodies, or meteor trails.

2. Origin and nature of the emissions

2.1 The cosmic radio emissions are generated by several distinct mechanisms: thermal emission from hot ionized and neutral gas (interstellar gas clouds, hot envelopes of stars etc.), solid bodies, and the universal microwave background; non-thermal emission, mainly synchrotron radiation from relativistic electrons spiralling in a magnetic field, but including gyro-synchrotron and electron-cyclotron maser emission, as well as plasma emission resulting from the scattering of plasma waves; spectral-line radiation, resulting from changes in the energy states of individual interstellar atoms and molecules.

In the frequency domain, the processes result in two types of radiation - wideband continuum radiation and narrowband line emission or line absorption.

2.2 Continuum radiation

The largest class of radio sources are associated with continuum radiation, emission that extends relatively smoothly over most of the spectrum. In general non-thermal sources show an intensity decrease with increasing frequency, while thermal emission shows the opposite behaviour, although such characteristics can be affected by large optical depths.
Continuum emission surveys of the sky have revealed the existence of many discrete radio sources superimposed on a widespread background (see e.g. Report 720 of Study Group 5). The background shows a ridge of intense emission associated with the plane of our Galaxy (i.e. the Milky Way), with a marked maximum occurring in the direction of the galactic centre. In some directions, spurs of emission extend out from the plane. The background emission is generally non-thermal, but the ridge along the galactic equator contains a thermal contribution from extended ionized gas.

Most of the discrete sources are extra-galactic. These are mainly non-thermal, identified optically with galaxies and quasistellar radio objects ("quasars"), and are distributed more or less randomly over the sky. The remaining sources belong to our Galaxy, and are associated with regions of ionized gas (HI regions), supernova remnants (the expanding remains of exploded stars), some stars (including the Sun) and the planets. For the most part they are confined to within a few degrees of the galactic equator. HI regions and supernova remnants in nearby galaxies have also been observed.

2.2.1 Time variability of emission is relatively common. It can take the form of bursts which persist from seconds to hours, pulsating emission with repetition periods ranging from milliseconds to seconds, non periodic changes taking place over weeks or months, or periodic sinusoidal variations.

The radio bursts are most intense in the HF and VHF bands. The Sun is an outstanding source of short-period bursts of radio energy of many types, which yield important knowledge of the processes of both solar and plasma physics [McLean and Labrum, 1985]. The bursts arising from disturbances in the solar atmosphere may progressively increase in frequency during their lifetimes. Correlated radio and optical flares have also been detected from some types of stars. Jupiter is a source of large bursts of radio energy; they have been observed sporadically at frequencies below about 30 MHz [Roberts, 1963].

The pulsating emission of pulsars was discovered in 1967 [Hewish et al., 1968] and is believed to be radiation from stars composed entirely of neutrons (i.e. from matter in its most condensed state). With three exceptions the 400 or so detected pulsars are located in our Galaxy - three are believed to be in the Magellanic Clouds, the two galaxies closest to ours. The rotation of the neutron stars creates the pulses, but the radiation mechanism is uncertain [Taylor and Stinebring, 1986]. Pulsar periods as low as 1.5 msec have been observed. Pulsars have been identified with supernova remnants; the best case is the optical and radio pulsar in the Crab nebula. In general the pulses are remarkably regular, though periods have been measured which suddenly change, or are gradually increasing. The emissions are most easily observed in the frequency range 30 MHz - 15 GHz. Only for the few strongest pulsars is the detection of single pulses possible. For weak emission, pulse-averaging techniques with integration times of up to some hours are used to define the mean pulse profile. The pulses become dispersed during their passage to the observer, and measurement of the dispersion and Faraday rotation using observations at several frequencies provides information about electron densities and magnetic fields of the interstellar and interplanetary media. Pulse arrival time measurements, extending over some years, give not only information about the positions and proper motions of the pulsars (with an accuracy of 0.01 arcsec in position), but also about the long-term stability of the pulsar periods. These may become the standard clocks for our time services.

Some radio sources, in particular quasars, show radio emission variability on a time-scale of weeks. The radio emission of others such as supernovae, novae and X-ray sources changes in step with variations in optical brightness.

Jupiter displays a special form of variability. In addition to the bursts mentioned previously, and the constant thermal emission from the disk, the planet has magnetospheric van Allen belts which give rise to non-thermal synchrotron emission concentrated towards the equator of the belts. Because the magnetic axis is offset from the rotational axis, the intensity of the non-thermal emission observed at the Earth varies sinusoidally as the planet rotates.
The Earth's ionosphere and the interplanetary medium of the solar system can cause the observed radio emission from sources of small angular size to scintillate. The rate of scintillation can be as high as several Hz. The observed characteristics of the high-frequency scintillation provide information about the source size as well as the clumpiness and motions of the interplanetary medium. There is also evidence that some pulsar emission is modified by interstellar scintillation.

2.2.2 Observations of radio continuum emission. To establish the frequency dependence of the radio emission (i.e., its "spectral index"), observations of the intensity are required at a number of frequencies. Because the spectrum of the continuum emission is usually quite smooth, such observations are not required at specific or closely-spaced frequencies; frequencies selected approximately at octave intervals are adequate. However, for some observations of sources showing self-absorption, of novae and pulsars, and of source polarization—more closely spaced intervals may be desirable. The sensitivity of observation is increased by the use of large bandwidths at each frequency. Where it is possible radioastronomers observe wider bands than those allocated to radio astronomy, in order to increase the sensitivity of their continuum measurements.

The continuum radiation from many extragalactic sources and non-thermal regions associated with the galactic plane (including both the background and supernova remnants) is partially linearly polarized. The intrinsic direction of polarization is perpendicular to the orientation of the source's magnetic field projected onto the plane of the sky. However, the observed direction is changed by Faraday rotation caused by line-of-sight electrons in magnetic fields. Polarization studies over a range of frequencies can be used to calculate the Faraday rotation, and hence the magneto-ionic conditions in the radio source and intervening interstellar medium and terrestrial ionosphere. For some lines-of-sight the galactic Faraday rotation is very high, and for observations below about 2 GHz frequencies more closely spaced than at octave intervals are desirable.

The detailed structure of radio sources can provide insight into how the radio emission is generated. Apart from the use of the special circumstances in which a source is occulted by the moon or a planet, high-detail mapping requires large radio astronomy systems (arrays). A system capable of producing detail with an angular resolution of a few seconds of arc must have the dimensions of around 100 000 wavelengths. Finer detail can be achieved using VLBI arrays, with antennas located thousands of kilometres apart in different countries or in Earth orbit. Because all antennas of a VLBI array must operate at the same frequency, world-wide protection of such frequencies is needed to ensure that no transmitter will produce interference in the output of any antenna.

Several phenomena of astrophysical interest are observable only at frequencies of 30 MHz and lower. Free-free absorption in ionized regions of the Galaxy, self-absorption in radio galaxies and quasars, and low-frequency emission from tenuous plasmas in clusters of galaxies are a few requiring extensive investigation.

The frequency bands allocated to the radio astronomy service in accordance with the Final Acts of the World Administrative Radio Conference, Geneva, 1979, represent a significant improvement over previous allocations to the service. The bands considered important for continuum measurements are listed in Table I. However, the present allocations are only a partial fulfillment of the requirements of the service, because many of the allocated bandwidths are too small, many bands are shared with non-passive services, and many allocations apply only to limited areas of the world.
TABLE I — Frequency bands allocated to the radioastronomy service that are preferred for continuum observations
(Secondary allocations are contained within brackets)

<table>
<thead>
<tr>
<th>Frequency band (MHz)</th>
<th>Bandwidth (%)</th>
<th>Frequency band (GHz)</th>
<th>Bandwidth (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.360-13.410</td>
<td>0.37</td>
<td>10.6-10.7</td>
<td>0.94</td>
</tr>
<tr>
<td>25.550-25.670</td>
<td>0.49</td>
<td>15.35-15.4</td>
<td>0.33</td>
</tr>
<tr>
<td>(37.5-38.25)</td>
<td>(1.98)</td>
<td>22.21-22.30</td>
<td>1.30</td>
</tr>
<tr>
<td>73-74.6 (1)</td>
<td>2.17</td>
<td>23.6-24.0</td>
<td>1.68</td>
</tr>
<tr>
<td>150.05-153 (2)</td>
<td>1.95</td>
<td>31.3-31.8</td>
<td>1.58</td>
</tr>
<tr>
<td>322-328.6</td>
<td>2.03</td>
<td>42.5-43.5</td>
<td>2.33</td>
</tr>
<tr>
<td>406.1-410</td>
<td>0.96</td>
<td>86-92</td>
<td>6.74</td>
</tr>
<tr>
<td>608.614 (2)</td>
<td>0.98</td>
<td>105-116</td>
<td>9.95</td>
</tr>
<tr>
<td>1400-1427</td>
<td>1.91</td>
<td>164-168</td>
<td>2.41</td>
</tr>
<tr>
<td>1660-1670</td>
<td>0.60</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2690-2700 (2655-2690)</td>
<td>0.37 (1.31)</td>
<td>217-231</td>
<td>6.25</td>
</tr>
<tr>
<td>4990-5000 (4800-4990)</td>
<td>0.20 (3.38)</td>
<td>265-275</td>
<td>3.70</td>
</tr>
</tbody>
</table>

(1) Allocation (primary) in Region 2, protection recommended in Regions 1 and 3.
(2) Allocation (primary) in Region 1, Australia and India.
(*) Allocation (primary) in Region 2, China and India.

2.3 Spectral line radiation

Line radiation is produced by atoms and molecules in interstellar gas clouds when they lose or gain energy due to collisions with other particles, or are radiatively excited by nearby stars. For a particular atom or molecule the "transitions" between energy states results in a series of discrete narrow spectral lines. The relative strengths, frequencies and widths of the lines are set by nature, depending on the molecules in question, their density, temperature and line-of-sight velocity. In some circumstances however the line strength can be greatly increased by maser action. Spectral lines can also be observed in absorption when molecules selectively absorb the radiation from a source of continuum emissions viewed through the gas cloud.

Although the intrinsic ("rest") frequency of a spectral line is defined by both the specific molecule and the specific transition, it is Doppler-shifted according to the radial velocity of the molecule relative to the observer. For large velocities the observed frequency may be significantly displaced from the intrinsic value, even to the extent of being beyond the limits of a spectral band allocated to protect the particular molecular-line observations.

2.3.1 Types of spectral lines.

"Recombination" lines are emitted by atoms of hydrogen, helium, carbon etc. when their electrons move from one orbit to another under different conditions of atomic excitation. The first recombination lines from space were discovered in 1964 by radio astronomers in the U.S.S.R. [Sorotchenko et al., 1964]. The lines are numerous and spread throughout the radio spectrum [Lilley and Palmer, 1968]; many are located in bands allocated for continuum observations or observations of other lines. Observations of the strengths and shapes of these lines enable radio astronomers to determine the physical conditions in the gas regions (usually ionized) where the lines originate.
Many emission and absorption lines arising in interstellar gas clouds, and identified with neutral atomic hydrogen and inorganic and organic molecules, have frequencies within the radio spectrum. The first detection, the hyperfine spin-flip transition of hydrogen near 1420 MHz, occurred in 1951 [Ewen and Purcell, 1951]. Neutral atomic hydrogen is so abundant and is distributed so widely throughout our Galaxy and many other galaxies that the 1 420 MHz ("21 cm") line is of fundamental importance in studying the interstellar gas in these galaxies. However, because of the high recession velocities of distant galaxies the spectral line is Doppler-shifted ("red-shifted") to frequencies below the lower limit of the protected radio astronomy band of 1 400 - 1 427 MHz. In fact, the line has been observed at frequencies as low as 500 MHz.

It was not until 1963 that the first molecular line was detected at radio frequencies [Weinreb et al., 1963], and a further five years passed before other molecules were detected. Since then, many hundreds of transitions have been observed for complex interstellar molecules and their isotopes. Lovas [1986] lists the detected transitions for 59 species in the frequency range 0.7 to 344 GHz. It is realized that all of these lines cannot be afforded protection in the Radio Regulations by frequency allocation, but protection should be sought for those lines which are considered astrophysically most important (see section 4.3).

The molecular lines arise in differing relative abundances from several types of interstellar gas cloud - diffuse low-density clouds, isolated cool dark clouds containing molecules that are unstable on Earth, and sometimes containing protostars, and giant dense molecular clouds with HII regions, hot young stars, and stars being formed. The clouds contain a substantial fraction of the total mass of the Galaxy. Studies of the spectral lines provide information not only about these clouds, but also about the processes of star formation and the spiral structure and chemical evolution of our Galaxy and other galaxies. Given sufficient sensitivity and angular resolution, similar properties of other galaxies can also be investigated.

2.3.2 Observations of spectral lines

Although the astrophysical interpretation may differ, there are certain common properties of spectral lines. The observed line profile defines an intensity variation as a function of frequency. The observed frequency of the line emission (or absorption) will be shifted from the natural rest frequency according to the motion relative to the observer along the line-of-sight. Turbulent motions within the gas cloud will also broaden the observed profile. The frequency shifts are usually converted to radial velocity units. In a sense the velocity data provides a third dimension to supplement the projected distribution of the cloud on the sky. Some spectral line sources, in particular maser sources, also show polarization, which provides information on the magnetic field in the gas cloud.

The profile intensity at a specific frequency depends on the temperature, column density, and optical depth of the molecular cloud at a specific velocity. Separation of these parameters can be effected in two ways: for spectra containing components due to hyperfine transitions, from a comparison of the components; or from a comparison of different transitions for the same molecule. The latter technique is adopted for the determination of interstellar isotope abundance ratios.

Integration times of many hours are sometimes required to obtain the signal-to-noise ratios necessary to form conclusions of astrophysical interest. Freedom from harmful interference is necessary over bandwidths which include the broadening and Doppler shifting effects together with comparison bands bordering the line emission.

The bands considered important for spectral line observations are listed in Tables II and III (see section 4.3). Annex I of Report 852 (Dubrovnik, 1986) describes some typical types of spectral line observations (for four common atoms and molecules) being carried out at observatories throughout the world. It describes the kinds of observations that are made, the variety of results obtained, and how radio spectroscopy contributes to an understanding of the nature of the Universe.
2.4 Summary

This outline of the nature of radio signals in radioastronomy shows two general facts. First, there is a wide variety of phenomena to be studied over the whole accessible range of radio frequencies. Second, the science is still growing at a rapid rate and enormously increasing our knowledge. These two facts demonstrate clearly the difficulties which face both the astronomer and the frequency allocation authorities in their search for the best solution to the problem of achieving the right degree of protection for the radioastronomy service.

3. Details of radioastronomy observatories

Appendix 3 (Section F) of the Radio Regulations describes the information on observatories and on the observations in progress or planned, which administrations should furnish to the IFRB for incorporation in the Master International Frequency Register. This information is published by the ITU from time to time, in the form outlined in the revision of Appendix 9 of the Radio Regulations (List VIII A). Collected information and the activities of radioastronomy and radar observatories can be obtained upon application to the Committee on Radio Frequencies, National Academy of Sciences, 2101 Constitution Avenue, NW, Washington DC, USA. This publication is intended to list radioastronomy stations of all countries and is revised from time to time to include information that has been provided by national radioastronomy organizations or observatories.

B. PREFERRED FREQUENCY BANDS

4. Frequency considerations of the radioastronomy service

4.1 General considerations

The choice of wavelength for astronomical observations naturally depends on the phenomena to be observed, but it may also be strongly influenced by the Earth's atmosphere (troposphere and ionosphere). The ionosphere strongly affects astronomical observations below 20 MHz; measurements suggest that the lowest practical frequency for ground-based observation is 1.5 MHz (see Report 699). The troposphere affects observations by absorption, primarily by oxygen and water vapour. The attenuation due to resonances of these molecules is shown schematically in Fig. 1 (Fig. 4 of Report 719, Dubrovnik, 1986). The effects of other atmospheric constituents, for example, CO, NO, NO$_2$, are negligible.

The curve in Fig. 1 shows the total one-way absorption in the vertical direction for an atmosphere with water vapour concentration of 7.5 g/m$^3$ at the Earth's surface. This curve is based partly on theoretical calculations and partly on measurements. The model atmosphere adopted is one in which the water vapour concentration decreases exponentially with increasing height, the scale height being 2 km. Thus, the effects of absorption can be reduced by choosing observing sites at high altitudes. Figure 2 shows the total zenith attenuation for a high altitude site (Mauna Kea, Hawaii) with water vapour concentration 0.75 g/m$^3$ and from an aircraft at an elevation of 12 500 m (water vapour concentration 0.003 g/m$^3$) [JPL, 1978].

Radioastronomers are pioneers in the use of frequencies above 100 GHz. Observations have been made above 300 GHz but the preferred frequencies have not yet been fully identified.
FIGURE 1 - Total zenith attenuation

Pressure: 1 atm
Temperature: 20°C at ground level
Water vapour: 7.5 g/m³
FIGURE 2 - Vertical atmospheric attenuation for precipitable water vapour of 1.5 mm
(0.75 g/m$^3$ at the surface)
(dashed curve - Mauna Kea, Hawaii) and 6 μm (0.003 g/m$^3$ at the surface)
(solid curve - aircraft)
4.2 Continuum observations

One purpose of continuum observations in radioastronomy is to define the frequency variation of the radiation in sufficient detail to draw conclusions concerning the physical mechanisms responsible. The experience has been that observations in each octave of the spectrum are, in general, adequate for this purpose although closer spacings may be needed for some specialized types of observation (see § 2.2). The set of observations spaced in frequency by factors of approximately 2 should extend from the lowest frequency to the highest frequency at which ground-based observations are possible; that is, from about 1.5 MHz (see Report 699) to beyond the 275 GHz limit of the frequency allocations in the Radio Regulations. At frequencies above 20 GHz the need to avoid the maxima in atmospheric absorption due to O\(_{1}\) and H\(_{2}O\) must take precedence over the desire to maintain the octave spacing. Thus, frequencies for continuum observations must be chosen to lie within the atmospheric absorption minima near 30 GHz, 90 GHz, 150 GHz, 240 GHz, 340 GHz, 410 GHz, 470 GHz, 670 GHz and 850 GHz.

In Report 224, equation (3), it is shown that for continuum observations, the minimum detectable signal is inversely proportional to the square root of the bandwidth. Therefore, in the absence of interference, radioastronomers can profit from the widest bandwidth that can be used without degradation of receiver noise temperature. Wider bandwidths and consequent better sensitivities lead to improved efficiency in the use of major astronomical instruments.

Table I gives a list of bands allocated to the radioastronomy service that are preferred for continuum observations. The nature of the protection accorded radioastronomy is not the same in each of these bands and in some cases is considered inadequate to permit full use of the band by radioastronomers. The sharing problems are considered in Report 696. However, the array of bands listed if they had adequate protection would satisfy most of radioastronomy requirements for frequency coverage. The exceptions are that the allocations at 13 MHz and 25 MHz do not meet the bandwidth criterion and the interval between 74 MHz and 322 MHz, while adequately covered in Region 1 with the band at 150 MHz, has no recognized frequency bands in Regions 2 and 3. In addition the bandwidths of the primary allocations at 2695 MHz and 4995 MHz are much too narrow. Also there is no band listed below 13 MHz. Report 699 specifies 1.5 MHz as the low frequency limit for ground-based radioastronomy. Thus there are 2 octaves below 13 MHz in which ground-based radioastronomy observations are possible but in which radioastronomy has not been recognized in the Radio Regulations.

4.3 Spectral line observations

Spectral line observations must be made at the specific frequency or frequencies set by nature for the spectral emission of the atoms or molecules of interest. Those lines which are considered of greatest astrophysical importance are listed in Tables II and III and also in Recommendation 314. These most important lines were selected by members of the International Astronomical Union [IAU, 1989] from among the hundreds of lines from interstellar space which have been observed. Table III, which lists lines above 275 GHz, will undoubtedly need modification as astronomers explore this newly-opened region of the radio spectrum. The bandwidths required for observations of the lines in both tables are determined by Doppler frequency shifts in the rest frequencies of the lines caused by the velocity of the emitting region relative to that of the observer on Earth. The velocity range is ± 300 km/s for sources within our own galaxy which can be accommodated by ± 0.1% of the rest frequency. For extra-galactic sources, velocities of +1000 km/s and —300 km/s require band limits of —0.33% to +0.1%.

An examination of the Frequency Allocation Table of the Radio Regulations reveals that most bands listed in Table I of Recommendation 314 have been recognized in the Radio Regulations as being of astronomical interest. In many cases, the recognized bandwidths are at least the equal of those specified in the table although little or no protection may be accorded by the recognition. For the hydroxyl lines at 1612 MHz and 1720 MHz, the three CH lines near 3300 MHz, the formaldehyde line at 4830 MHz, and the water vapour line at 22.235 GHz, the recognized bandwidths are adequate for observations within our own galaxy but do not show the downward extension of the lower frequency limit as required for observations of distant galaxies as shown in Table II.

Most detectable spectral lines are afforded no protection by the Radio Regulations. With increased use of the spectrum by various services the observation of many of these lines will be precluded. This is particularly true for lines in bands allocated to services with transmissions from satellites. Examples are the 1612 MHz line of hydroxyl, the 12.1 GHz line of methanol, the 18.3 GHz line of cyclopropenylidene and the 22.8 and 23.0 GHz lines of ammonia. (See Report 696 for background information and Report 697 for a discussion of the problem of geostationary satellite transmissions.)
<table>
<thead>
<tr>
<th>Substance</th>
<th>Rest frequency</th>
<th>Suggested minimum Band</th>
<th>Notes(1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deuterium (D)</td>
<td>327.384 MHz</td>
<td>327.0 - 327.7 MHz</td>
<td>(2), (3)</td>
</tr>
<tr>
<td>Hydrogen (H)</td>
<td>1420.406 MHz</td>
<td>1370.0 - 1427.0 MHz</td>
<td>(2), (3)</td>
</tr>
<tr>
<td>Hydroxyl radical (OH)</td>
<td>1612.231 MHz</td>
<td>1580.0 - 1613.8 MHz</td>
<td>(2), (3)</td>
</tr>
<tr>
<td>Hydroxyl radical (OH)</td>
<td>1660.718 MHz</td>
<td>1658.0 - 1665.8 MHz</td>
<td>(3)</td>
</tr>
<tr>
<td>Hydroxyl radical (OH)</td>
<td>1667.359 MHz</td>
<td>1661.8 - 1669.0 MHz</td>
<td>(4)</td>
</tr>
<tr>
<td>Hydroxyl radical (OH)</td>
<td>1720.530 MHz</td>
<td>1714.8 - 1722.2 MHz</td>
<td>(3), (4)</td>
</tr>
<tr>
<td>Methylidyne (CH)</td>
<td>3223.794 MHz</td>
<td>3217.9 - 3227.1 MHz</td>
<td>(3), (4)</td>
</tr>
<tr>
<td>Methylidyne (CH)</td>
<td>3335.481 MHz</td>
<td>3324.4 - 3338.8 MHz</td>
<td>(3), (4)</td>
</tr>
<tr>
<td>Methylidyne (CH)</td>
<td>3349.193 MHz</td>
<td>3338.0 - 3352.5 MHz</td>
<td>(3), (4)</td>
</tr>
<tr>
<td>Formylium (HCO+)</td>
<td>72.039 GHz</td>
<td>71.96 - 72.11 GHz</td>
<td>(3)</td>
</tr>
<tr>
<td>Silicon monoxide (SiO)</td>
<td>42.821 GHz</td>
<td>42.77 - 42.86 GHz</td>
<td>(3)</td>
</tr>
<tr>
<td>Silicon monoxide (SiO)</td>
<td>43.122 GHz</td>
<td>43.07 - 43.17 GHz</td>
<td>(3)</td>
</tr>
<tr>
<td>Carbon monosulphide (CS)</td>
<td>48.991 GHz</td>
<td>48.94 - 49.04 GHz</td>
<td>(3)</td>
</tr>
<tr>
<td>Deuterated formylium (DCO+)</td>
<td>72.039 GHz</td>
<td>71.96 - 72.11 GHz</td>
<td>(3)</td>
</tr>
<tr>
<td>Silicon monoxide (SiO)</td>
<td>86.243 GHz</td>
<td>86.16 - 86.33 GHz</td>
<td>(3)</td>
</tr>
<tr>
<td>Formylium (H13CO+)</td>
<td>86.754 GHz</td>
<td>86.66 - 86.84 GHz</td>
<td>(4)</td>
</tr>
<tr>
<td>Ethynyl radical (C2H)</td>
<td>87.3 GHz</td>
<td>87.21 - 87.39 GHz</td>
<td>(5)</td>
</tr>
<tr>
<td>Hydrogen cyanide (HCN)</td>
<td>88.632 GHz</td>
<td>88.34 - 88.72 GHz</td>
<td>(4)</td>
</tr>
<tr>
<td>Formylium (HCO+)</td>
<td>89.189 GHz</td>
<td>88.89 - 89.28 GHz</td>
<td>(4)</td>
</tr>
<tr>
<td>Hydrogen isocyanide (HNC)</td>
<td>90.664 GHz</td>
<td>90.57 - 90.76 GHz</td>
<td>(4)</td>
</tr>
<tr>
<td>Diazenylium (N2H+)</td>
<td>93.174 GHz</td>
<td>93.07 - 93.27 GHz</td>
<td>(4)</td>
</tr>
<tr>
<td>Carbon monosulphide (CS)</td>
<td>97.981 GHz</td>
<td>97.65 - 98.08 GHz</td>
<td>(4)</td>
</tr>
<tr>
<td>Carbon monoxide (C18O)</td>
<td>109.782 GHz</td>
<td>109.57 - 109.89 GHz</td>
<td>(4)</td>
</tr>
<tr>
<td>Carbon monoxide (13CO)</td>
<td>110.201 GHz</td>
<td>109.83 - 110.31 GHz</td>
<td>(4)</td>
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<tr>
<td>Carbon monoxide (17CO)</td>
<td>112.359 GHz</td>
<td>112.25 - 112.47 GHz</td>
<td>(6)</td>
</tr>
<tr>
<td>Carbon monoxide (CO)</td>
<td>115.271 GHz</td>
<td>114.88 - 115.39 GHz</td>
<td>(4)</td>
</tr>
<tr>
<td>Formaldehyde (H213CO)</td>
<td>137.450 GHz</td>
<td>137.31 - 137.59 GHz</td>
<td>(3), (6)</td>
</tr>
<tr>
<td>Formaldehyde (H2CO)</td>
<td>140.840 GHz</td>
<td>140.69 - 140.98 GHz</td>
<td>(3), (6)</td>
</tr>
<tr>
<td>Carbon monosulphide (CS)</td>
<td>146.969 GHz</td>
<td>146.82 - 147.12 GHz</td>
<td>(4)</td>
</tr>
<tr>
<td>Water vapour (H2O)</td>
<td>183.310 GHz</td>
<td>183.12 - 183.50 GHz</td>
<td>(4)</td>
</tr>
<tr>
<td>Carbon monoxide (C18O)</td>
<td>219.560 GHz</td>
<td>219.34 - 219.78 GHz</td>
<td>(4)</td>
</tr>
<tr>
<td>Carbon monoxide (13CO)</td>
<td>220.399 GHz</td>
<td>219.67 - 220.62 GHz</td>
<td>(4)</td>
</tr>
<tr>
<td>Carbon monoxide (CO)</td>
<td>220.538 GHz</td>
<td>220.17 - 220.77 GHz</td>
<td>(4)</td>
</tr>
<tr>
<td>Carbon monosulphide (CS)</td>
<td>244.953 GHz</td>
<td>244.72 - 245.20 GHz</td>
<td>(6)</td>
</tr>
<tr>
<td>Hydrogen cyanide (HCN)</td>
<td>265.886 GHz</td>
<td>265.62 - 266.15 GHz</td>
<td>(6)</td>
</tr>
<tr>
<td>Formylium (HCO+)</td>
<td>267.557 GHz</td>
<td>267.29 - 267.83 GHz</td>
<td>(6)</td>
</tr>
<tr>
<td>Hydrogen isocyanide (HNC)</td>
<td>271.981 GHz</td>
<td>271.71 - 272.25 GHz</td>
<td>(6)</td>
</tr>
</tbody>
</table>
(4) If Notes (*) or Note (‡) are not listed, the band limits are the Doppler-shifted frequencies corresponding to radial velocities of ± 300 km/s (consistent with line radiation occurring in our galaxy).

(2) An extension to lower frequency of the allocation of 1400-1427 MHz is required to allow for the higher Doppler shifts for HI observed in distant galaxies.

(‡) The current international allocation is not primary and/or does not meet bandwidth requirements. See the Radio Regulations for more detailed information.

(4) Because these line frequencies are also being used for observing other galaxies, the listed bandwidths include Doppler shifts corresponding to radial velocities of up to 1000 km/s. It should be noted that HI has been observed at frequencies redshifted to 500 MHz, while some lines of the most abundant molecules have been detected in galaxies with velocities of 50,000 km/s, corresponding to a frequency reduction of up to 17%.

(5) There are six closely spaced lines associated with this molecule at this frequency. The listed band is wide enough to permit observations of all six lines.

(8) This line frequency is not mentioned in Article 8 of the Radio Regulations.

<table>
<thead>
<tr>
<th>Substance</th>
<th>Rest frequency (GHz)</th>
<th>Suggested minimum band (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diazenylium (N₂H⁺)</td>
<td>279.511 GHz</td>
<td>279.23 - 279.79 GHz</td>
</tr>
<tr>
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<td>329.330 GHz</td>
<td>329.00 - 329.66 GHz</td>
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<tr>
<td>Carbon monoxide (¹³CO)</td>
<td>330.587 GHz</td>
<td>330.25 - 330.92 GHz</td>
</tr>
<tr>
<td>Carbon monosulphide (CS)</td>
<td>342.883 GHz</td>
<td>342.54 - 343.23 GHz</td>
</tr>
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<td>Carbon monoxide (CO)</td>
<td>345.796 GHz</td>
<td>345.45 - 346.14 GHz</td>
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<tr>
<td>Hydrogen cyanide (HCN)</td>
<td>354.484 GHz</td>
<td>354.13 - 354.84 GHz</td>
</tr>
<tr>
<td>Formylium (HCO⁺)</td>
<td>356.734 GHz</td>
<td>356.37 - 357.09 GHz</td>
</tr>
<tr>
<td>Diazenylium (N₂H⁺)</td>
<td>372.672 GHz</td>
<td>372.30 - 373.05 GHz</td>
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<tr>
<td>Water vapour (H₂O)</td>
<td>380.197 GHz</td>
<td>379.81 - 380.58 GHz</td>
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<tr>
<td>Carbon monoxide (C¹⁸O)</td>
<td>439.088 GHz</td>
<td>438.64 - 439.53 GHz</td>
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<tr>
<td>Carbon monoxide (¹³CO)</td>
<td>440.765 GHz</td>
<td>440.32 - 441.21 GHz</td>
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<td>Carbon monoxide (CO)</td>
<td>461.041 GHz</td>
<td>460.57 - 461.51 GHz</td>
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<td>Heavy water (HDO)</td>
<td>464.925 GHz</td>
<td>464.46 - 465.39 GHz</td>
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<tr>
<td>Carbon (Cl)</td>
<td>492.162 GHz</td>
<td>491.66 - 492.66 GHz</td>
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<tr>
<td>Water vapour (H₂¹⁸O)</td>
<td>547.676 GHz</td>
<td>547.13 - 548.22 GHz</td>
</tr>
<tr>
<td>Water vapour (H₂O)</td>
<td>556.936 GHz</td>
<td>556.37 - 557.50 GHz</td>
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<tr>
<td>Ammonia (¹⁵NH₃)</td>
<td>572.113 GHz</td>
<td>571.54 - 572.69 GHz</td>
</tr>
<tr>
<td>Ammonia (NH₃)</td>
<td>572.498 GHz</td>
<td>571.92 - 573.07 GHz</td>
</tr>
<tr>
<td>Hydrochloric acid (HCl)</td>
<td>625.918 GHz</td>
<td>625.29 - 626.54 GHz</td>
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<tr>
<td>Carbon monoxide (CO)</td>
<td>691.473 GHz</td>
<td>690.78 - 692.17 GHz</td>
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<tr>
<td>Hydrogen cyanide (HCN)</td>
<td>797.433 GHz</td>
<td>796.64 - 798.23 GHz</td>
</tr>
<tr>
<td>Formylium (HCO⁺)</td>
<td>802.653 GHz</td>
<td>801.85 - 803.46 GHz</td>
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<td>Carbon monoxide (CO)</td>
<td>806.652 GHz</td>
<td>805.85 - 807.46 GHz</td>
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<tr>
<td>Carbon (Cl)</td>
<td>809.350 GHz</td>
<td>808.54 - 810.16 GHz</td>
</tr>
</tbody>
</table>
REFERENCES


McLEAN, D.J. and LABRUM, N.R. [1985] - Studies of the sun at metre wavelengths [Cambridge University Press]


IONOSPHERIC LIMITATIONS TO GROUND-BASED RADIOASTRONOMY BELOW 20 MHz

(Question 5/2)

(1978-1982-1986)

1. Introduction

Although some of the first discoveries of galactic radio emission were made at decametre wavelengths, there has been a general progression in radio astronomy to measurements at shorter wavelengths. The high resolution attainable with paraboloidal antennas at the shorter wavelengths, the development of low noise pre-amplifiers and the succession of important discoveries at the higher frequencies have contributed to this trend.

There are, however, many phenomena of astrophysical interest which manifest themselves only at the longer radio wavelengths. "Free-free" absorption in ionized regions of the galaxy, self-absorption in extra-galactic radio sources, low-frequency emission mechanisms from tenuous plasmas in clusters of galaxies are some phenomena which require extensive investigation. To date (1985), extensive astronomical measurements below 20 MHz have been limited to a few source surveys [Bridle and Purton, 1968; Braude et al., 1969, 1978, 1979] with resolutions of one-half degree to a few degrees; measurements of galactic background emission [Ellis and Hamilton, 1966; Reber, 1968; Caswell, 1976; Cane, 1979] with resolutions of several degrees; and observations of the strong decametric bursts from Jupiter [Ellis, 1975]. The angular resolution of radio telescopes which have been used or are in use below 100 MHz, is summarized in Fig. 1.

The lack of high resolution instruments below 20 MHz is evident. There are three main technical reasons which account for this:

- antennas of several kilometres extent are required for resolution better than 1°. Dotted lines in Fig. 1 illustrate the resolution attainable with apertures of 3, 10, and 30 km width;
- conditions in the Earth's ionosphere vary with time of day, time of year, and solar activity. Observation is possible only when the electron density in the F-region is sufficiently low and relatively free of irregularities on the kilometre scale;
- there are no exclusive frequency allocations for radioastronomy below 20 MHz. World radio communications make extensive use of these frequencies for propagation via ionospheric reflections. For this reason it is extremely difficult to find radioastronomy sites on the Earth isolated from interfering signals. It is significant that the few ground-based measurements made below 10 MHz have been made from Tasmania which, with regard to freedom from interference, is an advantageous location.
FIGURE 1 — Resolution of fixed-frequency radio telescopes in current and past use
(Dotted lines indicate attainable resolution)

- fixed frequency  — broadband

The telescopes are described in the following references:

**Fixed frequency telescopes**

- Culgoora 80 MHz: See Culgoora 43 MHz.

**Broadband telescopes**

On the basis of measurements made between 1962 and 1964, Ellis and Hamilton [1966] suggest 1.5 MHz as a practical lower limit to ground-based measurements. The following sections contain an examination of the ionospheric factors which limit observations below 20 MHz and an assessment of the feasibility of observations both with and without interference from users of the allocated communication bands.

The ionosphere is a dynamic part of the atmosphere tied very closely to solar activity. Observations below 20 MHz made under disturbed ionospheric conditions cannot yield data of astronomical value. Hence, subsequent sections deal primarily with quiescent conditions such as usually prevail during the 4 to 5 years around sunspot minimum. From recent predictions of sunspot activity [Lamb and Andersen, 1980] the years 1984 to 1988 and 1995 to 1999 should be periods of relatively quiescent conditions. In addition, emphasis is placed on the night-time ionosphere (F layer only) when the electron density has dropped well below its daytime maximum. Observations are possible at other times but suitable conditions occur much less frequently.

2. Geographical limitations

The distribution of ionization at any time of year is strongly dependent upon latitude. This is due in part to the incident solar radiation at a given latitude, and in part to the Earth's geomagnetic field. Lines of constant geomagnetic latitude often form the boundaries between disturbed and quiet regions in the ionosphere (see Report 263). Both geographic and geomagnetic latitudes are important for a detailed consideration of the ionosphere above any site, but it is sufficient for the purposes of this Report to use the term latitude to refer to a rough mean of the two.

The ionosphere, both in the equatorial region (latitude < 30°) and in the polar-auroral zones (latitude > 60°) is known to be more subject to disturbed conditions than at mid-latitudes. A broad minimum in the F-region electron density of the night-time ionosphere near latitude 55° was detected many years ago [Reber and Ellis, 1956], and has been well documented with top-side sounding [Muldrew, 1965] and other techniques [Sharp, 1966; Liszka, 1967]. As we are primarily interested in optimum observation conditions at low frequencies, attention will be confined to the mid-latitude region. This is not to imply that useful radioastronomy cannot be pursued outside this range but simply that the probability at any time of encountering acceptable observing conditions is significantly higher at mid-latitudes.

3. Propagation through the ionosphere

Ground-based radioastronomical observations can be made only when propagation through the ionosphere is possible. The minimum frequency for which such transmission occurs is determined by the maximum value of the electron density. In a quiescent ionosphere this maximum usually occurs in the F region at a height of about 300 km.

Wavefronts impinging vertically on the ionosphere will penetrate if the index of refraction remains greater than zero along the path. Because of the Earth's magnetic field, two component parts of a wave, possessing elliptical polarizations of opposite sense, propagate with different refractive indices. The frequency at which the refractive index of each component (termed the ordinary and extraordinary modes) reaches zero at the height of maximum density, is its critical frequency, $v_c$. Because the critical frequency of the ordinary mode is lower than that of the extraordinary mode (by an amount of the order of 1 MHz) there is an obvious advantage in constructing a radio telescope whose polarization is close to that of the ordinary wave.

For waves at frequency $v > v_c$, penetration of the ionosphere is possible for angles within a cone defined by the limiting zenith angle,

$$\varphi_c(v) = \arccos \left( \frac{v}{v_c} \right)$$

(1)

This relation follows Snell's Law and applies to a plane, stratified ionosphere; for the spherically stratified ionosphere this is a slight underestimation of the limiting cone angle. The limiting angle is one for which the ray path becomes almost tangential to the stratification near maximum density. The spherical stratification introduces a small net refraction for traversing rays with the sense that the apparent zenith angle is always less than the true zenith angle. The amount of this refraction depends on the zenith angle and the total integrated electron content [Chvojková, 1958]. For an observing cone extending 60° from the zenith the net refraction would not exceed several degrees.
Horizontal gradients of total electron content provide another source of refraction, first measured by [Smith, 1952]. To a first-order approximation a uniform gradient has the effect of skewing the axis of the observing cone away from the vertical in the direction of decreasing density. This component of refraction may amount to a few degrees when the critical frequency is less by a factor of two, than the observing frequency. However, with multibeam antennas such as would be used for low frequency observations, the pointing errors caused by both sources of refraction can be allowed for by monitoring the apparent positions of the calibration sources.

4. Interference via the ionosphere

For angles of reception greater than the limiting zenith angle, \( \varphi_c \), the receiving antenna sees, in its sidelobes, a reflection of radiation from an annulus on the Earth's surface. The maximum radius of the annulus, corresponding to a zenith angle near 90° and to reflections from the F layer, is about 4000 km. This defines a limiting distance for interfering signals reaching a radioastronomy receiver after a single hop. However, given sufficient radiating power, interfering signals may reach a radioastronomy receiver, after multiple hops, from almost any point on the Earth's surface. In the lower portion of the frequency band considered in this Report, absorption in the sunlit ionosphere will limit the sources of interference to one-half of the Earth's surface at any one time.

The ratio of the critical frequency corresponding to vertical reflection to that needed to sustain a single reflection path length of 3000 to 4000 km, typically falls in the range 2.7 to 3.3. Since the electron density is proportional to the square of the critical frequency, a maximum electron density of at least one-tenth that required for vertical reflections is needed to sustain propagation paths of 3000 km. In support of this, it is the general experience of radioastronomers observing at 10 to 30 MHz that once the critical frequency falls below the observing frequency by a factor of 3 to 4, the band becomes quiet. Although the antenna may be designed for reception of the ordinary mode in the main beam, the sidelobes, which accept the interfering signal, will, in general, be equally sensitive to both modes. Since the extraordinary mode has the higher critical frequency the band becomes quiet only when its critical frequency falls sufficiently below the observing frequency.

5. Available observing time at mid-latitudes near sunspot minimum

Monthly median values of critical frequencies [Ionospheric Telecommunications Laboratory, 1965] for three stations at mid-latitudes have been used to estimate the average number of hours per day for which the ionosphere near sunspot minimum has a low enough density to allow observations at 3, 6 and 12 MHz.

In order to provide an observing cone extending to 45° from the zenith, the critical frequency must be less than 0.7 times the observing frequency. Table I lists the number of hours per day for which, on average, this is so for Hobart (latitude 42.9° S), Fort Monmouth (40.4° N) and Ottawa (45.4° N) for summer, winter, and equinox, 1965. In addition, listed in parentheses in Table 1 are the number of hours for which the ionosphere has a critical frequency "X-mode" which is less than 0.3 times the observing frequency and so is unlikely to support interfering communication signals.

Since the estimate for the number of hours is based on monthly medians, no account is taken of the days on which the densities are significantly lower than the median values. The tables indicate that at mid-latitudes near sunspot minimum, observations at all three frequencies are possible for several hours a day, except at 3 MHz near the summer solstice. However, one can, in general, expect interference from signals in communication bands during useful observing times except at 12 MHz during night-time.

6. Scintillation and the quality of observations

The major factor limiting the quality of observations at times of sufficiently low ionospheric density and no interference is the phenomenon of scintillation (see Report 263). Scintillation is caused by phase distortions imposed on the wavefront by electron density irregularities mainly in the F-region on a scale of 0.5 to 10 km. For antennas less than about 2 km in extent, the irregularities are in the far field of the antenna and r.m.s. phase deviations up to one radian can be tolerated. For larger antennas, the irregularities may be in the near field and will produce phase and amplitude variations which vary across the aperture. In this case irregularities of large horizontal scale with r.m.s. phase variations in excess of about one-quarter radian will distort the shape of the beam.
TABLE I - Number of hours per day of available observing time (zenith angle < 45°) at three frequencies for 3 times of the year 1965

Values in parentheses are estimates of the average number of hours per day for which interfering signals would not propagate by reflection.

<table>
<thead>
<tr>
<th>Location</th>
<th>3 MHz</th>
<th>6 MHz</th>
<th>12 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hobart, Tasmania</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Winter Solstice</td>
<td>9 (0)</td>
<td>16 (0)</td>
<td>24 (13)</td>
</tr>
<tr>
<td>Equinox</td>
<td>3 (0)</td>
<td>15 (0)</td>
<td>24 (7)</td>
</tr>
<tr>
<td>Summer Solstice</td>
<td>0 (0)</td>
<td>6 (0)</td>
<td>24 (1)</td>
</tr>
<tr>
<td><strong>Ottawa, Ontario</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Winter Solstice</td>
<td>9 (0)</td>
<td>16 (0)</td>
<td>24 (13)</td>
</tr>
<tr>
<td>Equinox</td>
<td>6 (0)</td>
<td>11 (0)</td>
<td>24 (8)</td>
</tr>
<tr>
<td>Summer Solstice</td>
<td>2 (0)</td>
<td>10 (0)</td>
<td>24 (5)</td>
</tr>
<tr>
<td><strong>Fort Monmouth, New Jersey</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Winter Solstice</td>
<td>1 (0)</td>
<td>15 (0)</td>
<td>24 (12)</td>
</tr>
<tr>
<td>Equinox</td>
<td>0 (0)</td>
<td>10 (0)</td>
<td>24 (7)</td>
</tr>
<tr>
<td>Summer Solstice</td>
<td>0 (0)</td>
<td>8 (0)</td>
<td>24 (3)</td>
</tr>
</tbody>
</table>

Because of the transient nature of scintillations, it is important to make full use of the best conditions. This implies use of antennas with extensive multibeam networks [Galt et al., 1967] and possibly some provision for final beam formation "off-line" with adjustment of the large scale phase errors which cause beam distortion. Observations with virtually scintillation free conditions at 10 MHz do, on occasion, persist for periods of several weeks at a time. Since the r.m.s. phase fluctuations introduced by irregularities vary directly as to wavelength, one can be fairly confident of useful observations at such times down to 2 to 3 MHz.

7. Absorption at low frequencies

Most of the absorption experienced by low frequency radio waves occurs in the D-region of the ionosphere which is present only during the day-time. An on-site riometer operating at the same frequency as the radio telescope can be used to monitor the absorption and to provide corrections. This technique has been used successfully at 10 and 22 MHz [Bridle and Purton, 1968; Roger et al., 1969].
REFERENCES


BIBLIOGRAPHY

INTERFERENCE PROTECTION CRITERIA FOR
THE RADIOASTRONOMY SERVICE
(Question 5/2 and Study Programme 5A/2)

1. **Introduction**

The radiation measured in radioastronomy has a Gaussian probability distribution in amplitude, and qualitatively cannot be distinguished from the noise generated in the receivers or from thermal radiation from the Earth and its atmosphere. Furthermore, the level of cosmic radiation as received by an antenna is usually much lower than the system noise/power, often by 30 dB or more. A full recognition of these facts is the key to understanding the interference problems encountered by the radioastronomy service. The radio astronomers' signal-to-noise ratio is usually -30 dB or worse; in extreme cases a signal-to-noise ratio as low as -60 dB may yield useful data. In the following paragraphs the theoretical considerations leading to the sensitivity criteria in radioastronomy are described. The characteristics of the radioastronomy service are described in Report 852.

2. **Sensitivity of radioastronomy systems**

2.1 **Theoretical considerations**

The simplest way to define the sensitivity of an observation in radioastronomy is to state the smallest power level change at the radiometer input which can, with high certainty, be detected and measured by the radiometer. It is convenient to express this as the smallest detectable change \((\Delta T)\) in the equivalent temperature at the output terminals of the antenna connected to the radiometer. The output of the radiometer detector is a function of the total power at the input of the receiver. (It is assumed that the gain and other parameters of the receiving system remain constant during the observation.) The total input power consists of the wanted signal power \(P_s\) and the unwanted noise power \(P_n\) (e.g. thermal and receiver noise). Both \(P_s\) and \(P_n\) are caused by random processes, and it is not possible to distinguish between them qualitatively. However, both have an average power level, and if these levels can be established with sufficient precision, the presence of the wanted signal can be detected. The statistical average of a stationary random variable such as noise power \((P)\) can be found with a precision which is inversely proportional to the square root of the number of samples \((N)\), and the standard deviation of this average is:

\[
\Delta P \sim \frac{P}{\sqrt{N}}
\]  

* This Report should be brought to the attention of Study Groups 1, 3, 4, 8, 9, 10 and 11.
The standard deviation ($\Delta P$) is often called root mean square or r.m.s. By observing a sufficient number of samples ($N$), the measurement of the radio noise power can be made with any desired precision. By reducing the fluctuations $\Delta P$ to a value less than the wanted signal power, $P_s$, detection of very weak signals is possible. $N$ can be made very large by using wide bandwidths and long observing times. Within a band $\Delta f$, approximately $\Delta f$ samples per second are measured by the radiometer, and by extending the observing time ($t$), (also called integration time), $N$ can be made very large.

Now,

$$N = \Delta f \cdot t$$

and if this relation is combined with (1),

$$\frac{\Delta P}{P} \sim \frac{1}{\sqrt{\Delta f \cdot t}}$$

which is the basic sensitivity relation in radioastronomy.

The proportionality factor which is needed to make (3) an equation is dependent on details of the equipment and the observing technique. Conditions making this factor $1/\sqrt{2}$ have been discussed by [Kraus, 1966]. With this value adopted, the sensitivity equation becomes:

$$\frac{\Delta P}{P} = \frac{1}{\sqrt{2}} \cdot \frac{1}{\sqrt{\Delta f \cdot t}}$$

As used above, $P$ and $\Delta P$ refer to noise powers, but equation (4) also holds if $P$ and $\Delta P$ are power spectral densities. Thus $\Delta P$, the noise fluctuation in power spectral density in the sensitivity equation (4), is related to the total system sensitivity (noise fluctuations) expressed in temperature units through the Boltzmann constant, $k$, as shown in equation (5):

$$\Delta P = k\Delta T; \quad \text{also} \quad P = kT$$

and we may express the sensitivity equation as:

$$\Delta T = \frac{T}{\sqrt{2\Delta f \cdot t}}$$

where:

$$T = T_A + T_R$$

and represents the sum of $T_A$, (the antenna noise temperature contribution from the cosmic background, the Earth’s atmosphere and radiation from the Earth), and $T_R$, the receiver noise temperature.

2.2 Sensitivity estimates

Equations (4) or (6) can be used to estimate the sensitivities and harmful interference levels for radioastronomical observations. The results are listed in Tables I and II; an observing (or integration) time $t$ of 2000 s is assumed. In Table I (continuum observations), $\Delta f$ is assumed to be the bandwidth of the allocated radioastronomy bands. In Table II (spectral line observations) $\Delta f$ is the channel bandwidth (corresponding to a velocity of 3 km/s) typical of a spectral line system.

The harmful interference levels given in Tables I and II are expressed as the interference level which introduces an error of 10% in the measurement of $\Delta P$ (or $\Delta T$), i.e.:

$$\Delta P_H = 0.1 \Delta P \Delta f$$
In summary, the appropriate columns in Tables I and II may be calculated using the following methods:

- $\Delta T$, using equations (6) and (7),
- $\Delta P$, using equation (5),
- $\Delta P_H$, using equation (8).

Harmful interference can also be expressed in terms of the power flux-density incident at the antenna, either in the total bandwidth or as a spectral power flux-density $S_H$ per 1 Hz of bandwidth*. For convenience, the values are given for an antenna having a gain, in the direction of arrival of the interference, equal to that of an isotropic antenna (which has an effective area of $c^2/4\pi f^2$, where $c$ is the speed of light and $f$ the frequency).

Consideration of the value of antenna gain to be used in different circumstances is presented in § 4. Values of $S_H\Delta f$, in dB(W/m$^2$), are derived from $\Delta P_H$ by adding:

$$20 \log f - 38.6 \text { dB}$$

(9)

where $f$ is in MHz. $S_H$ is then derived by subtracting $10 \log \Delta f$ to allow for the bandwidth.

Figure 1 shows graphically the harmful interference levels for the radioastronomy service expressed in Tables I and II where $S_H$ in dB(W/(m$^2$ · Hz)) is plotted as a function of frequency. The curves are not smooth because the different frequency bands have different bandwidths.

FIGURE 1 — Harmful interference limits versus frequency as expressed in Tables I and II for $t^* = 2000$ s

I: Continuum
II: Line

*In radioastronomy, $S_H$ is generally denoted by the term "flux density". In this Report the recommended CCIR terminology (Recommendation 574, Appendix I, § 1.4) is followed, in which "power flux-density" refers to quantities with units W/m$^2$ and "spectral power flux-density" refers to quantities like $S_H$ with units W/(m$^2$ · Hz).
### TABLE I  —  Sensitivities and harmful interference levels for radioastronomy continuum observations with 2000 s integration time

<table>
<thead>
<tr>
<th>Centre frequency (MHz)</th>
<th>Assumed bandwidth (MHz)</th>
<th>Minimum antenna noise temperature (K)</th>
<th>Receiver noise temperature (K)</th>
<th>System sensitivity (noise fluctuations)</th>
<th>Harmful interference levels</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Temperature (mK)</td>
<td>Temperature (mK)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>POWER SPECTRAL DENSITY (dB(W/Hz))</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>POWER FLUX-DENSITY (dB(W/m²))</td>
</tr>
<tr>
<td>13.385</td>
<td>0.05</td>
<td>60000</td>
<td>100</td>
<td>4250</td>
<td>-222</td>
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<tr>
<td>25.610</td>
<td>0.120</td>
<td>20000</td>
<td>100</td>
<td>917</td>
<td>-229</td>
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<tr>
<td>73.8</td>
<td>1.6</td>
<td>1000</td>
<td>100</td>
<td>14</td>
<td>-247</td>
</tr>
<tr>
<td>151.525</td>
<td>2.95</td>
<td>200</td>
<td>100</td>
<td>2.76</td>
<td>-254</td>
</tr>
<tr>
<td>325.3</td>
<td>6.6</td>
<td>40</td>
<td>100</td>
<td>0.86</td>
<td>-259</td>
</tr>
<tr>
<td>408.05</td>
<td>3.9</td>
<td>25</td>
<td>100</td>
<td>1.00</td>
<td>-259</td>
</tr>
<tr>
<td>611</td>
<td>6.0</td>
<td>15</td>
<td>100</td>
<td>0.74</td>
<td>-260</td>
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<tr>
<td>1413.5</td>
<td>27</td>
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<td>20</td>
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<td>31550</td>
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<td>100</td>
<td>0.083</td>
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<td>43000</td>
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<td>25</td>
<td>100</td>
<td>0.063</td>
<td>-271</td>
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<td>6000</td>
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<td>0.029</td>
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<td>166000</td>
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<td>150</td>
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<td>0.032</td>
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<td>10000</td>
<td>40</td>
<td>200</td>
<td>0.038</td>
<td>-273</td>
</tr>
</tbody>
</table>

(*) Calculation of harmful interference levels is based on the centre frequency shown in this column although not all regions have the same allocations.

Note:  — If an integration time of 15 minutes, one hour, two hours, five hours or ten hours is used, the relevant values in the Table should be varied by +1.7, -1.3, -2.8, -4.8 or -6.3 dB respectively.
### TABLE II — Sensitivities and harmful interference levels for radioastronomy spectral line observations * with 2000 s integration

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Assumed spectral line bandwidth</th>
<th>Minimum antenna noise temperature</th>
<th>Receiver noise temperature</th>
<th>System sensitivity (noise fluctuations)</th>
<th>Harmful interference levels</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$f$ (MHz)</td>
<td>$\Delta f_c$ (kHz)</td>
<td>$T_A$ (K)</td>
<td>$T_R$ (K)</td>
<td>$\Delta T$ (mK)</td>
</tr>
<tr>
<td>(1)</td>
<td>(2)</td>
<td>(3)</td>
<td>(4)</td>
<td>(5)</td>
<td>(6)</td>
</tr>
<tr>
<td>327</td>
<td>10</td>
<td>40</td>
<td>100</td>
<td>22.1</td>
<td>-245</td>
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<td>20</td>
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<td>4830</td>
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<td>20</td>
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<td>23700</td>
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<td>50</td>
<td>2.85</td>
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<td>150</td>
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<td>115000</td>
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<td>50</td>
<td>150</td>
<td>3.16</td>
<td>-254</td>
</tr>
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<td>2300</td>
<td>40</td>
<td>200</td>
<td>2.40</td>
<td>-255</td>
</tr>
<tr>
<td>265000</td>
<td>2500</td>
<td>40</td>
<td>200</td>
<td>2.40</td>
<td>-255</td>
</tr>
</tbody>
</table>

* This Table is not intended to give a complete list of spectral-line bands, but only representative examples throughout the spectrum.

**Note.** — If an integration time of 15 minutes, one hour, two hours, five hours or ten hours is used, the relevant values in the Table should be changed by +1.7, −1.3, −2.8, −4.8 or −6.3 dB, respectively.
COLUMN DESCRIPTIONS FOR TABLES I AND II

Column

(1) Centre frequency of the allocated radioastronomy band (Table I) or nominal spectral line frequency (Table II).

(2) Assumed or allocated bandwidth (Table I) or assumed typical channel widths used for spectral line observations (Table II).

(3) Minimum antenna noise temperature includes contributions from the ionosphere, the Earth's atmosphere and radiation from the Earth.

(4) Receiver noise temperature representative of a good radiometer system intended for use in high sensitivity radioastronomy observations.

(5) Total system sensitivity in millikelvins as calculated from equation (4) using the combined antenna and receiver noise temperatures, the listed bandwidth and an integration time of 2000 s.

(6) Same as (5) above, but expressed in noise power spectral density using the equation $\Delta P = k\Delta T$, where $k = 1.38 \times 10^{-23} \text{J/K}$ (Boltzmann's constant). The actual numbers in the Table are the logarithmic expression of $\Delta P$.

(7) Power level at the input of the receiver considered harmful to high sensitivity observations ($\Delta P_H$). This is expressed as the interference level which introduces an error of not more than 10% in the measurement of $\Delta P$: $\Delta P_H = 0.1 \Delta P \Delta f$. The numbers in the Table are the logarithmic expression of $\Delta P_H$.

(8) Power flux-density in a spectral line channel needed to produce a power level $\Delta P_H$ in the receiving system with an isotropic receiving antenna. The numbers in the Table are the logarithmic expression of $S_H \Delta f$.

(9) Spectral power flux-density in a spectral line channel needed to produce a power level $\Delta P_H$ in the receiving system with an isotropic receiving antenna. The numbers in the Table are the logarithmic expression of $S_H$.

The calculated sensitivities and harmful interference levels presented in Tables I and II are based on assumed integration times of 2000 s. Integration times actually used in astronomical observations cover a wide range of values. Continuum observations made with telescopes operating singly (rather than in interferometric arrays) are reasonably well represented by the integration time of 2000 s. It is representative of good quality observations. There are many occasions when this time is exceeded by an order of magnitude. There are also certain types of observations, such as observations of solar bursts, for which the greatest attainable sensitivity may not be required. On the other hand 2000 s is less representative of spectral line observations. Improvements in receiver stability and the increased use of correlation spectrometers have resulted in the more frequent use of longer integration times. Spectral line observations lasting several hours are now quite common. A more representative value would be 10 hours with a consequent improvement in sensitivity of 6 dB over that now shown in Table II.

The sensitivity of a radioastronomy receiving system to wideband radiation improves when the bandwidth is increased (equations (4) and (6)). The reason for this is the following: the noise power increases with bandwidth, but, since the signal also is broadband noise, so does the signal. Actually the signal-to-noise power ratio remains constant, independent of the bandwidth. However, as the bandwidth increases, the precision of the determination of the power levels improves (by a factor of $\sqrt{\Delta f}$), and thus the sensitivity is correspondingly improved.

Equations (4) or (6) suggest that one may achieve any desired sensitivity by making the bandwidth and/or the observing time, large enough. In reality, however, factors other than the statistical ones described above, sooner or later put a practical limit on the sensitivity of a radioastronomy observation. Examples of such other effects are the stability of the receiver, fluctuations in the Earth's atmosphere and the patience and endurance of the observer. The sensitivity levels given in Tables I and II use values for the bandwidth and integration time for which these other factors usually are insignificant. However, one should bear in mind that these sensitivity levels are not fundamental limits and that they actually have been exceeded in cases where the utmost sensitivity was required for a successful experiment.
It should be recognized that astronomical sources of radiation exist which may interfere with highly sensitive observations; their spectral power flux-densities can exceed those given in Table I. The Sun is a powerful source of emission. Because of solar interference, certain investigations can only be conducted at night. Other experiments are possible during daytime except during periods of solar activity, especially for frequencies below about 200 MHz. The quiet Sun is of large angular diameter and constant in flux; it usually presents no difficulties. Below 38 MHz, radiation from Jupiter may also exceed the limits given in Table I. At such frequencies Jupiter is a sporadic radio source which emits strongly only a few per cent of the time at highly predictable periods. These periods of emission can be avoided.

Below 1 GHz, many other cosmic radio sources exceed the spectral power flux-densities given in Table I. These sources however, are generally at known positions and of known constant strength and vary only slowly in frequency. In principle and in practice the radioastronomer can make corrections for their effects. This is necessary when performing observations at the highest possible sensitivity. On the other hand, low level terrestrial interference normally has an unknown position, flux density and spectrum, and can be highly time variable, so corrections cannot be made for its effects.

2.2.1 Observed sensitivities

The sensitivities in Tables I and II are extremely high, several orders of magnitude higher than often considered practical, or even obtainable, in other radio services. It is of interest to examine actual high sensitivity observations which have been made at various radioastronomy observatories, and compare these results with the calculated values in Tables I and II.

Table III gives examples of very sensitive continuum and line observations appearing in published literature.

Table III shows that very sensitive observations are being made at various radioastronomy observatories. The system temperatures, bandwidths and integration times chosen for the calculations leading to harmful interference limits given in Tables I and II and in Fig. 1, represent practical values currently being used by the radioastronomy service throughout the world. Were interference to be encountered with intensities increasing above these limits, radioastronomy observations would become increasingly untrustworthy.

Changes in receiving systems can be expected to give improved performance in the future. It is safe to assume that within ten years, observations will be made routinely at sensitivity levels better than those shown in Tables I and II. Such improvements might result from changes in any one of the factors entering into equations (6) and (7). It appears unlikely however, that major improvements could result from changes in receiver noise temperature. At frequencies of 150 MHz and less, the receiver temperature is not a large contributor to the total system temperature. At the high frequency end of the spectrum now being used by radio astronomers, improvements in receiver technology are likely to have their largest effect. If receiver temperatures of 10 K can be achieved at frequencies in excess of 30 GHz then improvements in sensitivity of 6 dB will result in this millimetric region of the spectrum.

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>Line or continuum</th>
<th>Observed spectral power flux-density (dB(W/(m²-Hz)))</th>
<th>Harmful limit (dB(W/(m²-Hz)))</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.7</td>
<td>Continuum</td>
<td>-283</td>
<td>-247</td>
<td>Wade and Hjellming [1971]</td>
</tr>
<tr>
<td>5.0</td>
<td>Continuum</td>
<td>-292</td>
<td>-241</td>
<td>Weiler et al. [1981]</td>
</tr>
<tr>
<td>1.42</td>
<td>Line (neutral hydrogen)</td>
<td>-283</td>
<td>-239</td>
<td>Giovanelli et al. [1981]</td>
</tr>
<tr>
<td>10.5</td>
<td>Line (helium 85\alpha)</td>
<td>-279</td>
<td>-223 ('')</td>
<td>Higgs et al. [1979]</td>
</tr>
</tbody>
</table>

(') Value interpolated from Fig. 1.
3. The radioastronomy antenna

3.1 Sensitivity within the main beam

The typical radioastronomy antenna has high directivity in order to obtain the best possible angular resolution of the observed sources, and a large collecting area (high gain) for good sensitivity. In modern systems, beamwidths of the order of minutes of arc to seconds of arc are used (100 millidegrees-10 millidegrees), corresponding to antenna gains of more than 70 dB. The high gain combined with the good sensitivity of a radioastronomy receiving system makes it possible for the radio astronomer to observe very faint power flux-densities indeed. For example at 1420 MHz, with a receiver sensitivity of $10^{-27}$ W/Hz ($-270$ dB(W/Hz)) and with an antenna of effective collecting area 4000 m$^2$ (61 dB gain), the detectable spectral power flux-density is:

$$S = \frac{10^{-27}}{4000} = 2.5 \times 10^{-31} \text{ W/(m}^2 \cdot \text{Hz})$$

or:

$$-306 \text{ dB(W/(m}^2 \cdot \text{Hz})}.$$ 

Obviously a different antenna would yield a different sensitivity level.

3.2 The effect of side lobes on the harmful interference levels

To obtain an estimate of the interference problems which may be applied to all radio telescopes, large and small, the conditions where the telescope is pointed away from the interfering source should be considered. The harmful power flux-density and spectral power flux-density shown in Tables I and II are based on the isotropic case and should be regarded as the general interference criteria for high sensitivity radioastronomy observations, when the interference does not enter the near side lobes. The levels given in Tables I and II are applicable to terrestrial sources of interfering signals, and are valid for intentional as well as unwanted emissions.

The power level of an interfering signal at the receiver terminals depends upon the side-lobe level of the receiving antenna as well as upon the power flux-density of the interfering signal. A model of the typical side-lobe levels for large paraboloid antennas in the frequency range 2 to 10 GHz is given in Recommendation 509. In this model, the side-lobe level decreases with angular distance (degrees) from the main beam axis, and is equal to $(32 - 25 \log \theta)$ dBi for $1^\circ < \theta < 48^\circ$. A level of 0 dBi occurs at $19^\circ$ from the main beam axis. A source of interference of power flux-density equal to the threshold values given in Table I would be harmful if such an antenna was pointed within $19^\circ$ of it. Thus, in some situations, interference at the harmful thresholds in Table I can be a problem to radioastronomers.

3.3 The special case of transmitters on geostationary satellites

Interference from geostationary satellites is a case of particular importance. Because the power levels in Tables I and II were calculated assuming 0 dBi antenna gain, harmful interference will be encountered when a reference antenna, such as described in Recommendation 509, is pointed within $19^\circ$ of a satellite radiating at levels in accordance with those listed in the tables. A series of similar transmitters located at intervals of $20^\circ$ around the geostationary-satellite orbit would preclude radioastronomy observations with high sensitivity from a band of sky $38^\circ$ wide and centred on the orbit. The loss of such a large area of sky would impose severe restrictions on radioastronomy observations.

In general, it would not be practical to suppress the unwanted emissions from satellites to below the harmful level when the main beam of a radio telescope is pointed directly towards the satellite. A workable solution is suggested in Fig. 2 of Report 697, which shows the projection of the geostationary-satellite orbit in celestial coordinates as viewed from the latitudes of a number of major radioastronomy observations. If it were possible to point a radio telescope to within $5^\circ$ of the orbit without encountering harmful interference, then for that telescope a band of sky $10^\circ$ wide would be unavailable for high sensitivity observations. For a given observatory this would be a serious loss. However, for a combination of radio telescopes located at northern and southern latitudes, operating at the same frequencies, the entire sky would be accessible. A value of $5^\circ$ should therefore be regarded as the requirement for minimum angular spacing between the main beam of a radioastronomy antenna and the geostationary-satellite orbit.
In the model antenna response of Recommendation 509, the side-lobe level at an angle of 5° from the main beam is 15 dBi. Thus, to avoid harmful interference to a radio telescope pointed within 5° from the transmitter, the satellite emissions must be reduced 15 dB below the power flux-densities given in Tables I and II. When satellites are spaced at intervals of only a few degrees along the orbit, the emission levels associated with the individual transmitters must be even lower to meet the requirement that the sum of the powers of all the interfering signals received should be 15 dB below \( \Delta P_R \) in Tables I and II. Report 713 reaches similar conclusions.

It is recognized that the emission limitations discussed above cannot, in practice, be achieved so as to enable sharing of the same frequency band between radioastronomy and down-link transmissions from satellites to take place. The limitations are, however, applicable to unwanted emission from the satellite transmitters which fall within the radioastronomy bands listed in Tables I and II. These emission limitations have implications for the space services responsible for the interference, which require careful evaluation. Furthermore, the design of new radioastronomy antennas should strive to minimize the level of side-lobe gain near the main beam as an important means of reducing interference from transmitters in the geostationary-satellite orbit.

4. Interference

4.1 Types of interference

It is convenient to divide harmful interference into three main categories:

**Category 1:** Strong interference that causes non-linear operation of the receiver, sometimes to the point of harming the sensitive input amplifier.

Fortunately, this type of interference is rare and unlikely to be caused by normal transmissions. However, radar transmitters in low flying aircraft are capable of physically damaging the electronics of a radioastronomy receiving system. Typically a power level at the radiometer input of 0.1 W would burn out the varactor in a parametric amplifier. This corresponds to a power flux-density of 10 W/m\(^2\) (10 dB(W/m\(^2\))) at 1400 MHz, if the interfering source is outside the main beam of the antenna. The corresponding spectral power flux-density, assuming a bandwidth of 27 MHz (1400 to 1427 MHz) would be \(3.7 \times 10^{-7} \text{ W/(m}^2 \cdot \text{Hz})\) or \(-64 \text{ dB(W/(m}^2 \cdot \text{Hz})}\). If the antenna is accidentally pointed at such a strong interference source, the power flux-density that could burn out the input varactor must be reduced by the gain of the antenna.

**Category 2:** Relatively strong interference which is easy to recognize.

Usually this is the case if the interference power is stronger than the noise power in the radiometer input. This type of interference is fatal to observations, and there is no doubt that it is interference. There is no choice but to discard the data. Typically, interference power flux-densities above \(-110 \text{ dB(W/m}^2\)) belong to this category. With an assumed bandwidth of 27 MHz (the 1413.5 MHz band), the corresponding spectral power flux-density is \(-184 \text{ dB(W/(m}^2 \cdot \text{Hz})}\).

**Category 3:** Very low-level interference with a very low interference to noise ratio (less than \(-20 \text{ dB}\)) that cannot be recognized.

The long integration times required to bring the wanted signal out of the noise will mask the characteristic features of the interfering signal. It cannot be recognized as interference and erroneous data result; this type of low-level interference is therefore particularly harmful. Furthermore, because the radio astronomer cannot determine by examination of the data that he has encountered interference, there is no possibility of identifying the source.

4.2 Interference reduction techniques

A number of techniques designed to reduce the effects of interference can be tried by the radio astronomer. Some of these are obvious and straightforward, and some are clever, complicated and often time consuming. They all suffer from the problem of being of limited usefulness. In general, the employment of interference reduction techniques leads to the need for more observing time.
4.2.1 Filtering techniques

Unwanted signal energy outside the observed band is rejected in the radioastronomy receiver by using bandpass filters. Normally, when the interfering signals are of low intensity and do not cause non-linear operation anywhere in the system, limiting the observed passband by a filter in the IF channel is useful. Since the IF frequencies are relatively low, typically between 100 to 300 MHz, relatively steep skirt selectivity is possible. However, limiting the observing band decreases the sensitivity of the system which is proportional to $\sqrt{\Delta f}$. Filtering in the radiometer input is also used, particularly when the potentially-interfering signals are strong. Again decreased sensitivity is the result, both because of the narrower bandwidth and because of the insertion loss of the filter which, when inserted in the receiver input, adds to the loss and the noise temperature of the system. Since the filtering takes place at the observing frequency, adequate skirt selectivity may be a problem. Typically, about 75% of an allocated band remains available after reasonable IF filtering (see Report 697) which corresponds to a sensitivity loss of about 13%. If input filtering is needed, sensitivity reduction of a factor of 2 or more could be expected.

In order to obtain 100 dB reduction of the midband response at the band edge of the radioastronomy band, one needs three or more 8-section filters in the IF channel. Although such a filter system is feasible, there are important phase considerations to be taken into account when observing with an antenna array or interferometer. This makes it questionable whether filtering really is a viable general solution to the band edge interference problem. Bandpass filters do not, of course, alleviate the in-band interference problem.

4.2.2 Observing techniques

It is possible, and often necessary, to reduce the effect of interference by using special observing techniques. One possibility is to repeat the observation several times, with the assumption that the interference is present only occasionally. It is also useful to move the telescope on and off the source during an observing run, assuming that the interference is present all the time. Both methods are of limited usefulness, because of the assumptions one has to make of the behaviour of the celestial source as well as of the interference. They also increase the required observing time by a sizeable factor. Furthermore, the technique of repeating the observations is not very useful in the case of sources of variable intensity, as it is not possible to distinguish between variations in the interference and intrinsic variations in the source. The on/off technique is not useful for observations of extended astronomical objects, such as the cosmic background, since there is no region of the sky which can be considered off-source. An assumption that the intensity of the interference is constant must also be made. This is not generally true; often the interference varies in intensity with time and in a complicated way across the frequency band.

4.2.3 Data processing techniques

After-the-fact reduction of the effects of very low-level interference is of very limited usefulness in radioastronomy. One reason for this is that in order to detect power at a very low level, long integration times, which mask the identifying characteristics of the interfering signals, have to be used. The added power caused by the interference is then no longer distinguishable from the random noise one is looking for. It might be possible, in some special cases such as pulsed radar interference where the characteristics of the interfering signals are accurately known, to process the data in a way that might reduce the effect of the interference.

Continuum observations, which require a large bandwidth in order to achieve good sensitivity, can be made by a receiver covering the desired bandwidth with a number of contiguous channels (a spectral line receiver). The spectral information can then be used to identify a narrow interfering signal. However, for interference covering a bandwidth comparable to the continuum bandwidth observed, this technique is not useful.

In very special and rare cases, when the characteristics of the wanted signal are known this information can be used to separate the signal from the interference and noise. However, for the general case of radioastronomy observations, there seems to be no useful data processing technique that can be used to identify and reduce interference.
The need for high angular resolution in radio astronomical observations has led to the development of interferometers and arrays of antennas, which play an increasingly important role in studies of sources with angular dimensions of a few minutes of arc or less. An interferometer achieves an angular resolution of about \( \lambda/L' \) radians, where \( \lambda \) is the wavelength, and \( L' \) is the largest projected spacing of the antennas as viewed from the radio source. With such instruments, two effects reduce the response to interference. These are related to the frequency of the fringe oscillations that are observed when the outputs of two antennas are combined, and to the fact that the components of the interfering signal received by different and widely-spaced antennas will suffer different relative time delays before they are recombined. The treatment of these effects is more complicated than that for single antennas in section 3. A discussion is given by Thompson et al., (1986). Broadly speaking the major effect is that the effective integration time over which interference affects the measurement is reduced from the total time of observation to the mean time of one natural fringe oscillation. This typically ranges from some seconds for a compact array with \( L' \sim 1000\lambda \) to less than a millisecond for intercontinental arrays with \( L' \sim 10^2\lambda \). Thus, compared to a single radio telescope, the interferometer has a degree of immunity to interference which under reasonable assumptions increases with the array size expressed in wavelengths. Results for some representative interferometers are shown in Figure 2. The Very Large Array (National Radio Astronomy Observatory, New Mexico, United States) is used here as an example of an array with antenna spacings up to tens of kilometres, and MERLIN (Nuffield Radio Astronomy Laboratories, Jodrell Bank, United Kingdom) is used as an example of a connected element array with antenna spacings exceeding a hundred kilometres. The curves shown for these two instruments are based on the simplifying assumptions that the interfering transmitter is stationary with respect to the Earth, and that the power of the interfering signal received through the antenna side lobes remains constant during the observation. For Very Long Baseline Interferometry (VLBI) where the telescopes are very widely separated, and the chance of occurrence of correlated interference is very small, the above considerations may not apply. In that case the tolerable interference level is determined by the requirement that the power level of the interfering signal should be no more than 1% of the receiver noise power [Thompson et al., (1986)]. This is the interference criterion for VLBI measurements plotted in Figure 2. It does not depend on the array configuration. The area between the VLBI curve and the total power curve covers the range of harmful thresholds for all types of radio telescopes. It must be emphasized that the use of interferometers and arrays is generally confined to studies of discrete high brightness sources with angular dimensions no more than a few minutes of arc for arrays like the VLA or a few tenths of a second of arc for VLBI. The results in Tables I and II, of section 2.2, thus remain valid for the general protection of radioastronomy.

Figure 2 also shows curves of the harmful thresholds of interference, expressed as power flux density, for Very Long Baseline Interferometry (VLBI) and for two configurations of the Very Large Array (VLA) in which the antenna spacings extend up to 1 km (configuration D) and 36 km (configuration A) and for the MERLIN array, in which antenna spacings extend to 233 km. Typical values of bandwidths and system temperatures are used. The curve for VLBI does not depend upon the configuration of the antennas. The curve for total power systems, included for comparison, is based on the same data as the lower curve in Figure 1, but is here plotted as dB(Wm\(^{-2}\)) rather than dB(Wm\(^{-2}\)Hz\(^{-1}\)). In all cases it is assumed that the interfering signal is received in side lobes of gain 0 dBi. Adapted from Thompson et al. (1986).
Harmful thresholds of interference for several types of radiotelescopes

REFERENCES


REPORT 696-2*

FEASIBILITY OF FREQUENCY SHARING BETWEEN RADIO ASTRONOMY AND OTHER SERVICES

(Question 5/2 and Study Programme 5A/2)


1. Introduction

1.1 The characteristics of the radioastronomy service are described in Report 852. In Report 224 the harmful interference levels are derived. The material contained in these Reports is applied here to a consideration of sharing between radioastronomy and other services. Sharing is first discussed in general terms and some examples of sharing problems are described. This is followed by a quantitative examination of sharing, starting with a consideration of the protection criteria and continuing with the application of these criteria to geographical sharing. An analysis of interference received from a transmitter within line-of-sight of a radioastronomy observatory emphasizes the difficulty of sharing with a space service or with a terrestrial service involving airborne transmitters. Finally there is a case-by-case examination of sharing problems in each of the bands below 40 GHz where a radioastronomy interest is recognized in the Radio Regulations.

1.2 Before proceeding with a discussion of conditions which can produce harmful interference, it is useful to consider the question of whether any harmful interference can be tolerated by the radioastronomy service. The answer must be somewhat subjective. Many radioastronomers would reply that no interference above the levels specified in Report 224 can ever be tolerated. Yet many radioastronomers do excellent work in the intervals between bursts of strong interference. The best answer is probably that strong, recognizable interference can sometimes be tolerated if it occurs in short bursts for a small fraction of the total time; but that an insidious danger to the radioastronomy service lies in interference which is just below the power level at which it can be recognized and is present for large fractions of the total time. In this case there may be no means of detecting that interference has occurred, even in subsequent examination of the data, and erroneous results may be deduced.

1.3 Interference to radioastronomy from spurious radiations of transmitters in other bands, and problems of adjacent band interference, are important factors which can reduce the efficient use of the radio spectrum. These matters are not discussed in detail in this Report although there are some brief references to the problem. A detailed discussion will be found in Report 697.

2. General remarks on sharing

2.1 Radioastronomy observatories are usually located at sites specially chosen to minimize interference from other services. The sites are usually at a considerable distance from the major terrestrial sources of interference and frequently are screened by nearby high ground. With this protection for the observatory and the protection afforded by the curvature of the Earth, sharing with terrestrial transmitters is possible when the transmitted power is low and there is sufficient geographical separation. However, with the very sensitive systems used by radioastronomers, large separations are usually necessary. Signals propagated via the mechanism of tropospheric scatter can lead to harmful interference levels at great distances and for a large fraction of the time. In meteorological conditions leading to anomalous tropospheric propagation, the distance from which interference can be caused by ground transmitters is likely to be increased by several hundred kilometres but these conditions will occur only infrequently in most parts of the world.

* This Report is brought to the attention of Study Group 5 with a view to their comment on the propagation data set out herein. This Report is also brought to the attention of Study Group 1, 4, 8, 9 and 11.
2.2 Transmitters carried in aircraft, spacecraft or balloons can remain within line-of-sight of an observatory to very great distances. The advantages associated with a carefully selected observatory site and the attenuation around the curvature of the Earth are both lost. It is shown in section 5 that sharing is not usually possible when the interfering transmitter is within line-of-sight of the radioastronomy antenna.

2.3 At HF any interference received is almost invariably propagated via the ionosphere. In this case too the selection of the observatory site and the curvature of the Earth do not provide protection. If the operating frequency is less than about 4 times the critical frequency of the F-layer, interference can be experienced from a transmitter located anywhere on the Earth. The special problems associated with interference at frequencies less than 20 MHz are outlined in Report 699. Some detail is also included in § 7.4 of this Report.

2.4 Reflections from aircraft are likely causes of harmful interference in a shared band even when the terrestrial transmitter is distant, and the possibility of interference by reflections from low-orbit satellites also exists. A single reflecting body will be effective for only a short time and the interference problem will depend on the density of the air or space traffic. As a result of space activities there are a large number of metallic objects in orbit around the Earth. Illustrative examples of interference due to reflections from aircraft or low-orbit satellites are given in section 2.4 of Report 696-1 (Dubrovnik, 1986).

2.5 For certain types of radioastronomical measurement in shared bands, reflections of terrestrial transmissions by the Moon can cause serious interference. The Moon is of importance to radioastronomy for two main reasons. The first is that because both the shape and the motion of the Moon are known, the observation of lunar occultations of radio sources provides an accurate method for determining their angular positions and, in some instances, their sizes. Occultation of a particular radio source by the Moon occurs very infrequently and it is important that there should be no harmful interference at these times. The second use of the Moon is as a calibration source, because its effective temperature over a range of frequencies is accurately known.

In both applications the main beam of the radio telescope is directed at the Moon and the observations are, therefore, particularly susceptible to interference by signals reflected from the lunar surface. Illumination of the Moon by terrestrial transmitters, either intentionally or otherwise, in frequency bands used by the radioastronomy service, can thus cause harmful interference.

2.6 In addition to those listed above a number of other propagation mechanisms can result in severe interference to the radioastronomy service. These include reflections from sporadic-E ionization and from meteor trails and scattering from free electrons in the ionosphere. These mechanisms are effective at metre wavelengths. The first two can result in severe interference but the frequency of occurrence is not high. The ionospheric scattering mechanism would require high-power transmissions to produce harmful interference levels. All of these mechanisms are effective over large distances. At centimetric and millimetric wavelengths scatter from heavy rain can produce interference at large separations between transmitter and observatory. In most climates such rain does not occur frequently enough to be a major concern.

3. Protection criteria for the radioastronomy service

3.1 An important protection criterion for radioastronomy is the power level of the interference considered harmful. Values are given in Table I of Report 224 for continuum observations and in Table II for spectral line observations. In each case these levels are presented for frequency bands for which there is some measure of protection for radioastronomy in the Radio Regulations. The specification of harmful interference as the input power to the receiver in dBW, presented in column 7 of Tables I and II of Report 224 is adopted in this Report.

3.2 A second criterion affecting the protection of the radioastronomy service relates to the fraction of the total sky for which radioastronomy observations are to be protected. This factor is discussed in section 3 of Report 224. For interferors operating from the Earth's surface a value of 0 dB is adopted for the gain of the radioastronomy antenna in the direction of the horizon. This value is adopted so that potentially interfering signals will not cause harmful interference to observations made at elevation angles greater than 19° (see Recommendation 509). The same antenna gain of 0 dB is acceptable for cases of interference from transmitters on aircraft or spacecraft in low orbit. However, for interference from geostationary spacecraft a value of +15 dB for
the gain of the radioastronomy antenna is required to permit observations at 5° from the geostationary satellite orbit (see section 3.3 of Report 224 and section 2.2.1.1 of Report 697).

3.3 A third criterion which must be considered is the percentage of time that a harmful interference level may be exceeded without serious damage to the operation of the service. This factor is not considered in Report 224 or in any other CCIR document pertaining to radioastronomy. In this Report a single percentage value has been chosen for all cases although it is clear that some observations are more susceptible to brief periods of interference than others. There is an improvement in the efficient use of the radio spectrum if protection criteria are no more rigorous than necessary. Consequently it has been accepted in this Report that the harmful interference levels of Report 224 may be exceeded no more than 10% of the time. This is sufficiently infrequent that observations affected by interference stand out from those not affected and at the same time does not exact an exorbitant penalty if observations must be repeated. During periods of interference from signals propagated by tropospheric scatter, observations 10 dB or 15 dB less sensitive than the noise-limited case, and a good chance of being successful. Strong interference occurring only 10% of the time because transmissions are limited to that period of time, would not be acceptable. Less sensitive observations would not be possible during the interference period. It should be noted that the detailed characteristics of the interference and their relation to the type of radioastronomical observation being made will need to be taken into account.

3.4 It must be emphasized that for some types of observation a 10% failure rate due to interference imposes severe restrictions on the radioastronomer. For some observations a high probability of success is desirable because of the difficulty or impossibility of repeating them. An example is an observation of a lunar occultation. It might be necessary to wait up to 19 years before the Moon returns to the same position in the sky so that the observation can be repeated. Some other types of observation require simultaneous measurements at a number of sites, at each of which success must be obtained if the experiment as a whole is to be successful. Very long base-line interferometry (VLBI) provides an example; observations are made simultaneously at a number of observatories hundreds or thousands of kilometres apart. The experiment may be severely damaged if observations at any one of the observatories are ruined due to interference. An observatory having difficulties of this type will require special national arrangements at certain frequencies at certain times.

3.5 The three protection criteria so far considered, the power threshold of harmful interference, the percentage of sky which is to be protected and the fraction of observing time which is to be protected, all relate directly to geographical sharing; that is, the geographical spacing of two services which permit both to work at the same frequency at the same time. In sharing between some services additional protection may be obtained by the use of orthogonal polarizations. This is not a useful technique for protecting radioastronomy since different polarizations must be used for some observations. Also the polarization of emissions from the far side-lobes of an antenna may be very different from that of the main beam. Consequently, there may be no reduction in interference to an observation made at a polarization orthogonal to the operating polarization of the interfering service.

3.6 It should be noted that except in rare cases sharing with the radioastronomy service is possible only with considerable geographical separation. Bands allocated to radioastronomy are too narrow to permit assignment of different parts of a shared band to the different services. Any reduction in bandwidth decreases the sensitivity of the observations. Time-sharing is of limited use and has not yet been a feature of any extended observational programme. Although no international mechanism exists for time-sharing a particular time-sharing scheme has been proposed as a solution to a specific interference problem in the United States (see section 7.13.2 and Report 1126). Limited time sharing to permit special observations at a radioastronomy site may be possible, and may indeed be necessary on occasion, as mentioned for lunar occultation observations in an earlier paragraph.

3.7 Only geographical sharing is considered in the remainder of this Report.
4. Basic relations for calculating geographical separation needed for sharing

4.1 If geographical sharing is to be successful the interfering transmitter and the interfered-with receiver must be separated by a distance at which interference is not considered harmful. Using the criteria developed in the previous section the attenuation over this distance must be sufficient to reduce the received signal below the appropriate level of Table I or II of Report 224 for all but 10% of the time. Report 382 defines a basic transmission loss \( L(b) \) as:

\[
L(b) = P_t + G_t - P_r
\]

where:

- \( L(b) \): minimum permissible basic transmission loss (in dB) for \( p\% \) of the time; this value must be exceeded by the actual transmission loss for all but \( p\% \) of the time;
- \( P_t \): transmitting power level (in dBW) in the reference bandwidth at the input to the antenna;
- \( G_t \): gain (in dB relative to isotropic) of the transmitting antenna;
- \( G_r \): gain (in dB relative to isotropic) of the receiving antenna in the direction of the transmitter;
- \( P_r(p) \): maximum permissible interference power (in dBW) in the reference bandwidth to be exceeded for no more than \( p\% \) of time at the receiver input.

Using the protection criteria of the previous section \( G_r = 0 \) dB, \( p = 10\% \), equation (1) assumes the form:

\[
L(b)(10) = P_t + G_t - P_r(10)
\]

where \( P_r \) is to be taken from column 7 of Table I or Table II of Report 224.

For line-of-sight transmission, \( L(b) \) has a simple analytical form and equation (2) may be written as:

\[
20 \log (4\pi d) - 20 \log (\lambda) = P_t + G_t - P_r
\]

where:

- \( d \): distance in metres between transmitter and receiver,
- \( \lambda \): wavelength in metres.

It should be noted that the free-space signal is not variable and the percentage of time criterion is not pertinent.

5. Sharing within line-of-sight

5.1 It is rarely possible for radioastronomy to share successfully with any other service whose transmitters are within line-of-sight of the observatory. Figure 1 exhibits this fact. Using equations (3) and (4) the maximum e.i.r.p. which would not result in harmful interference to the radioastronomy service has been calculated for two distances. One distance is representative of the maximum distance which is possible for a terrestrial station within line-of-sight. It is the horizon distance for an airborne transmitter at a height of 20,000 metres. The other is based on the distance of the geostationary orbit and is consequently representative of the maximum distance of most spaceborne transmitters not on deep-space missions. A special case of sharing with spacecraft on deep-space missions in bands not allocated to radioastronomy is described in Annex I.

The harmful interference levels of Table I of Report 224 are used in the case of the terrestrial transmitter and, as discussed in Section 3.2, an additional protection of 15 dB is required against transmissions from spaceborne transmitters to allow observations 5° from the geostationary satellite orbit. The curves are applicable for a clear dry atmosphere.
5.2 It is clear from Fig. 1 that sharing with a terrestrial transmitter within line-of-sight is not likely to be possible at frequencies below 10 GHz because of the severe restriction sharing would impose on the transmitter e.i.r.p. Even for frequencies up to 40 GHz either the transmitter power must be measured in milliwatts or the transmitting antenna must provide high discrimination towards the direction of the observatory, if sharing is to be possible. For transmitters in space with typical power in excess of 1 W, sharing will not be possible even outside the coverage area of the spaceborne antenna for frequencies up to about 20 GHz. Between 20 GHz and 50 GHz sharing is not likely to be possible within the coverage area of the spaceborne antenna.

5.3 Transmitters on satellites in earth orbits of heights less than 6400 km would be restricted to an e.i.r.p. lying between curves A and B.

FIGURE 1

The e.i.r.p. above which sharing is not feasible between radioastronomy and active services with transmitters within line-of-sight of a radioastronomy observatory

The reference bandwidths for the transmitter e.i.r.p. and for the radioastronomy receiver are those allocated to the radioastronomy service

Curves A: geostationary space transmitter

B: terrestrial transmitter at 600 km
6. Sharing with terrestrial services beyond the horizon

6.1 In § 7 there is a brief discussion of the sharing situation facing radioastronomy in each of the frequency bands below 40 GHz where the Radio Regulations recognize a radioastronomy interest. In many of these bands a calculation has been made to determine a separation distance necessary to protect radioastronomy from interference from a hypothetical active system operating in the band.

First the required minimum permissible basic transmission loss $L_b$ (10) is calculated using equation (2), where $P_{t}(10)$ is taken from column 7 of Tables I and II of Report 224 for continuum or spectral line observations respectively. $P_t$ and $G_a$ are derived from the choice of the hypothetical system with which radioastronomy must share. An attempt has been made to choose an active system representative of the most likely source of interference in a particular band. However in some bands the variety of systems used in different parts of the world means that there is no single representative system. $P_t$ is the power transmitted by the active service within the bandwidth $B$, of the radioastronomy receiver. If the transmitter power $P_t$ is distributed over a bandwidth $B$, where $B_1 > B$, then:

$$P_t (\text{dBW}) = P_t (\text{dBW}) - 10 \log (B_1/B_1) \quad \text{for } B_1 > B_1, \quad (4)$$

on the assumption that the transmitter power has a uniform spectral density. When the bandwidth of a single transmitter is less than that of the radioastronomy receiver then a number of transmitting channels within the receiver bandwidth may be occupied. It is unlikely that all such channels are operating simultaneously and at the same distance and an arbitrary decision has been made concerning the number of transmitters involved as shown in Table I.

6.2 The separation distance which will provide the necessary basic transmission loss is dependent on the propagation mechanism. For the radioastronomy bands at about 13 MHz, 25 MHz and 38 MHz ionospheric reflections dominate. This effect is described in Sections 7.4 and 7.5. For higher frequencies the propagation mechanism primarily responsible for interfering signals at the 10% level is tropospheric scatter. The separation distances for frequencies 74 MHz to 40 GHz have been calculated using Report 238-5 with the appropriate modifications described in Section 4 of Report 569-3. This approach is not known to be appropriate for frequencies above 12 GHz but has been applied in this report to frequencies up to 40 GHz in the absence of an alternate approach within Study Group 5 documentation.

6.3 Report 238-5 defines a number of climates which affect the strength of the tropospheric scatter signal. The calculations included here are appropriate to climates 2, 6 and 7a (continental sub-tropical, continental temperate and maritime temperate overland). The three climates give almost identical results for the 10% of time considered. For other inland climates (1 equatorial, 4 desert and 8 polar) the separation distances are smaller. For overwater transmission, greater separations are required. Most observatories are either sufficiently distant from the sea or, if near the sea, experience interference from the landward side. There are however a few observatories where over-water paths would be involved in most cases of interference and others where over-water paths would be involved over a limited range of azimuths. In such instances the separation distance could be as much as 200 km larger than those listed in this report.

6.4 Some additional assumptions must be made about the nature of the radioastronomy site. In each case it is assumed that the radioastronomy antenna is at a height of 25 m. The result is not strongly dependent on this assumption. Because most radioastronomy sites are chosen with the aim of reducing interference problems, it is appropriate to assume that the local horizon is above the horizontal. The results of two calculations are presented: one for a site which is moderately well protected with a horizon angle of 1° and the other for a well-protected site with a horizon angle of 4°.

7. Sharing considerations for all radio astronomy bands below 40 GHz

7.1 In the following paragraphs a brief description is given of the sharing situation in each of the radio astronomy bands below 40 GHz which are recognized in the Table of Allocations of the Radio Regulations. For most bands a separation distance necessary for sharing between a hypothetical reference circuit and a radioastronomy receiver has been calculated as described in the previous sections. The sharing details are summarized in Tables I and II.
7.2 Table I gives the sharing parameters which determine the minimum transmission loss required for sharing. The column descriptions are as follows:

Column

1) The radioastronomy allocated frequency bands for which the calculations were made.

2) The service in which the interfering transmitter operates (F-fixed, M-mobile, B-broadcasting, R-radiolocation, FS(E-S)-fixed satellite operations in the Earth-to-space direction; LMS (E-S)-land mobile satellite (Earth-to-space).

3) Transmitter power in decibels relative to 1 watt.

4) Gain of transmitting antenna in the direction of the radioastronomy observatory.

5) Transmitter e.i.r.p. in the direction of the radioastronomy observatory.

6) Bandwidth of emissions of a single transmitter.

7) The assumed number of transmitters transmitting simultaneously within the bandwidth of the radioastronomy receiver.

8) The type of radioastronomy observation "C" denotes continuum observations, "SL" denotes spectral line observations.

9) Level of harmful interference power into receiver, column 7 of Tables I and II of Report 224 for continuum and spectral line observations respectively.

10) Receiver bandwidth as listed in the above tables.

11) The required transmission loss as calculated using equations (2) and (4).

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>Assumed interfering transmitter</th>
<th>Assumed radioastronomy receiver</th>
<th>No. C/SL</th>
<th>Required transmission loss</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Service:</td>
<td>Pe</td>
<td>Ge</td>
<td>e.i.r.p.</td>
</tr>
<tr>
<td>----------------</td>
<td>----------</td>
<td>-----</td>
<td>-----</td>
<td>----------</td>
</tr>
<tr>
<td>13</td>
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</tr>
<tr>
<td>35</td>
<td>F</td>
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<td>0.02</td>
<td>5</td>
</tr>
<tr>
<td>74</td>
<td>F</td>
<td>15</td>
<td>0.03</td>
<td>7</td>
</tr>
<tr>
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</tr>
<tr>
<td>408</td>
<td>H</td>
<td>14</td>
<td>0.03</td>
<td>12</td>
</tr>
<tr>
<td>610</td>
<td>B</td>
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<td>1</td>
</tr>
<tr>
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<td>1</td>
</tr>
<tr>
<td>22200</td>
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<td>50</td>
</tr>
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<td>31000</td>
<td>F</td>
<td>-10</td>
<td>45</td>
<td>100</td>
</tr>
</tbody>
</table>
7.3 Table II contains the calculated separation distances for the situations described in Table I. Section 6 describes the method used in determining the distances which reduce the interference to a level acceptable to the radioastronomy service. For separation distances less than 100 km the dominant propagation mechanism is diffraction rather than tropospheric scatter. A detailed knowledge of the terrain is required to calculate the separation distance. The column descriptions are as follows:

Column

1) The radioastronomy allocated frequency bands for which the calculations were made.

2) The required transmission loss copied from column 11 of Table I.

3) The separation distance required to avoid harmful interference to radioastronomy observations where the horizon at an observatory is at an elevation of 0°.

4) The same as 3) but where the elevation angle is 1°.

5) The same as 3) but where the elevation angle is 4°.

6) Marginal change in separation distance to change in required transmission loss. The change in separation distance is given for a 10 dB change in transmission loss. The separation distances can be adjusted for changes in the nature of the transmitting system. Limitations to the use of the numbers listed here are as indicated by the asterisks.

7) Number of sub-section containing additional sharing information for that frequency.

### TABLE II - Separation distances

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Required transmission loss from Table I</th>
<th>Separation Distance</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>dB</td>
<td>km</td>
<td>km</td>
</tr>
<tr>
<td>MHz</td>
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<td></td>
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<td>195</td>
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<td>&gt;4000</td>
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<td>198</td>
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<tr>
<td>38</td>
<td>213</td>
<td>1100</td>
<td>990</td>
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<tr>
<td>74</td>
<td>228</td>
<td>900</td>
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<td>232</td>
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<td>820</td>
<td>.760</td>
</tr>
<tr>
<td>408</td>
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<td>900</td>
<td>810</td>
</tr>
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</tr>
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<td>610</td>
<td>525</td>
</tr>
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<td>.650</td>
</tr>
<tr>
<td>205</td>
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<td>250</td>
</tr>
<tr>
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<td>220</td>
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</tr>
<tr>
<td>255</td>
<td>255</td>
<td>900</td>
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<td>360</td>
</tr>
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</tr>
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<td>470</td>
</tr>
<tr>
<td>499</td>
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<td>255</td>
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<tr>
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<td>180</td>
</tr>
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<td>24,000</td>
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<td>360</td>
<td>280</td>
</tr>
<tr>
<td>28,000</td>
<td>233</td>
<td>290</td>
<td>229</td>
</tr>
</tbody>
</table>

(1) For an elevation angle of 4° this number can only be used for positive values of δd and δL.
(2) For an elevation angle of 4° this number cannot be used. For an elevation angle of 1° the number can only be used for positive values of δd and δL.
7.4 Sharing in band 7, 13.36-13.41 MHz and 25.55-25.67 MHz

7.4.1 The Radio Regulations show two allocations for radioastronomy in band 7. The band 13 360-13 410 kHz is shared with the fixed service. The band 25 550-25 670 kHz is to become an exclusive radioastronomy band but fixed stations will continue to operate during an extended transition period.

7.4.2 Radio communications in these bands rely principally upon reflections from the F region of the ionosphere for long-distance propagation. Radioastronomical observations from the Earth are possible only when the electron density is sufficiently low and relatively free of irregularities on the kilometre scale (Report 699).

7.4.3 Conditions in the ionosphere affecting both radioastronomical observations on the one hand, and reflection propagation on the other, vary with time of day, time of year and solar activity as well as with the latitude of the observatory. Three situations relating to band sharing can be distinguished depending on the relative values of the observing frequency $v_o$ and the critical frequency of the F-region $v_r$:

(a) $v_G < v_c$: ground-based observations are not possible due to the total reflectivity of the ionosphere. Reflection propagation is possible.

(b) $v_c < v_o < 4v_r$: observations can be made within a zenith cone angle. $\varphi = \arccos v_o/v_c$ (Report 699): reflection propagation is possible. Radioastronomical observations will be susceptible to interference received at zenith angles greater than $\varphi$. A system radiating 10 W from an antenna of low directivity at 4000 km distance will produce interference more than 100 dB in excess of the harmful levels.

(c) $v_o > 4v_r$: reflection propagation is not generally possible. Observations are susceptible only to directly propagated interference.

7.4.4 For the allocation near 13 MHz, it is apparent from Table I, Report 699 that, even in years near sunspot minimum, situation (b) will apply for at least 50% of the time at mid-latitude sites, and sharing is not realistic. Situation (a) may prevail for a few hours near midday at times of maximum sunspot activity.

7.4.5 For the allocation near 25 MHz, situation (c) may prevail for about 80 to 90% of the time at mid-latitudes for a few years around minimum sunspot activity. However, averaged over a typical sunspot cycle, situation (b) will prevail for more than 20% of the time. Hence sharing is undesirable in this band as well.

7.5 37.50-38.25 MHz

7.5.1 In the band at 38 MHz, radioastronomy has a world-wide secondary allocation and there is a footnote urging administrations to take all practicable steps to protect the service from harmful interference. The fixed and mobile services have primary status in the band. Although the systems operating within these services, in this band, display a wide range of characteristics, radiated power of 20 W or 30 W from an antenna of low directivity is representative of many systems. An e.i.r.p. of 16 dBW has been chosen for the standard system used in interference calculations. Bandwidths are typically of the order of 20 kHz to 30 kHz and five transmitters are arbitrarily assumed to be operating within the 0.75 MHz band allocated to radioastronomy.

7.5.2 The large separation distances, large even for a well-shielded site, make sharing difficult. In addition, propagation via reflections from sporadic-E layers in the ionosphere needs to be taken into account. Recommendation 534 provides the data. Basic transmission loss over paths of 1000 km to 2500 km will be less than 213 dB for more than 10% of the time during summer months in much of the world. This propagation mode will be much less important during winter months and sharing considerations will be dominated by the tropospheric scatter field.
7.6 73-74.6 MHz and 79.75-80.25 MHz

7.6.1 There are different regional allocations to radioastronomy in this part of the spectrum. The bands are 73 MHz to 74.6 MHz and 79.75 MHz to 80.25 MHz and the sharing is with the fixed, mobile, aeronautical radionavigation and broadcasting services. With this variety of services and different regional allocations there is no one system which characterizes the general usage. However a reference system with a 30 W transmitter feeding an antenna of 10 dB gain has been chosen as representative of the fixed service. The antenna height is taken to be 10 m and seven similar transmitters are assumed to be operating in the band at approximately the same distance from the observatory. Low power mobile systems with e.i.r.p. between 10 dBW and 15 dBW are also in frequent use in this band.

7.6.2 With a separation distance as large as 780 km for a well-shielded site, sharing with radioastronomy is difficult. An additional difficulty may be the affect of propagation via the sporadic-E layer although Recommendation 534 indicates that this mechanism is more likely to be important at the 1% level rather than 10%.

7.7 150.05-153 MHz

The fixed and mobile services have primary allocations in all three regions. Radio astronomy has a primary allocation in Region 1, but is given no recognition elsewhere except for a primary allocation, by footnote, in Australia and India. A narrow band mobile system has been chosen as a typical reference system. Ten transmitters are assumed to be operating simultaneously within the radio astronomy band.

7.8 322-328.6 MHz

Radio astronomy has a primary worldwide allocation shared with the fixed and mobile services. In some areas of the world high-power terrestrial transmitters might cause interference. In other locations the most likely source of interference could be airborne transmitters. In the latter case Figure 1 shows that an e.i.r.p. of less than 1uW could cause interference at a distance of 600 km if within line of sight. The hypothetic reference system used for the calculation of the separation distance is similar to that used for the mobile service at 150 MHz.

7.9 406.1-410 MHz

7.9.1 In the band 406.1-410 MHz, radioastronomy shares primary status with the fixed and mobile, except aeronautical mobile, services. A typical system in the land mobile service has a transmitter power of 25 W into an antenna of low gain at a height of 10 m. With a bandwidth of 25 kHz there is in excess of 150 possible channels within the 3.9 MHz bandwidth. It is assumed that just 12 are operating at the same time and within a narrow interference range.

There are systems operating in the mobile service of considerably higher transmitter power. A power of 125W is not exceptional.

7.10 608-614 MHz

7.10.1 Radioastronomy has different levels of protection in the three Regions in this television band near 610 MHz. Since high power television stations may be located in the adjacent channels, adjacent-channel interference can be a problem. This is considered in Report 697. Here only the possibility of co-channel interference from a sharing television transmitter is considered.
7.10.2 There exists, around the world, a great variety of television stations with a large range of transmitter powers and antenna heights. One national classification of television stations which illustrates the variety is as follows:

- **Class A**: 10 kW e.i.r.p. antenna height = 100 m
- **Class B**: 100 kW e.i.r.p. antenna height = 150 m
- **Class C**: 1000 kW e.i.r.p. antenna height = 300 m

7.10.3 The reference system chosen for the calculation of separation distance is that of Class A above. Even for this lowest power system the separation distances are large and Class B and C systems of higher power and higher antenna heights would require such large separation distances as to eliminate any possibility of sharing.

7.11 1330-1400 MHz

7.11.1 The region of the frequency spectrum in the vicinity of the 21 cm wavelength spectral line of hydrogen is of very great importance to radioastronomy. This importance has been recognized by the world-wide allocation to radioastronomy, in the exclusively passive band 1400 MHz to 1427 MHz for both line and continuum observations. In recent years, observations of the same hydrogen spectral line, Doppler-shifted to lower frequencies, have grown in importance. This shift to lower frequencies is the result of the large velocities at which distant galaxies are moving away from the galaxy in which the Sun is located. The importance of these observations of the redshifted hydrogen line was recognized in a footnote which gives some protection to radioastronomy in a band below 1400 MHz. In this band radiolocation has primary status in Regions 2 and 3 and shares primary status with the fixed and mobile services in Region 1.

7.11.2 A typical radiolocation system used for aeronautical purposes in this band is a ground-based radar with 500 kW peak pulse power and an antenna gain of 34 dB. If the dynamic range of the radioastronomy receiver is sufficient to accommodate the radar peak power, the important parameter, with respect to interference, is the average power into the radioastronomy receiver during its integration period. For a radar scanning 360°, the average power transmitted in the direction of the radioastronomy observatory is of the order of the average power from the transmitter. The actual power so transmitted is a function of the radar antenna pattern and of the nature of the scan. With the assumption that the radar has a duty cycle of 0.001, the average power is 500 W. The radar output power of 500 W is assumed to be distributed uniformly over 0.5 MHz (a 2 µs pulse). This reduces the power into a single channel of the radioastronomy receiver by 10 log (500/20) = 14 dB.

7.11.3 It must be noted that the peak power into the receiver input is -142 dBW when the average interference is just at the harmful level. This is about 15 dB above the receiver noise power in a 0.5 MHz band and, particularly if more than one radar signal is in the passband of the receiver front end, non-linear effects may invalidate the analysis in terms of average power.

7.11.4 Pulse compression radars are, in some cases, replacing the system described above. Sharing will be made easier because the pulse power is spread over a larger frequency range and because the peak power is reduced. In Sec. 7.11.2 the power into a single channel of the radioastronomy receiver is calculated to be reduced by 14 dB because the interfering radar signal is spread over 0.5 MHz. With the pulse compression radar the reduction may be as large as 24 dB. The reduction in peak power may be 10 dB and the problem of non-linearity described in Sec. 7.11.3. reduced.

7.12 1400-1427 MHz

7.12.1 This is an exclusively passive band and there is consequently no interference to radioastronomy from shared services. The possible sources of interference are transmitters in adjacent bands and spurious emissions from other out-of-band transmitters. This topic is dealt with in Report 697.
7.13.1 These three bands are used for observations of spectral lines of the hydroxyl radical. The wider bandwidth of the middle allocation permits Doppler-shifted observations of lines from extra-galactic sources. Although the observing requirements are similar, the sharing problems are very dissimilar. The band 1660-1670 MHz is also used for continuum observations.

7.13.2 In the band 1610.6 - 1613.8 MHz radio astronomy has a secondary allocation [FN 734]. In the wider band 1610 - 1626.5 MHz a variety of other services have allocations. The aeronautical radionavigation service has a primary allocation. The aeronautical mobile-satellite service has a primary allocation subject to the procedures set forth in Article 14 [FN 733]. Also the use and development of airborne electronic aids to air navigation and any directly associated ground-based or satellite-borne facilities has an allocation subject to Article 14 [FN 732]. Sharing with satellite-borne transmitters is unlikely to be possible as noted elsewhere in this report (section 5 and Figure 1). In addition to the above the radio determination-satellite service (Earth-to-space) has allocations, primary in Region 2 and secondary in Regions 1 and 3. However the RDSS in Regions 1 and 3 is required to protect the 1610.6 - 1613.8 MHz radio astronomy band [FN 733E]. In the United States a plan has been proposed to protect radio astronomy in its allocated band. It is proposed to time-share the frequency band within a protected area around the radio astronomy observatory. The particular nature of the time-sharing proposal and calculations of the dimensions of the protected area are described in Report 1126.

Transmissions from satellites operating in the radionavigation-satellite service in the band 1559 - 1610 MHz and by FN 732 in the band 1610 - 1626.5 MHz result in harmful interference world-wide and prevent the acquisition of useful data during half or more of the observing time.

7.13.3 The band 1660-1670 MHz consists of three sub-bands. In each sub-band radioastronomy has a primary allocation but the sharing services are different. In the most important sub-band, 1660.5-1668.4 MHz, the fixed and mobile, except aeronautical mobile, services are listed in the Table as secondary services although (footnote 737) lists forty administrations in which these services have primary status until 1990. There are a variety of fixed systems in this region of the spectrum. A reasonable representative is a low capacity system with 3.5 MHz bandwidth transmitting 5 W through an antenna of 38 dB gain. Separation distances have been calculated for both continuum and spectral line observations and for situations where the fixed service antennas are pointing at, and away from, the observatory.

The band 1660.0 - 1660.5 MHz is allocated on a primary basis to the land mobile-satellite service (Earth-to-space). Provision has also been made for aircraft and ship earth stations to communicate with space stations in the land mobile-satellite service [FN 730A]. Aircraft earth stations are likely to remain within line-of-sight of the radio astronomy observatory to a great distance and sharing will be difficult. For the land mobile satellite earth station an average e.i.r.p. of 0 dBW is chosen as representative. A single co-channel interferor with a bandwidth of 4 kHz is assumed. Separation distances have been calculated and listed in Tables I and II. The characteristics of the LMSS earth stations are taken from Report 1182 where a detailed examination of sharing in this band may be found.
The meteorological aids service has a primary allocation in the band 1668.4-1670 MHz and in the adjacent bands above 1670 MHz. Transmissions from balloons at altitudes up to 30 km can cause interference to radio astronomy over large distances.

7.13.4 In the band 1718.8-1722.2 MHz, the fixed service has a world-wide primary allocation and the mobile service is primary in Regions 2 and 3 and secondary in Region 1. Radioastronomy has a secondary allocation. The requirements for separation distances to protect radioastronomy from fixed-service operations would be very similar to those set for the 1660-1670 MHz band in § 7.13.3.

7.14 2655-2700 MHz

7.14.1 In the upper 10 MHz of this band, radioastronomy has a primary allocation and an attempt has been made to create a purely passive band. However, a large number of administrations have additional allocations by footnote to the fixed and mobile except aeronautical mobile services. The calculated separation distances presented in Table II are based on sharing with a low power transmitter operating in the fixed service.

7.14.2 In the 2655-2690 MHz band, radioastronomy has a secondary allocation and the primary services are the fixed and mobile and broadcasting satellite. The fixed-satellite service is also present in the Table for Regions 2 and 3. Clearly the development of this band by the broadcasting-satellite service would make the band unusable for radioastronomy. Figure 1 shows that a geostationary transmitter radiating 1 mW from the far side lobes of a satellite antenna (0 dB gain) can result in harmful interference to radioastronomy observations being conducted in directions far from the satellite position.

7.15 3260-3267 MHz, 3332-3339 MHz, 3345.8-3352.5 MHz

In footnote 778 of the Radio Regulations administrations are urged to take all practical steps to protect spectral line observations in the three bands mentioned above. The radical CH is responsible for all three lines. The primary table allocation is to the radiolocation service. Calculations to determine the separation distance required to protect radioastronomy have not been made. However, for sharing with ground-based radars the situation will be similar to that described in § 7.11 for the 1330-1400 MHz band but the basic transmission loss will be some 10 dB larger at the higher frequency. A more difficult sharing problem exists if the radars are airborne and are within line-of-sight of the observatory to a distance of perhaps 600 km.

7.16 4800-5000 MHz

7.16.1 In the 4800-4990 MHz band, radioastronomy has a secondary allocation in the Table. Fixed and mobile are the primary services. However, footnotes single out the bands 4825-4835 MHz and 4950-4990 MHz for special treatment. The first of these bands is for the observation of formaldehyde in interstellar space; one footnote excludes the use of aeronautical mobile and another urges administrations to take all practicable steps to protect radioastronomy. The use of aeronautical mobile is also excluded from the band 4950-4990 MHz. With the exclusion of the aeronautical service the sharing situation is similar to that described in the next paragraph.

7.16.2 Radioastronomy is on an equal primary basis with the fixed and mobile except aeronautical mobile services in the band 4990-5000 MHz. Fixed-service usage in this band may be either low power radio-relay systems or tropospheric scatter systems. Because of the very high average power used in the latter system, sharing with radioastronomy is very difficult. The radio-relay systems with perhaps 10 W transmitter power, 40 MHz RF bandwidth and 44 dB antenna gain presents an easier sharing problem. Separation distances have been calculated for the situation where the fixed service antenna is directed at the radio astronomy observatory and for the situation where it is directed well away from the observatory and a gain of 0 dB can be assumed. Sharing would normally be feasible if the radio-relay system was designed to avoid pointing transmitting antennas at the observatory.
7.17 10.6-10.7 GHz

7.17.1 Radioastronomy has an allocation in the passive band 10.68-10.70 GHz and shares primary status with the fixed and mobile services, except aeronautical mobile, between 10.60 GHz and 10.68 GHz. Generally, the systems in use are low-powered in both the fixed and mobile services. Except that tropospheric scatter is not used at this frequency, the situation is very similar to that at 5000 MHz. A reference system with 5 W into an antenna of 44 dB gain has been chosen. For the same distances the basic transmission loss at 10 GHz is 8 to 9 dB greater than at 5 GHz. The harmful interference level from Report 224 is 2 dB higher. If high gain antennas in the fixed service are not directed at the observatory, the system can work within 100 km of a well-shielded observatory. Within 350 km, care would be required to avoid directing an antenna at the same observatory. For many radio relay systems operating at this frequency the transmitter power could be about 1 W and the required transmission loss for sharing would then be 7 dB less.

7.18 14.47-14.50 GHz

7.18.1 Radioastronomy has a secondary allocation in the Table for the observation of a spectral line from formaldehyde. The primary services are fixed and mobile, except aeronautical mobile and the fixed-satellite service (Earth-to-space). Sharing with the fixed and mobile (except aeronautical mobile) services presents much the same problem as in the band 10.6-10.7 GHz discussed in the preceding paragraph.

7.18.2 An earth-to-space link in the fixed satellite service has been used as a reference system for calculations of separation distances. It is assumed that the transmitter power is 500 W in a band of 50 MHz and the antenna is at a sufficiently high elevation to have a gain of 0 dB in the horizontal direction of the observatory.

7.19 15.35-15.40 GHz

7.19.1 This is a passive band and all emissions are prohibited except for an additional allocation on a secondary basis to the fixed and mobile services of 15 administrations.

7.19.2 Separation distances are calculated using the same earth-to-space reference system described in 7.18.2. The primary aim here is to demonstrate the difference between interference to continuum observations appropriate to this band and the interference to spectral line observations considered in Section 7.18.2.

7.20 22.01-22.21 GHz, 22.21-22.5 GHz

7.20.1 In the first of these two bands, administrations are urged to protect radioastronomy observations but in the second, radioastronomy has a primary shared allocation. Fixed and mobile, except aeronautical mobile, are primary services in both bands. The total bandwidth is wide enough for continuum measurements but there is also an important spectral line of water at 22.235 GHz and it is sharing with spectral line observations which is considered here.

7.20.2 Operational use of this band is not heavy, but one system in use has the following characteristics; transmitter power of 200 mW in a 50 MHz band and an antenna gain of 45 dB.

7.20.3 The separations distances required to reduce interference to acceptable levels when the fixed service antenna is directed at the radio astronomy observatory are given in Table II. If the antenna is pointed away from the observatory the separation distances are less than 100 km for all three values of elevation of the horizon, and sharing should not be difficult.
7.21 22.81-22.86 GHz, 23.07-23.12 GHz

There is an ammonia line observable in space in each of these two bands. The use by radioastronomy of the bands is notified by a footnote. In addition to the fixed and mobile services the inter-satellite service is in both bands on a primary basis. The broadcasting-satellite service has a primary allocation in the lower of the two bands in Regions 2 and 3. These frequencies above 20 GHz are not now heavily used by active services, but the fixed service is developing. The system described in section 7.20 is appropriate. The operation of broadcasting-satellites could present problems in the future but it appears from Figure 1 that the inter-satellite service is unlikely to cause harmful interference to radioastronomy unless the space antenna is directed at the observatory.

7.22 23.6-24 GHz

7.22.1 This is a passive band and radioastronomy does not have a sharing problem. The most likely cause of interference would be emissions of the second harmonic from broadcasting satellites or fixed satellites (space-to-Earth) in bands near 12 GHz. However, a sharing situation is set out in Tables I and II at this frequency. It is generally appropriate to continuum observations in the 20 GHz region of the spectrum.

7.23 31.2-31.3 GHz, 31.3-31.5 GHz, 31.5-31.8 GHz

7.23.1 The middle band, 31.3-31.5 GHz, is for passive services only. In the band 31.5-31.8 GHz, the passive services are primary but the fixed and mobile, except aeronautical services, have secondary status in Regions 1 and 3. In comparison the lowest band 31.2-31.3 GHz is not of great value to radioastronomy since it is covered by only a notification-of-use footnote and fixed and mobile services have primary status and space research and standard frequency and time signal satellite (space-to-Earth) services are secondary.

7.23.2 A fixed service of low power has been chosen as a representative service. As with other frequencies above 20 GHz sharing is not likely to be a problem if the transmitting antenna of the fixed service is directed away from the observatory.

7.24 36.43-36.50 GHz

7.24.1 A footnote in this band urges administrations to take all practicable steps to protect spectral line observations from interference. The spectral line referred to is a recombination line of hydrogen. Sharing is with the fixed and mobile services. Some few fixed systems are in use and the calculations made for the 31 GHz case are appropriate here.

7.25 Above 40 GHz

7.25.1 There are a number of allocations for the radioastronomy service above 40 GHz for both continuum and spectral line observations. Some of these are allocations to passive services only but many are shared allocations with a variety of active services.

7.25.2 There are very few active systems operating above 40 GHz and consequently there are few problems of interference to radioastronomy at this time. Certainly the choice of reference systems must await the development of active systems in this region of the spectrum.

7.25.3 No calculations have been made of separation distances required for sharing. Apart from the lack of suitable reference systems there is a lack of propagation information.

7.25.4 Sharing in the future will continue to be easier above than below 40 GHz. The sensitivity of receivers available to radioastronomers will probably continue to be poorer at the higher frequencies. The power available to a potentially interfering transmitter will probably continue to be lower at the higher frequencies. Although there is a paucity of propagation data, the basic transmission loss at a given distance is higher above 40 GHz than below. The troposphere scatter signal decreases monotonically with increasing frequency and also the atmospheric attenuation is higher and at some frequencies above 40 GHz it is very high.
8. Some conclusions on the possibilities of frequency sharing

8.1 Because of the nature of the phenomena observed in radioastronomy, only under special conditions will it be feasible to devise time-sharing programmes between radioastronomy and other services.

8.2 It is very difficult for the radioastronomy service to share frequencies with stations from which line-of-sight paths to the observatories are involved.

8.3 For frequencies at which interfering signals can be transmitted via the ionosphere over long distances (below about 30 MHz, depending on ionospheric conditions) it is extremely difficult for radioastronomy to share with other services using transmitters anywhere on the Earth.

8.4 Sharing with other services may be feasible if transmitters in the radioastronomy bands are on the ground, of low power, and at an adequate distance from the observatory; and also, if account is taken of any site-shielding, the occasional occurrence of abnormally good propagation and the possibility of reflections from aircraft. Typically, separations of several hundred kilometres may be involved at frequencies below 1 GHz, but shorter separations might be acceptable at much higher frequencies.

8.5 If frequencies are shared, special precautions might be needed to avoid the irradiation of the Moon by transmitter beams when the Moon is being used for occultation experiments or for calibration purposes.

8.6 To improve the chances of successful frequency sharing, radioastronomy observatories should be sited as far as possible from urban areas and transmitters with interfering potential, and should be shielded to the greatest extent possible by surrounding terrain. These precautions are, however, likely to affect only the sharing possibilities discussed above. At frequencies above 10 GHz and particularly above 20 GHz, the need to site observatories at high altitudes to minimize atmospheric absorption may limit the extent to which site-shielding is practicable.

ANNEX I

Sharing with the deep-space research (space-to-Earth) service

The bands allocated to deep-space research (space-to-Earth) transmissions at 2.3 and 8.4 GHz, and sometimes parts of adjoining bands, are routinely used for certain radioastronomy observations. This practice has arisen from the similarity of the requirements for reception of signals from cosmic sources and from deep-space vehicles: in both cases fully steerable antennas with large apertures and low-noise receiving systems are required.

During the development of Very Long Baseline Interferometry (VLBI), radioastronomers sought to use a number of such large antennas at widely spaced locations to provide the long baselines required. These included some antennas constructed primarily for deep-space communications, which are instrumented for reception in the 2.3 and 8.4 GHz bands. Simultaneous observation at two frequencies allows the interferometric data to be corrected for the effects of the earth's ionosphere, which is particularly important in studies involving high angular precision such as astrometry, geodesy and monitoring of time and polar motion. Thus, as VLBI systems for geodesy and timekeeping have been established, the 2.3 and 8.4 GHz bands have become widely used for such observations. Considerations of sharing with the fixed and mobile services, to which these bands are also allocated, are similar to those discussed in section 7 with respect to the 4800-5000 MHz and 10.6-10.7 GHz bands.
Another development which has led to further sharing of facilities between radioastronomy and deep-space communications has been the use of certain radiotelescopes for reception of signals from space vehicles, to supplement the collecting area of deep-space ground stations and to assure full 24-hour coverage of important space missions.

As defined in the Radio Regulations, deep space is the region of space beyond $2 \times 10^6$ km from the earth. Missions to deep space involve exploration of planets, comets, asteroids and the solar wind. Typical parameters for space-to-earth transmission from deep-space vehicles are 20 W for the transmitter power and 4 meters for the diameter of the antenna, which provides a gain of 36 dBi at 2.3 GHz or 47 dBi at 8.4 GHz in the direction of the earth. At a distance of $2 \times 10^6$ km from the earth, the corresponding levels of power flux density are $-148$ dB(W m$^{-2}$) at 2.3 GHz and $-137$ dB(W m$^{-2}$) at 8.4 GHz. These flux density levels exceed the harmful thresholds for interference to radioastronomy, as obtained by interpolation from Table 1 of Report 224, by 30 dB at 2.3 GHz and 27 dB at 8.4 GHz. For a spacecraft with the same transmitter parameters, and in the vicinity of the nearest planet, Venus, at its closest distance of approach ($4 \times 10^7$ km), the signals would exceed the thresholds in Report 224 by 4 dB.

For the outer planets, the distances of closest approach range from $6.3 \times 10^8$ km for Saturn to $5.8 \times 10^9$ km for Pluto, and spacecraft on missions to these planets would be close enough to earth to cause harmful interference to radioastronomy observations for only a few percent of the mission lifetimes. Thus, in terms of the harmful thresholds in Report 224, signals from spacecraft in the nearer parts of deep space could cause harmful interference to radiotelescopes sharing the same band, whereas spacecraft on missions to the outer planets would cause very little interference. Note that it is here assumed that the spacecraft signals would be received by sidelobes of the radiotelescope of gain no greater than 0 dBi.

In general, sharing between radioastronomy and deep-space usages is not possible. However, for the particular technique of VLBI (see e.g. [Thompson, Moran and Swenson, 1986]), the differences in the frequencies of the fringe-pattern responses for the interfering transmitter and the source under observation result in the response to the interfering signal being suppressed. Thus, as shown in Figure 2 of Report 224, the harmful thresholds for interference to VLBI observations are typically 40 dB higher than those for the widely used techniques based on total-power measurement, to which the limits in Tables I and II of Report 224 apply. Experience to date shows that for the particular case of VLBI observations, sharing between radioastronomy and deep-space communications is practicable.

REFERENCES

COORDINATION BETWEEN THE RADIO ASTRONOMY SERVICE
AND THE RADIODETERMINATION SATELLITE SERVICE AT FREQUENCIES NEAR 1.612 MHz

(Question 5/2 and Study Programme 5A/2)

1990

1. The radiodetermination satellite service

A system of the RDSS being developed in the United States (Rothblatt, 1987) includes a procedure designed to prevent harmful interference to the radio astronomy service at frequencies near 1.612 MHz. The purpose of the present report is to describe this procedure and to examine the requirements under which it is effective. Other administrations may wish to adopt the same procedure, or modifications of it, as the RDSS is developed world-wide.

The Radiodetermination Satellite Service (RDSS) provides radiolocation and limited communication for users of aeronautical, marine and terrestrial vehicles and is described in Report 1050. In the U.S. system referred to above, signals from a control center are transmitted to transceivers on users' vehicles through one of a series of two or three satellites spaced along the geostationary satellite orbit, and responses are received through each of these satellites. If three satellites are used, locations of vehicles can be determined from the measured times of transmission from the control center to the user and back via different satellite paths. If two satellites are used the timing data must be supplemented by information such as altitude data from a terrain map, or an altimeter reading from the user's vehicle which can be encoded in the response transmitted back. Computation of the vehicle location is performed at the control center. The equipment at the vehicle can be relatively simple since its basic function is that of a transponder, and intervention by the vehicle operator is not necessarily required. However, provision can also be made for the inclusion of short coded messages from the vehicle, so the unit on the vehicle is usually referred to as a transceiver.

At the WARC (World Administrative Radio Conference) on the Mobile Services, Geneva, 1987, frequency bands were allocated to the RDSS, as follows:

- **vehicle-to-satellite**: 1610.0 - 1626.5 MHz
- **satellite-to-vehicle**: 2483.5 - 2500.0 MHz and 2500.0 - 2516.5 MHz

Links for communication between the satellites and the RDSS control center use frequencies within the allocations to the fixed satellite service. The signal of particular concern to radioastronomers is the uplink from vehicle to

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*This Report should be brought to the attention of Study Groups 1 and 8.
**See also Annex V of Report 538*.
satellite which covers the secondary allocation to radio astronomy in the band 1610.6 - 1613.8 MHz. In radioastronomy, this band is used for observations of the 1612 MHz hydroxyl line. Coordination between the RDSS and the radioastronomy service in this band is the main subject of this report.

In Regions 1 and 3 the allocation of the band 1 610.0 - 1 626.5 MHz to the RDSS is secondary, and footnote 743E of the Radio Regulations states that in this band the RDSS shall not cause harmful interference to the radio astronomy Service. In Region 2 the RDSS allocation is primary in the 1 610.0 - 1 626.5 MHz band.

2. Time-coordination between the RDSS and radio astronomy

As a means of reducing interference to radioastronomy from RDSS vehicle-to-satellite transmissions, the system under development in the United States includes a procedure in which transmissions from user transceivers within specified zones surrounding radioastronomy observatories occur only during the first 200 ms of each second of Coordinated Universal Time (UTC) (Rothblatt, 1987, 1988). The scheme is put into effect during periods for which an observatory has notified the RDSS system operator that observations in the 1610.6 - 1613.8 MHz band are to be made. The radioastronomy receivers at the observatory are blanked during these 200 ms intervals, and the resulting 20% loss in observing time results in an overall loss in sensitivity of 10%.

The control of the vehicle transmissions is achieved through the timing sequence established at the RDSS control center, which consists of a series of time frames approximately 12 ms long. Signals defining the time frames are transmitted from the central station via the satellites. Transmissions from users are triggered by time marks within the frames. Users within a radioastronomy protection zone will have a flag set in the control logic of their transceivers so that they can be triggered only in time frames in which the signal from the control centre contains a special enabling code. Such time frames will be chosen so that user transmissions fall within the 200 ms interval described above. The flag in the user’s transceiver will be set or reset by transmissions from the RDSS control centre. Transmissions from vehicles within a radioastronomy zone, but outside the 200 ms intervals, may occur when a user enters a radioastronomy zone with the vehicle’s RDSS transceiver switched off, and then switches it on before leaving the zone. Such occurrences can be eliminated if, whenever a transceiver is switched on, the flag is initially set for transmission in the 200 ms intervals only.

The transmitter output power of an RDSS transceiver is approximately 40 W (Report 1050), and the gain of the transmitting antenna in a horizontal direction is close to 0 dBi. Thus the power level received in a radiotelescope through sidelobes of gain 0 dBi from a transceiver at a distance of 100 m is less than 10^-8 W. So long as a distance of at least 100 m is maintained between a radiotelescope and any RDSS user, low-noise input stages of gain 20-30 dB in the radiotelescope should not be overloaded. If a diode switch to reject input signals during the 200 ms intervals is placed following such input stages, no significant increase in receiver noise will result from the insertion loss of the switch. There should therefore be no technical problems in blanking of the radiotelescope during the 200 ms intervals.
3. Radioastronomy Protection Zones

3.1. General Considerations

The feasibility of the proposed time sharing between radioastronomy and the RDSS is determined mainly by the possibility of defining zones that are large enough to provide effective protection for radioastronomy, without causing an unacceptable restriction to the radiodetermination service. Article 11 of the Radio Regulations indicates that in international coordination of assignments to earth stations in the radiodetermination satellite service, the distances over which effects on services should be considered extend to 100 km from ground-based RDSS earth stations, and to 400 km from airborne earth stations. These regulations apply to interference between RDSS users in one country and services in another country. For coordination within any individual country, the size of the protection zones will be determined by the administration concerned.

The transmission from any user takes place in a series of 12 ms time frames, and for each position determination is expected to last no more than about 0.1s. For any single user such a transmission will occur, perhaps, about once per hour for a terrestrial vehicle. In that case the average power radiated by the user is about 46 dB below the level during a transmission. Note that it is the average power within a time interval determined by the type of observation, rather than the peak power, that is important with regard to interference thresholds, provided that the peaks do not cause non-linear responses in the radioastronomy system. The total signal level will depend upon the number of users, and will vary with time in a quasi-random manner. The principal uncertainty in calculating the required sizes of radioastronomy protection zones is the number and distribution of RDSS users when the system becomes fully developed. The United States system uses 8 beams to cover the continental U.S., each beam being approximately 2.5° wide and having a footprint of width 1600 km and area $2.0 \times 10^6 \text{ km}^2$. Coding of the transmissions allows for reception of up to 32 simultaneous signals from users within the footprint of each beam, and this represents the peak capacity. The planned average capacity is approximately 10 simultaneous users per beam (Report 1050).

For a transceiver output power of 40 W, and a gain of 0 dBi in the horizontal direction of the transmitting antenna, the total isotropically radiated power that contributes to the signal level at an observatory is, on average, 400 W per beam footprint area, or $2 \times 10^4 \text{ W}$ in each square kilometer. The data transmission uses spread spectrum modulation with a chip rate of 8.192 MHz. This radiated spectrum has a central lobe of width 16.384 MHz between first nulls, and the spectral power flux density at the band center is equal to that for a rectangular spectrum of width 8.19 MHz. The power density of $2 \times 10^4 \text{ W km}^{-2}$ thus corresponds to a spectral power density of $2.4 \times 10^{11} \text{ W Hz}^{-1}$ per square kilometer at 1618.25 MHz, which is the peak of the transmitted spectrum. At the nearest edge of the radioastronomy band, 1613.8 MHz, the spectral power density is 5 dB lower, and this level will be used in calculation of interference to spectral line observations. The mean level over the radioastronomy band, which is 11 dB lower than that at the peak of the spectrum, will be used for continuum observations.
3.2 Protection zones from transceivers on terrestrial vehicles

Consider a radio telescope at the center of a circular zone, within which transmissions occur only when the radio telescope receiver is blanked. The radius of the zone must be chosen so that the cumulative effect of transmissions outside of it does not exceed the maximum tolerable level for the type of radio telescope at the center. Since the signals are broadband, we specify the maximum tolerable level in terms of spectral power flux density. Values for five types of radioastronomy observations are shown in column 2 of Table I. The total power values are equivalent to those in Tables I and II of CCIR Report 224-6, except that they have been adjusted for more appropriate receiver bandwidths. These are 1 kHz for spectral line observations of OH at 1612 MHz, and 3 MHz, equal to the width of the (secondary) allocated band, for continuum observations. For synthesis arrays and very long baseline interferometry (VLBI) the maximum tolerable levels are adapted from Thompson, Moran, and Swenson (1986). For very long baseline interferometry (VLBI) the maximum tolerable levels are the same for both the spectral line and continuum cases, and the spectral power density levels at 1613.8 MHz will be used. Note that at this time the 1612 MHz radio astronomy band is used almost exclusively for spectral line observations, but calculations for continuum observations have been included here for completeness.

In calculations of the interference from terrestrial vehicles, the total spectral power density values discussed in Section 3.1 were used, since other users are expected to be only a minor fraction of the total. The integration over distance was approximated by summing contributions from consecutive annular rings of width 10 km. Values for the radius of the coordination zone that result in signal levels equal to the maximum tolerable values in column 2 of Table I are given in column 3. These results include the effects of diffraction, computed using methods in Report 715, and tropospheric scatter, computed using methods in Report 238-3. The tropospheric scatter calculations correspond to path loss exceeded for 90% of time, and to a continental temperate climate. For distances up to approximately 60 km, propagation is mainly by diffraction, but for greater distances tropospheric scatter becomes the dominant mechanism. For scatter propagation the rate of increase of path loss with distance is much smaller than for diffraction, and as a result the coordination zone radii are less precisely defined for tolerable interference levels greater than -220 dBW m^-2 Hz^-1 in Table I. However, the propagation loss for tropospheric scatter depends strongly upon the horizon angles at the transmitting or receiving sites, and the smooth earth model thus represents the worst case. A 1° increase in horizon angle brings the radius for total power (continuum) down to about 180 km, and all other cases in column 3 to less than 70 km.

The values in column 3 of Table I indicate that for a smooth earth model the radius of the protection zone should be more than 150 km for all but the least sensitive observations. However, many observatory sites are chosen to provide some degree of shielding by the surrounding terrain. Columns 4 and 5 of Table I indicate the required radius of the protection zone for an observatory surrounded by mountains at a distance of 10 km that subtend horizon angles of 1° and 4° respectively. Computational methods in Report 715
TABLE I

Protection of radio astronomy observatories from ground-based RDSS transmissions for five types of observations. These are spectral line and continuum observations with both total power radiotelescopes and synthesis arrays, and observations using very long baseline interferometry. Column 3 gives the radius of the required protection zone for a smooth earth model. Columns 4 and 5 give the radii for an observatory surrounded by mountains at a distance of 10 km which subtend horizon angles of 1° and 4°, respectively. Asterisks indicate that the protection zone need only extend to a point beyond the mountains at which the altitude at ground level has fallen to a value similar to that at the observatory.

<table>
<thead>
<tr>
<th>Maximum Tolerable Level (dB(W/m² Hz⁻¹))</th>
<th>Radius of Protection Zone</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Smooth Earth</td>
</tr>
<tr>
<td></td>
<td>0°</td>
</tr>
<tr>
<td>Total Power, Spec. Line</td>
<td>-230</td>
</tr>
<tr>
<td>Total Power, Continuum</td>
<td>-250</td>
</tr>
<tr>
<td>Synthesis Array, Spec. Line</td>
<td>-215</td>
</tr>
<tr>
<td>Synthesis Array, Continuum</td>
<td>-232</td>
</tr>
<tr>
<td>VLBI</td>
<td>-209</td>
</tr>
</tbody>
</table>
Radius of protection zone for an observatory with mountains at a distance of 10 km which provide shielding from airborne RDSS systems. Three aircraft heights, and two mountain heights with subtended horizon angles of $1^\circ$ and $4^\circ$, are considered.

<table>
<thead>
<tr>
<th></th>
<th>Aircraft Height - 1 km</th>
<th>Aircraft Height - 5 km</th>
<th>Aircraft Height - 10 km</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$1^\circ$</td>
<td>$4^\circ$</td>
<td>$1^\circ$</td>
</tr>
<tr>
<td>Total Power, Spec. Line</td>
<td>(km)</td>
<td>(km)</td>
<td>(km)</td>
</tr>
<tr>
<td>165</td>
<td>35</td>
<td>300</td>
<td>85</td>
</tr>
<tr>
<td>Total Power, Continuum</td>
<td>220</td>
<td>120</td>
<td>360</td>
</tr>
<tr>
<td>Synthesis Array, Spec. Line</td>
<td>60</td>
<td>~ 20</td>
<td>195</td>
</tr>
<tr>
<td>Synthesis Array, Continuum</td>
<td>135</td>
<td>30</td>
<td>265</td>
</tr>
<tr>
<td>VLBI</td>
<td>40</td>
<td>~ 20</td>
<td>175</td>
</tr>
</tbody>
</table>
were followed, and the mountain ridge was assumed to have a radius of 200 m at the top. The four-thirds earth radius approximation was used to take account of atmospheric refraction here and in all calculations of diffraction and horizon distances in this report. Contributions from the annular zones were included out as far as the horizon as seen from the mountain top. For distances beyond this horizon, the path loss increases rapidly. Propagation by tropospheric scatter should be unimportant for the horizon angles shown.

From columns 4 and 5 of Table I it can be seen that the presence of shielding with a horizon angle of 1° reduces the required radius of the protection zone to less than 100 km. A horizon angle of 4° reduces the required radius to 35 km or less, except in the case of the most sensitive observations. (In this last case the required radius increases with the height of the mountain. This is because the line-of-sight distance from the mountain top is increased, allowing signals from user vehicles at greater distances to propagate to the observatory by diffraction over the mountain top.)

An example of a particularly well shielded observatory site is provided by the Dominion Radio Astrophysical Observatory at Penticton, Canada, at which the horizon elevation is greater than 5° in almost all directions. A more representative example of what may be considered well shielded is the facility of the U.S. National Radio Astronomy Observatory (NRAO) at Green Bank, West Virginia. At most positions within the observatory grounds the horizon angle is at least 2-1/2° for more than 330° of azimuth, and at some positions it is in the range 3-1/2° to 4-1/2° for all azimuths. In contrast, many radio observatories have very little mountain shielding. This is particularly true for sites of large antenna arrays which require extensive flat areas. For example, at the NRAO Very Large Array (VLA) site in New Mexico, the mountains that define the horizon are largely at distances of 20 km and greater, and subtend angles of only 1° or 2° over limited azimuth ranges. Array sites with even less protection by mountains include the site of the Westerbork Synthesis Radio telescope in the Netherlands and the Australia Telescope at Culgoora, Australia. For terrestrial vehicles, in the United States, a value for the radius of the protection zone of 25 km has been proposed. From the results in Table I, this might provide adequate protection only for observations with mountain shielding of several degrees at all azimuths.

3.3. Protection Zones from Transceivers on Aircraft

The number of aircraft which may be fitted with RDSS transceivers is expected to be much less than the number of terrestrial vehicles. Here it will be assumed that an average of one in twenty-five of all transceiver transmissions are radiated from aircraft. This would correspond to, say, one airborne user for every 100 ground-based users, but obtaining locations about four times more often. Thus the mean spectral power density for airborne RDSS transceivers becomes $9.6 \times 10^{-13}$ W Hz$^{-1}$ per square kilometer at the peak of the transmitted spectrum. An aircraft at 10,000 m would be within line of sight for distances up to 410 km. For aircraft at heights of 1,000 m and 5,000 m the corresponding line-of-sight ranges are 130 km and 290 km respectively. For a smooth earth model, the radius of the protection zone must exceed these distances to avoid line-of-sight propagation.

Table II gives the radii of protection zones required for three aircraft heights and two horizon angles. Again these are based on diffraction effects, and methods in Report 715 were used. The signal levels at the observatory were calculated for annular rings of width 50 km and summed for distances out to that for which the aircraft would be on the horizon as seen from the mountain top.
The required sizes of the zones in Table II clearly depend strongly on both the degree of shielding and the aircraft heights. A protection zone radius of 150 km, which has been proposed for aircraft in the United States system, would require mountain shielding of 4° or more in the case of altitudes approaching 10,000 m.

4. Discussion of Protection Zones

Two features of the RDSS system currently being implemented in the United States distinguish it from most other radiolocation or communication systems and allow the possibility of coordination with radioastronomy observatories. These are the knowledge of the positions of the users at the central control station, and the control of the timing of the transmissions of the user transceivers by the central control system. Thus coordination of the RDSS and radioastronomy services is possible using geographical and timing parameters to separate the signals.

The results in Tables I and II are based on a number of simplifying assumptions. The uniform area density of user transmitters is clearly an over-simplification, but provides a basis for a general analysis rather than one for a particular radioastronomy observatory site. In practice the density of users will vary significantly reaching peaks at points where major highways converge and near cities and airports. The single mountain range surrounding the observatory is also a simplification, since in real situations multiple peaks or ridges between the radio telescope and the transmitter may introduce further loss. Also, the fraction of the total transmissions emanating from transceivers on aircraft when the system is fully developed can only be roughly estimated. However, the conclusion can be drawn that for a smooth terrain without mountains, radioastronomy protection zones of radius 50-200 km may be required for terrestrial users and about 400 km for airborne ones. At observatory sites that are heavily shielded by surrounding mountains, smaller protection zones can be used without interference to radio astronomy. It is important to note that such levels of shielding are mainly found in mountain valleys of dimensions that limit the radiotelescopes to single antennas or compact arrays. In the case of the VLA, for example, the antennas are spread over an area approximately 40 km in diameter, and a high plains area was chosen to accommodate the array.

For transceivers on high altitude aircraft, the protection zones required to avoid line-of-sight propagation to observatories with little or no mountain shielding may include a large fraction of the aircraft flight paths. If, however, such aircraft are a small fraction of the total users, and account for only a few percent of the total transmissions, it should be possible to accommodate them within the 200 ms coordination intervals.

The planning of coordination zones should ideally be done on an individual site basis, and should include an appraisal of the terrestrial features and distribution of RDSS users within several hundred kilometers of each observatory, as well as the types of observations made there. The results in Tables I and II are intended only to provide some initial estimates of the probable requirements, and specific national arrangements may have to be made on a case by case basis.
5. Other considerations and further studies

5.1 The down link signal

There is a possibility of interference from the second harmonic of the 2 483.5 - 2 500.0 MHz down link signal from the RDSS satellites to radio astronomy observations in the 4 800 - 4 990 MHz (secondary) and 4 990 - 5 000 MHz (primary) radio astronomy bands. The expected spectral power flux density of the down link signal from the geostationary orbit, at the Earth's surface, is -181 dB(Wm"2 Hz"-1) (Report 1050). The second harmonic radiation from the RDSS satellite should be 75 dB below the fundamental to be tolerable to radio astronomy (Report 224).

5.2 Sidebands of the up link signals

The RDSS signals in the 1 610.0 - 1 626.5 MHz band involve spread spectrum modulation with a chip-rate of 8.192 MHz and the power spectrum generated by the transmitter on the user's vehicle has a form (sin^2 x/x^2). To prevent interference to radio astronomy in nearby bands such as 1 660 - 1 670 MHz and 1 400 - 1 427 MHz, the company developing the RDSS system in the United States has agreed to install filters to control the emitted spectrum to meet the following requirement. The mean power density of airborne and spacecraft RDSS emissions at a frequency which is removed from the assigned frequency by more than 50 per cent of the assigned bandwidth shall be attenuated below the mean power density at the assigned centre frequency as specified in the following equation (attenuation greater than 75 decibels is not required):

$$ A = 12 + 0.2(P-50) $$

where,

A = attenuation (in decibels) below the mean power density level; and,  
P = per cent of assigned bandwidth removed from the carrier frequency.

5.3 Observations of pulsars and time-critical phenomena

In observations of pulsars the received signals are averaged over time intervals that are submultiples of the pulsar period, and the resulting values for corresponding intervals of different pulsar cycles are further averaged. The effect of the peak signal levels from the RDSS system may thus be more serious than is the case for many other types of observations in which the signals are averaged continuously over periods of seconds or minutes. Further study of the effects of RDSS signals on pulsar observations is required. However, pulsar observations are not often made in the 1 610.6 - 1 613.8 MHz band since the 1 660 - 1 670 MHz band is preferred for these observations. Studies should also be made of effects on observations of burst phenomena (such as solar bursts) and occultation of radio sources.

5.4 Radiotelescopes in space

Further study is required to determine the effects of RDSS transmission on observations using radiotelescopes in space, such as VLBI observations with orbiting antennas.

5.5 Improved data on RDSS usage

Since the calculations described above are based upon preliminary estimates of the numbers and distributions of RDSS users, they should be revised as improved information on these points becomes available.
6. Conclusions

It has been shown that coordination between the RDSS and the Radio Astronomy Service at frequencies near 1.612 MHz is possible using a combination of geographical and timing factors to separate the signals. The coordination relies upon unique features of the RDSS system and the particular type of radio astronomy observations usually performed at this frequency. Calculations of propagation losses indicate that the sizes of the protection zones required around radio astronomy observatories depend strongly upon the degree of shielding provided by the natural terrain. A number of effects have been identified that require further study. These include the effects of RDSS transmissions on the observations at pulsars, burst phenomena, and time-critical events such as occultations, and on radio astronomical measurements from spacecraft.

REFERENCES


1. Introduction

The sensitivity limit of most radioastronomy observations is at a flux density level far below that used for reception of radio communication signals. Reports 696 and 224 discuss harmful interference and protection criteria for frequency sharing between radioastronomy and other services; in Tables I and II of the latter the sensitivity limits are listed for different frequencies. However, as a consequence of the sensitivity of radioastronomy observations, interference can occur from transmitters which do not share the same band. This may be classified as band-edge interference and interference from harmonic and intermodulation signals.

1.1 Band-edge interference, resulting from a transmitter in an adjacent band, can arise by three mechanisms of interaction. It can occur if the response of the radioastronomy receiver to signals outside the radioastronomy band is not sufficiently low; this may be due to the practical limitations on the fall-off of receiver gain at the band edges. Secondly, non-linear effects in the receiver may, in the presence of two or more signals near the edge of the passband, give rise to intermodulation products falling within the passband of the receiver. Thirdly, interference may result from low-level signals from a transmitter (modulation sidebands etc.) which fall within the radioastronomy band. In dealing with band-edge interference, the problem common to both transmitting and receiving services is the design of filters which will adequately suppress the unwanted energy without introducing unacceptable modifications, e.g. attenuation or phase distortion, into the wanted signals.

1.2 Interference from harmonic radiation or by the intermodulation of two or more signals may be caused by transmitters well separated in frequency from the radioastronomy band. The problems are generally less severe than those of band-edge interference firstly because filter requirements are less demanding and secondly because the transmitting antennas are likely to be considerably less efficient radiators at frequencies remote from those for which they are designed.

2. The role of the transmitter in the production of interference

Some of the mechanisms of interaction depend strongly upon the characteristics of the transmitter involved, and therefore should be examined separately for different services. UHF television and services using satellite transmissions are examples of services which have been found to be troublesome to radioastronomy. In particular, transmitters on satellites or aircraft present a problem because when there are line-of-sight paths to observatories, interference cannot always be avoided. To make matters worse, the requirements for radioastronomy instruments such as extensive arrays or millimetre-wavelength telescopes do not always allow observatory sites to be chosen primarily for their freedom from man-made interference.

2.1 Interference from terrestrial UHF television transmissions

Although interference to a radioastronomy receiver may result from a transmitter operating in any service in another band, it is more likely to occur with services using high-power transmitters. Such a service is television broadcasting, which occupies a substantial fraction of the UHF band. Because radioastronomy measurements are required at octave or smaller intervals in frequency, in some parts of the radio-frequency spectrum the two services have been allocated frequency bands in close proximity to each other. Band-edge interference may then
occur. The normal spectrum of the television transmission extends outside its nominal band and additional filtering may be needed to reduce the radiated energy in the radioastronomy band to an acceptable level. Normal filtering is accomplished largely in the low-power stages of the transmitter, but additional undesirable components may be generated as a result of non-linear operation of the power amplifier and these would need to be removed by filters operating at high power levels. However, two problems may arise in connection with such filters. Firstly, the passband attenuation in the region of the vision carrier-frequency may be significant, and this may necessitate a transmitting power or an antenna gain greater than would otherwise be required. Secondly, phase distortion may be appreciable and affect the quality of the television picture. Although phase correction at low-power levels is possible, the waveform to be handled by the transmitter will then contain overshoots, and this could require a further increase in the power rating of the transmitter, if distortion is to be avoided. There is therefore a preference for phase-corrected filters. Unless the radioastronomy station is remotely situated from the transmitter there must clearly be a “guard band” to allow for the finite slope of the attenuation characteristics of the high-power filters at the transmitter. The width of this guard band depends upon the degree of attenuation required and upon the complexity which is envisaged for the high-power filters but guard bands of the order of 2 MHz would seem reasonable. The potential for interference is increased when two or more transmitters are operated with the same antenna, since intermodulation may then be produced.

It is not easy to predict the strength of the band-edge interference. Because the interference would be caused by sideband components of the picture transmission as well as by discrete components derived from the sound sub-carrier and sound signals, the level of interference depends upon the bandwidth of the radioastronomy receiver and cannot be uniquely specified as with a single spectral component. The level also depends upon the picture content and, if integration techniques are adopted at the receiver, upon the duration of a particular picture. As a reasonable guide, the interference can be deduced assuming a 1 MHz receiver bandwidth and those pictures which occur fairly frequently and which are most likely to cause interference.

Suppression of the out-of-band radiation from a television transmitter to the low levels required for radioastronomy is justified only if the radioastronomy receiver can reject the energy in the adjacent television band to a comparable level. A typical parametric amplifier may start to overload at an input level of 1 μW, but it is considered that avoidance of overload is not the main problem. The more difficult problem in general is to reduce the interference by the shaping of the intermediate-frequency passband, since some 110 dB of rejection below the 1 μW input level is required to achieve the measurement sensitivity which is possible in the absence of interference, as indicated in this Report.

In general, band-edge interference introduces more serious technical problems than does harmonic or intermodulation interference. Special filtering may be needed but in the latter cases the design problems will be less difficult. The protection of radioastronomy stations in highly developed areas may call for the addition of filters, capable of handling the full transmitter output, at several television broadcasting stations. This means that, apart from technical feasibility and cost, the question of organizing checks of the degree of suppression will need consideration.

2.1.1 Band-edge interference from UHF television transmissions in the 608-614 MHz radioastronomy bands

As an example, band-edge interference presents a severe problem to transmission on European Channel 39 (or a US Channel 38) because, with the vision carrier frequency of 615.25 MHz, the fully-transmitted portion of the lower (vestigial) sideband extends downwards by 0.75 MHz, or by as much as 1.25 MHz with CCIR Standards 1 and L, thus reaching 614 MHz. Below this frequency, the lower sideband is attenuated, but the residual level constitutes a potential source of interference with the nominal radioastronomy band. If it is assumed that a high degree of band-edge suppression has been applied to the modulated signal before the final stage in the transmitter, the signals in the radioastronomy band generated in the final stage (asssuming no output filter) will then extend to just below 610 MHz at a level typically about —55 dB relative to the vision carrier, when the measurement is made in a 1 MHz bandwidth. In addition there will be a narrow-band signal at about 611 MHz with a colour transmission, and this may reach a level of —42 dB under the worst picture conditions. An intermodulation product at 609.25 MHz produced as the result of power from the sound transmitter reaching the vision transmitter via the combining unit or diplexer will be at a level of —55 dB. Otherwise the signals over most of the lower half of the Channel will be at a level of —80 dB or lower. Since the signal will reach —42 dB only
occasionally during the worst picture conditions, and since transmitters often include a simple notch filter at the output to reduce the regenerated colour sideband it seems realistic to take a round figure of $-50 \text{ dB}$ as a likely relative signal in a typical receiver bandwidth of 4 MHz when no special filtering is used. If high-power filters with group-delay correction were added in the outgoing feeders handling the Channel transmission, then because of the sharp rate of cut-off of these filters, one or two decibels of loss may be unavoidable. In such a case, higher power transmitter would be required. It is probably technically feasible, though expensive, to reduce the out-of-band signal in the radioastronomy band to $-100 \text{ dB}$, but greater suppression would probably be impracticable.

Other cases of possible band-edge interference are listed in Table 1.
TABLE 1 — Services in adjacent bands which could cause harmful interference to the radioastronomy service *

<table>
<thead>
<tr>
<th>Band allocated to radioastronomy on world-wide primary basis</th>
<th>Adjacent band</th>
<th>Adjacent-band services (')</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.36-13.41 MHz</td>
<td>13.26-13.36 MHz</td>
<td>AERONAUTICAL MOBILE (R)</td>
</tr>
<tr>
<td>25.55-25.67 MHz</td>
<td>25.67-26.10 MHz</td>
<td>BROADCASTING</td>
</tr>
<tr>
<td>322-328.6 MHz</td>
<td>273-322 MHz</td>
<td>MOBILE, including satellite</td>
</tr>
<tr>
<td>328.6-335.4 MHz</td>
<td></td>
<td>AERONAUTICAL RADIONAVIGATION</td>
</tr>
<tr>
<td>1400-1427 MHz</td>
<td>1350-1400 MHz</td>
<td>RADIOLOCATION</td>
</tr>
<tr>
<td></td>
<td>1429-1525 MHz</td>
<td>MOBILE (Region 1)</td>
</tr>
<tr>
<td></td>
<td>1.656.5 - 1.660.5 MHz</td>
<td>LAND MOBILE-SATELLITE (Earth-to-space)</td>
</tr>
<tr>
<td>1660-1670 MHz</td>
<td>1670-1690 MHz</td>
<td>METEOROLOGICAL AIDS</td>
</tr>
<tr>
<td></td>
<td></td>
<td>METEOROLOGICAL-SATELLITE (space-to-Earth)</td>
</tr>
<tr>
<td>2690-2700 MHz</td>
<td>2655-2690 MHz</td>
<td>BROADCASTING-SATELLITE (space-to-Earth)</td>
</tr>
<tr>
<td></td>
<td>2700-2900 MHz</td>
<td>FIXED-SATELLITE (Region 2)</td>
</tr>
<tr>
<td>4990-5000 MHz</td>
<td>4800-4990 MHz</td>
<td>MOBILE</td>
</tr>
<tr>
<td></td>
<td>5000-5250 MHz</td>
<td>AERONAUTICAL RADIONAVIGATION</td>
</tr>
<tr>
<td>10.6-10.7 GHz</td>
<td>10.55-10.6 GHz</td>
<td>Radiolocation</td>
</tr>
<tr>
<td></td>
<td>10.7-11.7 GHz</td>
<td>FIXED-SATELLITE (space-to-Earth)</td>
</tr>
<tr>
<td>15.35-15.4 GHz</td>
<td>14.8-15.35 GHz</td>
<td>MOBILE</td>
</tr>
<tr>
<td></td>
<td>15.4-15.7 GHz</td>
<td>AERONAUTICAL RADIONAVIGATION</td>
</tr>
<tr>
<td>22.21-22.5 GHz</td>
<td>22.5-22.55 GHz</td>
<td>MOBILE</td>
</tr>
<tr>
<td></td>
<td></td>
<td>BROADCASTING-SATELLITE (Regions 2 and 3)</td>
</tr>
<tr>
<td>23.6-24 GHz</td>
<td>23.55-23.6 GHz</td>
<td>MOBILE</td>
</tr>
<tr>
<td></td>
<td>24-24.05 GHz</td>
<td>AMATEUR AMATEUR-SATELLITE</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ISM (*)</td>
</tr>
<tr>
<td>31.3-31.8 GHz</td>
<td>31-31.3 GHz</td>
<td>MOBILE</td>
</tr>
<tr>
<td></td>
<td>31.8-32 GHz</td>
<td>RADIONAVIGATION</td>
</tr>
</tbody>
</table>

* Fixed and mobile except aeronautical mobile services are not included (see § 2.3).

(') The category of service of these allocations is shown in conformity with the provision of Nos. 413-418 of the Radio Regulations.

(1) Under study (see Resolution No. 505 of the WARC-79).

(2) See also FN 730A (MOB-87) of the Radio Regulations.

(3) ISM: industrial, scientific and medical.
2.1.2 Harmonic and intermodulation interference

This type of interference can occur in any band, and is generated mainly in the output stages of the transmitters. The usual type of output valve for a high-power transmitter is the klystron. Figure 1 shows a typical arrangement of combining filters when four programmes (each involving a vision carrier, \( f_v \) and a sound carrier, \( f_s \)) are combined and fed into a common antenna. At some stations the equipment shown in Fig. 1 is duplicated, as a precaution against breakdown, and the two duplicated combined outputs may be split and fed by two feeders to two halves of the antenna.

The second and third harmonics of the carrier frequency may occur at a fairly high level at the klystron output, but transmitters are normally provided with filters (tuned or low-pass) which attenuate all harmonics at the output of the transmitter to at least 60 dB below peak (sync.) power. Carrier intermodulation will also occur when a proportion of the signal from one transmitter breaks through the combining filters to the output circuit of another transmitter. The levels of these terms cannot be predicted accurately but, assuming 30 dB cross-insertion loss between the outputs of all transmitters, it is likely that second or third order products involving two vision transmitters will be generated at about —60 dB, those involving two sound transmitters at about —80 dB, and those involving three sound or vision transmitters at about —100 dB relative to peak (sync.) power. Higher-order products in each category would be somewhat lower in level. Many stations may have two separate two-channel antennas rather than a single four-channel antenna but coupling will still occur between transmitters because of the mutual coupling between the antennas. In this case, it is reasonable to assume a cross-insertion loss of 40 dB and thus to reduce by 10 dB the levels given above if the intermodulation term involves transmitters connected to the different antennas. Relatively simple additional filters would attenuate these unwanted products, assuming they are not too close in frequency to that of the transmitter. It is current practice in some transmitters to employ harmonic filters of the low-pass type in which case intermodulation products whose frequencies lie above the cut-off frequency will already be suppressed to levels lower than those given above.

![Diagram](image-url)
The levels discussed in the previous paragraph apply to interference generated in the klystrons. In addition, harmonics and intermodulation products may be generated by non-linearity in the feeders and antennas. Experience in the United Kingdom, when implementing the Band II service, showed that intermodulation products could not be reliably suppressed below about —100 dB relative to the level of the transmitted signals because of this type of non-linearity. Since the results of measurements at multi-programme UHF transmitters are not yet available, it is unwise at the present stage to assume that a great degree of suppression is feasible in the main antenna feeder at a UHF station. Therefore the addition of further filters at transmitters may only achieve an improvement up to the point where the level of any particular product in the feeders reaches —100 dB relative to peak (sync.) power. Improvement thereafter may not be economically practicable.

In any practical antenna, the gain in horizontal or near-horizontal directions, at frequencies far removed from the design frequency, may be anything from a few decibels to 50 dB below that at the design frequency. It will vary with frequency in a largely unpredictable manner, depending upon detailed aspects of the antenna design. Whilst it may later be found that the radiation characteristics of the antenna give a useful reduction of the interference at the majority of stations, it would be rash to rely on this reduction in every case.

Specific examples of harmonic and intermodulation products falling in radioastronomy bands may be mentioned, for the transmitters of the United Kingdom using CCIR Standard I. For a Channel 50 transmitter (carrier frequencies $f_c = 703.25$ MHz vision, and $f_s = 709.25$ MHz sound), $2f_c$, $f_c + f_s$, and $2f_s$ are in the 1400 to 1427 MHz hydrogen-line band. With a group of channels such as 21, 24, 27 and 31 radiated from the same site, third order intermodulation products of the $f_1 + f_2 - f_3$ type may fall in the 406 to 410 and 606 to 614 MHz bands. The third harmonic of Channel 21 is in the hydrogen band. Other examples are listed in Table II.
<table>
<thead>
<tr>
<th>Band allocated to radioastronomy on world-wide primary basis</th>
<th>Interfering service</th>
<th>Harmonic of allocated frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.36-13.41 MHz</td>
<td>Aeronautical mobile</td>
<td>2</td>
</tr>
<tr>
<td>25.55-25.67 MHz</td>
<td>Maritime mobile</td>
<td>2, 3</td>
</tr>
<tr>
<td>322-328.6 MHz</td>
<td>Mobile (Regions 2 and 3)</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Broadcasting</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Aeronautical radionavigation</td>
<td>3</td>
</tr>
<tr>
<td>1400-1427 MHz</td>
<td>Broadcasting</td>
<td>2, 3</td>
</tr>
<tr>
<td></td>
<td>Mobile</td>
<td>2, 3 (Regions 2, 3, 3</td>
</tr>
<tr>
<td></td>
<td>Meteorological-satellite (space-to-Earth)</td>
<td>3 (')</td>
</tr>
<tr>
<td>1660-1670 MHz</td>
<td>Broadcasting</td>
<td>2, 3</td>
</tr>
<tr>
<td></td>
<td>Mobile (Regions 2 and 3)</td>
<td>2, 3 (Region 3)</td>
</tr>
<tr>
<td></td>
<td>Radionavigation (Region 3)</td>
<td>3</td>
</tr>
<tr>
<td>2690-2700 MHz</td>
<td>Aeronautical radionavigation</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Radiolocation</td>
<td>2 ('), 3 ('</td>
</tr>
<tr>
<td></td>
<td>Broadcasting (Regions 1 and 3)</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Mobile (Region 3)</td>
<td>3</td>
</tr>
<tr>
<td>4990-5000 MHz</td>
<td>Mobile</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Radiolocation</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>ISM (')</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Radiodetermination-satellite (space-to-Earth)</td>
<td>2</td>
</tr>
<tr>
<td>10.6-10.7 GHz</td>
<td>Radiolocation</td>
<td>2, 3 ('</td>
</tr>
<tr>
<td></td>
<td>Mobile (Region 1)</td>
<td>3 ('</td>
</tr>
<tr>
<td></td>
<td>Fixed-satellite (space-to-Earth)</td>
<td>3</td>
</tr>
<tr>
<td>15.35-15.4 GHz</td>
<td>Fixed-satellite (space-to-Earth)</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Aeronautical radionavigation</td>
<td>3</td>
</tr>
<tr>
<td>22.21-22.5 GHz</td>
<td>Fixed-satellite (space-to-Earth)</td>
<td>2, 3</td>
</tr>
<tr>
<td>23.6-24 GHz</td>
<td>Broadcasting (Regions 1 and 3)</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Broadcasting-satellite (Regions 1 and 3)</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Fixed-satellite (Region 2)</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Mobile</td>
<td>3</td>
</tr>
</tbody>
</table>

* Fixed and mobile except aeronautical mobile services are not included (see § 2.3).
(') Secondary allocation.
(') ISM: industrial, scientific and medical.
<table>
<thead>
<tr>
<th>Band allocated to radioastronomy on world-wide primary basis</th>
<th>Interfering service</th>
<th>Harmonic of allocated frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>31.3-31.8 GHz</td>
<td>Aeronautical radionavigation</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Radiolocation</td>
<td>2, 3</td>
</tr>
<tr>
<td></td>
<td>Mobile</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Amateur</td>
<td>3 (')</td>
</tr>
<tr>
<td></td>
<td>Amateur-satellite</td>
<td>3 (')</td>
</tr>
<tr>
<td>42.5-43.5 GHz</td>
<td>Mobile</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Radionavigation</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Radionavigation-satellite</td>
<td>3 (')</td>
</tr>
<tr>
<td></td>
<td>Space research</td>
<td>3 (')</td>
</tr>
<tr>
<td>86-92 GHz</td>
<td>Mobile</td>
<td>2, 3</td>
</tr>
<tr>
<td></td>
<td>Mobile-satellite</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Radionavigation</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Radionavigation-satellite</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Standard signals-satellite (space-to-Earth)</td>
<td>3 (')</td>
</tr>
<tr>
<td>105-116 GHz</td>
<td>Inter-satellite</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Mobile</td>
<td>2, 3</td>
</tr>
<tr>
<td></td>
<td>Space research</td>
<td>3 (')</td>
</tr>
<tr>
<td></td>
<td>Meteorological aids</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Radiolocation</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Fixed-satellite (space-to-Earth)</td>
<td>3</td>
</tr>
<tr>
<td>164-168 GHz</td>
<td>Fixed-satellite (space-to-Earth)</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Mobile</td>
<td>2, 3</td>
</tr>
<tr>
<td></td>
<td>Mobile-satellite (space-to-Earth)</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Inter-satellite</td>
<td>3</td>
</tr>
<tr>
<td>182-185 GHz</td>
<td>Mobile</td>
<td>2, 3</td>
</tr>
<tr>
<td></td>
<td>Radiolocation</td>
<td>2, 3</td>
</tr>
<tr>
<td></td>
<td>Inter-satellite</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>ISM (')</td>
<td>3</td>
</tr>
<tr>
<td>217-231 GHz</td>
<td>Mobile</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Amateur</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Amateur-satellite</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Radiolocation</td>
<td>3</td>
</tr>
<tr>
<td>265-275 GHz</td>
<td>Inter-satellite</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Mobile</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Mobile-satellite</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Radionavigation</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Radionavigation-satellite</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Radiolocation</td>
<td>2</td>
</tr>
</tbody>
</table>

2.1.3. **Absolute levels of interference from UHF transmitters**

The levels of unwanted components have so far been considered relative to the peak signal of the vision transmitter. As a guide to the absolute levels of interference as a function of distance from the transmitter, we may estimate the field-strength of the television emission and assume that the interference will be propagated similarly, so that the field strength of the interference remains at the same level relative to the television signal.

Normally a television service is discussed in terms of the field strength at 10 m above ground level. For example, it has been estimated from CCIR propagation data that a 1000 kW (e.r.p.) transmitter with an antenna 300 m high will produce fields exceeding 80 dB above 1 μV/m at 50 km for 1% of the time. If it were possible to suppress the out-of-band part of the signal to a relative level of —100 dB (i.e. about 50 dB additional suppression at high-power level) the resulting field would be 20 dB below 1 μV/m. The importance of this field would depend on how near to the direction of the transmitter the radioastronomy antenna beam was intended to be used, but even if the gain in the transmitter direction never exceeded
0 dB, relative to an isotropic antenna, the interference level would be up to 20 dB above the values shown in Table I of Report 224 for continuum measurements for a small percentage of the time. It should be noted, moreover, that the mean heights of some large radioastronomy antennas are considerably greater than 10 m and correspondingly larger interfering fields may be expected. Depending on the topography, parts of such an antenna could be in a field equal to, or even greater than, that in free space, which at 50 km would be about 25 dB stronger than the field assumed for the 10 m height. It is evident that the possibility of interference needs to be estimated for each path, taking into account the path profile, and the size of, and the requirements for, the radioastronomy antenna.

In the 606 to 614 MHz band a field of 80 dB above 1 μV/m corresponds to a power at the receiving antenna of −82 dBW if the gain is 0 dB. This is well below the overload point of the preamplifier so the main receiver problem is to reduce the received power from the television band by about 100 dB, by a combination of filtering at radio-frequency and intermediate-frequency, to achieve the CCIR limits. This degree of suppression is technically feasible, though probably near the limits of what can be done without introducing other undesirable effects such as phase distortion.

Finally, a similar example can be used to study the effects of harmonic radiation. Assuming that the same field of 80 dB above 1 μV/m is produced by a Channel 50 transmitter at 50 km, having its second harmonic in the hydrogen band, this harmonic might, in normal circumstances, be 60 dB below the fundamental in the transmitter itself. Additional attenuation of about 60 dB would be required to achieve the limits of Report 224 with a 0 dB gain receiving antenna. Some of this additional attenuation will be derived from the reduced radiation efficiency of the transmitter antenna, and extra filtering should not be difficult with the wide frequency separations involved. Intermodulation products occurring at frequencies well removed from the nominal transmitter frequencies should in general be less of a problem than harmonics.

2.2 Interference from satellite transmissions

Satellite transmissions, in particular those associated with television and sound broadcasting, may cause severe interference to radioastronomy. By the nature of a satellite broadcasting system, large areas of the Earth will be illuminated and line-of-sight conditions will exist. Terrestrial interfering sources are normally in the far side-lobe region of a radio telescope, whereas a satellite transmission is likely to be received also in the main beam and near side lobes, with considerably higher gain. For example, as far as 5° from the main beam, the gain may be 25 dB higher than in the far side-lobe region (see Recommendation 509).

Geostationary satellites which are above the horizon at any observatory could be particularly troublesome. The radius of the geostationary-satellite orbit is approximately 6.6 times the radius of the Earth. The position of the orbit in celestial coordinates as seen from the latitudes of a number of major radioastronomy observatories is shown in Fig. 2. Plans for the development of some active services call for a large number of closely spaced geostationary satellites. Such a series of potential sources of interference which may be viewed in the near side-lobes of a telescope present an interference problem not otherwise faced by radioastronomers. In § 2.2.1 this problem is examined geometrically for two levels of interference but without considering the source or nature of the interference. Then in § 2.2.2 and 2.2.3 band edge and harmonic interference are examined for a number of specific services.

The very special concern for the interference which might result from the high levels of radiated power of the proposed satellite power system is treated separately in Report 853.
Harmful thresholds for interference to radioastronomy are given in Report 224. Listed there is the level, in each radioastronomy band, of the power into the receiver which is just sufficient to cause harmful interference. Also listed are the power flux-densities (dB(W/m²)) causing harmful interference which are calculated with the assumption that the gain of the radio telescope is 0 dB in the direction of the interfering source. Such a gain is appropriate for consideration of terrestrial sources of interference confined to the neighbourhood of the horizon. The very different result for geostationary sources is demonstrated in sections 2.2.1.1 and 2.2.1.2. In the second case, it is assumed that the power flux-density of the interfering signal is 30 dB less. A harmful interference level from a single interfering source is experienced when the radio telescope gain is 30 dB at an angular distance of 1.2° from the source.

FIGURE 2 — Projection of geostationary-satellite orbit on to the celestial sphere
2.2.1.1 Interference at the interference threshold levels given in Report 224

If we assume that the radioastronomy antenna has the side-lobe characteristics assumed in Recommendation 509, the side-lobe gain would fall to 0 dBi at 19° from the axis of the main beam. For such an antenna the harmful interference level will be exceeded if the main beam is pointed within 19° of a satellite that produces within the radioastronomy bandwidth a power flux-density at the radio observatory equal to the harmful threshold in Report 224. A series of satellites spaced at intervals of about 30° along the geostationary-satellite orbit radiating interference at this level would result in a zone of width approximately 38° centred on the orbit in which radioastronomy observation free from harmful interference would be precluded. The width of this precluded zone would increase with the number of interfering satellites in the orbit, and could in principle cover the whole sky. The effective number of interfering satellites will depend upon whether the interfering signals are beamed by the satellites' transmitting antennas or are more widely radiated. Out-of-band emission that is not widely separated from the satellite's transmitter frequency is likely to be beamed by a satellite antenna. Interference that is widely separated in frequency, such as harmonics, may be radiated more widely, but is also likely to be less difficult to suppress.

2.2.1.2 Interference 30 dB below the interference threshold levels of Report 224

A more detailed, but arbitrary, examination has been undertaken for the situation where the geostationary satellites are assumed to be emitting unwanted interference at a level 30 dB below the harmful values in Report 224. In this case the interference to be expected at Nobeyama Radio Observatory in Japan is examined for a series of satellites distributed in orbit (see also § 7.5.3.1 of [CCIR, 1978-82]). The calculations were performed for the sample plans worked out for a number of fixed-satellite bands. The results are shown in Fig. 3 for the 6/4 GHz and 30/20 GHz bands. In each case the directivity of the satellite antenna is assumed to be the same at the interfering frequency as at the fixed-satellite frequency. The plan calls for 55 geostationary satellites using the 6/4 GHz band in a 120° arc of the orbit over Region 3, and 224 satellites in the same arc using the 30/20 GHz band. The cross-hatched areas in Fig. 3 show the areas of the sky where harmful interference would be experienced at the Nobeyama Observatory. At the lower frequency there are isolated areas surrounding the satellites, the largest area being centred on a satellite for which the observatory falls within the main beam response. At the higher frequency the satellites are sufficiently close together that they create a continuous zone of interference about 3° wide. With the interference levels assumed in this case, interference at the harmful threshold is experienced when the radioastronomy antenna is pointed at a distance of 1.2° from a single satellite for which the main beam of the transmitting antenna illuminates the observatory. In this situation the other satellites contribute a negligible amount to the total interference received in the 6/4 and 11/14 GHz band, and less than half in the higher frequency bands, where the number of satellites is greater.
2.2.1.3 Some additional considerations

A severe problem of interference to radioastronomy observations could result as large numbers of geostationary satellites are put into service. A solution to this problem clearly involves a compromise between the area of sky lost to radioastronomy observations and the difficulty of suppressing unwanted emissions from the satellites. Such a solution may involve conditions intermediate between the two cases above. It is useful to examine such an intermediate case in detail. In considering the area of sky lost to radioastronomy, it should be noted that Fig. 2 indicates that if observations can be made to within a distance of about 5° from the geostationary-satellite orbit, each position in the sky can be observed from at least one existing observatory provided that it is suitably equipped.

The discussion of radiation from geostationary satellites presented in 2.2.1.1, 2.2.1.2 and above is based upon the assumption that the orbits of such satellites are located in the equatorial plane of the Earth. However, IFRB Circular letter No. 737, Table ARL, page 15, defines all geosynchronous satellites with orbital inclination angles of less than 5° as geostationary satellites. The effect of the orbital inclinations upon the considerations discussed in this report will depend upon the distribution of inclination angles of those geostationary satellites whose transmissions are potential sources of interference to radio astronomy. This effect requires further study.

It should also be noted that not all types of radio telescopes are as sensitive to interference as the single-antenna telescopes to which Tables I and II of Report 224 applies. Interferometers and synthesis arrays have higher thresholds for harmful interference [Thompson, 1982]. However, these instruments are useful mainly for studying sources with very small angular structure, while single-antenna telescopes fulfil an important role in astronomy in observing extended sources in space.
2.2.2 Band-edge interference

In discussing the possibilities of interference, the situation in and near the radioastronomy band 2690 to 2700 MHz may be taken as an example, in respect of potential interference from proposed broadcasting satellites in the band 2550 to 2690 MHz; other examples are listed in Table I. Maximum power flux-densities have been specified in the Radio Regulations, to protect the terrestrial fixed service with which the broadcasting-satellite service shares the band. The appropriate criterion is that the power flux-density should not exceed $-137 \text{ dB}(W/m^2)$ in any 4 kHz band when the angle of elevation of the satellite exceeds $2^\circ$ (see No. 2562 of the Radio Regulations).

The spectral density of the broadcasting-satellite transmission should decrease towards the band-edge and into the radioastronomy band. On the assumptions of a square cut-off for the transmitter spectrum and typical receiver cut-off characteristics, then as a broad indication the energy in the upper 1 MHz of a broadcasting-satellite signal producing the full permitted power flux-density is likely to interfere with a radioastronomical observation if there is a separation less than 4 MHz between the nominal band edges. Whether this separation would be sufficient to prevent sidebands from the broadcast transmission extending harmfully into the radioastronomy band is not yet known. Furthermore, the radioastronomy observations will be less susceptible if the observatory is well outside the service area of the satellite, but again to an unknown extend. A reduction of 30 dB in the e.i.r.p. of the satellite in the observatory direction would enable the separation to be reduced to the order of 1 MHz provided that this was sufficient to exclude harmful satellite sideband signals from the radioastronomy band.

Careful control of the radiated spectrum can alleviate the problem of band-edge interference. Annex I describes some results of measurements of interference in the radioastronomy band 2690 to 2700 MHz, showing the benefits of filtering satellite transmissions. Annex II shows how the use of a carefully designed band-rejection filter on the geostationary meteorological satellite of Japan has been effective in reducing interference in the radioastronomy band 1660 to 1670 MHz. In Annex I the results of the measurements are compared with the harmful interference levels of Report 224. However, in Annex II the results show that the interference level is well below that given in Report 224 and is indeed below the level used in § 2.2.1.2 above.

2.2.3 Harmonic interference

2.2.3.1 Second-harmonic radiation in the 23.6 - 24.0 GHz band from broadcasting satellites

A possible mode of interference to radioastronomy is second-harmonic radiation from broadcasting satellites in the band 11.7 to 12.5 GHz (see Report 807). The harmonic range 23.4 to 25.0 GHz includes the exclusive passive band 23.6 to 24.0 GHz. For Regions 1 and 3, Annex 8 of Appendix 30 to the Radio Regulations lists for individual reception a minimum power flux-density in the 11.7-12.5 GHz band of $-103 \text{ dB}(W/m^2)$ at the edge of the coverage area, and the power flux-density in the centre of the coverage area would normally be $-100 \text{ dB}(W/m^2)$. These values of power flux-density are applicable to each channel of the broadcasting-satellite service. The second harmonic of channels 5-15 falls within the radioastronomy band and of these a total of 8 channels may illuminate an observatory. The total power flux-density within the band 11.8-12.0 GHz may reach a value of $-91 \text{ dB}(W/m^2)$. According to Table I of Report 224, radioastronomy would be affected by interfering signals greater than $-147 \text{ dB}(W/m^2)$ in a bandwidth of 400 MHz at 24 GHz, with a side-lobe gain of 0 dB. The radio-telescope antenna may, for example, have a gain of about 70 dB and signals of $-217 \text{ dB}(W/m^2)$ from a single satellite would therefore cause interference if the antenna were directed towards the satellite. The required suppression of the second harmonic referred to the fundamental of the broadcasting signal would therefore be 126 dB and special precautions would need to be taken in the design of the transmitter to avoid interference through
the main beam of the radio-telescope. If, instead, a radioastronomy gain of 0 dB is considered, the
required harmonic suppression would be 56 dB, and for a 30 dB gain the required suppression would be
86 dB. These are the antenna gain values used in § 2.2.1.1 and 2.2.1.2. However, these sections deal with a
more detailed distribution of satellites and a similar treatment in this section might lead to somewhat
different values of required suppression than those listed above. If observations could be made to within
5° of the geostationary-satellite orbit, it was indicated in § 2.2.1.3 that with the use of existing major
observatories all the sky would be accessible. The gain of the reference antenna of Recommendation 509 at
5° from its axis is 15 dBi. Therefore a harmonic suppression of 71 dB would be required, which can be
achieved with established design techniques.

2.2.3.2 Second-harmonic radiation near 22.2 GHz from the fixed-satellite
service

A corresponding possibility exists of harmonic interference to radioastronomy in the water vapour
band at 22.2 GHz from transmissions in the fixed-satellite service in the band 10.95 to 11.2 GHz, but the
permitted power flux-densities at the Earth from transmitters in the fixed-satellite service are lower than in
the broadcasting-satellite service, and the interference problems will be correspondingly less. This also
applies to the passive bands at 15.35-15.4 GHz and 164-168 GHz, which also contain second harmonics of
frequencies allocated to space-to-Earth transmissions. Further examples are listed in Table II.

2.2.3.3 Second-harmonic radiation in the 4 990 - 5 000 MHz band from the
radiodetermination-satellite service

A third and important example concerns the radiodetermination-satellite
service (RDSS), one system of which is described in Report 1050. For the system
described in Annex I of that report, down-links from geostationary satellites to
mobile stations are in the band 2 483.5 - 2 500.0 MHz, allocated to the RDSS at
the Mobile WARC 1987. From Table II of that annex, the pfd at the surface of the
Earth in this band is -108 dB(W/m²). The second harmonics of the down-link
signal extend over the world-wide primary radio astronomy band 4 990 - 5 000 MHz
(4 950 - 5 000 MHz in Argentina, Australia and Canada). The harmful threshold
for interference to radio astronomy in the 4 990 - 5 000 MHz band is
-171 dB(W/m²) from Table I of Report 224. To enable radio astronomy observations
at 5° from the geostationary satellite orbit (see Recommendation 611) this value
should be decreased a further 15 dB. Thus, on the assumption that the
second-harmonic power is uniformly distributed over the band 4 967 - 5 000 MHz,
the required suppression of the second harmonic to avoid harmful interference to
radio astronomy in the world-wide band is 73 dB relative to the fundamental
emission.

2.2.3.4 Third-harmonic radiation in the 1 400 - 1 427 MHz band from the
meteorological-satellite service

Some meteorological satellites collect data from platforms on or near the surface of the Earth and
relay the information to data collection centres. The systems include the interrogation of the platforms by
means of transmissions from the satellites in the band 460 to 470 MHz. For example, Annex 1 of
Report 395 mentions the use of 468.825 MHz with powers up to 40 W. Because the third harmonic of this
transmission (1406.475 MHz) falls in the passive band 1400 to 1427 MHz, the possibility of interference
needs to be studied. Proposals for the future use of the band 460 to 470 MHz for interrogation appear, at
present, to be restricted to geostationary satellites. Although the gain of the satellite antenna is said to be
7.4 dB at the fundamental frequency, its performance at a harmonic frequency is unknown, and its gain in
the direction of any particular radioastronomy observatory is unlikely to be known. For the purposes of this initial discussion, therefore, harmonic radiation will be assumed to be isotropic. The power flux-density at the surface of the Earth, in the region of the sub-satellite point, is then \(-146\,\text{dB}(\text{W/m}^2)\) from a 40 W transmitter at the fundamental frequency. According to Report 224 in the band 1400 to 1427 MHz the power flux-density of interfering signals should not exceed \(-180\,\text{dB}(\text{W/m}^2)\) if the gain of the radio-telescope is 0 dB relative to isotropic. In these circumstances it is unlikely that the harmonic radiation will be sufficient to cause interference. On the other hand, if a radio-telescope with a gain of 60 dB were directed towards the satellite, then the power flux-density which would cause interference would be \(-240\,\text{dB}(\text{W/m}^2)\) and so 94 dB of harmonic suppression would be necessary. Special precautions might be necessary to achieve this suppression. If an antenna gain of 30 dBi is assumed, as was done in § 2.2.1.2, the harmonic suppression required would be 64 dB.

2.3 Interference from other services

Signal levels encountered in adjacent bands vary widely with the nature of the service. In addition, designations of services are of a very general nature and each one covers many different types of transmitting systems. The highest peak signal levels are likely to be found in the bands designated for radiolocation and aeronautical radionavigation since these include high-powered radars in aircraft. Mean power flux-densities of such signals at relatively isolated observatory sites commonly exceed \(-100\,\text{dB}(\text{W/m}^2)\), and may even exceed \(-50\,\text{dB}(\text{W/m}^2)\). Observations in one of the most important bands to radioastronomy, 1400-1427 MHz, may suffer from band-edge interference from radiolocation allocated to the adjacent band 1350-1400 MHz. The radioastronomy band 4990-5000 MHz is adjacent to an aeronautical radionavigation band at 5000-5250 MHz which will be used by the new International Civil Aviation Organization microwave landing system (MLS). This will operate ground-based transmitters in the band 5030.85-5090.85 MHz. A peak effective radiated power of approximately 20-25 dBW can be expected on-channel within the scanning beam. The interference specifications for the system require that the mean power flux-density measured in a 150 kHz bandwidth centred 840 kHz or more from the nominal channel frequency shall not exceed \(-100.5\,\text{dB}(\text{W/m}^2)\) for angle guidance transmissions and \(-95.5\,\text{dB}(\text{W/m}^2)\) for data transmissions at heights above 600 m. The signal level at 5030 MHz does not exceed a spectral power flux-density of \(-147\,\text{dB}(\text{W/(m}^2 \cdot \text{Hz})\)).

The Earth-to-space transmissions of the aeronautical mobile-satellite service may be troublesome to radioastronomy because the transmitters on aircraft may be in the line-of-sight of an observatory.

Services designated as fixed and mobile use various transmission techniques. Typical high spectral power flux-densities likely to be encountered at an observatory are \(-127\,\text{dB}(\text{W/(m}^2 \cdot \text{Hz})\)) — this corresponds to a transmitter with an e.i.r.p. of 100 W over a bandwidth of 10 kHz at a distance of 60 km. Fixed and mobile (except aeronautical mobile) services are generally expected to have a short-range nature, and should not present too many band-edge interference problems; several frequency bands are in fact allocated to the fixed, mobile (except aeronautical mobile) and radioastronomy services.
2.3.1 Unwanted emissions from broadband modulation

In certain types of transmissions, often associated with data in digital form, spectral sidebands are generated over a much broader frequency band than is used in the reception of such signals. In particular, the biphase phase-shift keying (2-PSK) modulation technique produces a power spectrum of the form \((\sin x/x)^2\) with recurring subsidiary maxima outside the wanted bandwidth which decrease only slowly with frequency. If unfiltered, the sidebands which occur at about ten bandwidths 3 dB from the carrier frequency are reduced in power spectral density only about 36 dB below the power level at the band centre. If, in addition, the keying frequency of this 2-PSK transmission is 10-20 MHz, then these ten bandwidths encompass several hundred megahertz from the assigned frequency. For example, assume a simple 2-PSK transmitter with a keying frequency of 10 MHz centred on 1615 MHz with 40 W of power and an isotropic transmitting antenna mounted on an aircraft at a line-of-sight distance of 400 km, which is the distance of the horizon at an aircraft flying at an altitude of about 10 000 m. Unwanted emissions from this transmitter would result in a power flux-density level even in the band 1400-1427 MHz at the receiver site which is 40 dB above the harmful interference threshold given in Table I of Report 224; emission in the band 1660-1670 MHz, also allocated to radioastronomy, would, of course, be at a significantly higher level. Transmitters of this type located on spacecraft could be even more troublesome sources of interference to radioastronomy. It is important that care be taken in the design of these types of transmitters to ensure adequate suppression of the unwanted emissions.

2-PSK with a keying frequency of several megahertz is used in some types of spread-spectrum modulation. A characteristic of common spread-spectrum techniques is a wideband signal with low power density which resembles random noise. This characteristic usually reduces the possibility of these spread-spectrum systems causing interference to conventional, narrow-band communication systems, but not to the radioastronomy service. In radioastronomy, the cosmic signals have the form of random noise, and wide bandwidths are often used. At the low signal levels with which radioastronomers are concerned, there is usually no practical way to distinguish between spread-spectrum signals and cosmic signals. The harmful thresholds of power flux-density for man-made signals falling within a radioastronomy band, which are given in Report 224, apply to unwanted, as well as intentional, emissions and to all types of modulation, including that discussed above.

2.4 Services which may cause interference to the radioastronomy service

Table I lists the services that could present adjacent-band problems to the radioastronomy service. Table II lists the services that could cause harmonic interference; only the second and third harmonic frequencies have been considered.

3. Band-edge interference and the radioastronomy receiver

3.1 The overall response

To calculate the effective input signal power \(P\) received in a radiometer from adjacent-band signals, consider a band edge at frequency \(f_b\) beyond which a uniform spectral power flux-density \(S \text{ (W/Hz)}\) is encountered (Fig. 4). Let \(A\) be the telescope collecting-area in the corresponding direction, \(-a_0\) (dB) be the level to which the gain of the radiometer has been reduced at the band edge, and \(-k\) (dB/Hz) be the slope of the radiometer response beyond the band edge. Since most of the signal is picked up within an effective bandwidth of 4.35/k which is typically 0.5 MHz, the upper limit of infinity in the integral is justified if the frequency range beyond the radioastronomy band edge is fully utilized over a few megahertz. Then we have

\[
P = AS \int_{f_b}^{\infty} 10^{-\left(a_0 + k (f - f_b)/10\right)} df = 4.45 \times 10^{-a_0/10} AS/k
\]
The maximum tolerable power levels for radioastronomy operation given in Table I of Report 224 are in the range $10^{-17}$ to $10^{-21}$ W for typical bandwidths at frequencies greater than 1 GHz. For a continuous signal with $S = 2 \times 10^{-13}$ W/(m² • Hz), the level $10^{-21}$ W will not be exceeded if, for example, the response at the band edge, $a_0$, is 102 dB and the slope, $k$, is 50 dB/MHz, assuming a value of $A$ of $10^{-3}$ m² (isotropic gain at approximately 3 GHz). The value of $k$ is much less critical than $a_0$, and for $k = 10$ dB/MHz the same power level is received with $a_0 = 109$ dB. Some examples of required response characteristics are summarized in Table III in which isotropic response of the radio telescope is assumed.

For pulsed radar signals, assuming the same collecting area and a response at least 100 dB down, the peak power received will not exceed $10^{-21}$ W for power flux-density levels below $10^{-8}$ W/m². The effect of pulsed interference of low duty cycle in a radioastronomy system depends upon the type of observation being made, and may sometimes be no greater than that of a continuous signal at the same mean power level. In such cases, the $-100$ dB band edge response may allow operation in the presence of strong radar signals. On the other hand, the effects of overloading during the pulse could be important and lead to intermodulation effects as described below.

<table>
<thead>
<tr>
<th>Service</th>
<th>Assumed distance of transmitter (km)</th>
<th>Typical mean signal levels at observatory</th>
<th>Required band-edge response of receiver (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Broadcasting satellite (maximum allowable flux)</td>
<td>36000</td>
<td>$5 \times 10^{-18}$ W/(m² • Hz)</td>
<td>$-56$ to $-63$</td>
</tr>
<tr>
<td>Typical radio-relay transmitter</td>
<td>60</td>
<td>$2 \times 10^{-13}$ W/(m² • Hz)</td>
<td>$-102$ to $-109$</td>
</tr>
<tr>
<td>Airborne radar (10 W mean power)</td>
<td>10</td>
<td>$10^{-8}$ W/m²</td>
<td>$-100$</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>$10^{-11}$ W/m²</td>
<td>$-70$</td>
</tr>
</tbody>
</table>
Two or more signals, present simultaneously at the receiver input but each falling outside the receiver passband, can, due to non-linearity or overloading within the receiver, give rise to a signal within the receiver passband. The most important effect is likely to be third-order intermodulation in which signals at frequencies $f_1$ and $f_2$, near one edge of the passband, regenerate components $(2f_1 - f_2)$ or $(2f_2 - f_1)$ within the band.

The intermodulation performance of a given amplifier is conveniently described in terms of an intermodulation intercept point [McVay, 1967], typical values of which range from about $-55$ dBW for a parametric amplifier to about $-40$ dBW for a transistor amplifier, both values being referred to the amplifier input.

An effective interfering signal of $A_{PH}$ (dBW) could result from intermodulation of out-of-band signals of equal amplitude. $S_{IM}$, given by:

$$S_{IM} = \frac{1}{3} (2IP + \Delta P_H) \text{ dBW} \quad (2)$$

where $IP$ (dBW) is the input level to which the intercept point corresponds. Adopting the values of $\Delta P_H$ given in Report 224 and assuming an isotropic antenna, the corresponding power flux-density limits can be derived. Values appropriate to the primary radioastronomy bands are given in Table IV, using the values of $IP$ quoted above. If the power flux-density of signals in the vicinity of the radioastronomy bands exceeds these levels, additional attenuation by means of passive filters at the input of the receiver would be needed.

The overall design requirements are summarized in Fig. 4; the values apply to a parametric amplifier operating in the 5.0 GHz band and assume an isotropic antenna response. Taken in conjunction with the data of Table III it appears that the response of a radiometer should be $-100$ to $-110$ dB down at the band-edge for frequencies in the GHz range, and correspondingly greater if the out-of-band source lies in a direction in which the telescope response is greater than isotropic. For radar or other signals having a peak power flux-density greater than about $10^{-7}$ W/m$^2$ filtering at the input stages would also be necessary.

### TABLE IV — Typical values of power flux-density of signals of equal strength which might cause interference by intermodulation

<table>
<thead>
<tr>
<th>Examples of bands allocated to radioastronomy</th>
<th>Mean power flux-density (dB(W/m$^2$))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Parametric amplifier</td>
</tr>
<tr>
<td>25.55-25.67 MHz</td>
<td>-112</td>
</tr>
<tr>
<td>1400-1427 MHz</td>
<td>-80</td>
</tr>
<tr>
<td>2690-2700 MHz</td>
<td>-76</td>
</tr>
<tr>
<td>10.68-10.7 GHz</td>
<td>-63</td>
</tr>
<tr>
<td>15.35-15.4 GHz</td>
<td>-58</td>
</tr>
<tr>
<td>23.6-24.0 GHz</td>
<td>-52</td>
</tr>
<tr>
<td>31.3-31.5 GHz</td>
<td>-50</td>
</tr>
<tr>
<td>86-92 GHz</td>
<td>-40</td>
</tr>
<tr>
<td>105-116 GHz</td>
<td>-36</td>
</tr>
<tr>
<td>217-231 GHz</td>
<td>-25</td>
</tr>
</tbody>
</table>

### 3.3 The attainable performance of practical receivers

The precise design of any receiving system is likely to be influenced by the practical limitations of complexity and cost and also by the application for which the receiver is required, for example, as between continuum and line measurements or between single antenna and interferometer applications. The figures quoted here are intended to represent the best which can be achieved using current techniques without a disproportionate expenditure. In some cases, a slightly better performance might, in principle, be possible; in others, for example, where interferometric and more particularly, interferometric spectral line measurements are involved, owing to the additional requirements of phase matching and stability and uniform passband response, a lower limit to the achievable rejection of adjacent-channel signals may be appropriate.
3.3.1 Intermediate-frequency filtering

For reasons of sensitivity, it is desirable that the effective (—3 dB) bandwidth of the receiver be as large as practicable. Since, for a given design of filter, the ratio of the —3 dB bandwidth to, say, the —100 dB bandwidth is a constant, it follows that the percentage of the radioastronomy band effectively available will be independent of the actual allocated bandwidth. The relative rate of cut-off provided by different filter designs depends on the filter type and on the number of filter sections employed.

Catalogue specifications of filter manufacturers indicate that a single filter of twelve sections, or three filters each of six sections placed in different parts of the receiver, could provide a —3 dB bandwidth of 60% of the —100 dB bandwidth. Filters having a total of more than about twenty sections are likely to introduce severe problems of alignment and stability and the use of the three eight section filters, providing a —3 dB bandwidth of 75% of the —100 dB bandwidth is likely to represent the limit of practicability. The overall receiver response provided by the latter filter arrangement is shown in Fig. 5. For interferometers, however, use of three eight section filters is likely to be prohibited by the phase requirements of the system.

![FIGURE 5 — Relationship between a radioastronomy band and the required receiver characteristic](image)

- A: Slope —k dB/MHz
- B: Half-power bandwidth

3.3.2 Signal frequency filtering

Severe restrictions are placed on the design of any input filter due to the requirement for very low loss in the passband. Overall system input noise temperatures of less than 100 K are readily obtainable in the 1 to 10 GHz range by the use of uncooled parametric amplifiers and an input filter having an in-band...
attenuation of only 0.15 dB is then sufficient to degrade the performance of the system by over 10%. In cases where the filter can be incorporated in a cooling system already in use by the amplifier, this difficulty can be largely overcome, but the addition of cooling to an otherwise uncooled system would result in a considerable increase in cost and operational complexity.

The development [Atia and Williams, 1971] of wave-guide cavity filters may also have application to radioastronomy receivers, but it would appear that signals having levels near the upper limit of those listed in Table III could, if situated within about 5 MHz of the band edge, present severe problems of receiver design.

4. Conclusions

An examination of the problem of interference to the radioastronomy service from transmitters in other bands has yielded a number of conclusions.

— Transmitters operating in bands adjacent to radioastronomy bands, particularly if high powered, may require output filters and close attention to good design to reduce out-of-band radiation to acceptable levels.

— Satellite transmissions are a particular hazard to radioastronomy observations in adjacent channels.

— Harmonics and intermodulation products from high-powered terrestrial transmitters or from satellites pose a problem to radioastronomical observations. Such transmitters may require filters but the design problem is not a difficult one.

— In general, allocating bands which are adjacent to radioastronomy bands, to services using high-powered terrestrial transmitters or transmissions from satellites, may lead to difficult, and expensive, technical problems. In addition the need for guard bands may lead to an inefficient use of the radio spectrum.

— Radioastronomy receivers may need to be equipped with very carefully designed IF filters to discriminate against radiation in adjacent bands. In spite of the best design procedures 25% to 50% of the radioastronomy band may need to be sacrificed to achieve the necessary discrimination.

REFERENCES


CCIR Documents

BIBLIOGRAPHY


ANNEX I

EMISSION MEASUREMENTS OF THE ATS-6 SATELLITE IN THE 2690-2700 MHz RADIOASTRONOMY BAND

1. Introduction

The band 2500 to 2690 MHz is allocated to the broadcasting-satellite service, in addition to other space and terrestrial services. Adjacent to this band is the 2690 to 2700 MHz band which is allocated to the radioastronomy service. The first opportunity to make measurements of the potential interference to radioastronomy from a broadcasting satellite in orbit occurred after the launching of the United States of America's Application Technology Satellite (ATS-6) which was launched into the geostationary-satellite orbit on 30 May 1974, and positioned at 94° W longitude. This Annex provides the results of the measurements made by the Pennsylvania State University Radio Astronomy Observatory (PSURAO), during the periods June 1974 and April 1975 [Hagen and Swanson, 1975; Hagen et al., 1975]. A more detailed account of these measurements and of the operation of the satellite is given in Report 698 (Kyoto, 1978).
2. ATS-6 2670 MHz system characteristics

A major ATS-6 experiment during the first year of operations was the Health, Education, and Telecommunications Experiment (HET). HET featured daily transmissions in the 2600 MHz band of quality colour television in wideband FM format to small receiving systems located at schools, hospitals, and other institutions in Alaska, the Rocky Mountain States, and Appalachia [Whalen, 1975]. The TV-FM signals from earth stations were received in the 6 GHz band on the Earth Coverage Horn (ECH) of the satellite. The signals were then amplified, down-converted to IF where they were further amplified, filtered and limited. The signals were then converted to the 2560 or 2670 MHz band for final high power amplification and fed to the 9.1 m paraboloid antenna from its prime focus. A diplexer which coupled the output in the 2670 MHz band to the transmitting antenna was specifically designed to reduce the ATS-6 emissions in the 2690 to 2700 MHz band. This diplexer provided a minimum of 17 dB attenuation at 2690 MHz while maintaining an acceptable insertion loss in the 2655 to 2685 MHz band. The diplexer design criterion was to reduce the spectral power flux-density in the radioastronomy band below $-247\,\text{dB}(\text{W}/(\text{m}^2 \cdot \text{Hz}))$. This criterion of $-247\,\text{dB}(\text{W}/(\text{m}^2 \cdot \text{Hz}))$ is given in Report 224.

3. The PSURAO radiometer

The radiometer used for these tests was normally used for solar observations and thus did not have the high sensitivity upon which the CCIR interference criterion was based (Report 224). The radiometer receiving antenna was pointed directly at ATS-6 for all tests and the results were later referred to the isotropic gain condition for comparison with the CCIR criteria. The radiometer used conventional crystal mixing, a 30 MHz IF, and diode Dicke switching against a 300 K load. An 8-pole filter was inserted between the 1st and 2nd IF amplifiers to sharpen the passband. A signal generator and frequency counter replaced the normal 2725 MHz local oscillator. This permitted the radiometer passband to be accurately centred about different frequencies. The radiometer bandwidth, determined primarily by the filter, was 7 MHz at $-3\,\text{dB}$, 12 MHz at $-10\,\text{dB}$ and 15 MHz at $-40\,\text{dB}$.

The r.m.s. fluctuation temperature was approximately 0.5 K for a one second integration time. With the receiving antenna used, this corresponds to a spectral power flux-density of $-241\,\text{dB}(\text{W}/(\text{m}^2 \cdot \text{Hz}))$, or 6 dB above the CCIR interference criterion. The receiving antenna was a fully steerable 9.1 m diameter paraboloid fed with a linearly polarized horn. The half-power beamwidth was approximately 1° in the horizontal plane.

4. June 1974 test programme

During this period the following 3 radiometric measurements were made:

- centred at 2670 MHz; to determine the mean incident flux-density of the main in-band TV signal;
- centred at 2695 MHz; to determine the mean incident flux-density of the out-of-band signal appearing in the radioastronomy band;
- centred at a succession of frequencies across both bands to determine the power spectral density in the region of the edge of the band.

These results, shown in Fig. 6, were observed at the satellite footprint $-4.5\,\text{dB}$ contour and at a point where the incremental spreading loss relative to nadir was approximately 0.5 dB. Thus, they are not the maximum flux-density produced on the surface of the Earth; they must be increased by 5 dB when referenced to beam centre at nadir. Curve B in Fig. 6 shows the satellite spectrum near the edge of the radioastronomy band and was obtained from curve A by a deconvolution process to correct for the effect of the radiometer frequency response.

While most of the interference observed with the radiometer tuned to 2695 MHz (signal level $-240^{+5}_{-1}\,\text{dB}(\text{W}/(\text{m}^2 \cdot \text{Hz}))$ was due to the response of the radiometer to the main broadcast in-band signal (that is below 2690 MHz), a significant amount was due to the radiation of the satellite within the radioastronomy band (dashed curve in Fig. 6). The measured flux would have been greater if the 8-pole IF filter had not been used to improve the selectivity of the radiometer, and had the low pass filter on the transmitter output not been used.
From Fig. 6, it is seen that the interference contained in the radioastronomy band (2690-2700 MHz) is almost all contained within one megahertz of the edge of the band. It is $-223 \text{ dB}(\text{W}/(\text{m}^2 \cdot \text{Hz}))$ at band edge and falls off at approximately 25 dB/MHz. The interference would have been well below the CCIR limit ($-247 \text{ dB}(\text{W}/(\text{m}^2 \cdot \text{Hz})))$ (see Recommendation 314) had the carrier frequency of the transmitter been 2 or 3 MHz lower than that used.

5. The April 1975 test programme

The purpose of this test was to characterize the out-of-band emissions as a function of the carrier modulation, the up-link signal strength and the spacecraft received carrier-to-noise ratio. Analysis and pre-launch test data indicated that under normal satellite operating conditions the principal source of ATS-6 emissions in the radioastronomy band was re-radiated satellite receiver noise and therefore dependent upon the satellite received signal strength. The results showed an inverse relationship between the strength of the up-link signal and the power flux spectral density in the radioastronomy band, in rough agreement with the expected result. Further details can be found in Report 698 (Kyoto, 1978).
6. Conclusions

The series of ATS-6 measurements have demonstrated that if mutual precautions are taken, there can be reasonable assurance that radioastronomy observations will not suffer harmful interference from satellites with the characteristics of ATS-6. As illustrated in Fig. 6, not only must the output of the satellite-borne transmitter be filtered to sharply reduce the amount of spurious emission in the neighbouring band, but the radiometers must exhibit sharp adjacent band rejection to minimize the effects of the large power spectral density associated with broadcasting satellites. With the best available filters, the CCIR limits can be achieved without excessive loss in bandwidth by the transmitter and without incurring severe penalties in system design or operation.

REFERENCES


ANNEX II

SUPPRESSION OF INTERFERENCE TO THE RADIOASTRONOMY SERVICE FROM OUT-OF-BAND RADIATION FROM A JAPANESE METEOROLOGICAL SATELLITE

A band-rejection filter was inserted in the output of the band 9 (1681.6 MHz) transmitter of the geostationary meteorological satellite (GMS) of Japan (see Report 395) which was launched in July 1977 and which is used to transmit data from a visible and infra-red spin-scan radiometer (VISSR) to an earth station. In Fig. 7, two curves are shown: one shows the estimated spectral power flux-density in the radioastronomy band from GMS before insertion of the band rejection filter (pfd0) and the other after insertion of the filter (pfd1); both are based on the actual output power measurement of the satellite transmitter. The insertion loss of the filter at the centre frequency of 1681.6 MHz is a small fraction of 1 dB and the effect on the error ratio of the VISSR signal (with the filter inserted) received at the earth station is negligible. The interference to the radioastronomy service due to other signals transmitted by the GMS is expected to be less than that of the VISSR. In Fig. 7, the results of actual measurements are also shown. The measurements were made at the radioastronomical observatory at Parkes, Australia, after the GMS launch. It can be seen that the results shown are in general agreement with the calculations discussed above.

Report 224 lists the harmful interference level in the band 1660 to 1670 MHz as $-237 \text{ dB(W/(m}^2 \cdot \text{Hz})}$, if the gain of the radioastronomy antenna is 0 dB in the direction of the satellite. When equipped with the band-rejection filter the signal from the GMS is much below this level at all frequencies within the radioastronomy band. In fact, over most of the band the margin is about 60 dB for the estimated level and about 50 dB for the measured level. Thus harmful interference will be caused only when the radioastronomy antenna is observing so that its gain in the direction of the satellite is close to the latter value. Observations at any observatory should be unaffected except within a few beamwidths of the satellite.
The power signal at 2.45 GHz would have a typical flux-density of 0.01 W/m² at an observatory no closer than 100 km to the nearest rectenna. This level, received in the side lobes of a radio telescope, could cause overloading of a parametric or FET amplifier, or loss of sensitivity resulting from the insertion loss of the necessary filtering. Harmonics of the power signal could cause overloading when antennas are pointed close to the satellites, and when observing in the radioastronomy band close to the second harmonic.
Noise generated by the transmitting tubes, which might be klystrons or magnetrons, could be spread over many mehagerz in frequency, and would not be beamed towards the rectenna but radiated widely.

Thermal noise from solar cell arrays could exceed the harmful limits of flux density for radioastronomy given in Report 224. 

Unwanted signals associated with failures of transmitting tubes, failure of phase-lock circuits, and warm-up and switching transients would require careful study. For example, with 70 kW klystrons a total of over $5 \times 10^6$ tubes would be required in orbit. With a mean time to failure of 25 years per tube, the failure rate would be over 20 per hour.

Noise and intermodulation products with other signals would be generated at the rectenna.

The effects upon radio and radar astronomy should be interpreted in terms of the discussion of harmful interference levels in Report 224. In particular, the band of sky centred upon the geostationary-satellite orbit within which observations would be precluded presents a serious problem. Interference from the satellites would be most serious in bands close to the fundamental frequency and its harmonics. Natural shielding between observatories and rectenna sites would be important.

For further details of the system and its predicted interference effects, see Report 679 and the Bibliography below.

REFERENCES


BIBLIOGRAPHY


REPORT 854-1*

INTERFERENCE TO RADIOASTRONOMY FROM MICROWAVE OVENS OPERATING IN THE 2450 MHz ISM BAND

(Question 5/2) (1982-1986)

1. Introduction

The band 2450 ± 50 MHz is designated for Industrial, Scientific and Medical (ISM) equipment and is widely used for domestic microwave ovens. Although not a radio service, the power levels involved (0.5 to 2 kW) are such that out-of-band spurious or harmonic radiation can represent a potential problem for these services and, in particular, the radioastronomy service, since energy is not entirely confined within the oven. This Report considers the possible levels of interference at radioastronomy observatories from such equipment.

* This Report should be brought to the attention of Study Group 1 and the CISPR.
2. Characteristics of the radiation

Microwave ovens typically use a magnetron which is operated from rectified (but unsmoothed) AC power. To avoid dominant standing-wave patterns, the oven cavity often incorporates a rotating paddle. The resulting fundamental radiation comprises a number of frequencies, covering a range of some 10 to 30 MHz around the nominal frequency, pulsed at 100 Hz and swept in frequency over a few MHz by the rotation of the paddle. In addition to this primary radiation, intermodulation products exist over a frequency range from some tens of MHz up to 7 to 8 GHz. Of these, the components above about 1 GHz are the more likely to be important for radioastronomy.

The results of measurements in the United Kingdom on three ovens are shown in Fig. 1 comprising one commercial and two domestic examples [Anderson et al., 1979]. The values refer to the measured peak field strength in a 30 kHz band (normalized to a distance of 30 m) from a measurement distance of 3 m from the front of the oven. The radiation showed no preferred polarization. These data essentially corroborate earlier measurements by the United Kingdom Post Office. Outside the allocated band, peak field strengths are typically 30 dB(μV/m) with values some 20 dB higher in the vicinity of the radioastronomy bands near 2700 MHz and the second harmonic frequency of the ovens (4900 ± 100 MHz). Mean values in a 10 MHz band are some 15-20 dB lower.

![Figure 1 - Field strengths in a bandwidth of 30 kHz, normalized from a measurement distance of 3 m](image)

Results of measurements of emissions from four microwave ovens have recently been published [Kashyap and Hunt, 1982]. The measurements on both horizontal and vertical polarization covered the range 30-10 000 MHz. Results obtained in the band 1000-6000 MHz are plotted in Fig. 1 as dB(μV/m) in a band of 30 kHz at a distance of 30 m. The observations were actually taken with a bandwidth of 100 kHz and 5 dB was subtracted from the measured values to convert to 30 kHz on the assumption of uniform spectral density within the 100 kHz band. If peak field strengths are independent of bandwidth then these values should have been plotted 5 dB higher in Fig. 1. The leakage at the fundamental frequency of 2450 MHz and at the second harmonic at 4900 MHz was lower in these tests than in those mentioned in the previous paragraph and no emissions were observed between 3000 MHz and 4900 MHz. All four ovens showed relatively strong spurious signals at 1413 MHz in the centre of the radioastronomy band.
Spurious emissions were also observed [Kashyap and Hunt, 1982] from two of the four ovens at 7350 MHz and 4900 MHz. The observed levels were close to those shown in Fig. 1 for 4900 MHz.

Attempts to measure the spurious emissions in the 30-1000 MHz range were hindered by high background noise levels. There was no noticeable radiation between 500 MHz and 1000 MHz from any of the ovens. Between 100 MHz and 500 MHz emissions were observed but at levels below the noise and only upper limits could be assigned. Below 100 MHz, spurious emissions were observed from all four ovens and from two of the ovens at measurable levels. The field strengths at a distance of 30 m were in the range 20-35 dB(µV/m) but were measured in a bandwidth of 1 MHz and are not directly comparable with the measurements at higher frequencies.

3. Interference to radioastronomy observations

Levels of harmful interference in the allocated radioastronomy bands are quoted in Report 224. Several factors have to be considered when applying these criteria to the case of microwave ovens:

- Microwave ovens will normally be operated inside buildings. In favourable circumstances this may provide an additional attenuation of 30 dB but it could be as little as 2 to 3 dB. For the present an additional attenuation of 15 dB will be assumed.

- With the currently increasing use of microwave ovens it is likely that a number of such devices will be within the vicinity of a radioastronomy observatory. An additional factor of +10 dB is included to allow for multiple interfering sources operating simultaneously.

- The pulsed nature of the radiation may be particularly serious for observations of, for example, the pulse-profile of pulsars or the scintillation spectrum of radio sources. In such cases the peak value of the interfering signal must be considered. On the other hand, for continuum observations using long time-constants the mean power is the relevant quantity. Consider, as two extreme cases:

(a) continuum observations as described in Report 224, and

(b) pulsar observations in which integrated pulse profiles are determined with a time resolution of $10^{-3}$ s and an effective integration time of 10 s, corresponding, for example, to observing a pulsar of pulse-period 0.1 s for $10^3$ s.

The calculations have been made for three of the radioastronomy bands most likely to be affected and are based on the measurements of [Anderson et al., 1979]. Table I gives, for each of the two cases (a) and (b):

- the level of harmful interference; and

- the corresponding mean and peak flux-densities measured in a 10 MHz band at a distance of 30 m from a microwave oven.

<table>
<thead>
<tr>
<th>Nominal radioastronomy frequency (MHz)</th>
<th>Harmful level of interference (dB(W/m²)) in a 10 MHz band</th>
<th>Power flux-density in a 10 MHz band at 30 m from a microwave oven (dB(W/m²))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Continuum (*)</td>
<td>Pulsar measurement</td>
</tr>
<tr>
<td>1420</td>
<td>-182</td>
<td>-170</td>
</tr>
<tr>
<td>2700</td>
<td>-177</td>
<td>-165</td>
</tr>
<tr>
<td>5000</td>
<td>-171</td>
<td>-159</td>
</tr>
</tbody>
</table>

(*) Harmful levels for continuum are from Report 224, modified where necessary for a 10 MHz bandwidth.
Table II lists the respective distances within which a microwave oven would exceed the harmful level under the assumptions of:

- a factor of $-15 \text{ dB}$ for the attenuation provided by a building;
- a factor of $10 \text{ dB}$ to allow for a number of ovens operating simultaneously; and
- free-space propagation between the interfering sources and the radioastronomy antenna.

**TABLE II — Estimated distance within which harmful interference would be experienced**

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>Continuum measurement (km)</th>
<th>Pulse-profile measurement (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1420</td>
<td>6.7</td>
<td>7.5</td>
</tr>
<tr>
<td>2700</td>
<td>47.5</td>
<td>168.7</td>
</tr>
<tr>
<td>5000</td>
<td>1.5</td>
<td>3.8</td>
</tr>
</tbody>
</table>

4. **Conclusions**

Although for distances of more than a few kilometres it is not valid to assume free-space propagation, it is nevertheless clear from Table II that microwave ovens are a potential source of interference to radioastronomical observations, particularly in the 2700 MHz band, and that further studies are called for. In particular, detailed measurements of the out-of-band emission from a large sample of ovens and investigation of the attenuation provided by buildings in typical installations would be valuable. Such data would allow more precise calculations of the probable levels of interference and be of value in assessing the suitability of particular observatory sites.

**REFERENCES**


FACTORS AFFECTING THE POSSIBILITY OF FREQUENCY SHARING BETWEEN GROUND BASED RADAR ASTRONOMY AND OTHER SERVICES


1. Introduction

In radar astronomy, unlike radioastronomy, both transmission and reception of signals must be considered in frequency coordination. Radar astronomy receivers have sensitivities comparable with the best radioastronomy receivers and also need to have protection from severe interference. Radar astronomy transmitters develop, and antennas radiate high power, so that they are capable of interfering with other services over significant distances, which may be appreciably extended by scattering from space objects such as the Moon and spacecraft, or by means of scattering media such as the troposphere and the ionosphere.

Although radar astronomy is a relatively new discipline, it is responsible for a number of notable achievements. For example, the accuracy of orbital information on the planets has been improved by a factor of more than one thousand by these means. It has likewise been shown that Venus rotates on its axis in the direction opposite to the rotation of most solar system objects (retrograde rotation). Contrary to the inference drawn from optical observations, it has been shown by radar observations that the rotation of the planet Mercury is synchronous at 2/3 of its orbital period. The radar reflectivity of the Sun varies with solar activity, and the spectrum of the echoes shows effects which are believed to be due to large mass motions of the solar plasma and outward flow of the solar wind. As with other advances made using radar astronomy, much of this knowledge is based on information that cannot at present be obtained using any other ground-based technique [Pettengill, 1978].

Radar astronomy systems in the past have generally been outgrowths of components developed for other services; indeed, many systems put to radar astronomy use have had some other primary purpose. This situation now appears to be changing however, with the most sensitive current systems being designed specifically to optimize radio and radar performance in astronomical research. Thus, the specific needs of radar astronomy should be separately stated.

Unlike a radioastronomy system detecting cosmic noise, the channel bandwidth required for radar astronomy can be much smaller, in general only that required to encompass the modulation band, Doppler spread, and Doppler shift encountered. Radio- and radar-astronomy systems are similar, in that they require large antennas, sensitive receivers and low tracking rates.

Many similarities exist between radar astronomy systems and deep-space tracking facilities. These, or other similar facilities on Earth, may also be used in a bistatic mode, where the second terminal (receiver or transmitter) is in a space probe, for important radar studies of the planets and the interplanetary medium.

2. The problem of radar astronomy

The salient problem in radar astronomy is the detection and study of targets at long ranges. These targets may be small in angular extent relative to the antenna beam, e.g. the planets; or extended, e.g. the terrestrial ionosphere.

* This Report is brought to the attention of Study Group 1.
The detection range of a system for a quasi-point target is as follows:

\[ R^4 = \frac{\text{Const. } PA^2}{T \lambda^2} \]  

(1)

where, \( R \) is the range, \( P \) the transmitted power, \( A \) the effective area of the duplexed antenna, \( T \) the operating noise-temperature and \( \lambda \) the wavelength. For extended targets, we have

\[ R^2 = \text{Const. } PA / T \]  

(2)

Both relations point to the fundamental importance of large powers, large antennas and sensitive receivers.

The detectability of the planets, asteroids, cometary and meteor ionization trails by radar has been established by a number of observers [Pettengill, 1970]. Current emphasis is being placed on the detection and detailed study of asteroids and cometary nuclei and planetary satellites, as well as on high-resolution mapping of the solid surface planets and the Earth's moon.

The problem of signal design for radar astronomy has been treated in a way that allows consideration of propagation, multipath, and reflection effects in the optimization of the modulation, as well as the associated detection features [Green, 1968]. In general, the frequency spectrum, occupied by such transmitted signals and those reflected from the target, is narrow compared with that desirable for observation of cosmic noise. The spectral width of radar astronomy signals is more akin to that commonly used in spectral-line radioastronomy. However, because of the coherent nature of radar signals, and because correlation with the transmitted wave form is generally used, several orders of magnitude of interference tolerance can be gained, as compared with radioastronomy. Unwanted narrow-band emissions are less likely to cause trouble because there is little probability that they will fall in the receiver passband. Incoherent interference can be suppressed to a degree by correlation techniques in signal processing.

An estimate of the channel bandwidth required to allow an adequate receiver offset for Doppler shift, can be obtained by considering a specific problem in planetary detection. Beyond this, little can be said regarding susceptibility of the system to interference without some detailed discussion of a particular system.

The radar Doppler shift is given approximately by: \( f_d = f_c \frac{2 v}{c} \) where \( f_c \) is the Doppler frequency shift, \( f_c \) the carrier frequency, \( v \) the radial velocity of the target and \( c \) the speed of light. Considering the entire orbit of some planets, for example, the fraction \( 2 v/c \) can be evaluated, and is about \( 3 \times 10^{-4} \) for Mercury. The Doppler spread is a result of differing Doppler shifts from the various parts of a target reflecting volume.

Radar astronomy receivers have many features in common with the radiometers used in radioastronomy. Receiver designs have progressed to the point where the sensitivity of the system is limited by environmental background noise. As a result, any generalized approach to the appraisal of the susceptibility to interference of radar astronomy receiving systems would be along lines identical to those used for communication-satellite stations and for radioastronomy. Reports on this subject have already been prepared [Evans and Hagfors, 1968; Evans, 1969] (Report 224).

3. Frequency characteristics of experimental radar astronomy systems

Most experimental radar astronomy systems have operated at frequencies allocated to radiolocation services, because these services have borne the costs of transmitter component developments and radar astronomy makes use of the available equipment in the interest of economy. However, there are a few specific cases wherein the nature of the scientific study strongly affects the choice of frequency. For example, studies of the solar plasma to certain depths by radar astronomy techniques require the use of frequencies in the 20 to 60 MHz range.
4. Susceptibility of radar astronomy receiving systems to other signals

Any signal that significantly increases the operating noise-temperature of the receiving system would be troublesome to the radar astronomer. This effect is primarily a function of the average power of the interfering signal. As an illustration, a 400 MHz system at the Lincoln Laboratory's Millstone Hill site and airborne altimeters, shared the same band in the frequency allocation table. Ideally, in this specific case, the unwanted signal level at the output terminals of the radar astronomy antenna should not exceed $5 \times 10^{-23} \text{ W/Hz}$. At higher frequencies, where the background noise is lower, the unwanted signal level should be reduced further. To achieve these levels of protection will require time sharing or other special arrangements that may not always be possible on a local basis.

5. Indirect sources of interference

Scattering of the transmitted signal (or harmonics thereof), for example from the Moon, troposphere, and orbiting objects, can, under certain conditions, be a hazard. In questions of sharing, these effects should be considered on a case-to-case basis.

6. Interference by radar astronomy to terrestrial receivers

High power is produced by radar astronomy transmitters and this power is usually confined to a fairly narrow beam by the large antenna. In many instances, the antenna beam is directed at such high elevation angles that interference is effectively limited to that radiated from the side lobes. (For large parabolic reflectors, a reference side-lobe pattern is contained in Recommendation 509.) This holds also for systems operating in the 20 to 60 MHz range, where the path angle of elevation limits ionosphere forward-scatter primarily to the side lobes. Typical powers for radar astronomy transmitters are given in Table 1.

7. Conclusions

7.1 Adequate management of interference, involving high-power radars, is normally effected on a local basis.

7.2 Many functions of radar astronomy installations can be carried out on a frequency-sharing basis. There are instances, however, where a channel of modest bandwidth within the radiolocation bands concerned, may be cleared or protected on a local or regional area basis for certain radar astronomy experiments.

7.3 When the frequency range in use is dictated by natural phenomena (e.g., solar and other plasma investigations), local or regional arrangements may be required.

7.4 From the point of view of availability of equipment, it is desirable that radar astronomy systems be operated in or near frequency bands for which high-power transmitting technology has reached a suitable degree of development.

7.5 As with other high-power installations, radiolocation stations used for radar astronomy observations should be sited with great care, to minimize mutual interference problems with stations operating in the same and adjacent bands.
<table>
<thead>
<tr>
<th>Organization</th>
<th>Location</th>
<th>Approximate frequency (MHz)</th>
<th>Antenna Diameter (m)</th>
<th>Gain (dB)</th>
<th>Effective area (m²)</th>
<th>Mean power (kW)</th>
<th>Peak power (kW)</th>
<th>Pulse duration</th>
<th>System noise-temperature (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calif. Inst. Tech. JPL</td>
<td>Goldstone Lake, Calif.</td>
<td>2.30</td>
<td>70</td>
<td>64</td>
<td>2.40</td>
<td>4.00</td>
<td>4.00</td>
<td>CW</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8.50</td>
<td>70</td>
<td>75</td>
<td>2.70</td>
<td>4.00</td>
<td>4.00</td>
<td>CW</td>
<td>25</td>
</tr>
<tr>
<td>Cornell Univ. National</td>
<td>Arecibo, Puerto Rico</td>
<td>4.30</td>
<td>30</td>
<td>60</td>
<td>3.90</td>
<td>1.50</td>
<td>2.50</td>
<td>0.001 to 2.0 ms CW</td>
<td>35</td>
</tr>
<tr>
<td>Astronomy and Ionosphere</td>
<td></td>
<td>2.40</td>
<td>21</td>
<td>72</td>
<td>2.00</td>
<td>1.40</td>
<td>1.40</td>
<td>CW</td>
<td></td>
</tr>
<tr>
<td>Center</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Instituto de Geofisica de</td>
<td>Jicamarca Radar Observatory</td>
<td>5.0</td>
<td>285</td>
<td>42.6</td>
<td>8.40</td>
<td>2.50</td>
<td>6.00</td>
<td>0.01-1000 ms</td>
<td>2000-3000</td>
</tr>
<tr>
<td>Peru</td>
<td>Lima (Peru)</td>
<td></td>
<td>(Square array)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

REFERENCES


1. Introduction

Many scientists believe that life may be common in our galaxy and that it could have developed into advanced forms that possess a telecommunication capability similar or superior to ours. We do not know the frequencies, modulations, polarizations and locations of transmitting stations used by extra-terrestrial civilizations, if they exist. To discover signals from these stations, it is necessary to make an extensive search of the radio frequency spectrum, in all directions from Earth. The conduct of such a systematic search with great sensitivity has become feasible in recent years.

The possibility of receiving radio signals from extra-terrestrial intelligent life was first pointed out in 1959 [Cocconi and Morrison, 1959]. The first search in the microwave region was carried out in 1960, [Drake, 1960]. Since then at least 47 searches have been conducted by 8 countries, utilizing 24 observatories. [Tarter, 1985]. These efforts have not detected evidence of signals from extra-terrestrial beings. The searches, however, covered only a tiny fraction of the frequencies, modulation schemes, and directions that are considered reasonable choices from the point of view of a comprehensive search, and at sensitivities that may not have been adequate.

Additional comprehensive searches are being planned and implemented. Some additional background discussion of SETI may be found in papers by Bates [1988] and Oliver [1987].

2. Search considerations

Assuming that signals from extra-terrestrial beings are reaching the Earth, our ability to detect them depends upon

a. the flux density of the signals arriving at Earth,
b. the collecting area of our antenna, and its illumination efficiency,
c. the sensitivity of our receiver,
d. our ability to point our antenna in the correct direction,
e. and our ability to distinguish the received signal from natural noise and from the man made electromagnetic environment.

The flux density of an extra-terrestrial signal depends on the transmitted e.i.r.p. and the characteristics of the path of propagation.
The flux density of the signal to be detected is unknown. Because of the very great distances that are necessarily involved, the flux density may be very low, and detection would therefore be limited by the sensitivity of the receiving system.

For a receiving system on the surface of the Earth, the attenuation of the atmosphere reduces the strength of the unknown signal. The attenuation is a function of frequency and weather condition [Reports 719, 721].

For a receiving system located outside the atmosphere of the Earth, for example, on the Moon, the attenuation of the atmosphere is avoided and the possibility of signal detection is correspondingly improved.

Fig. 1 presents curves of signal power flux density as a function of e.i.r.p. for several assumed distances, not including the attenuation of the atmosphere.

* Signal power flux density*

<table>
<thead>
<tr>
<th>e.i.r.p. (dBW)</th>
<th>Received power flux density (dBW/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-50</td>
</tr>
<tr>
<td></td>
<td>-100</td>
</tr>
<tr>
<td></td>
<td>-150</td>
</tr>
<tr>
<td></td>
<td>-200</td>
</tr>
<tr>
<td></td>
<td>-250</td>
</tr>
<tr>
<td></td>
<td>-300</td>
</tr>
<tr>
<td></td>
<td>-350</td>
</tr>
<tr>
<td></td>
<td>-400</td>
</tr>
<tr>
<td>D = 10</td>
<td>+</td>
</tr>
<tr>
<td>10²</td>
<td></td>
</tr>
<tr>
<td>10³</td>
<td></td>
</tr>
</tbody>
</table>

Figure 1 — Received power flux density versus e.i.r.p.

D: Distance, light years. (1 light year = 9.46 x 10¹⁵ m)
* : From geostationary satellite
+ : From Voyager spacecraft at Neptune

4. Receiving system sensitivity.

For a given antenna gain, the sensitivity of the receiving system to be used for SETI search is determined by its system noise temperature, the resolution bandwidth chosen for the search, and by the integration time.

4.1 System noise temperature.

System noise temperature is determined by the characteristics of the equipment plus the sky noise temperature seen by the receiving antenna. For receiving equipment with a very low noise temperature, e.g., less than 30 K, sky noise can be a fundamental limitation to system sensitivity at some frequencies.

* In the context of this report, the term "power flux density" refers to power per unit area. This meaning is consistent with definitions and usage of the International Telecommunication Union. Some readers may use the term in a different way.
For a receiving system outside the atmosphere of the Earth, the sky noise is determined by the cosmic background noise (3 K) plus radio noise emissions from our galaxy. The total sky noise temperature is less than 7 K between approximately 1 and 100 GHz, and this range is called the free-space microwave window.

Sky noise as seen from the surface of the Earth during clear weather, with an atmospheric water vapor density of 7.5 gm/m³, 90 deg elevation angle, is less than 7 K between approximately 1 and 15 GHz. [Report 683] In the 15 to 100 GHz range, the sky noise contributed by the atmosphere rises appreciably, primarily due to H₂O and O₂, thereby reducing the probability of detecting extra-terrestrial signals that may be present.

As limited by sky noise temperature and its effect on receiver sensitivity, the frequency range over which maximum sensitivity may be realized is much reduced for a station located on the surface of the Earth, as compared to one located outside the atmosphere.

4.2 Signal integration time

By integrating the signal-plus-noise power over a period of time, the signal to noise ratio for a continuously present signal may be improved by approximately (bandwidth x integration time)⁰.⁵. Integration is one of several effective modes for signal detection. The time of integration is limited by two factors: signal frequency stability, and the observation time available on desired antenna systems.

4.2.1 Frequency stability

The frequency of the arriving signal will include a Doppler shift that depends on the relative velocity between the transmitter (at the time of transmission) and the receiver. This shift may change with time as a result of relative acceleration of the transmitter and receiver. The signal to noise ratio improvement that results from integration depends upon the ability to track the Doppler shifted signal. The improvement in signal to noise ratio resulting from non-coherent integration may be reduced as a result of imperfect signal frequency tracking.

4.2.2 Available search time

The total time it will take to search the volume of space in which there might be extra-terrestrial intelligent life depends on the signal integration time per channel, the number of antenna pointing directions, and the range of frequencies to be included. If the time available for use of particular search antennas is limited, the integration time for each channel and for each pointing direction is correspondingly limited. Under these circumstances the search sensitivity is constrained by the time available for the planned search.
4.3 Minimum detectable signal power

For a signal that remains within the detection bandwidth during the integration time, the minimum detectable signal power of the search receiver, assuming a signal-to-noise ratio of 1, is given by [NASA 1973]:

\[
P_{\text{min}} = 10 \cdot \log \left( \frac{kT_B \cdot (1 + (1 + B \cdot \tau)^{0.5})}{B \cdot \tau} \right) \text{ dBW}
\]

where

- \(k\) = Boltzman's constant
- \(T\) = Temperature (K)
- \(B\) = detection bandwidth (Hz)
- \(\tau\) = integration time (sec)

Fig. 2 shows \(P_{\text{min}}\) as a function of integration time for several bandwidths. Points A and B in the Figure identify \(P_{\text{min}}\) for two candidate search receivers with the characteristics listed in the legend.

**FIGURE 2 – Minimum detectable signal power**

30 K system noise temperature. \(\text{BW}\): Bandwidth (Hz)

Candidate system A: \(\text{BW} = 10\) Hz, integration time = 2 sec

Candidate system B: \(\text{BW} = 1\) Hz, integration time = 1000 sec
Fig. 3 illustrates the relationship between the received power flux density for the conditions assumed in Figure 1, and the search sensitivity of two candidate receiving systems. The dashed horizontal line represents the sensitivity of a system using a 34 m diameter antenna with 50% efficiency, 30 K noise temperature, 10 Hz bandwidth, and 2 sec integration time. The solid line represents the sensitivity of a system using a 300 m diameter antenna with 50% efficiency, 30 K noise temperature, 1 Hz bandwidth, and 1000 sec integration time. Combinations of e.i.r.p and distance that result in detectable flux densities are those that lie above the respective sensitivity lines for the hypothetical systems.

![Graph showing signal detection capability](image)

**FIGURE 3 - Signal detection capability**

- **Sensitivity**: System A using 34 m antenna. (see text for System B using 300 m antenna, and Fig. 2)
- **D**: Distance, light years. (1 light year = 9.46 x 10^{15} m)
- ***: Satellite in geostationary orbit
- **+**: Voyager spacecraft at Neptune

When detection bandwidth is not limited by signal frequency drift, the most sensitive receiver is obtained by use of a detection bandwidth which matches the spectral width of the received signal. The problem is that this bandwidth is not known in advance. An associated problem is that, for a single receiver, reducing the detection bandwidth correspondingly increases the time needed to search a particular frequency range, unless a large number of narrow detection channels can be used simultaneously. For example, to search the range from 1 to 2 GHz with a single channel receiver having a bandwidth of 1 Hz and an integration time of 10 sec would require 317 years. It is for this reason that comprehensive searches utilize receivers that are able to simultaneously examine millions of spectral channels, each having a narrow detection bandwidth.
5. Antenna pointing direction

Antennas with high gain (large collecting area) are desirable in order to increase search sensitivity and correspondingly enhance the probability of detection. The associated difficulty is that an increase in gain results in a decrease in beamwidth, with a corresponding increase in the number of pointing directions needed to search a given fraction of the sky. For a given integration time, an increase in pointing directions results in an increase in total search time.

Antenna pointing strategies and the selection of integration time and other system parameters are important elements of the design of a SETI search.

6. Signal identification and interference rejection

A principal problem facing the discovery of extra-terrestrial signals from another intelligence is the successful determination that the detected signal is not the result of noise, natural or man-made.

The probability that the amplitude of random noise will exceed a given value is well understood. A noise peak that exceeds a given threshold value will be detected and is called a false alarm. The threshold value determines the false alarm rate, and this rate may be calculated for the case of Gaussian white noise. Raising the threshold in order to reduce the false alarm rate reduces the receiver sensitivity.

With the exception of natural astrophysical emissions or an extra-terrestrial signal, signals received by a search station will be man-made. It is therefore necessary that the search station have the ability to classify these signals and reject them as candidates for possible further observation and analysis. The rejection may be based on a-priori knowledge of signals in the environment of the search station, or be based on measurements made by the station. The success of excluding these interfering signals from the data base used for further detailed analysis is a major component in the feasibility of a successful search.

The increasing use of the radio frequency spectrum as time passes suggests that SETI searches should be conducted as soon as possible in order to minimize the problem of radio frequency interference. It should be noted that, from the point of view of SETI, all man-made radio emissions, authorized or not, represent potential radio frequency interference.

The rapidly growing use of the geostationary satellite orbit will increasingly preclude the possibility of searching a zone of the sky above the equator of the Earth within the frequency ranges used by satellite transmitters. The size of the zone is determined by the number of geostationary satellites and their e.i.r.p.

7. Candidate bands to be searched.

Keeping in mind that the frequency and other characteristics of extra-terrestrial signals are unknown, it is nevertheless necessary to decide the bands of frequencies with which a search should begin. For search stations on the surface of the Earth, maximum sensitivity is limited by the noise temperature and attenuation of the atmosphere, as described earlier. Additionally, a number of particular bands have been postulated as likely candidates for search on the basis of physical principles.

A detailed discussion of the rationale for selecting particular frequencies as candidates for early or intensive search is beyond the scope of this report. Report 700-1, Geneva 1986, presents some of the rationale for certain frequencies. A common aspect of proposals for particular search frequencies is that they lie near spectral lines of natural radiation, e.g., atomic hydrogen (1420 MHz), the hydroxyl radical (1612, 1665, 1667, and 1720 MHz), formaldehyde (4830 MHz), and the ground state spectral line of the lightest artificial atom, positronium (203.385 GHz). The assumption is that extra-terrestrial beings may elect to transmit on frequencies near to these emission lines, or perhaps some multiple of them, with the idea that other civilizations would be aware and would listen accordingly.
Several bands allocated to the radioastronomy service are protected from man-made emissions, and there are similar bands for passive sensing. Because of their protection from interference, these bands are also candidates for use in connection with SETI searches.

There are many points of view concerning the frequencies that may be used for extra-terrestrial communication. It must be remembered that we have no reliable a-priori knowledge about the character or existence of signals we are attempting to receive. It is for this reason that comprehensive searches over wide frequency ranges and in all directions from Earth are proposed.

8. Conclusion

The possibility of detecting radio signals from other civilizations in our galaxy, if they exist, is strongly dependent upon a quiet radio environment at sites where searches for these signals are conducted. Although it is true that modern technology will allow some discrimination against man-made signals, it is also true that the use of the radio spectrum for a wide variety of telecommunication services and functions is rapidly increasing the need for such discrimination. As time passes, the probability of successful detection is correspondingly reduced.

It is therefore important that the requirements for the search for extraterrestrial signals be kept in mind, and that cooperation be encouraged to the maximum degree possible to protect search sites from interference.

REFERENCES


DECISIONS

DECISION 87 *
DETERMINATION OF THE COORDINATION AREA
(Appendix 28 of the Radio Regulations)
(1989)

This text may be found in the Annex to Part 2 of Volumes IV and IX.

DECISION 101

ESTABLISHMENT OF INTERIM WORKING PARTY 2/2

CCIR Study Group 2,

CONSIDERING

(a) that the ITU Plenipotentiary Conference, Nice 1989, by Resolution No. PL-B/1, has decided:

- that a World Administrative Radio Conference for Dealing with Frequency Allocations in Certain Parts of the Spectrum, shall be held in the first quarter of 1992;
- that the agenda for this Conference shall be established by the Administrative Council, taking into account the Resolutions and Recommendations of WARC HFBC-87, WARC MOB-87 and WARC ORB-88 relating to frequency allocations;
- that, in addition, this Conference may consider defining certain new space services and consider allocations to these services in frequency bands above 20 GHz;

(b) that the WARC ORB-88 (Recommendation 716) has invited the CCIR to carry out certain studies in preparation for the Conference;

* According to the decision of Chairmen and Vice-Chairmen's Meeting (Geneva, 4-6 July, 1990) the tasks of JIWP 2-4-5-8-9-10-11/1 on the determination of the coordination area are transferred to Study Group 12 for study by Task Group 12/3.
(c) that WARC MOB-87 and WARC ORB-88 adopted other Resolutions and Recommendations which will be considered by the Conference and which may have impact on the frequency sharing criteria for radio services of interest to Study Group 2;

(d) that the CCIR has already developed basic concepts and recommended technical criteria for frequency sharing which may facilitate the work of the Conference;

(e) that a CCIR report which will be prepared by JIWP [WARC-92], should be submitted to administrations 10 months in advance of the Conference, i.e. about March 1991;

(f) that the interim meeting of Study Group 2 for study period 1990-1994 will be held after this date;

(g) the options offered by Resolution 24 for CCIR preparatory work for conferences,

DECIDES

1. that Interim Working Party 2/2 be established with the following terms of reference:

1.1 to examine the potential inter-service frequency sharing problems that may arise between Study Group 2 services and other radio services as a result of the various Resolutions and Recommendations mentioned in CONSIDERING (b) and (c);

1.2 to study any proposed new space services in frequency bands above about 20 GHz with a view to defining their technical characteristics and to establish sharing criteria between those new services and existing services to which the bands are allocated;

1.3 to study other services, technical regulations and frequency bands which may be included on the agenda of WARC-1992 by the Administrative Council;

1.4 to report under provision of §2.3.8 of Resolution 24-6;

2. that the chairmanship of the Interim Working Party 2/2 and the coordination of the work be undertaken by Mr. H.G. Kimball, United States;

3. that the Interim Working Party 2/2 be composed of representatives nominated by the following:

    Federal Republic of Germany, Australia, United States, France, Japan, United Kingdom, USSR

4. that, in accordance with §§2.3.5 and 2.3.6 of Resolution 24-6, the Interim Working Party 2/2 shall carry out as much as possible of its work by correspondence but may have a brief meeting just prior to any scheduled meeting of JIWP WARC-92.