INTERNATIONAL TELECOMMUNICATION UNION

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INTERNATIONAL
RADIO CONSULTATIVE
COMMITTEE

RECOMMENDATIONS AND REPORTS OF THE CCIR, 1982

(ALSO QUESTIONS, STUDY PROGRAMMES, RESOLUTIONS, OPINIONS AND DECISIONS)

XVth PLENARY ASSEMBLY
GENEVA, 1982

VOLUME VII

STANDARD FREQUENCIES AND TIME SIGNALS

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PLAN OF VOLUMES I TO XIV
XVTH PLENARY ASSEMBLY OF THE CCIR

(Geneva, 1982)

VOLUME I	Spectrum utilization and monitoring.
VOLUME II	Space research and radioastronomy.
VOLUME III	Fixed service at frequencies below about 30 MHz.
VOLUME IV-1	Fixed-satellite service.
VOLUME IV/IX-2	Frequency sharing and coordination between systems in the fixed-satellite service and radio-relay systems.
VOLUME V	Propagation in non-ionized media.
VOLUME VI	Propagation in ionized media.
VOLUME VII	Standard frequencies and time signals.
VOLUME VIII	Mobile services.
VOLUME IX-1	Fixed service using radio-relay systems.
VOLUME X-1	Broadcasting service (sound).
VOLUME X/XI-2	Broadcasting-satellite service (sound and television).
VOLUME XI-1	Broadcasting service (television).
VOLUME XII	Transmission of sound broadcasting and television signals over long distances (CMTT).
VOLUME XIII	Vocabulary (CMV).
VOLUME XIV-1	Information concerning the XVth Plenary Assembly: Minutes of the Plenary Sessions. Administrative texts. Structure of the CCIR. Lists of CCIR texts.
VOLUME XIV-2	Alphabetical index of technical terms appearing in Volumes I to XIII.

All references within the texts to CCIR Recommendations, Reports, Resolutions, Opinions, Decisions, Questions and Study Programmes refer to the 1982 edition, unless otherwise noted; i.e., only the basic number is shown.

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DISTRIBUTION OF TEXTS OF THE XVTH PLENARY ASSEMBLY OF THE CCIR IN VOLUMES I TO XIV

Volumes I to XIV, XVth Plenary Assembly, contain all the valid texts of the CCIR and succeed those of the XIVth Plenary Assembly, Kyoto, 1978.

1. Recommendations, Reports, Resolutions, Opinions, Decisions

1.1 *Numbering of these texts*

Recommendations, Reports, Resolutions and Opinions are numbered according to the system in force since the Xth Plenary Assembly.

In conformity with the decisions of the XIth Plenary Assembly, when one of these texts is modified, it retains its number to which is added a dash and a figure indicating how many revisions have been made. For example: Recommendation 253 indicates the original text is still current; Recommendation 253-1 indicates that the current text has been once modified from the original. Recommendation 253-2 indicates that there have been two successive modifications of the original text, and so on. Within the text of Recommendations, Reports, Resolutions, Opinions and Decisions, however, reference is made only to the basic number (for example Recommendation 253). Such a reference should be interpreted as a reference to the latest version of the text, unless otherwise indicated.

The tables which follow show only the original numbering of the current texts, without any indication of successive modifications that may have occurred. For further information about this numbering scheme, please refer to Volume XIV-1.

1.2 *Recommendations*

Number	Volume	Number	Volume	Number	Volume
48, 49	X-1	374-376	VII	485, 486	VII
80	X-1	377-379	I	487-494	VIII
100	I	380-393	IX-1	496	VIII
106	III	395-405	IX-1	497	IX-1
139, 140	X-1	406	IV/IX-2	498, 499	X-1
162	III	407-412	X-1	500, 501	XI-1
182	I	414-416	X-1	502-505	XII
205	X-1	417, 418	XI-1	508	I
214-216	X-1	419	XI-1	509-511	II
218, 219	VIII	422, 423	VIII	513-517	II
239	I	428	VIII	518-520	III
240	III	430, 431	XIII	521-524	IV-1
246	III	433	I	525-530	V
257	VIII	434, 435	VI	531-534	VI
265, 266	XI-1	436	III	535-538	VII
268	IX-1	439	VIII	539-550	VIII
270	IX-1	441	VIII	552-554	VIII
275, 276	IX-1	443	I	555-557	IX-1
283	IX-1	444	IX-1	558	IV-1
290	IX-1	445	I	559-564	X-1
302	IX-1	446	IV-1	565	XI-1
305, 306	IX-1	447	X-1	566	X/XI-2
310, 311	V	450	X-1	567-572	XII
313	VI	452, 453	V	573, 574	XIII
314	II	454-456	III	575	I
326-329	I	457, 458	VII	576-578	II
331, 332	I	460	VII	579, 580	IV-1
335, 336	III	461	XIII	581	V
337	I	463	IX-1	582, 583	VII
338, 339	III	464-466	IV-1	584-591	VIII
341	V	467, 468	X-1	592-596	IX-1
342-349	III	469-472	XI-1	597-599	X-1
352-354	IV-1	473, 474	XII	600	X/XI-2
355-359	IV/IX-2	475, 476	VIII	601, 602	XI-1
362-364	II	478	VIII	603-606	XII
367	II	479	II	607, 608	XIII
368-370	V	480	III		
371-373	VI	481-484	IV-1		

1.3 *Reports*

Number	Volume	Number	Volume	Number	Volume
19	III	363, 364	VII	581	VIII
32	X-1	368, 369	I	584, 585	VIII
93	VIII	371, 372	I	587-589	VIII
106, 107	III	374-376	IX-1	599	VIII
109	III	378-380	IX-1	607	IX-1
111	III	382	IV/IX-2	610	IX-1
122	XI-1	383-385	IV-1	612-615	IX-1
137	IX-1	386-388	IV/IX-2	616, 617	X-1
176, 177	III	390, 391	IV-1	619, 620	X-1
179	I	393	IV/IX-2	622	X-1
181	I	395, 396	II	623	XII
183	III	401	X-1	624-626	XI-1
184	I	404, 405	XI-1	628, 629	XI-1
195	III	409	XI-1	630	XI-1
196	I	411, 412	XII	631-634	X/XI-2
197	III	419, 420	I	635-637	XII
200, 201	III	422	I	639	XII
203	III	430-432	VI	642, 643	XII
204-208	IV-1	434-437	III	646-648	XII
209	IV/IX-2	439	VII	651-668	I
212	IV-1	443-445	IX-1	670, 671	I
214	IV-1	448, 449	IV/IX-2	672-685	II
215	X/XI-2	451	IV-1	687, 688	II
222	II	453-455	IV-1	690	II
224	II	456	II	692-697	II
226	II	457, 458	X-1	699, 700	II
227-229	V	461	X-1	701-705	III
236	V	463-465	X-1	706-713	IV-1
238, 239	V	468	X-1	714-724	V
249-251	VI	468	XI-1	725-729	VI
252	VI (1)	469	XI-1	730-732	VII
253-255	VI	472	X-1	735-738	VII
258-260	VI	473	X/XI-2	739-749	VIII
262, 263	VI	476-478	XI-1	751, 752	VIII
265, 266	VI	481-485	XI-1	754	VIII
267	VII	488	XII	758	VIII
270, 271	VII	491	XII	760-775	VIII
272, 273	I	493	XII	778	VIII
275-280	I	496, 497	XII	779-789	IX-1
284-289	IX-1	499-501	VIII	790-793	IV/IX-2
292, 293	X-1	509	VIII	794-800	X-1
294	XI-1	516	X-1	801-806	XI-1
299-304	X-1	518	VII	807-812	X/XI-2
306	XI-1	519-526	I	814	X/XI-2
311-313	XI-1	528	I	815-823	XII
314	XII	530	I	825-842	I
319	VIII	532-534	I	843-854	II
322	VI (1)	535, 536	II	855-865	III
324-326	I	538-541	II	866-875	IV-1
327	III	542	VIII	876, 877	IV/IX-2
329	III	543-546	II	878-885	V
336	V	548	II	886-895	VI
338	V	549-551	III	896-898	VII
340	VI (1)	552-561	IV-1	899-929	VIII
342	VI	562-565	V	930-942	IX-1
345	III	567	V	943-950	X-1
347	III	569	V	951-955	X/XI-2
349	III	571	VI	956-964	XI-1
352-357	III	574, 575	VI	965-970	XII
358	VIII	576-580	VII	971	XIII

(1) Published separately.

1.3.1 *Note concerning Reports*

The individual footnote "Adopted unanimously" has been dropped from each Report. Reports in this volume have been adopted unanimously except in cases where reservations have been made which will appear as individual footnotes.

1.4 *Resolutions*

Number	Volume	Number	Volume	Number	Volume
4	VI	39	XIV-1	71	I
14	VII	44	I	72, 73	V
15	I	61	XIV-1	74, 75	VI
20	VIII	62	I	76	X-1
23	XIII	63	VI	77	XIV-1
24	XIV-1	64	X-1	78	XIII
26, 27	XIV-1	66	XIII	79-87	XIV-1
33	XIV-1	67-70	XIV-1		

1.5 *Opinions*

Number	Volume	Number	Volume	Number	Volume
2	I	41	XII	64	I
11	I	42, 43	VIII	65	XIV-1
13, 14	IX-1	45, 46	VI	66	III
15, 16	X-1	49	VIII	67-69	VI
22, 23	VI	50	IX-1	70-72	VII
26-28	VII	51	X-1	73	VIII
32	I	56	IV-1	74	X-1
35	I	59	X-1	75	XI-1
38	XI-1	60	XI-1	76	XIII
40	XI-1	61-63	XIV-1	77-81	XIV-1

1.6 *Decisions*

Number	Volume	Number	Volume	Number	Volume
2	IV-1	28, 29	VII	47-49	VIII
3-5	V	32	VIII	50	V
6	VI	33	XI-1	51	X/XI-2
9-11	VI	36	VI	52	X-1
18	XII	39-40	X-1	53, 54	I
19	XIII	41, 42	XI-1	55	IX-1
21	VI	43, 44	X/XI-2	56	I
27	I	45	III		

1.6.1 *Note concerning Decisions*

Since Decisions were adopted by Study Groups, use was made of the expression "Study Group..., Considering" and the expression "Unanimously decides", replaced by "Decides".

2. Questions and Study Programmes

2.1 *Text numbering*

2.1.1 *Questions*

Questions are numbered in a different series for each Study Group: where applicable a dash and a figure added after the number of the Question indicate successive modifications. The number of a Question is completed by an *Arabic figure indicating the relevant Study Group.* For example:

— Question 1/10 would indicate a Question of Study Group 10 with its text in the original state;

— Question 1-1/10 would indicate a Question of Study Group 10, whose text has been once modified from the original: Question 1-2/10 would be a Question of Study Group 10, whose text has had two successive modifications.

2.1.2 *Study Programmes*

Study Programmes are numbered to indicate the Question from which they are derived if any, the number being completed by a capital letter which is used to distinguish several Study Programmes which derive from the same Question. The part of the Study Programme number which indicates the Question from which it is derived makes no mention of any possible revision of that Question, but refers to the current text of the Question as printed in this Volume.

Examples:

— Study Programme 1A/10, which would indicate that the current text is the original version of the text of the first Study Programme deriving from Question 1/10;

— Study Programme 1C/10, which would indicate that the current text is the original version of the text of the third Study Programme deriving from Question 1/10;

— Study Programme 1A-1/10, would indicate that the current text has been once modified from the original, and that it is the first Study Programme of those deriving from Question 1/10.

It should be noted that a Study Programme may be adopted without it having been derived from a Question; in such a case it is simply given a sequential number analogous to those of other Study Programmes of the Study Group, except that on reference to the list of relevant Questions it will be found that no Question exists corresponding to that number.

References to Questions and Study Programmes within the text are made to the basic number as well as for other CCIR texts.

2.2 *Arrangement of Questions and Study Programmes*

The plan shown on page II indicates the Volume in which the texts of each Study Group are to be found, and so reference to this information will enable the text of any desired Question or Study Programme to be located.

VOLUME VII

STANDARD FREQUENCIES AND TIME SIGNALS

(Study Group 7)

TABLE OF CONTENTS

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PAGE LAISSEE EN BLANC INTENTIONNELLEMENT

INDEX OF TEXTS WHICH HAVE BEEN DELETED AT THE END OF THE STUDY PERIOD 1978-1982

(In order to facilitate the retrieval of a given text, the page No. of Volume VII of the XIVth Plenary Assembly, Kyoto 1978, is indicated.)

* Incorporated in Report 518-3.

** Incorporated in Report 271-6.

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NUMERICAL INDEX OF TEXTS

Note. – Questions, Study Programmes, Resolutions, Opinions and Decisions which already appear in numerical order in the table of contents, are not reproduced in this index.

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INDEX OF THE TEXTS PUBLISHED IN OTHER VOLUMES BUT CONTAINING INFORMATION OF INTEREST TO STANDARD-FREQUENCY AND TIME-SIGNAL SERVICES

Text	Title	Volume
Report 657	Statistical model for the determination of band sharing criteria	I
Report 829	Calculation of the probability of interference	I
Report 670	Worldwide minimum external noise levels, 0.1 Hz to 100 GHz	I
Recommendation 328	Spectra and bandwidths of emission	I
Report 181	Frequency tolerance of transmitters	I
Recommendation 329	Spurious emissions	I
Recommendation 331	Noise and sensitivity of receivers	I
Recommendation 332	Selectivity of receivers	I
Report 841	Spectrum management and computer aided techniques	I
Question 18/1	System design for maximizing the efficiency and utility of spectrum use	I
Question 44/1	System models for the evaluation of compatibility in spectrum use	I
Question 45/1	Technical criteria for frequency sharing	I
Decision 56	Transfer of technology	I
Report 546	Space systems technology in the space research service: attitude control technology	II
Report 396	Maintenance telemetering, tracking and telecommand for developmental and operational satellites. Possibilities of frequency sharing between earth-satellite telemetering or telecommand links and terrestrial services	II
Recommandation 364	Telecommunication links for manned and unmanned near-Earth research satellites. Frequencies, bandwidths and criteria for protection from interference	II
Recommendation 517	Protection of the radioastronomy service from transmitters in adjacent bands	II
Study Programme 15C/2	Protection of telecommunications equipment from radio-frequency radiation from space research earth stations	II
Question 19	Spurious emissions radiated from and received by stations of space services	II
Question 25/4	Unwanted emissions radiated and by earth stations and space stations of the fixed-satellite service	IV
Question 26/4	Provision of feeder links between fixed-earth stations and space stations of various services in frequency bands allocated to the fixed-satellite service	IV
Report 719	Attenuation by atmospheric gases	V
Report 720	Radio emission from natural sources above about 50 MHz	V
Report 721	Attenuation by hydrometeors, in particular precipitation, and other atmospheric particles	V

Text	Title	Volume
Report 722	Cross-polarization due to the atmosphere	V
Report 723	Worst-month statistics	V
Recommendation 530	Propagation data required for the design of tropospheric-scatter trans-horizon radio-relay systems, terrestrial line-of-sight radio-relay systems, and Earth-space telecommunication systems	V
Report 564	Propagation data required for space telecommunication systems	V
Recommendation 452	Propagation data required for the evaluation of interference within and between the space and terrestrial services and for the calculation of coordination distances	V
Report 569	The evaluation of propagation factors in interference problems between stations on the surface of the Earth at frequencies above about 0.5 GHz	V
Report 724	Propagation data required for the evaluation of coordination distance in the frequency range 1 to 40 GHz	V
Report 885	Propagation data required for evaluating interference between stations in space and those on the surface of the Earth	V
Recommendation 373	Definitions of maximum transmission frequencies	VI
Report 266	Ionospheric propagation characteristics pertinent to terrestrial radiocommunication systems design. *Fading*	VI
Report 892	Computation of reliability for HF radio systems	VI
Report 895	Sky-wave propagation and circuit performance at frequencies below about 30 kHz	VI
Study Programme 28D/6	Propagation factors affecting the sharing of the radio-frequency spectrum between terrestrial systems involving ionospheric propagation	VI
Recommendation 589	Interference to radionavigation services from other services in the bands between 70 kHz and 130 kHz	VIII
Report 915	Interference between fixed and maritime mobile and radionavigation services in the bands between 70 kHz and 130 kHz	VIII
Study Programme 2E/10-11	Radiation of unwanted emissions from space stations in the broadcasting-satellite service (sound and television)	X/XI
Recommendation 573	Radiocommunication vocabulary	XIII
Recommendation 971	A general terminology of telecommunications. *Terms common to CCIR and CCITT*	XIII
Recommendation 607	Terms and abbreviations for information quantities in telecommunications	XIII
Recommendation 431	Nomenclature of the frequency and wavelength bands used in telecommunications	XIII
Recommendation 574	Logarithmic quantities and units	XIII
Resolutions 66	Terms and definitions	XIII
Decision 19	Terms and definitions	XIII

STANDARD FREQUENCIES AND TIME SIGNALS

STUDY GROUP 7

Terms of reference:

1. To coordinate services of standard frequency and time-signal dissemination on a world-wide basis.

2. To study the technical aspects of emission and reception, including the use of satellite techniques in these services, and means to improve the accuracy of measurement.

1978-1980	*Chairman:*	G. BECKER (Germany (Federal Republic of))
	Vice-chairman:	J. McA. STEELE (United Kingdom)
1980-1986	*Chairman:*	J. McA. STEELE (United Kingdom)
	Vice-chairman:	S. LESCHIUTTA (Italy)

INTRODUCTION BY THE CHAIRMAN, STUDY GROUP 7

General

This introduction to the texts of Study Group 7 surveys the substantial progress which has been made over the past three years in the topics indicated below. It also seeks to establish the broad guidelines for the development of Study Group activities in the next study period.

Coordinated Universal Time (UTC)

The year 1982 will see the tenth anniversary of the system of Coordinated Universal Time (UTC) which was introduced in essentially its present form on 1 January 1972 by Recommendation 460. In the past ten years the UTC system has gained widespread acceptance as the reference time scale for timekeeping purposes throughout the world, not only for technical and scientific applications but also for time in everyday affairs. It is particularly gratifying to the Study Group that the World Administrative Radio Conference in 1979 (WARC-79) accepted the terms of Recommendation 535 and adopted UTC as the reference time scale for all radiocommunication activities. Likewise, UTC was also accepted in 1980 by the VIIth Plenary Assembly of the CCITT as the time scale for all other telecommunications activities. Together, these two actions constitute a powerful endorsement of the careful work and the intensive discussions extending over more than one plenary period which led to the present UTC system, as specified in Recommendation 460.

The general acceptance of UTC may have been assisted to some extent by the relative uniformity in the Earth's rate of rotation from 1972 until 1979, enabling a "leap second" to be introduced regularly in the last minute of the year to accommodate the difference in the rates of UTC and astronomical time. It is, of course, the responsibility of the Bureau international de l'heure (BIH) to decide upon the incidence of leap seconds as part of its implementation of the UTC system and in recognition of the excellent and indispensable work of the BIH the Study Group adopted a new Opinion 70. This expresses appreciation of the cooperation of the BIH in furtherance of the UTC system and draws the attention of administrations to the need for continued support of the BIH activities. In this, the Study Group was supporting similar views expressed earlier by two other bodies, the CCDS (Consultative Committee for the Definition of the Second) at its 9th session in September 1980 and the URSI (International Union of Radio Science) at its XXth General Assembly in August 1981.

The UTC system took a different form prior to 1972, transmitted time signals being subject to both time steps and adjustements in rate to maintain the signals within prescribed limits of astronomical time. Some national services have been adequately documented but at its Final Meeting the Study Group adopted a new Opinion 71 requesting all administrations to provide information on the adjustments applied to their respective services in the period 1955 to 1972. A new Report 896 contains this information as supplied by the United States Administration.

Relativistic effects in time transfer and coordination

At the time of the adoption of Recommendation 460 in 1970 the Study Group had also given consideration, in Report 439, to the relativistic effects which arise in executing precise time transfers in a terrestrial, and therefore non-inertial, framework. It was appreciated that it was necessary to define a suitable operational procedure which would establish a coordinate time system and thus ensure synchronism over an extended spatial region. This concept was accepted without question until the Interim Meeting in 1980 when serious doubts were raised in regard to the coordinate nature of UTC. It was decided to refer the question to the forthcoming meeting of the CCDS later in that same year and happily the CCDS was able to confirm the correctness of the views contained in Report 439, the text of which is consistent with the conclusions of the CCDS but also extends the synchronization procedures to heights which include the geostationary orbit.

The satisfactory result from this dialogue between the two consultative bodies is of practical importance for relativistic corrections are now applied as a *routine* measure in all precise time transfers over extended regions and indeed the corrections may be many times greater in magnitude than the stated precision in some time transfer experiments.

T/F distribution in the allocated bands

Taking firstly distribution from terrestrial stations, Report 267 in its several tables emphasizes the wide frequency spectrum embraced by the services, either from "dedicated" stations which radiate only a standard time and frequency service or the "host" stations which have a different major function but are able to combine it with the dissemination of a time and/or frequency reference.

Table I lists the existing HF stations operating in bands 6 and 7. The limitations of these bands due to variable propagation or interference from various sources are well known. A particular difficulty which has occupied the attention of the Study Group for many years lies in the mutual interference between stations of the standard-frequency and time-signal service operating on the same allocation. A number of possible measures to alleviate this situation are included in Report 732, including single-sideband operation with or without suppressed carrier, offset carrier and also offset sub-carrier for the modulation frequencies. The provisions of the WARC-79 have also introduced additional flexibility by allowing operation on frequencies of 4, 8 and 16 MHz in Region 3, in addition to the previous allocations at 2.5, 5, 10, 15, 20 and 25 MHz.

The usefulness of the HF service and also emissions in other bands providing a time and frequency reference has been examined from time to time by a number of administrations. The results of these user surveys are given in Report 731 and contain several features of interest; for example in the U.S.S.R. more than 70% of users of the HF stations prefer the offset emissions with the attendant reduction in interference. In other areas the existence of alternative services in band 5 has weakened the case for continuation of the HF services and at least one administration has indicated that it will cease operation in bands 6 and 7 towards the end of the present decade. Report 732 enjoins all administrations to review periodically their needs for the services in these bands.

T/F distribution in additional frequency bands

The stations operating a T/F service in the additional frequency bands appear in Tables II and III of Report 267. They include dedicated stations, mainly in band 5 and also a large number of either navigational, communication or broadcast transmitters. Report 735 enumerates the advantages of this band for the provision of a stable and effective T/F distribution to ranges of between 1000 and 2000 km from the transmitter. In addition, Recommendation 375 supports the continued exploitation of stations in bands 4, 5, 6, 8 and 9 for either long-range frequency and time transfer using LF and VLF emissions or the dissemination of a T/F reference by line-of-sight operation taking advantage of existing frequency-modulated and television transmissions in bands 8 and 9.

Report 567 records the results which have been obtained so far in standard-frequency dissemination using stabilized broadcast station carriers. An equivalent service for time transfer over short ranges is provided by the methods listed in a new Report 897.

Time codes

One of the results of the user survey was the very favourable reaction to the existence of time codes radiated either by dedicated stations or added to the normal programme of FM or AM broadcast services. The ability to receive valid and accurate time information regularly updated and sometimes allied to day/week/day-of-year indication is proving extremely useful in a wide range of applications. An expanded version of Report 578 reflects the increasing interest in time codes and it now includes also information on a range of serial binary, serial decimal and parallel grouped binary codes. The interesting development of a phase-modulated code added to an amplitude-modulated transmitter (Allouis on 163.84 kHz) is described in Report 577. Too great a proliferation of possible code formats is clearly to be avoided and new Recommendation 583 suggests that any additional code transmissions should make use of one of the existing code structures.

Interim Working Parties

IWP 7/4

The discussions within this Working Party will have an important bearing on the future shape of a world-wide service of time and frequency distribution from space. Satellite services will hopefully circumvent many of the difficulties and limitations which have attended the ground-based services of various kinds. In the present state of development in the space segment there are very many competing systems providing a basis for time and frequency dissemination and coordination and one of the first tasks of IWP 7/4 has been to prepare a much enlarged version of Report 518 in which the relative merits of both existing and projected satellite systems are examined and compared. This Report is now the equivalent of Report 363 for ground-based systems and the opportunity has been taken to incorporate within it some of the relevant information contained previously in Reports 733 and 363: as a consequence Report 733 is now deleted.

The consideration of future satellite systems by the Working Party has given rise to two new texts. A new Recommendation 582 is designed to stimulate increased experiment and evaluation of time and frequency dissemination and coordination by satellite, preferably with on-site antennas to eliminate troublesome ground transfers. A new Opinion 72 addressed primarily to the world meteorological community advocates the extension of the successful programme of time dissemination by the US GOES satellites to other satellites, the European Meteosat and the Japanese CMS, which form part of the same world-wide meteorological satellite system.

As the work of IWP 7/4 is far from complete it will continue to function in the next study period. It will also continue to provide the input to IWP 4/1 on the consideration of the goestationary orbit, having contributed already Chapter 15 in the provisional Report of the latter Working Party.

IWP 7/5

This Working Party will also extend its operation to the next period with somewhat clarified terms of reference given in an amended Decision 29. The genesis of this IWP lies in the request from CCITT Study Group XVIII for advice and information from Study Group 7 on the performance and reliability of frequency standards and reference clocks. A very full analysis together with comprehensive results on the frequency stability of standard-frequency generators is contained in Report 364. The Study Group documentation also includes in Report 737 a study of the failure statistics of caesium standards. This approach has now been extended by the Working Party to include other atomic standards and also quartz crystal generators and the preliminary results of a comprehensive world-wide survey are now assembled in a new Report 898. Confidence in the conclusions which are drawn will increase as more data become available.

Documentation

Considerable progress has been made in revising and re-structuring the Reports of the Study Group. In some cases, e.g. Report 518 (T/F dissemination by satellite) and Report 271 (use of LF and VLF signals) separate Reports have been combined to produce a comprehensive and authoritative text giving a broad overview of the subject. These texts and others such as Report 363 and Report 364 constitute self-contained essays on the subject matter and could possibly have a viable existence outside the Study Group documentation as a source of up-to-date material to supplement existing text books. The possibility was discussed at the Final Meeting that Study Group 7 might engage in the production of a suitable manual in its specialized field, with the needs of the developing countries very much in mind. However, the consensus of opinion was not in favour of such an exercise at present, in view of the availability of a range of very well-conceived literature produced by the National Bureau of Standards and which appeared to fill all immediate needs.

Terms of reference of Study Group 7

The possibility of changes in the terms of reference of the Study Group were also discussed at the Final Meeting and any such changes very positively rejected. It is already apparent that the activities in time and frequency are divided between a number of stations, some of which are indeed part of a "standard-frequency and time-signal service". However many others participate in that service only by virtue of the control of some of their functions by means of a precise frequency or time standard which enables them to fulfil an additional useful role in the dissemination of a T/F reference. The terms under which the Study Group operates should recognize this dual aspect of its operation and avoid any limitation to its coordinating a variety of "services" which contribute to the totality of time and frequency dissemination.

RECOMMENDATIONS AND REPORTS

REPORT 730

GLOSSARY

(1978)

1. Introduction

The list of terms below is a glossary for the use of Study Group 7 and users of standard-frequency and time-signal services. Precise time measurements may often be affected by relativity effects. The terms and definitions below do not in all cases imply incorporation of, or indicate the need for, the consideration of these effects. Two types of terms are presented; those typically used within the standard-frequency and time-signal services and those of more general use, but specifically relevant to this field. For the latter, an attempt has been made to provide substantial agreement with the definitions contained in the International Electrotechnical Vocabulary (IEV). The list has been submitted to the Joint CCIR/CCITT Study Group on Vocabulary (CMV) for their consideration. The equivalence of the terms are given in French and Spanish (terms printed in italics).

2. Definitions

The numbering of definitions follows the order given by Interim Working Party 7/2; missing terms will be defined at a later stage.

3.25 **Time**, *Temps, Tiempo* (explanation)

Since time is a general concept, the definition of this term cannot be unambiguously expressed.

Note. – In the different languages of the world it is used with several different meanings.

3. Index (in alphabetical order)

Accuracy	0.1	Normalized offset	0.12
Atomic time scale	3.2	Offset	0.11
Calibration	0.9	Phase	2.1
Carrier frequency	1.2	Phase shift	2.7
Clock	3.23C	Precision	0.2
Clock time difference	4.1	Primary frequency standard	1.15
Coherence of frequency	2.4	Primary time standard	3.23A
Coherence of phase	2.3	Proper time	3.7
Coordinate clock	4.2	Reproducibility	0.7
Coordinate time	3.6	Resettability	0.8
Coordinated time scale	3.5	Secondary frequency standard	1.16
Coordinated Universal Time (UTC)	3.4	Secondary time standard	3.23B
Date	3.12	Standard frequency	1.4
DUT1	3.21	Standard frequency and/or time-signal station	1.6
Error	0.4	Standard-frequency emission	1.5
Frequency	1.1	Standard Frequency-Satellite Service	1.6A
Frequency departure	1.7	Standard time-signal emission	1.5A
Frequency difference	1.12	Synchronism	4.15
Frequency drift	1.10	Time (explanation)	3.25
Frequency instability	0.5	Time code	4.8
Frequency shift	1.9	Time comparison	3.16
Frequency standard	1.14	Time interval	4.9
Instant	4.3	Time marker	3.15
International Atomic Time (TAI)	3.3	Time scale difference	3.14
Julian date	4.10	Time scales in synchronism	3.17
Julian day number	4.11	Time scale reading	3.13
Leap second	4.4	Time scale unit	3.18
Modified Julian Date (MJD)	4.13	Time Signal-Satellite Service	1.6B
Nominal value	0.10	Time standard	3.23
Normalized frequency	1.3	Time step	3.20
Normalized frequency departure	1.8	Uncertainty	0.3
Normalized frequency difference	1.13		
Normalized frequency drift	1.11		

0.1 **Accuracy**, *Exactitude, Exactitud*

Generally equivalent to systematic uncertainty of a measured value. (See also Uncertainty (0.3)).

0.2 **Precision**, *Précision, Precisión*

Random uncertainty of a measured value, expressed by the standard deviation or by a multiple of the standard deviation. (See also Uncertainty (0.3)).

0.3 **Uncertainty**, *Incertitude, Incertidumbre*

The uncertainty of a measured value expresses the magnitude of a possible deviation of this value from the true value.

Frequently it is possible to distinguish two components, the systematic uncertainty and the random uncertainty.

The random uncertainty is expressed by the standard deviation or by a multiple of the standard deviation. The systematic uncertainty is generally estimated on the basis of the parameter characteristics.

The term "accuracy" is generally equivalent to "systematic uncertainty", whereas the term "precision" is equivalent to "random uncertainty". Similarly, the "total" accuracy of a measurement is equivalent to an "overall" uncertainty, comprising both parts, the systematic and the random.

0.4 **Error** *, *Erreur, Error*

An unintentional difference: measured value minus true value.

0.5 **Frequency instability**, *Instabilité de fréquence, Inestabilidad de frecuencia*

It is expressed by the frequency change within a given time interval τ. Generally one distinguishes between frequency drift effects (see 1.10) and stochastic frequency fluctuations. Special variances have been developed for the characterization of these fluctuations.

0.7 **Reproducibility**, *Reproductibilité, Reproducibilidad*

(a) With respect to a set of independent devices of the same design, is the standard deviation of the values produced by these devices.

(b) With respect to a single device put into operation repeatedly, is the standard deviation of the values produced by this device.

0.8 **Resettability** ([1]), *Défaut de fidélité, Reposicionabilidad*

It is the unavoidable deviation between values produced by a device, when specified parameters are independently adjusted under stated condition of use.

Note. – It is given by the estimate of the confidence limits (i.e. uncertainty of the observed values).

([1]) This term replaces the previous term "repeatability", considered as not pertinent to frequency generators, but to measuring procedures.

0.9 **Calibration** *, *Etalonnage, Calibración*

The process of identifying and measuring errors in instruments and/or procedures.

Note. – In many cases, e.g. in a frequency generator, the calibration is related to the stability of the device and therefore its result is a function of time.

0.10 **Nominal value** *, *Valeur nominale, Valor nominal*

A specified or intended value independent of any uncertainty in its realization.

Note. – In a device, that realizes a physical quantity, it is the value of such a quantity specified by the manufacturer. Since it is an ideal value, it is free from tolerance.

0.11 **Offset** *, *Décalage, Separación*

An intentional difference between the realized value and the nominal value. (See also "Normalized offset".)

0.12 **Normalized offset**, *Décalage normé, Separación normalizada*

The offset divided by the nominal value.

Note. – Often also called relative offset. The term "fractional offset" is to be avoided.

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* These definitions differ from those in the IEV, but Study Group 7 is of the opinion that they are more appropriate for the standard-frequency and time-signal service.

1.1 **Frequency** *, *Fréquence, Frecuencia*

If T is the period of a repetitive phenomenon, then the frequency is $f = 1/T$. In SI units the period is expressed in seconds, and the frequency is expressed in hertz.

1.2 **Carrier frequency**, *Fréquence porteuse, Frecuencia portadora*

The frequency of the carrier.

Note. – Attention is directed to the fact that "carrier" is not satisfactorily defined in the IEV.

1.3 **Normalized frequency**, *Fréquence normée, Frecuencia normalizada*

The ratio between the actual frequency and its nominal value.

1.4 **Standard frequency**, *Fréquence étalon, Frecuencia patrón*

A frequency with a known relationship to a frequency standard.

Note. – The term standard frequency is often used for the signal whose frequency is a standard frequency.

1.5 **Standard-frequency emission**, *Emission de fréquences étalon, Emisión de frecuencias patrón*

An emission which disseminates one or more standard frequencies at regular intervals with a specified average daily frequency accuracy.

Note. – In Recommendation 460, the CCIR recommends a normalized departure of less than 1×10^{-10}.

1.5A **Standard-time-signal emission**, *Emission de signaux horaires, Emisión de señales horarias*

An emission which disseminates a sequence of time signals at regular intervals with a specified accuracy.

Note. – In Recommendation 460, the CCIR recommends standard time-signals to be emitted within 1 ms with reference to UTC and to contain DUT1 information in a specified code.

1.6 **Standard frequency and/or time-signal station**, *Station de fréquence étalon et/ou de signaux horaires, Estación de frecuencias patrón y/o de señales horarias*

A station whose primary purpose is to provide a standard-frequency and/or time-signal emission.

1.6A **Standard Frequency-Satellite Service**, *Service des fréquences étalon par satellite, Servicio de frecuencias patrón por satélite*

A radiocommunication service using space stations on earth satellites for the same purpose as those of the standard frequency service.

1.6B **Time Signal-Satellite Service**, *Service des signaux horaires par satellite, Servicio de señales horarias por satélite*

A radiocommunication service using space stations on earth satellites for the same purpose as those of the time signal service.

1.7 **Frequency departure**, *Ecart de fréquences, Desajuste de frecuencia*

An unintentional deviation from the nominal frequency value.

Note. – The term "frequency deviation" is to be avoided, because it is used in connection with frequency modulation.

1.8 **Normalized frequency departure**, *Ecart de fréquence normé, Desajuste de frecuencia normalizado*

The frequency departure divided by the nominal frequency value.

Note. – Often also called relative frequency departure. The term "fractional frequency departure" is to be avoided.

1.9 **Frequency shift**, *Déplacement de fréquence, Desplazamiento de frecuencia*

An intentional frequency change used for modulation purposes or unintentional due to physical laws.

Note. – Since the term "frequency shift" in the framework of other CCIR Study Groups is applied only for intentional frequency changes in connection with modulation purposes, it is recommended to avoid the use of "frequency shift" in the sense of unintentional frequency changes.

1.10 **Frequency drift** *, *Dérive de fréquence, Deriva de frecuencia*

An undesired progressive change in frequency with time.

1.11 **Normalized frequency drift**, *Dérive de fréquence normée, Deriva normalizada de frecuencia*

The frequency drift divided by the nominal frequency value.

Note. – Often also called relative frequency drift. The term "fractional frequency drift" is to be avoided.

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* These definitions differ from those in the IEV, but Study Group 7 is of the opinion that they are more appropriate for the standard-frequency and time-signal service.

1.12 **Frequency difference**, *Différence de fréquence*, *Diferencia de frecuencia*

The algebraic difference between two frequencies. These two frequencies can be of identical or different nominal values.

1.13 **Normalized frequency difference**, *Différence de fréquence normée*, *Diferencia de frecuencia normalizada*

The algebraic difference between two normalized frequencies. The two nominal values can be identical or different.

Note. – Often also called relative frequency difference. The term "fractional frequency difference" is to be avoided.

1.14 **Frequency standard**, *Etalon de fréquence*, *Patrón de frecuencia*

A generator, the output of which is used as a precise frequency reference.

1.15 **Primary frequency standard**, *Etalon primaire de fréquence*, *Patrón primario de frecuencia*

A frequency standard whose frequency corresponds to the adopted definition of the second, with its specified accuracy achieved without calibration of the device.

Note. – The internationally recognized metrological authority is the CGPM, and at present the adopted reference is a specific transition of the caesium atom 133.

1.16 **Secondary frequency standard**, *Etalon secondaire de fréquence*, *Patrón secundario de frecuencia*

A frequency standard which is calibrated with respect to a primary frequency standard. The term "secondary" thus describes the position of the standard in a hierarchy, it does not necessarily refer to the quality of its performance.

2.1 **Phase**, *Phase*, *Fase*

Generally in a periodic phenomenon, analytically described by a function of time (or space), the phase is any possible and distinguishable state of the phenomenon itself.

It can be identified through the time of its occurrence, elapsed from a specified reference, to be called correctly "phase time" *. Particularly, if the phenomenon is sinusoidal, the phase can be identified either by the angle or by the time, both measured from an assigned reference, depending on the dimensions assigned to the reference period (namely 2π or T).

In the standard-frequency and time-signal service, phase-time differences are mainly considered, i.e. time differences between two identified phases of the same phenomenon or of two different phenomena.

2.3 **Coherence of phase**, *Cohérence de phase*, *Coherencia de fase*

The condition of two frequencies M and N to resume the same phase difference after M cycles of the first and N cycles of the second, M/N being a rational number, obtained through multiplication and/or division from the same fundamental.

2.4 **Coherence of frequency**, *Cohérence de fréquence*, *Coherencia de frecuencia*

Same as coherence of phase.

2.7 **Phase shift**, *Déphasage*, *Desplazamiento de fase*

An intentional or unintentional change in phase.

3.2 **Atomic time scale**, *Echelle de temps atomique*, *Escala de tiempo atómico*

A time scale based on the periodicities of atomic or molecular phenomena.

3.3 **International Atomic Time (TAI)**, *Temps atomique international*, *Tiempo atómico internacional*

The time scale established by the Bureau International de l'Heure (BIH) on the basis of data from atomic clocks operating in several establishments conforming to the definition of the second, the unit of time of the International System of Units (SI).

3.4 **Coordinated Universal Time (UTC)**, *Temps universal coordonné*, *Tiempo universal coordinado*

The time scale, maintained by the BIH which forms the basis of a coordinated dissemination of standard frequencies and time signals. It corresponds exactly in rate with TAI, but differs from it by an integral number of seconds.

The UTC scale is adjusted by the insertion or deletion of seconds (positive or negative leap seconds) to ensure approximate agreement with UT1.

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* Frequently abbreviated to "phase".

3.5 **Coordinated time scale**, *Echelle de temps coordonné, Escala de tiempo coordinada*

A time scale synchronized within given limits to a reference time scale.

3.6 **Coordinate time**, *Temps-coordonnée, Tiempo-coordenada*

The concept of time in a specific coordinate frame, valid over a spatial region with varying gravitational potential.

Note. – If a time scale is realized according to the coordinate time concept, it is called a coordinate time scale.

Example:

TAI is a coordinate time scale. Its reference is the Earth's surface at sea level.

3.7 **Proper time**, *Temps propre, Tiempo propio*

The concept of time inherent to a specific location.

If a time scale is realized according to the proper time concept, it is called a proper time scale.

Examples:

(a) for proper time: the second is defined in the proper time of the caesium atom;

(b) for proper time scale: a time scale produced in a laboratory, not transmitted outside the laboratory.

3.12 **Date**, *Date, Fecha*

Synonymous with "time-scale reading", but usually referred to a calendar.

Note. – The date can be expressed in years, months, hours, minutes, seconds and fractions thereof.

3.13 **Time scale reading**, *Lecture d'une échelle de temps, Lectura de una escala de tiempo*

The value read on a time scale at a given instant. The reading of a time scale should be denoted by giving the time scale name followed, in parenthesis, by the clock name, transmitting station, astronomical observatory, or standards laboratory such as UTC (. . .).

3.14 **Time scale difference**, *Différence entre échelles de temps, Diferencia entre escalas de tiempo*

The difference between the readings of two time scales at the same instant.

Note. – In order to avoid confusion in sign, algebraic quantities should be given, applying the following convention. At a time T of a reference time scale, let a denote the reading of a time scale A, and b the reading of a time scale B; the time scale difference is expressed by

$A - B = a - b$ at the instant T.

The same convention applies to the case where A and B are clocks.

3.15 **Time marker**, *Repère de temps, Marca de tiempo*

A reference signal, often repeated periodically, enabling the assignment of numerical values to specify events on a time scale.

3.16 **Time comparison**, *Comparaison de temps, Comparación de tiempo*

The determination of time scale difference.

3.17 **Time scales in synchronism**, *Echelles de temps en synchronisme, Escala de tiempo en sincronismo*

Two time scales are in synchronism, when they assign the same date to an event.

Note. – If the time scales are produced in spatially separated locations, the propagation time of transmitted time signals and relativistic effects are to be taken into account.

3.18 **Time scale unit**, *Unité d'une échelle de temps, Unidad de escala de tiempo*

The basic time interval in a time scale.

3.20 **Time step**, *Saut de temps, Salto de tiempo*

An intentional discontinuity introduced in a time scale at a specified date. Time step is positive (+) if the time scale reading is increased, and negative (–) if the reading is decreased by making the step.

3.21 **DUT1**, *DUT1, DUT1*

The value of the predicted difference UT1 – UTC, as disseminated with the time signals. DUT1 may be regarded as a correction to be added to UTC to obtain a better approximation to UT1.

The values of DUT1 are given by the BIH in integral multiples of 0.1 s.

3.23 **Time standard**, *Etalon de temps, Patrón de tiempo*

(a) A device used for the realization of the time unit.

(b) A continuously operating device used for the realization of a time scale in accordance with the definition of the second.

3.23A **Primary time standard**, *Etalon primaire de temps, Patrón de tiempo primario*

A time standard which operates according to the adopted definition of the second without calibration of the device.

3.23B **Secondary time standard**, *Etalon secondaire de temps, Patrón de tiempo secundario*

A time standard which requires calibration.

3.23C **Clock**, *Horloge, Reloj*

A device for time measurement and time display, generally using periodic phenomena.

3.25 **Time**, *Temps, Tiempo*

See explanation at the begining of § 2, Definitions.

4.1 **Clock time difference**, *Différence entre temps d'horloge, Diferencia de tiempo de reloj*

See "Time scale difference".

4.2 **Coordinate clock**, *Horloge coordonnée, Reloj coordinado*

A clock in a set of clocks distributed over a spatial region, producing time scales which are synchronized to the time scale of a reference clock at a specified location (see def. 3.17).

4.3 **Instant**, *Instant, Instante*

A point in time, not necessarily with reference to a time scale.

4.4 **Leap second**, *Seconde intercalaire, Segundo intercalar*

A time step of one second used to adjust UTC to ensure approximate agreement with UT1.

An inserted second is called positive leap second and an omitted second is called negative leap second.

4.8 **Time code**, *Code horaire, Código horario*

An information format used to convey time information.

4.9 **Time interval**, *Intervalle de temps, Intervalo de tiempo*

The duration between two instants read on the same time scale.

4.10 **Julian date**, *Date julienne, Fecha juliana*

The Julian Day Number followed by the fraction of the day elapsed since the preceding noon (12 hours UT).

Example:

The date 1900 January 0.5 d UT corresponds to JD = 2 415 020.0.

4.11 **Julian day number**, *Numéro de jour julian, Número de día juliano*

A number of a specific day from a continuous day count having an initial origin of 12 hours UT on 1 January 4713 BC, Julian Calendar (start of Julian Day zero).

Example:

The day extending from 1900 January 0.5 d UT to 1900 January 1.5 d UT has the number 2 415 020.

4.13 **Modified Julian Date (MJD)**, *Date julienne modifiée, Fecha modificada del calendario Juliano*

Julian Date less 2 400 000.5 days.

4.15 **Synchronism**, *Synchronisme, Sincronismo*

(See Time scales in synchronism).

RECOMMENDATION 374-3

STANDARD-FREQUENCY AND TIME-SIGNAL EMISSIONS

(Question 1/7)

(1951-1953-1956-1959-1963-1966-1970-1974)

The CCIR,

CONSIDERING

(a) that the World Administrative Radio Conference, Geneva, 1979, allocated the frequencies 20 kHz ± 0.05 kHz, 2.5 MHz ± 5 kHz (2.5 MHz ± 2 kHz in Region 1), 5 MHz ± 5 kHz, 10 MHz ± 5 kHz, 15 MHz ± 10 kHz, 20 MHz ± 10 kHz and 25 MHz ± 10 kHz, to the standard-frequency and time-signal service;

(b) that the same Conference allocated the following frequencies for use by the standard-frequency and time-signal satellite service:

400.1 MHz ± 25 kHz (Earth-to-space),
4202 MHz ± 2 MHz (Space-to-Earth),
6427 MHz ± 2 MHz (Earth-to-space),
13.4 to 14.0 GHz (Earth-to-space),
20.2 to 21.2 GHz (Space-to-Earth),
25.25 to 27.0 GHz (Earth-to-space),
30.0 to 31.3 GHz (Space-to-Earth);

(c) that additional standard frequencies and time signals are emitted in other frequency bands;

(d) the provisions of Article 33 of the Radio Regulations;

(e) the continuing need for close cooperation between Study Group 7 and the Inter-Governmental Maritime Consultative Organization (IMCO), the International Civil Aviation Organization (ICAO), the General Conference of Weights and Measures (CGPM), the Bureau international de l'heure (BIH) and the concerned Unions of the International Council of Scientific Unions (ICSU),

UNANIMOUSLY RECOMMENDS

1. that CCIR Study Group 7 continue its study of world-wide standard-frequency and time-signal services and explore the application of new techniques for this purpose;

2. that existing standard-frequency and time-signal services be operated in conformity with the detailed Recommendations of the CCIR;

3. that increased efforts be made to reduce the mutual interference between emissions in the allocated bands of item *(a)* above;

4. that all administrations consider alternative methods of disseminating standard frequencies and time signals before adding new emissions in bands 6 and 7.

RECOMMENDATION 376-1

AVOIDANCE OF EXTERNAL INTERFERENCE WITH EMISSIONS OF THE STANDARD-FREQUENCY SERVICE IN THE BANDS ALLOCATED TO THAT SERVICE

(Question 1/7)

(1959-1963-1966)

The CCIR,

CONSIDERING

(a) the importance and increasing use of standard-frequency and time-signal emissions in the allocated bands;

(b) that interference reduces the usefulness of the standard-frequency and time-signal service to a serious degree;

(c) that, despite the efforts made by administrations and the IFRB to clear the standard-frequency bands, some registered users, and many unnotified emissions, remain in these bands, which continue to cause interference with the standard-frequency services,

UNANIMOUSLY RECOMMENDS

1. that to avoid external interference, administrations and the IFRB should continue their efforts to clear the standard-frequency bands;

2. that, in the territory under its jurisdiction, each administration should make every effort to prevent all users of the radio-frequency spectrum from operating other stations in the standard-frequency bands, capable of causing harmful interference to the standard-frequency service;

3. that national monitoring stations should carry out a regular search for external interfering stations in the standard-frequency bands and should make every effort to identify each interfering station, if necessary with international cooperation;

4. that, in each case of external interference, the users of standard-frequency emissions should request the monitoring service of their own country to identify the interfering station;

5. that, in cases of external interference with the standard-frequency service, administrations should apply the provisions of Articles 18, 19, 21 and 22 of the Radio Regulations, and, if desired, should send a copy of relevant correspondence to the IFRB;

6. that, when interference is observed in the standard-frequency bands, even if the source cannot definitely be identified, representatives of administrations, participating in the work of Study Group 7, should exchange information from users of standard-frequency and time-signal transmissions and from the monitoring service. This may later permit identification of the interfering station.

RECOMMENDATION 457-1

USE OF THE MODIFIED JULIAN DATE BY THE STANDARD-FREQUENCY AND TIME-SIGNAL SERVICES

(Question 1/7)

(1970–1974)

The CCIR,

CONSIDERING

(a) that for dating purposes a decimal day count is desirable in connection with the use of radio time signals and radio time codes;

(b) that a decimal day count with reference to Universal Time, the Julian Date (JD), has long been established for dating in astronomy, chronology and related sciences;

(c) that a decimal day count is necessary, by which the start of a day is defined at 0000 hours and not at 1200 hours as in the case of the Julian Date;

(d) that a decimal day count is necessary, in particular in association with the time scales UTC and TAI;

(e) that it is necessary to avoid a proliferation of different dating systems;

(f) that a simple change from the Julian Date mentioned above to a modern decimal day count would be advantageous;

(g) that the existing and established Julian Date, based on the start of the day being Greenwich Mean Noon, should be continued without break;

(h) that a Modified Julian Date (MJD), which meets the requirements stated above, is already in use,

UNANIMOUSLY RECOMMENDS

1. that for modern timekeeping and dating requirements, wherever necessary, a decimal day count should be used; the calendar day should be counted from 0000 hours TAI, UTC or UT and be specified by a number with five significant figures;

2. that this "Modified Julian Date" (MJD) equals the Julian Date less 2 400 000.5 and therefore has its origin, in the case of UT, at 0000 hours UT, 17 November 1858.

RECOMMENDATION 458-1

INTERNATIONAL COMPARISONS OF ATOMIC TIME SCALES

(Question 1/7)

(1970–1978)

The CCIR,

CONSIDERING

(a) the need for comparisons between independent local atomic time scales of various laboratories and observatories;

(b) the need for clarity, precision and the minimum delay in the communication of data so as to facilitate the work of the Bureau international de l'heure (BIH) in forming International Atomic Time,

UNANIMOUSLY RECOMMENDS

1. that when a laboratory or observatory "i" keeps both independent local atomic time and an approximation to coordinated universal time, designated herein as TA(i) and UTC(i), the laboratory or observatory should publish the numerical expression of the difference TA(i) – UTC(i) for each period of validity;

2. that time markers having a negligible time departure from UTC(i) should be immediately accessible;

3. that the published time comparisons should relate to UTC(i);

4. that the published phase comparisons should relate to UTC(i);

5. that the published times of emission of radio time signals conforming to the UTC system should relate to UTC(i);

5.1 in the case of a radio time-signal emission generated directly by the laboratory or observatory "i", the measured delay between the time signals and UTC(i) should be published;

5.2 in the case of a radio time-signal emission controlled by a clock at the transmitting station and measured at the laboratory or observatory "i", it should be stated explicitly whether the published times in relation to UTC(i) refer to reception or emission and what corrections for propagation and receiver delays should be or have been applied;

6. that any laboratories or observatories not conforming to the UTC system, but desiring to take part in international comparisons and in the formation of International Atomic Time, should publish detailed data compatible, as far as possible, with the principles of § 1 to 5.

RECOMMENDATION 460-3

STANDARD-FREQUENCY AND TIME-SIGNAL EMISSIONS

(Question 1/7)

(1970–1974–1978–1982)

The CCIR,

CONSIDERING

(a) that the World Administrative Radio Conference, Geneva, 1979, allocated the frequencies 20 kHz ± 0.05 kHz, 2.5 MHz ± 5 kHz (2.5 MHz ± 2 kHz in Region 1), 5 MHz ± 5 kHz, 10 MHz ± 5 kHz, 15 MHz ± 10 kHz, 20 MHz ± 10 kHz and 25 MHz ± 10 kHz to the standard-frequency and time-signal service;

(b) that additional standard frequencies and time signals are emitted in other frequency bands;

(c) the provisions of Article 33 of the Radio Regulations;

(d) the continuing need for close cooperation between Study Group 7 and the Inter-Governmental Maritime Consultative Organization (IMCO), the International Civil Aviation Organization (ICAO), the General Conference of Weights and Measures (CGPM), the Bureau international de l'heure (BIH) and the concerned Unions of the International Council of Scientific Unions (ICSU);

(e) the desirability of maintaining world-wide coordination of standard-frequency and time-signal emissions;

(f) the need to disseminate standard frequencies and time signals in conformity with the second as defined by the 13th General Conference of Weights and Measures (1967);

(g) the continuing need to make Universal Time (UT) inmmediately available to an accuracy of one-tenth of a second,

UNANIMOUSLY RECOMMENDS

1. that all standard-frequency and time-signal emissions conform as closely as possible to Coordinated Universal Time (UTC) (see Annex I); that the time signals should not deviate from UTC by more than one millisecond; that the standard frequencies should not deviate by more than 1 part in 10^{10}, and that the time signals emitted from each transmitting station should bear a known relation to the phase of the carrier;

2. that standard-frequency and time-signal emissions, and other time-signal emissions intended for scientific applications (with the possible exception of those dedicated to special systems) should contain information on the difference between UT1 and UTC (see Annexes I and II);

3. that this document be transmitted by the Director, CCIR, to all Administrations Members of the ITU, to IMCO, ICAO, the CGPM, the BIH, the International Union of Geodesy and Geophysics (IUGG), the International Union of Radio Science (URSI) and the International Astronomical Union (IAU);

4. that the standard-frequency and time-signal emissions should conform to RECOMMENDS 1 and 2 above as from 1 January 1975.

ANNEX I

TIME SCALES

A. Universal Time (UT)

In applications in which an imprecision of a few hundredths of a second cannot be tolerated, it is necessary to specify the form of UT which should be used:

UT0 is the mean solar time of the prime meridian obtained from direct astronomical observation;

UT1 is UT0 corrected for the effects of small movements of the Earth relative to the axis of rotation (polar variation);

UT2 is UT1 corrected for the effects of a small seasonal fluctuation in the rate of rotation of the Earth;

UT1 is used in this document, since it corresponds directly with the angular position of the Earth around its axis of diurnal rotation. (GMT may be regarded as the general equivalent of UT.)

Concise definitions of the above terms and the concepts involved are available in the glossary of the annual publication, *The Astronomical Almanac* (US Government Printing Office, Washington DC and H.M. Stationery Office, London).

B. International Atomic Time (TAI)

The international reference scale of atomic time (TAI), based on the second (SI), as realized at sea level, is formed by the Bureau international de l'heure (BIH) on the basis of clock data supplied by cooperating establishments. It is in the form of a continuous scale, e.g. in days, hours, minutes and seconds from the origin 1 January 1958 (adopted by the CGPM 1971).

C. Coordinated Universal Time (UTC)

UTC is the time-scale maintained by the BIH which forms the basis of a coordinated dissemination of standard frequencies and time signals. It corresponds exactly in rate with TAI but differs from it by an integral number of seconds.

The UTC scale is adjusted by the insertion or deletion of seconds (positive or negative leap-seconds) to ensure approximate agreement with UT1.

D. DUT1

The value of the predicted difference UT1 − UTC, as disseminated with the time signals is denoted DUT1; thus DUT1 ≈ UT1 − UTC. DUT1 may be regarded as a correction to be added to UTC to obtain a better approximation to UT1.

The values of DUT1 are given by the BIH in integral multiples of 0.1 s.

The following operational rules apply:

1. Tolerances

1.1 The magnitude of DUT1 should not exceed 0.8 s.

1.2 The departure of UTC from UT1 should not exceed ± 0.9 s. *

1.3 The deviation of (UTC plus DUT1) should not exceed ± 0.1 s.

2. Leap-seconds

2.1 A positive or negative leap-second should be the last second of a UTC month, but first preference should be given to the end of December and June, and second preference to the end of March and September.

2.2 A positive leap-second begins at 23h 59m 60s and ends at 0h 0m 0s of the first day of the following month. In the case of a negative leap-second, 23h 59m 58s will be followed one second later by 0h 0m 0s of the first day of the following month (see Annex III).

2.3 The BIH should decide upon and announce the introduction of a leap-second, such an announcement to be made at least eight weeks in advance.

3. Value of DUT1

3.1 The BIH is requested to decide upon the value of DUT1 and its date of introduction and to circulate this information one month in advance. **

3.2 Administrations and organizations should use the BIH value of DUT1 for standard-frequency and time-signal emissions, and are requested to circulate the information as widely as possible in periodicals, bulletins, etc.

3.3 Where DUT1 is disseminated by code, the code should be in accordance with the following principles (except § 3.5 below):

- the magnitude of DUT1 is specified by the number of emphasized second markers and the sign of DUT1 is specified by the position of the emphasized second markers with respect to the minute marker. The absence of emphasized markers indicates DUT1 = 0;
- the coded information should be emitted after each identified minute if this is compatible with the format of the emission. Alternatively the coded information should be emitted, as an absolute minimum, after each of the first five identified minutes in each hour.

Full details of the code are given in Annex II.

3.4 Alternatively, DUT1 may be given by voice or in Morse code.

3.5 DUT1 information primarily designed for, and used with, automatic decoding equipment may follow a different code but should be emitted after each identified minute if this is compatible with the format of the emission. Alternatively, the coded information should be emitted, as an absolute minimum, after each of the first five identified minutes in each hour.

3.6 Other information which may be emitted in that part of the time-signal emission designated in § 3.3 and 3.5 for coded information on DUT1 should be of a sufficiently different format that it will not be confused with DUT1.

3.7 In addition, UT1 – UTC may be given to the same or higher precision by other means, for example, in Morse code or voice, by messages associated with maritime bulletins, weather forecasts, etc.; announcements of forthcoming leap-seconds may also be made by these methods.

3.8 The BIH is requested to continue to publish, in arrears, definitive values of the differences UT1 – UTC, UT2 – UTC.

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* The difference between the maximum value of DUT1 and the maximum departure of UTC from UT1 represents the allowable deviation of (UTC + DUT1) from UT1 and is a safeguard for the BIH against unpredictable changes in the rate of rotation of the Earth.

** In exceptional cases of sudden change in the rate of rotation of the Earth, the BIH may issue a correction not later than two weeks in advance of the date of its introduction.

ANNEX II

CODE FOR THE TRANSMISSION OF DUT1

A positive value of DUT1 will be indicated by emphasizing a number (n) of consecutive second markers following the minute marker from second marker one to second marker (n) inclusive; (n) being an integer from 1 to 8 inclusive.

$$DUT1 = (n \times 0.1)\ s$$

A negative value of DUT1 will be indicated by emphasizing a number (m) of consecutive second markers following the minute marker from second marker nine to second marker ($8 + m$) inclusive, (m) being an integer from 1 to 8 inclusive.

$$DUT1 = -(m \times 0.1)\ s$$

A zero value of DUT1 will be indicated by the absence of emphasized second markers.

The appropriate second markers may be emphasized, for example, by lengthening, doubling, splitting or tone modulation of the normal second markers.

Examples:

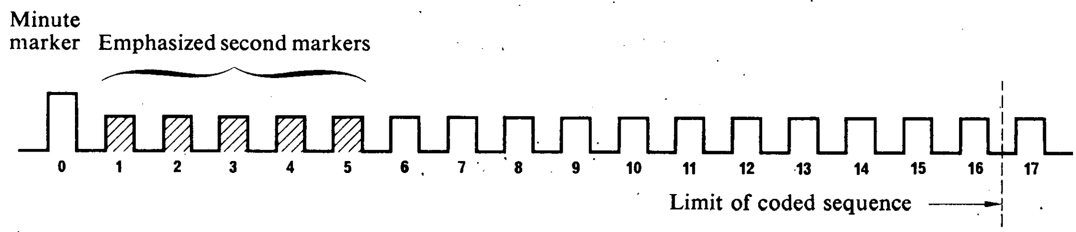

FIGURE 1

DUT1 = +0·5 s

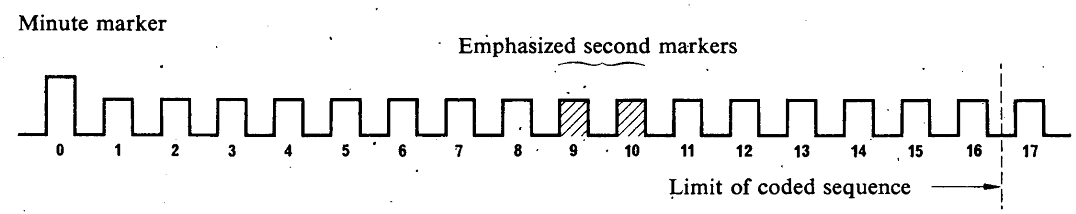

FIGURE 2

DUT1 = −0·2 s

ANNEX III

DATING OF EVENTS IN THE VICINITY OF A LEAP-SECOND

The dating of events in the vicinity of a leap-second shall be effected in the manner indicated in the following figures:

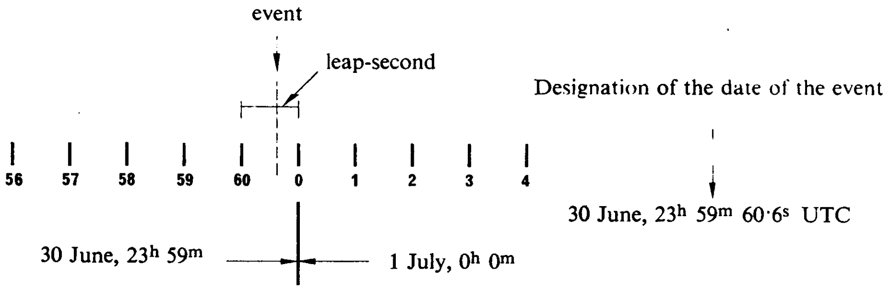

FIGURE 3 – *Positive leap-second*

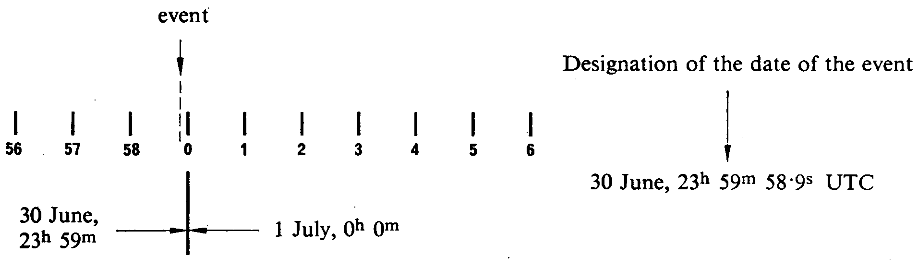

FIGURE 4 – *Negative leap-second*

RECOMMENDATION 535-1 *

USE OF THE TERM UTC

(Question 1/7)

(1978–1982)

The CCIR,

CONSIDERING

(a) that according to Recommendation 460 all standard-frequency and time-signal emissions should conform to the Coordinated Universal Time (UTC);

(b) that since 1972 UTC has been available as a world-wide time reference;

(c) that in 1975 the General Conference of Weights and Measures (CGPM) recommended the use of UTC as the basis of civil time;

(d) that other scientific organizations, particularly the International Astronomical Union (IAU) and the International Union of Radio Science (URSI) have recommended the general use of UTC;

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* The Director, CCIR, is requested to bring this Recommendation to the attention of the Joint Advisory Group of the Institute of Navigation (JAG/ION), the International Astronomical Union (IAU), the International Civil Aviation Organization (ICAO), the Inter-Governmental Maritime Consultative Organization (IMCO) and the World Meteorological Organization (WMO).

(e) that UTC enables the time of events to be determined with an uncertainty of 1 μs;

(f) that according to Recommendation 536 and in accordance with the recommendation of the General Conference of Weights and Measures the designation UTC is to be used in all languages,

(g) that the World Administrative Radio Conference (Geneva, 1979) has decided that UTC shall be used in international radiocommunication activities,

UNANIMOUSLY RECOMMENDS

that UTC should be used to designate the time in all other international telecommunication activities and in all official documents of the International Telecommunication Union.

RECOMMENDATION 485-1

USE OF TIME SCALES IN THE FIELD OF STANDARD-FREQUENCY AND TIME SERVICES

(Question 1/7)

(1974-1982)

The CCIR,

CONSIDERING

(a) that the International Atomic Time scale has been defined by the General Conference of Weights and Measures, 1971;

(b) that in accordance with Recommendation 460, the UTC time scale has been generally accepted since 1972;

(c) that the World Administrative Radio Conference, (Geneva, 1979) has decided that UTC shall be used in international radiocommunication activities;

(d) that UTC and TAI are closely related and differ only by a known integral number of seconds;

(e) that the time-service laboratories, in accordance with Recommendation 458, should relate datings to their own time scale UTC(i),

UNANIMOUSLY RECOMMENDS

that time data should be issued wherever possible either with reference to Coordinated Universal Time (UTC) or to International Atomic Time (TAI).

RECOMMENDATION 536

TIME-SCALE NOTATIONS

(Question 1/7)

(1978)

The CCIR,

CONSIDERING

(a) that language independent time-scale notations should be introduced;

(b) that the XIVth General Conference of Weights and Measures (CGPM) in October 1971 defined the International Atomic Time, using the designation TAI;

(c) that the XVth CGPM in May 1975 recommended the use of Coordinated Universal Time, using the designation UTC,

UNANIMOUSLY RECOMMENDS

1. that for all forms of atomic time, the following notations consistent with TAI be used in all languages:

TAI: International Atomic Time, as formed by the BIH,

TA: atomic time; general designation of a time variable which may be realized on the basis of an atomic or molecular transition,

TA(i): atomic time-scale, as realized by the institute "i";

2. that for all forms of Universal Time, the following notations consistent with UTC be used in all languages:

UT: Universal Time,

UTC: Coordinated Universal Time; this time-scale is maintained by the BIH, according to Recommendation 460,

UTC(i): time-scale realized by the institute "i" and kept in close agreement with UTC,

DUT1: predicted difference UT1 – UTC, as disseminated with time signals.

Note. – The Director, CCIR, is asked to transmit this Recommendation to the International Civil Aviation Organization (ICAO), the Inter-Governmental Maritime Consultative Organization (IMCO), the General Conference of Weights and Measures (CGPM) and also to the International Union of Radio Science (URSI), the International Astronomical Union (IAU), the International Union of Geodesy and Geophysics (IUGG), the International Union of Pure and Applied Physics (IUPAP), the Bureau international de l'heure (BIH), the International Organization for Standardization (ISO) and the International Association of Institutes of Navigation (IAIN).

ANNEX I

1. Where there may be danger of confusion, UTC (BIH) may be used instead of UTC.

2. Different forms of UT are listed in Annex I of Recommendation 460.

3. Except for TA, which refers to a principle and not to a specific time-scale, the notations may also be used for characterizing time instants and time-scale differences.

Examples:

(1) 1975 January 1, 0^h UTC

(2) TAI – UTC = 14s, 1975 July 1, 0^h UTC

(3) UTC(i) – UTC = 1 μs, 1976 February 24, 0^h UTC

4. TAI and UTC are evaluated in arrear and are only accessible by means of corrections (published by the BIH) to existing (realized) time-scales such as TA(i) or UTC(i) including extrapolation.

5. According to Recommendation 458, UTC(i) should be a realized time-scale.

REPORT 267-5

STANDARD FREQUENCIES AND TIME SIGNALS

Characteristics of standard-frequency and time-signal emissions in allocated bands and characteristics of stations emitting with regular schedules with stabilized frequencies, outside of allocated bands

(Question 1/7)

(1956-1959-1963-1966-1970-1974-1978-1982)

The characteristics of stations appearing in the following tables are valid as of 1 March, 1982. For information concerning changes which may have occurred, reference may be made to the Annual Report of the Bureau international de l'heure (BIH) or directly to the respective authority for each service as listed in Annex I.

TABLE I – *Characteristics of standard-frequency and time-signal emissions in the allocated bands, valid as of 1 March 1982*

Station			Antenna(s)		Number of simultaneous transmissions	Period of operation		Standard frequencies used		Duration of emission		Uncertainty of frequency and time intervals (parts in 10^{12})(16)	Method of DUT1 indication
Call sign	Approximate location	Latitude Longitude	Type	Carrier power (kW)		Days/week	Hours/day	Carrier (MHz)	Modulation (Hz)	Time signal (min)	Audio-modulation (min)		
ATA	New Delhi, India	28° 34′ N 77° 19′ E	Horizontal Folded dipole	8 (PEP)	3	7	11(13)	5, 10, 15	1, 1000	continuous	4/15	± 100	
BPM(14)	Pucheng, China	35° 00′ N 109° 31′ E	Omni-directional	10 - 20	2	7	24(15)	5, 10, 15	1, 1000	15/30 (UTC) 9/30 (UT1)	nil	± 10	Direct emission of UT1 time signal
FFH(1)	Paris, France	48° 33′ N 02° 34′ E	Vertical dipole	5	1	5	$8\frac{1}{2}$	2.5	1	continuous	nil	± 20	CCIR code by lengthening to 0.1 s
IAM(1)	Roma, Italy	41° 47′ N 12° 27′ E	Vertical $\lambda/4$	1	1	6	2	5	1	continuous	nil	± 10	CCIR code by double pulse
IBF(1)	Torino, Italy	45° 02′ N 07° 46′ E	Vertical $\lambda/4$	5	1	7	$2\frac{3}{4}$	5	1	continuous	nil	± 10	CCIR code by double pulse
JJY(1)	Sanwa, Sashima, Ibaraki, Japan	36° 11′ N 139° 51′ E	(3)	2	4	7	24(3)	2.5, 5, 10, 15	1(6) 1000(7)	continuous	30/60	± 10	CCIR code by lengthening
LOL(1)	Buenos Aires, Argentina	34° 37′ S 58° 21′ W	Horizontal 3-wire folded dipole	2	3	7	5	5, 10, 15	1, 440, 1000	continuous	3/5	± 20	CCIR code by lengthening
MSF(1)	Rugby, United Kingdom	52° 22′ N 01° 11′ W	Horizontal quadrant dipoles: (vertical monopole, 2.5 MHz)	5	3	7	24	2.5, 5, 10	1	5/10	nil	± 2	CCIR code by double pulse
OMA(1)	Praha, Czechoslovak S.R.	50° 07′ N 14° 35′ E	T	1	1	7	24	2.5	1, 1000(8)	15/30	4/15	± 1000	

TABLE I *(continued)*

Station			Antenna(s)		Number of simultaneous transmissions	Period of operation		Standard frequencies used		Duration of emission		Uncertainty of frequency and time intervals (parts in 10^{12})(16)	Method of DUT1 indication
Call sign	Approximate location	Latitude Longitude	Type	Carrier power (kW)		Days/week	Hours/day	Carrier (MHz)	Modulation (Hz)	Time signal (min)	Audio-modulation (min)		
RCH(1)	Tashkent, USSR	41° 19′ N 69° 15′ E	Horizontal dipole	1	1	7	21.5	2.5	1, 10	39/60	nil	± 100	CCIR code by double pulse, additional information dUT1(12)
RID(1)	Irkutsk, USSR	52° 46′ N 103° 39′ E	Horizontal dipole	1 1 1	3	7	24	5.004, 10.004 15.004	1, 10	41/60	nil	± 50	CCIR code by double pulse, additional information dUT1(12)
RIM(1)	Tashkent, USSR	41° 19′ N 69° 15′ E	Horizontal dipole	1	1	7	20 1/2	5, 10	1, 10	39/60	nil		CCIR code by double pulse, additional information dUT1(12)
RTA(1)	Novosibirsk, USSR	55° 04′ N 82° 58′ E	Horizontal dipole	5	1	7	20 1/2	10, 15	1, 10	41/60	nil	± 50	CCIR code by double pulse, additional information dUT1(12)
RWM(1)	Moskva, USSR	55° 19′ N 38° 41′ E	Horizontal dipole	5 5 8	3	7	24	4.996 9.996 14.996	1, 10	39/60	nil	± 50	CCIR code by double pulse, additional information dUT1(12)
WWV(1)	Fort Collins, Colorado, USA	40° 41′ N 105° 02′ W	Vertical λ/2 dipoles	2.5 - 10	5	7	24	2.5, 5, 10, 15, 20, (4)	1, 440, 500, 600	continuous (2)	continuous (10)	± 10	CCIR code by double pulse, additional information on UT1 corrections

TABLE I *(continued)*

Station			Antenna(s)		Number of simultaneous transmissions	Period of operation		Standard frequencies used		Duration of emission		Uncertainty of frequency and time intervals (parts in 10^{12})(16)	Method of DUT1 indication
Call sign	Approximate location	Latitude Longitude	Type	Carrier power (kW)		Days/week	Hours/day	Carrier (MHz)	Modulation (Hz)	Time signal (min)	Audio-modulation (min)		
WWVH(1)	Kekaha, Kauai, Hawaii, USA	21° 59′ N 159° 46′ W	Vertical $\lambda/2$ dipole arrays	2.5 - 10	4	7	24	2.5 5, 10, 15, (4)	1, 440, 500, 600	continuous (2)	continuous (10)	± 10	CCIR code by double pulse, additional information on UT1 corrections
ZLFS	Lower Hutt, New Zealand	41° 14′ S 174° 55′ E		0.3	1	1	3	2.5	nil	nil	nil	± 100	
ZUO(1)	Olifantsfontein, Republic of South Africa	24° 58′ S 28° 14′ E	Vertical monopole	4	1	7	24 (11)	2.5, 5	1	continuous	nil	± 10	CCIR code by lengthening

Notes to Table I

The daily transmission schedule and hourly modulation schedule is given, where appropriate, in the form of Figs. 1 and 2 supplemented by the following notes:

(1) These stations have indicated that they follow the UTC system as specified in Recommendation 460. Since 1 January 1972 the frequency offset has been eliminated and the time signals remain within about 0.8 s of UT1 by means of occasional 1 s steps as directed by the Bureau international de l'heure.

(2) In addition to other timing signals and time announcements, a modified IRIG-H time code is produced at a 1-pps rate and radiated continuously on a 100 Hz sub-carrier on all frequencies. A complete code frame is 1 minute. The 100 Hz sub-carrier is synchronous with the code pulses, so that 10 ms resolution is obtained. The code contains DUT1 values and UTC time-of-year information in minutes, hours and days of the year.

(3) Vertical $\lambda/4$ for 2.5 MHz, horizontal $\lambda/2$ dipole for 5 MHz, and vertical $\lambda/2$ dipoles for 10 and 15 MHz.

(4) As of Feb. 1, 1977 transmissions on 25 MHz from WWV and 20 MHz from WWVH were discontinued, but may be resumed at a later date.

(5) Interrupted from 35 to 39 minutes of each hour.

(6) Pulse consists of 8 cycles of 1600 Hz tone. First pulse of each minute proceded by 655 ms of 600 Hz tone.

(7) 1000 Hz tone modulation between the minutes of 0-5, 10-15, 20-25, 30-35, 40-45, 50-55 except 40 ms before and after each second's pulse.

(8) In the period from 1800-0600 hours UTC, audio-frequency modulation is replaced by time signals.

(9) Effective 1 July 1972, regularly scheduled transmissions from WWVL were discontinued. Since that date, this station has been broadcasting experimental programme on an intermittent basis only.

(10) Except for voice announcement periods and the 5-minute semi-silent period each hour.

(11) 2.5 MHz: from 1800-0400 hours UTC; 5 MHz: continuous.

(12) The additional information about the value of the difference UT1-UTC is transmitted by code dUT1. It provides more precisely the difference UT1-UTC down to multiples of 0.02s. The total value of the correction is DUT1 + dUT1. Possible values of dUT1 are transmitted by marking of p second pulses between the 21st and 24th seconds of the minute, so that dUT1 $= +\ 0.02\text{s} \times p$. Negative values of dUT1 are transmitted by marking of q second pulses between the 31st and 34th second of the minute, so that dUT1 $= -\ 0.02\text{s} \times q$.

(13) 11 hours per day, Monday to Saturday, 0330-1430 UTC, 4 hours per day on 2nd Saturday of the month and Sundays, 0430-0830 UTC.

(14) Call sign in Morse and language.

(15) 15 MHz: 0000-1400 UTC; 5 MHz: from 1400-2400 UTC; 10 MHz, continuous.

(16) This value applies at the transmitter; to realize the quoted uncertainty at the point of reception it could be necessary to observe the received phase time frequency over a sufficiently long period in order to eliminate noise and random effects.

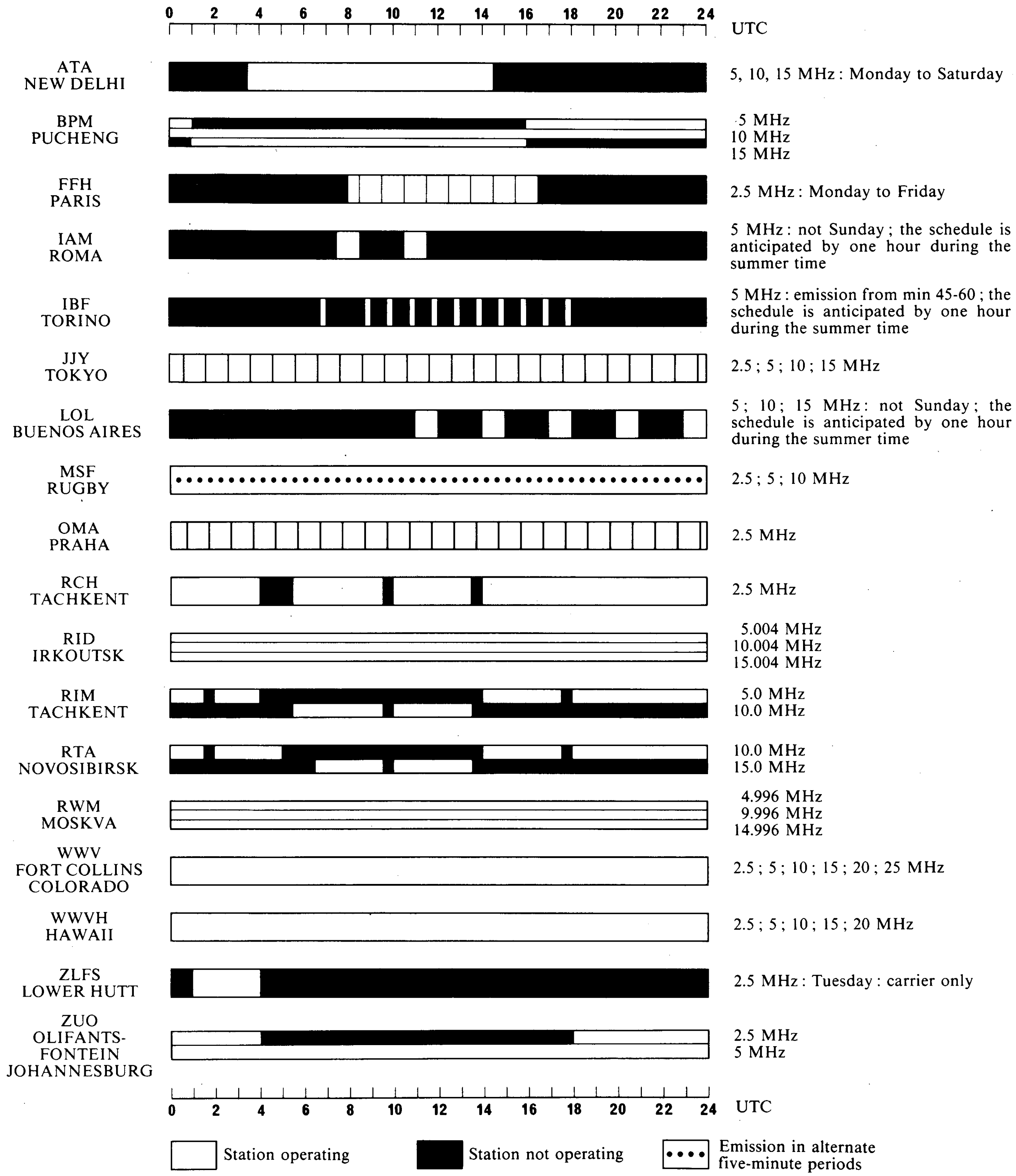
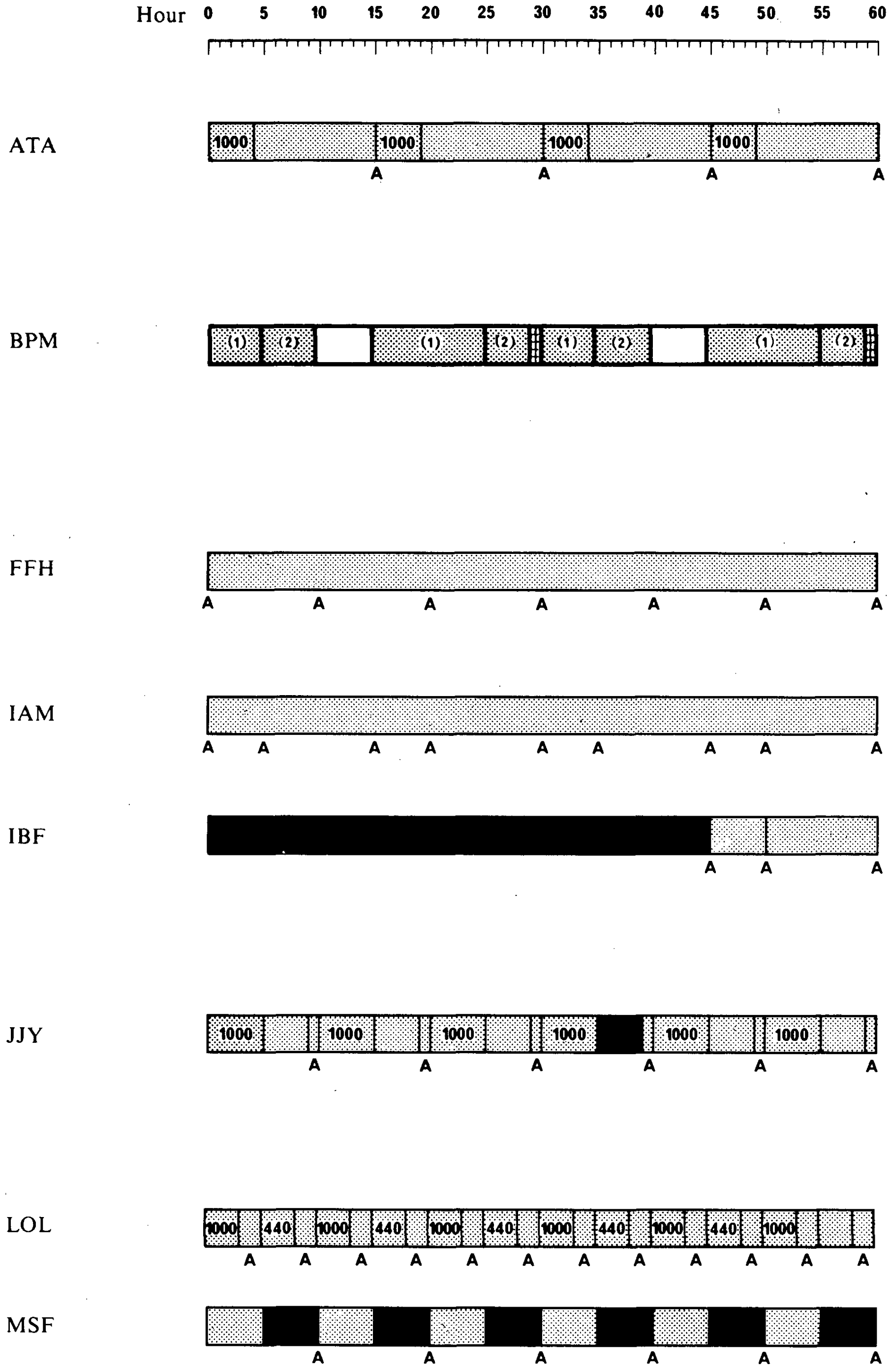


FIGURE 1 – *Daily emission schedule*



Form of second and minute signals: Morse and voice announcements (A).

ATA: Pulse of 5 cycles of 1000 Hz tone, lengthened to 100 ms at the beginning of each minute. Call sign and time (UTC) in Morse.

BPM:

(1) Pulse of 5 cycles of 1000 Hz tone (UTC time signal), the first pulse of every minute is a 300 ms pulse of 1000 Hz tone. In order to avoid mutual interference the second pulses of UTC of BPM precede UTC of BIH by 10 ms.

(2) 100 ms pulse of 1000 Hz tone UT1 time signal, the first pulse of every minute is a 300 ms pulse of 1000 Hz tone.

FFH: Pulse of 5 cycles of 1000 Hz tone: minute pulse lengthened to 500 ms DUT1 code by lengthened second pulses to 100 ms. Call sign in Morse between the 32nd second and 42nd second of the minutes 0, 10, 20, 30, 40 and 50.

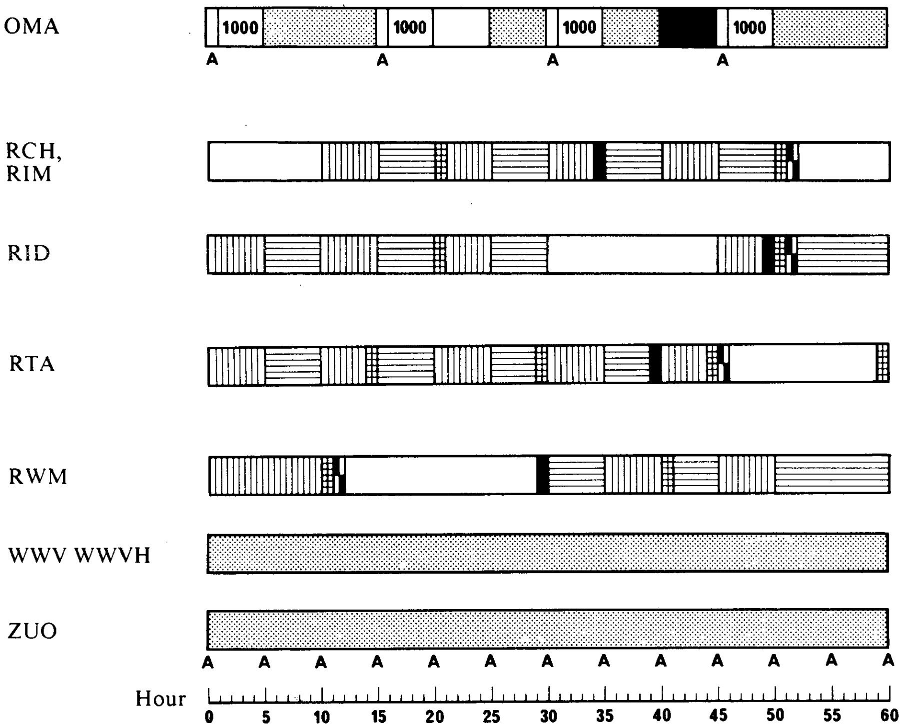
IAM: Pulse of 5 cycles of 1000 Hz tone: minute pulse of 20 cycles of 1000 Hz tone. Call sign and time (UTC) in Morse and voice identification.

IBF: Pulse of 5 cycles of 1000 Hz tone repeated 7 times at minute. Call sign and time (UTC) in Morse, voice identification at the beginning and end of emission.

JJY: Pulse of 8 cycles of 1600 Hz tone: minute pulse is preceded by a 600 Hz tone of 655 ms duration. Call sign and time (JST) in Morse and voice. Radio propagation warnings in letter code: N (normal), U (unstable) or W (disturbed). DUT1 is indicated, by the number and position of the lengthened second's pulses of 45 ms duration, instead of the 5 ms duration of the normal second's pulse.

LOL: Pulse of 5 cycles of 1000 Hz tone, 59th pulse omitted. Call sign in Morse: identification and time (UTC – 3 h) in voice.

MSF: Pulse of 5 cycles of 1000 Hz tone, 100 ms pulse at minute. Call sign in Morse and voice announcement.



Pulse of 5 cycles of 1000 Hz tone, 100 ms pulse at minute and 500 ms pulse every 5th minute. Last 5 pulses in each quarter hour 100 ms long. From minute 55-60 in every 3rd hour 100 ms pulses lengthned to 500 ms at minutes. Call sign in Morse.

The 56th, 57th, 58th and 59th second signals are omitted in every 14th, 19th, 24th, 29th, 39th, 44th and 49th minute.

The 56th, 57th, 58th and 59th second signals are omitted in every 4th, 9th, 14th, 19th, 24th, 29th and 44th minute.

The 56th, 57th, 58th and 59th second signals are omitted in every 4th, 9th, 14th, 19th, 24th, 29th, 34th, 44th and 59th minute.

The 56th, 57th, 58th and 59th second signals are omitted in every 4th, 9th, 34th, 39th, 44th, 49th, 54th and 59th minute.

See *

Pulse of 5 cycles of 1000 Hz tone, lengthened to 0.5 s at minute. Announcements by Morse code.

FIGURE 2 – *Hourly modulation schedule*

* Pulse of 5 cycles of 1000 Hz (WWV) or 6 cycles of 1200 Hz (WWVH) tone, lengthened to 0.8 s at beginning of each minute. An 0.8 s pulse of 1500 Hz begins each hour at both stations. 29th and 59th pulses each minute are omitted. Voice time announcements preceding each minute. 45-second audio tones alternating between 500 and 600 Hz each minute, except when special announcements or station identification messages are given in voice. One 45-second segment of 440 Hz is included each hour at one minute (WWVH) or two minutes (WWV) past the hour. A modified IRIG-H time code, giving day, hour, minute and UT1 information, is broadcast continuously on a 100 Hz sub-carrier. DUT1 information is provided by the number and position of doubled second pulses each minute. All modulations interrupted for 40 ms around each second's pulse.

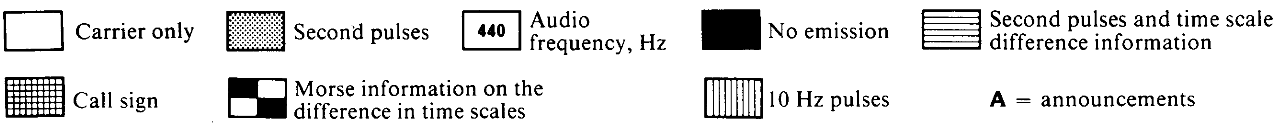


TABLE II – *Characteristics of standard-frequency and time-signal emissions in additional bands, valid as of 1 March 1982*

Station			Antenna(s)		Number of simultaneous transmissions	Period of operation		Standard frequencies used		Duration of emission		Uncertainty of frequency and time intervals (parts in 10^{12})(46)	Method of DUT1 indication
Call sign	Approximate location	Latitude Longitude	Type	Carrier power (kW)		Days/week	Hours/day	Carrier (kHz)	Modulation (Hz)	Time signal (min)	Audio-modulation (min)		
	Allouis, France	47° 10′ N 02° 12′ E	Omni-directional	1000 to 2000	1	7	24	163.84(33) (45)	1(48)	continuous	countinuous A3E	± 10	No DUT1 transmission
CHU(1)	Ottawa, Canada	45° 18′ N 75° 45′ W	Omni-directional	3, 10, 3	3	7	24	3330, 7335, 14 670	1(4)	continuous	nil	± 5	CCIR code by split pulses
	Donebach, F.R. of Germany	49° 34′ N 09° 11′ E	Omni-directional	250	1	7	24	155(45)	nil	nil	continuous A3E	± 2	
DCF77(1)	Mainflingen, F.R. of Germany	50° 01′ N 09° 00′ E	Omni-directional	20(2)	1	7	24	77.5	1	continuous (6)	continuous (7)	± 0.5	No DUT1 transmission
	Droitwich, United Kingdom	52° 16′ N 02° 09′ W	T	400	1	7	22	200 (44)(45)	nil	nil	A3E broadcast continuously	± 20	
	Westerglen, United Kingdom	55° 58′ N 03° 50′ W	T	50	1	7	22	200 (44)(45)	nil	nil	A3E broadcast continuously	± 20	
	Burghead, United Kingdom	57° 42′ N 03° 28′ W	T	50	1	7	22	200 (44)(45)	nil	nil	A3E broadcast continuously	± 20	
GBR(1)(31)	Rugby, United Kingdom	52° 22′ N 01° 11′ W	Omni-directional	750 60(2)	1	7	22(8)	15.95 16.00	1(9)	4 × 5(10) per day	nil	± 2	CCIR code by double pulse
HBG(39)	Prangins, Switzerland	46° 24′ N 06° 15′ E	Omni-directional	20	1	7	24	75	1(28)	continuous	nil	± 1	No DUT1 transmission
JJF-2(1) JG2AS	Sanwa, Sashima, Ibaraki, Japan	36° 11′ N 139° 51′ E	Omni-directional	10	1	7	24(17)	40	1(21)	continuous (29)	nil	± 10	

TABLE II – *(continued)*

Station			Antenna(s)		Number of simultaneous transmissions	Period of operation		Standard frequencies used		Duration of emission		Uncertainty of frequency and time intervals (parts in 10^{12})(46)	Method of DUT1 indication
Call sign	Approximate location	Latitude Longitude	Type	Carrier power (kW)		Days/week	Hours/day	Carrier (kHz)	Modulation (Hz)	Time signal (min)	Audio-modulation (min)		
MSF	Rugby, United Kingdom	52° 22′ N 01° 11′ W	Omni-directional	25(2)	1	7	24(5)	60	1(12)	continuous	nil	± 2	CCIR code by double pulse
	Milano, Italy	45° 20′ N 09° 12′ E	Omni-directional	600	1	7	24	900	nil	nil	continuous A3E	± 2	
NAA(1)(22)(32)	Cutler, Maine, USA	44° 39′ N 67° 17′ W	Omni-directional	1000(2)	1	7	24(34)	17.8	nil	nil	nil	± 10	
NTD(1)(22)(32)	Yosami, Japan	34° 58′ N 137° 01′ E	Omni-directional	50(2)	1	7	24(14)	17.4	nil	nil	nil	± 10	
NLK(1)(22)(32)	Jim Creek, Washington, USA	48° 12′ N 121° 55′ W	Omni-directional	125(2)	1	7	24(35)	18.6	nil	nil	nil	± 10	
NPM(1)(22)(32)	Lualualei, Hawaii, USA	21° 25′ N 158° 09′ W	Omni-directional	600(2)	1	7	24(15)	23.4	nil	nil	nil	± 10	
NSS(1)(22)(32)	Annapolis, Maryland, USA	38° 59′ N 76° 27′ W	Omni-directional	400(2)	1	7	24(36)	21.4	nil	nil	nil	± 10	
NWC(1)(22)(32)	North West Cape, Australia	21° 49′ S 114° 10′ E	Omni-directional	1000(2)	1	7	24(37)	22.3	nil	nil	nil	± 10	
OMA	Podebrady, Czechoslovak S.R.	50° 08′ N 15° 08′ E	T	5	1	7	24	50	1(9)	23 hours per day(16)	nil	± 1000	No DUT1 transmission
RBU(1)	Moskva, USSR	55° 19′ N 38° 41′ E	Omni-directional	10	1	7	24	66⅔	1, 10	6/60	nil	± 10	CCIR code by double pulse(41)

TABLE II – *(continued)*

Station			Antenna(s)		Number of simultaneous transmissions	Period of operation		Standard frequencies used		Duration of emission		Uncertainty of frequency and time intervals (parts in 10^{12})(46)	Method of DUT1 indication
Call sign	Approximate location	Latitude Longitude	Type	Carrier power (kW)		Days/week	Hours day	Carrier (kHz)	Modulation (Hz)	Time signal (min)	Audio-modulation (min)		
RTZ(1)	Irkutsk, USSR	52° 18′ N 104° 18′ E	Omni-directional	10	1	7	23	50	1, 10	6/60	nil	± 10	CCIR code by double pulse(41)
RW-166	Irkutsk, USSR	52° 18′ N 104° 18′ E	Omni-directional	40	1	7	23	200		nil	broadcast	± 10	
SAJ	Stockholm, Sweden	59° 15′ N 18° 06′ E	Omni-directional	0.02 (ERP)	1	2(18)	2(19)	150 000	nil	10(20)		± 2	
UQC3	Khabarovsk, USSR	48° 30′ N 134° 51′ E	Omni-directional	300	1	7	2.7	25.0 25.1 25.5 23.0 20.5	1, 10, 40 (42)	40 min 4 times per day (27)	nil		
UTR3	Gorky, USSR	56° 11′ N 43° 58′ E	Omni-directional	300	1	7	2	25.0 25.1 25.5 23.0 20.5	1, 10, 40 (42)	40 min 4 times per day (30)	nil		
VNG(1)	Lyndhurst, Victoria, Australia	38° 03′ S 145° 16′ E	Omni-directional	10	2	7	24(23)	4500 7500 12 000	1 1000 (24)	continuous	nil	± 100	CCIR code by 45 cycles of 900 Hz immediately following the normal second markers
WWVB(1)	Fort Collins, Colorado, USA	40° 40′ N 105° 03′ W	Top-loaded vertical	13(2)	1	7	24	60	1(3)	continuous	nil	± 10	No CCIR code
Y3S	Nauen, German Democratic Republic	52° 39′ N 12° 55′ E	Omni-directional	5	1	7	24	4525	nil	continuous (43)	continuous	(44)	CCIR code by split pulses

TABLE II – *(continued)*

Station			Antenna(s)		Number of simultaneous transmissions	Period of operation		Standard frequencies used		Duration of emission		Uncertainty of frequency and time intervals (parts in 10[12])(46)	Method of DUT1 indication
Call sign	Approximate location	Latitude Longitude	Type	Carrier power (kW)		Days/week	Hours/day	Carrier (kHz)	Modulation (Hz)	Time signal (min)	Audio-modulation (min)		
ZUO(26)	Olifantsfontein, Republic of South Africa	24° 58′ S 28° 14′ E	Omni-directional	0.08	1	7	24	100000	1	continuous	nil	± 10	CCIR code by lengthening
	Motala, Sweden	58° 26′ N 14° 59′ E	Omni-directional	300	1	7	17	191 (45)	nil	21 s once per day (49)	A3E broadcast continuously	± 50 (44)	CCIR code by decreased audio-modulation frequency
EBC	San Fernando, Cadiz, Spain	36° 28′ N 06° 12′ W	Omni-directional	1	1	7	1	12.008 6.840	(50)	10	(51)	± 100	CCIR code by double pulse

Notes to Table II

(1) These stations have indicated that they follow one of the systems referred to in Recommendation 460.

(2) Figures give the estimated *radiated* power.

(3) Time code used which reduces carrier by 10 dB at the beginning of each second.

(4) Pulses of 300 cycles of 1000 Hz tone : the first pulse in each minute is prolonged.

(5) The transmission is interrupted during the maintenance period from 1000 to 1400 hours UTC (on the first Tuesday of each month).

(6) At the beginning of each second (except the 59th second) the carrier amplitude is reduced to 25% for a duration of 0.1 or 0.2s corresponding to "binary 0" or "binary 1", respectively. The number of the minute, hour, day of the month, day of the week, month and year are transmitted in BCD code from the 21st to the 58th second. The time signals are generated by the Physikalisch-Technische Bundesanstalt (PTB) and are in accordance with the legal time of the Federal Republic of Germany which is UTC (PTB) + 1 h (Central European Time CET) or UTC (PTB) + 2 h (Central European Summer Time CEST). In addition, CET and CEST are indicated by a binary 1 at the 18th or 17th second, respectively.

(7) Call sign is given by modulation of the carrier with 250 Hz tone three times every hour at the minutes 19, 39 and 59, without interruption of the time signal sequence.

(8) Maintenance period from 1000 to 1400 hours UTC each Tuesday.

(9) A1A telegraphy signals.

(10) From 0255 to 0300, 0855 to 0900, 1455 to 1500 and 2055 to 2100 hours UTC.

(11) Maintenance period from 1300 to 1600 hours UTC on the first Sunday of each month.

(12) Carrier interrupted for 100 ms at each second and 500 ms at each minute ; fast time code, 100 bit/s, BCD NRZ emitted during min-interruption giving month, day-of-month, hour and minute. Slow time code, 1 bit/s, BCD PWM emitted from seconds 17 to 51 giving year, month, day-of-month, day-of-week, hour and minute together with 8-bit Identifier from seconds 52 to 59. CCIR DUT1 code by double pulse.

(13) Time pulses occur in groups of 8, one millisecond apart, 20 groups per second.

Notes to Table II (continued)

(14) 2300 to 0900 hours UTC just first Thursday-Friday, 2300 to 0700 hours UTC all other Thursday-Fridays. Half power 2200 to 0200 hours UTC each Monday and Friday.

(15) 1800 to 0200 hours Wednesday and Thursday.

(16) From 1000 to 1100 hours UTC, transmission without keying except for call-sign OMA at the beginning of each quarter-hour.

(17) JJF-2 : telegraph, JG2AS : in the absence of telegraph signals.

(18) Each Wednesday and Friday.

(19) From 0930 to 1130 hours UTC. When Summer Time, add one hour to the instants given.

(20) Second pulses of 8 cycles of 1 kHz modulation during 5 minutes beginning at 1100 hours UTC and 1125 hours UTC. When Summer Time, add one hour to the instants given.

(21) Emission of the carrier of 500 ms duration at the beginning of each second where the 59th pulse is of 100 ms duration each minute.

(22) MKS used. Phase stable.

(23) 4500 kHz, from 0945 hours UTC to 2130 hours UTC, 12000 kHz, from 2145 UTC to 0930 UTC, 7500 kHz, continuous service, with a technical interruption from 2230 hours UTC to 2245 hours UTC.

(24) Pulses of 50 cycles of 1000 Hz tone, shortened to 5 cycles from the 55th to the 58th second ; the 59th pulse is omitted. At the 5th, 10th, 15th, etc. minutes, pulses from the 50th to the 58th second are shortened to 5 cycles ; voice identification between the 20th and 50th pulses in the 15th, 30th, 45th and 60th minutes.

(25) Except first minute of each hour.

(26) Transmitter phase modulated ; time signals and announcements as for ZUO 2.5 and 5 MHz (see Table I).

(27) From 0036 to 0117, 0336 to 0417, 0636 to 0717 and 1836 to 1917 hours UTC.

(28) Interruption of the carrier during 100 ms at the beginning of each second ; double pulse each minute ; triple pulse each hour ; quadruple pulse every 12 hours.

(29) In absence of telegraph traffic.

(30) From 0536 to 0617, 1436 to 1517 and 1836 to 1917 hours UTC.

(31) FSK is used, alternatively with CW ; both carriers are frequency controlled.

(32) This station is primarily for communication purposes ; while these data are subject to change, the changes are announced in advance to interested users by the US Naval Observatory, Washington, DC, USA.

(33) Temporary.

(34) Except from 1400 to 1800 hours UTC each Monday. If holiday falls on Monday, maintenance will be performed on preceding Friday. Half power 1200 to 2000 hours UTC each Wednesday and Thursday.

(35) Except from 1600 to 2400 hours UTC each Thursday. During Daylight Saving Time 1500 to 2300 UTC hours each Thursday.

(36) Except from 1200 to 2000 hours UTC each Tuesday.

(37) Except from 2300 to 0700 UTC each Monday.

(38) Time signal on FSK 5 minutes before each even hour except 2355 to 2400 hours UTC.

(39) Coordinated time signals.

(40) *DUT1 information in CCIR code*

dUT1 information. This additional information specifies more precisely the difference UT1 – UTC down to multiples of 0.02 s, the total value of the correction being DUT1 + dUT1. A positive value of dUT1 is indicated by doubling a number *(p)* of consecutive second markers from second marker 21 to second marker (20 + *p*) inclusive ; (*p*) being an integer from 1 to 5 inclusive

$$\mathrm{dUT1} = p \times 0.02\ \mathrm{s}$$

A negative value of dUT1 is indicated by doubling a number (*q*) of consecutive second markers following the minute marker from second marker 31 to second marker (30 + *q*) inclusive ; (*q*) being an integer from 1 to 5 inclusive

$$\mathrm{dUT1} = -(q \times 0.02)\ \mathrm{s}$$

The second marker 28 following the minute marker is doubled as parity bit, if the value of (*p*) or (*q*) is an even number, of dUT1 = 0.

Notes to Table II (continued)

(41) The additional information about the value of the difference UT1 – UTC is transmitted by code dUT1. It provides more precisely the difference UT1 – UTC down to multiples of 0.02s. The total value of the correction is DUT1 + dUT1. Possible values of dUT1 are transmitted by marking of *p* second pulses between the 21st and 24th seconds of the minute, so that dUT1 = + 0.02s × *p*. Negative values of dUT1 are transmitted by marking of *q* second pulses between the 31st and 34th second of the minute, so that dUT1 = –0.02s × *q*.

(42) Two types of signal are transmitted during a duty period :

(a) A1A signals with carrier frequency 25 kHz, duration 0.0125 ; 0.025 ; 0.1 ; 1 and 10 s with repetition periods of 0.025 ; 0.1 ; 1 ; 10 and 60 s respectively.

(b) N0N signals with carrier frequencies 25.0 ; 25.1 ; 25.5 ; 23.0 ; 20.5 kHz. The phases of these signals are matched with the time markers of the transmitted scale.

(43) A1A time signals of 0.1 s duration (minute marker of 0.5 s duration) followed by code pulses from 0.25 to 0.3 s for information about DUT1, dUT1 and time of the day (minute, hour) in UTC.

(44) No coherence between carrier frequency and time signals.

(45) The carrier frequency of these stations will be reduced by 2 kHz over the period 1 February 1986 to 1 February 1990 in accordance with Resolution No 500 of the World Administrative Radio Conference, Geneva, 1979.

(46) This value applies at the transmitter : to realize the quoted uncertainty at the point of reception it could be necessary to observe the received phase time frequency over a sufficiently long period in order to eliminate noise and random effects.

(47) Westerglen and Burghead are phase-locked to Droitwich.

(48) Phase modulation of the carrier by + and – 1 radian in 0.1 s every second except the 59th second of each minute. This modulation is doubled to indicate binary 1.
The numbers of the minute, hour, day of the month, day of the week, month and year are transmitted each minute from the 21st to the 58th second, in accordance with the French legal time scale. In addition, a binary 1 at the 17th second indicates that the local time is 2 hours ahead of UTC (summertime), a binary 1 at the 18th second indicates when the local time is one hour ahead of UTC (wintertime) ; a binary 1 at the 14th second indicates that the current day is a public holiday (Christmas, 14 July, etc.)

(49) A3E time signals of 0.1 s duration between $11^h\ 58^m\ 55^s$ and $11^h\ 59^m\ 16^s$ UTC. The minute marker is of 0.5 s duration. When Summer Time, add one hour to the instants given.

(50) Seconds pulses of a duration of 0.1 s, modulated at 1000 Hz.
Minutes pulses of a duration of 0.5 s, modulated at 1250 Hz.

(51) Minutes 00 to 10, 12008 kHz, A2A,
15 to 25, 12008 kHz, J3E,
30 to 40, 6840 kHz, A2A,
45 to 55, 6840 kHz, J3E.

During the minute immediately preceding each of the periods indicated, transmission of call sign in slow Morse twice.

TABLE III – *Characteristics of some navigational aids, valid as of 1 March 1982*

Station			Antenna(s)		Number of simultaneous transmissions	Period of operation		Standard frequencies used		Duration of emission		Uncertainty of frequency and time intervals (parts in 10^{12})(12)
Call sign	Approximate location	Latitude Longitude	Type	Carrier power (kW)		Days/week	Hours/day	Carrier (kHz)	Pulse repetition in microseconds	Time signal	Audio-modulation	
Loran-C(6) (7980-Z, 9660-Y)	Carolina Beach, NC, USA	34° 03.8′ N 77° 54.8′ W	Omni-directional	550(4)	1	7	24	100	99600 79800(1)	continuous (5)	nil	± 1
Loran-C (7980-Y)	Jupiter, Florida, USA	27° 02.0′ N 80° 06.9′ W	Omni-directional	275	1	7	24	100	79800(1)	continuous (5)	nil	± 1
Loran-C(6) (5930-Y, 7930-Z)	Cape Race, Newfoundland	46° 46.5′ N 53° 10.5′ W	Omni-directional	1500(4)	1	7	24	100	79300 59300(1)	continuous (5)	nil	± 1
Loran-C(6) (5930-X, 9960-X)	Nantucket Island, USA	41° 15.2′ N 69° 58.6′ W	Omni-directional	275(4)	1	7	24	100	59300(1) 99600	continuous (5)	nil	± 1
Loran-C(6) (8970-M, 9960-Z)	Dana, Indiana, USA	39° 51.1′ N 87° 29.2′ W	Omni-directional	400(4)	1	7	24	100	89700(1) 99600	continuous (5)	nil	± 1
Loran-C (7930-M)	Angissog, Greenland	59° 59.3′ N 45° 10.5 W	Omni-directional	760(4)	1	7	24	100	79300(1)	continuous (5)	nil	± 1
Loran-C(6) (7970-M, 7930-X)	Ejde, Faeroe Is.	62° 18.0′ N 7° 04.4′ W	Omni-directional	325(4)	1	7	24	100	79300 79700(1)	continuous (5)	nil	± 1
Loran-C (7970-W)	Sylt, F.R. of Germany	54° 48.5′ N 8° 17.6′ E	Omni-directional	325(4)	1	7	24	100	79700(1)	continuous (5)	nil	± 1
Loran-C (7970-X)	Boe, Norway	68° 38.1′ N 14° 27.8′ E	Omni-directional	165(4)	1	7	24	100	79700(1)	continuous (5)	nil	± 1
Loran-C(6) (7970-Y, 7930-W)	Sandur, Iceland	64° 54.4′ N 23° 55.4′ W	Omni-directional	1500(4)	1	7	24	100	79300(1)	continuous (5)	nil	± 1
Loran-C (7970-Z)	Jan Mayen, Norway	70° 54.9′ N 8° 44.0′ W	Omni-directional	165(4)	1	7	24	100	79700(1)	continuous (5)	nil	± 1

TABLE III *(continued)*

Station			Antenna(s)		Number of simultaneous transmissions	Period of operation		Standard frequencies used		Duration of emission		Uncertainty of frequency and time intervals (parts in 10^12)(12)
Call sign	Approximate location	Latitude Longitude	Type	Carrier power (kW)		Days/week	Hours/day	Carrier (kHz)	Pulse repetition in microseconds	Time signal	Audio-modulation	
Loran-C (5930-Z)	Fox Harbour, Canada	Scheduled for operation 1982										
Loran-C (7990-M)	Sellia Marina, Italy	38° 52.3′ N 16° 43.1′ E	Omni-directional	165(4)	1	7	24	100	79 900(1)	continuous (5)	nil	± 1
Loran-C (7990-X)	Lampedusa, Italy	35° 31.3′ N 12° 31.5′ E	Omni-directional	325(4)	1	7	24	100	79 900(1)	continuous (5)	nil	± 1
Loran-C (7990-Y)	Kargabarun, Turkey	40° 58.3′ N 27° 52.0′ E	Omni-directional	165(4)	1	7	24	100	79 900(1)	continuous (5)	nil	± 1
Loran-C (7990-Z)	Estartit, Spain	42° 03.6′ N 3° 12.3′ E	Omni-directional	165(4)	1	7	24	100	79 900(1)	continuous (5)	nil	± 1
Loran-C (4990-M)	Johnston Is.	16° 44.7′ N 169° 30.5′ W	Omni-directional	275(4)	1	7	24	100	49 900(1)	continuous (5)	nil	± 1
Loran-C (4990-X)	Upolu Point, Hawaii, USA	20° 14.8′ N 155° 53.1′ W	Omni-directional	275(4)	1	7	24	100	49 900(1)	continuous (5)	nil	± 1
Loran-C (4990-Y)	Kuré, Hawaii, USA	28° 23.7′ N 178° 17.5′ W	Omni-directional	275(4)	1	7	24	100	49 900(1)	continuous (5)	nil	± 1
Loran-C (9970-M)	Iwo Jima, Japan	24° 48.1′ N 141° 19.5′ E	Omni-directional	1800(4)	1	7	24	100	99 700(1)	continuous (5)	nil	± 1
Loran-C (9970-W)	Marcus Is., Japan	24° 17.1′ N 153° 58.9′ E	Omni-directional	1800(4)	1	7	24	100	99 700(1)	continuous (5)	nil	± 1
Loran-C (9970-X)	Hokkaido, Japan	42° 44.6′ N 143° 43.2′ E	Omni-directional	1000(4)	1	7	24	100	99 700(1)	continuous (5)	nil	± 1
Loran-C (9970-Y)	Gesashi, Okinawa, Japan	26° 36.4′ N 128° 08.9′ E	Omni-directional	1000(4)	1	7	24	100	99 700(1)	continuous (5)	nil	± 1

TABLE III *(continued)*

Station			Antenna(s)		Number of simultaneous transmissions	Period of operation		Standard frequencies used		Duration of emission		Uncertainty of frequency and time intervals (parts in 10^12)(12)
Call sign	Approximate location	Latitude Longitude	Type	Carrier power (kW)		Days/week	Hours/day	Carrier (kHz)	Pulse repetition in microseconds	Time signal	Audio-modulation	
Loran-C (9970-Z)	Yap, Caroline Is.	9° 32.8′ N 138° 09.9′ E	Omni-directional	1000(4)	1	7	24	100	99 700(1)	continuous (5)	nil	± 1
Loran-C (9990-M)	St. Paul Pribiloff Is., Alaska	59° 09.2′ N 170° 15.0′ W	Omni-directional	275(4)	1	7	24	100	99 900(1)	continuous (5)	nil	± 1
Loran-C (9990-X)	Attu, Alaska	52° 49.7′ N 173° 10.8′ E	Omni-directional	275(4)	1	7	24	100	99 900(1)	continuous (5)	nil	± 1
Loran-C(6) (9960-M, 8970-X)	Seneca, NY, USA	42° 42.8′ N 76° 49.6′ W	Omni-directional	800(4)	1	7	24	100	99 600(1) 89 700(1)	continuous (5)	nil	± 1
Loran-C(6) (9960-W, 5930-M)	Caribou, ME, USA	46° 48.5′ N 67° 55.6′ W	Omni-directional	350(4)	1	7	24	100	59 300(1) 99 600(1)	continuous (5)	nil	± 1
Loran-C(6) (8970-W, 7980-M)	Malone, FL, USA	30° 59.6′ N 85° 10.2′ W	Omni-directional	800(4)	1	7	24	100	89 700(1) 79 800(1)	continuous (5)	nil	± 1
Loran-C (8970-Y)	Baudette, MN, USA	48° 36.8′ N 94° 33.3′ W	Omni-directional	800(4)	1	7	24	100	89 700(1)	continuous (5)	nil	± 1
Loran-C (7980-W)	Grangeville, LA, USA	30° 43.6′ N 90° 49.7′ W	Omni-directional	800(4)	1	7	24	100	79 800(1)	continuous (5)	nil	± 1
Loran-C (7980-X)	Raymondville, TX, USA	26° 31.9′ N 97° 50.0′ W	Omni-directional	400(4)	1	7	24	100	79 800(1)	continuous (5)	nil	± 1
Loran-C (9990-Y)	Pt. Clarence, Alaska	65° 14.7′ N 166° 53.2′ W	Omni-directional	1000(4)	1	7	24	100	99 900(1)	continuous (5)	nil	± 1
Loran-C(6) (9990-Z, 7960-X)	Narrow Cape, Alaska	57° 26.3′ N 152° 22.2′ W	Omni-directional	400(4)	1	7	24	100	99 900 79 600(1)	continuous (5)	nil	± 1

TABLE III *(continued)*

Station			Antenna(s)		Number of simultaneous transmissions	Period of operation		Standard frequencies used		Duration of emission		Uncertainty of frequency and time intervals (parts in 10^{12})(12)
Call sign	Approximate location	Latitude Longitude	Type	Carrier power (kW)		Days/week	Hours/day	Carrier (kHz)	Pulse repetition in microseconds	Time signal	Audio-modulation	
Loran-C (7960-M)	Tok, Alaska	63° 19.7′ N 142° 48.5′ W	Omni-directional	540(4)	1	7	24	100	79600(1)	continuous (5)	nil	± 1
Loran-C(6) (7960-Y, 5990-X)	Shoal Cove, Alaska	55° 26.4′ N 131° 15.3′ W	Omni-directional	540(4)	1	7	24	100	79600 59900(1)	continuous (5)	nil	± 1
Loran-C (5990-M)	Williams Lake, BC, Canada	51° 58.0′ N 122° 22.0′ W	Omni-directional	400(4)	1	7	24	100	59900(1)	continuous (5)	nil	± 1
Loran-C(6) (5990-Y, 9940-W)	George, Washington, USA	47° 03.8′ N 119° 44.7′ W	Omni-directional	1600(4)	1	7	24	100	59900 99400(1)	continuous (5)	nil	± 1
Loran-C (9940-M)	Fallon, Nevada, USA	39° 33.1′ N 118° 49.9′ W	Omni-directional	400(4)	1	7	24	100	99400(1)	continuous (5)	nil	± 1
Loran-C (9940-X)	Middletown, California, USA	38° 46.9′ N 122° 29.7′ W	Omni-directional	400(4)	1	7	24	100	99400(1)	continuous (5)	nil	± 1
Loran-C (9940-Y)	Searchlight, Nevada, USA	35° 19.3′ N 114° 48.3′ W	Omni-directional	540(4)	1	7	24	100	99400(1)	continuous (5)	nil	± 1
Loran-C (5990-Z)	Port Hardy, BC, Canada	50° 36.5′ N 127° 21.5′ W	Omni-directional	400(4)	1	7	24	100	59900(1)	continuous	nil	± 1
RNS-E(A)	Karachev, USSR	53° 09′ N 34° 56′ E	Omni-directional	800(4)	1	6(7)	7(8)	100	80000(10)	continuous	nil	± 5
RNS-E(D)	Syzran, USSR	53° 18′ N 48° 09′ E	Omni-directional	800(4)	1	6(7)	7(8)	100	80000(10)	(11)	nil	± 5
RNS-W(A)	Aleksandrovsk, Sakhalinsky	51° 06′ N 142° 43′ E	Omni-directional	400(4)	1	6(7)	12(9)	100	50000(10)	continuous	nil	± 5

TABLE III *(continued)*

Station			Antenna(s)		Number of simultaneous transmissions	Period of operation		Standard frequencies used		Duration of emission		Uncertainty of frequency and time intervals (Parts in 10^{12}) [12]
Call sign	Approximate location	Latitude Longitude	Type	Carrier power (kW)		Days/week	Hours/day	Carrier (kHz)	Pulse repetition in microseconds	Time signal	Audio-modulation	
Omega Ω/N	Aldra, Norway	66° 25′ N 13° 08′ E	Omni-directional	10[2]	1	7	24	11.05-F 10.2-A[3] 11 1/3-C 13.6-B	nil	[3]	nil	± 5
Omega Ω/ND	Lamoure, North Dakota, USA	46° 22′ N 98° 20′ W	Omni-directional	10[3]	1	7	24	11.05-A 10.2-D[3] 11 1/3-F 13.6-E	nil	[3]	nil	± 1
Omega Ω/H	Haiku, Hawaii, USA	21° 24′ N 157° 50′ W	Omni-directional	10[2]	1	7	24	11.05-H 10.2-C[3] 11 1/3-F 13.6-D	nil	[3]	nil	± 1
Omega Ω/J	Tsushima Is., Japan	34° 37′ N 129° 27′ E	Omni-directional	10[2]	1	7	24	11.05-E 10.2-H[3] 11 1/3-B 13.6-A	nil	[3]	nil	± 1
Omega Ω/L	Monrovia, Liberia	06° 18′ N 10° 40′ W	Omni-directional	10[2]	1	7	24	11.05-G 10.2-B[3] 11 1/3-D 13.6-C	nil	[3]	nil	± 1
Omega Ω/LR	La Reunion	20° 58′ S 55° 17′ E	Omni-directional	10[2]	1	7	24	11.05-B 10.2-E[3] 11 1/3-G 13.6-F	nil	[3]	nil	± 1
Omega Ω/A	Golfo Nuevo, Argentina	43° 03′ S 65° 11′ W	Omni-directional	10[2]	1	7	24	11.05-C 10.2-F[3] 11 1/3-H 13.6-G	nil	[3]	nil	± 1

Notes to Table III

(1) Time pulses appear in groups of 9 for the master station (M) and groups of 8 for the secondary stations (W, X, Y, Z).

(2) Figures give the estimated radiated power.

(3) See Table IV.

(4) Peak radiated power.

(5) Maintained within ± 5 μs of UTC. Time of Coincidence (TOC) with the UTC second changes with the recurrence of leap-seconds and is designated in TOC Tables issued to interested users by the US Naval Observatory, Washington DC, USA.

(6) Dual-rated stations.

(7) Not on Sundays and holidays or on the last two days of each month.

(8) From 0700 to 1000 and 1400 to 1800 hours UTC.

(9) From 2300 to 2400 and 0000 to 1100 hours UTC.

(10) The signals of primary stations (A) are marked by the transmission of an additional ninth pulse in each group. Each pulse group coinciding with a UTC second marker is marked by the transmission of an additional (tenth) pulse. In the event of coincidence with the minute marker, the subsequent ten groups are additionally marked, and in the event of coincidence with the five-minute marker after 12 seconds, the subsequent 11 groups are also marked. The UTC second markers are accompanied by characteristic points situated at the leading edges of the eighth pulses at a level of 0.6 of the maximum signal value.

(11) Generally operates without a second marker. In individual cases operates with a second marker shifted in relation to UTC.

(12) This value applies at the transmitter : to realize the quoted uncertainty at the point of reception it could be necessary to observe the received phase time/frequency over a sufficiently long period in order to eliminate noise and random effects.

TABLE IV – *OMEGA signal format*

Segment	A	B	C	D	E	F	G	H
Duration	0,9	1	1,1	1,2	1,1	0,9	1,2	1
kHz: 10.2	Norway	Liberia	Hawaii	North Dakota	La Reunion	Argentina		Japan
$11^1/_3$		Japan	Norway	Liberia	Hawaii	North Dakota	La Reunion	Argentina
13.6	Japan	Norway	Liberia	Hawaii	North Dakota	La Reunion	Argentina	
11.05	North Dakota					Norway		

Note 1. – Segment A does not begin at 0.0 second UTC. Time of segments changes with leap-seconds. Segment A begins at 58.0 seconds in January 1973.

Note 2. – The OMEGA stations are for general navigation purposes: while these data are subject to change, the changes are announced in advance to interested users by the United States Coast Guard Commandant*.

Note 3. – In addition to the navigational frequencies of 10.2 kHz, 13.6 kHz and $11^1/_3$ kHz transmitted by all the stations, two stations transmit "unique frequencies". These stations and their frequencies/segments are:

Hawaii 11.8/A, B, F, G
North Dakota 13.1/B, C, G, H

Efforts are presently underway to standardize the entire eight segments of each OMEGA station ten seconds format to include the use of the remaining unused segments.

* United States Coast Guard Commandant (G-WAN-3/73), 400 Seventh Street, S.W., Washington, D.C. 20590.

TABLE V – *Omega radionavigation system signal transmission format*

Station \ Segment	1	2	3	4	5	6	7	8
Norway (A)	10.2	13.6	11 1/3	12.1([1])	12.1([1])	11.05	12.1([1])	12.1([1])
Liberia (B)	12.0([1])	10.2	13.6	11 1/3	12.0([1])	12.0([1])	11.05	12.0([1])
Hawaii (C)	11.8([1])	11.8([1])	10.2	13.6	11 1/3	11.8([1])	11.8([1])	11.05
North Dakota (D)	11.05	13.1([1])	13.1([1])	10.2	13.6	11 1/3	13.1([1])	13.1([1])
La Reunion (E)	12.3([1])	11.05	12.3([1])	12.3([1])	10.2	13.6	11 1/3	12.3([1])
Argentina (F)	12.9([1])	12.9([1])	11.05	12.9([1])	12.9([1])	10.2	13.6	11 1/3
Australia([2]) (G)	11 1/3	13.0([1])	13.0([1])	11.05	13.0([1])	13.0([1])	10.2	13.6
Japan (H)	13.6	11 1/3	12.8([1])	12.8([1])	11.05	12.8([1])	12.8([1])	10.2
Transmission Interval	0.9, 0.2	1.0, 0.2	1.1, 0.2	1.2, 0.2	1.1, 0.2	0.9, 0.2	1.2, 0.2	1.0, 0.2

10 seconds

Frequencies in kHz.

([1]) is the unique frequency for the respective station.

([2]) Omega Station Trinidad is presently occupying the Australian time slot and transmits only the 10.2, 11 1/3 and 13.6 kHz frequencies. Trinidad is a low power station and will be discontinued once Australia is completed.

ANNEX I

AUTHORITIES RESPONSIBLE FOR STATIONS APPEARING IN TABLES I AND II

Station	*Authority*
ATA	Time and Frequency Section National Physical Laboratory Hillside Road New Delhi-110012, India
BPM	Time and Frequency Division Shaanxi Astronomical Observatory Chinese Academy of Sciences Lintong, Xian, China
CHU	National Research Council Time and Frequency Section Physics Division (m-36) Ottawa K1A OS1, Ontario, Canada. Attn. Dr. C. C. Costain
DCF77	Physikalisch-Technische Bundesanstalt Laboratorium 1.21 3300 Braunschweig Bundesallee 100, Federal Republic of Germany
EBC	Instituto y Observatorio de Marina (Spanish Naval Observatory) San Fernando (Cadiz), Spain
FFH	Centre National d'Etudes des Télécommunications Département FRE 196, rue de Paris 92220 Bagneux, France
GBR	1. Time information Royal Greenwich Observatory Herstmonceux Castle Hailsham, East Sussex BN27 1RP United Kingdom 2. Standard frequency information National Physical Laboratory Electrical Science Division Teddington, Middlesex TW11 OLW United Kingdom
HBG	Service horaire HBG Observatoire cantonal CH-2000 – Neuchâtel, Switzerland
IAM	Istituto Superiore Poste e Telecomunicazioni Viale Europa 00100 – Roma, Italy
IBF	Istituto Elettrotecnico Nazionale Galileo Ferraris Corso Massimo d'Azeglio, 42 10125 – Torino, Italy
JJY JG2AS	Frequency Standard Division The Radio Research Laboratories Ministry of Posts and Telecommunications Nukuikita-machi, Koganei, Tokyo 184, Japan
LOL	Director Observatorio Naval Av. Costanera Sur, 2099 Buenos Aires, Argentine Republic
MSF	National Physical Laboratory Electrical Science Division Teddington, Middlesex, TW11 OLW, United Kingdom
NAA, NDT, NLK, NPM, NSS, NWC, NMO, NPN	Superintendent US Naval Observatory Washington, DC 20390 USA

OMA	1. Time information Astronomický ústav ČSAV, Budečská 6 12023 Praha 2 Vinohrady, Czechoslovak S. R. 2. Standard frequency information: Ústav radiotechniky a elektroniky ČSAV Lumumbova 1 18088 Praha 8, Kobylisy, Czechoslovak S. R.
RAT, RCH, RID, RIM, RWM	Comité d'Etat des Normes Conseil des Ministres de l'U.R.S.S. Moscou, U.S.S.R. Leninski prosp., 9
SAJ Motala	Swedish Telecommunications Administration Radio Services S-123 86 Farsta, Sweden
VNG	Section Head (Time and Frequency Standards) A.P.O. Research Laboratories 59 Little Collins Street Melbourne, Victoria 3000, Australia
WWV, WWVH WWVB	Time and Frequency Services Group Time and Frequency Division National Bureau of Standards Boulder, Colorado 80303, USA
Y3S	Amt für Standardisierung, Messwesen und Warenprüfung Fachgebiet Zeit und Frequenz DDR-1162 Berlin Fürstenwalder Damm 388 German Democratic Republic
ZUO	Time Standards Section Precise Physical Measurements Division National Physical Research Laboratory P.O. Box 395 0001 – Pretoria, South Africa

REPORT 896

DOCUMENTATION OF CHANGES IN TRANSMITTED TIME SIGNALS

(Question 1/7)

(1982)

1. Introduction

The transmitted time signals of the different standard time stations have been maintained close to the time determined from the rotation of the Earth by either steps or changes in rate of the time signals. Now most countries transmit UTC.

2. USA time signals

Time and frequency steps by WWV of the National Bureau of Standards and the Master Clock (MC) of the US Naval Observatory (USNO) are shown for 1956-1971 in Table I. Corrections to UTC have been made since 1972.

TABLE I – *Time and frequency steps by WWV and MC (USNO)*

Prior to 1 January, 1956, WWV did not make time steps. Instead WWV steered its frequency to follow closely the Earth's rotation. Steps were therefore unnecessary. (The system followed by WWV was the system N2, used by the US Naval Observatory from 1 April, 1953 until 31 December, 1955.)

Date	MJD	UTC	Step (1)	Notes
1956 January 4	35476	1900	60	
March 7	35539	1900	20 advance	
March 28	35560	1900	20 advance	
July 25	35679	1900	20	
August 22	35707	1900	20	
September 19	35735	1900	20	
October 31	35777	1900	20	
November 14	35791	1900	20	
1957 January 23	35861	1900	20	On 13 March, 1957, step made at 1900 UTC from log books, but step made at 2000 UTC from TS Bulletins.
March 13	35910	2000	20	
May 1	35959	1900	20	
June 5	35994	2000	20	
June 19	36008	1900	20	
July 3	36022	1900	20	
July 17	36036	1900	20	
August 14	36064	1900	20	
October 16	36127	1900	20	
November 6	36148	1900	20	
December 11	36183	1900	20	
1958 January 15	36218	1900	20	WWV controlled at an offset of *about* -100×10^{-10} during 1958.
February 5	36239	1900	20	
February 19	36253	1900	20	
April 9	36302	1900	20	
June 11	36365	1900	20	
July 2	36386	1900	20	
July 16	36400	1900	20	
October 22	36498	1900	20	
November 26	36533	1900	20	
December 24	36561	1900	20	
1959 January 28	36596	1900	20	WWV controlled at an offset of -100×10^{-10} during 1959.
February 25	36624	1900	20	
April 5	36663	1900	20	
August 26	36806	1900	20	
September 30	36841	1900	20	
November 4	36876	1900	20	
November 18	36890	1900	20	
December 16	36918	1900	20	USNO began controlling NBA at an offset of -170×10^{-10} during December, 1959.

(1) All steps are retardations in milliseconds unless otherwise noted.

TABLE I – *(continued)*

Date	MJD	UTC	Step (1)	Notes
1960 No time steps				UTC began 1 January, 1960. (See *Trans. IAU Reports,* Vol. XIA, 362–364.) The initial participating observatories and laboratories were USNO, RGO, NBS NRL and NPL. The original offset was -150×10^{-10}. No international "UTC offset" was in effect before 1960.
1961 January 1	37300	0000	5	UTC offset during 1961 was -150×10^{-10}.
August 1	37512	0000	50 advance	
1962 No time steps				UTC offset during 1962 was -130×10^{-10}.
1963 November 1	38334	0000	100	UTC offset during 1963 was -130×10^{-10}.
1964 April 1	38486	0000	100	UTC offset during 1964 was -150×10^{-10}.
September 1	38639	0000	100	
October 1	38669	0000	1 (Note 1)	*Note 1.* – MC (USNO) advanced 1.6 ms 1 October, 1964. WWV retarded 1.0 ms 1 October, 1964.
1965 January 1	38761	0000	100	UTC offset during 1965 was -150×10^{-10}.
March 1	38820	0000	100	
July 1	38942	0000	100	
September 1	39004	0000	100	
1966 No time steps				UTC offset during 1966 was -300×10^{-10}.
1967 September 20	39753	0000	200 µs (Note 2) advance	*Note 2.* – WWV only ; MC (USNO) was not advanced 20 September, 1967. UTC offset during 1967 was -300×10^{-10}.
1968 February 1	39887	0000	100 advance	UTC offset during 1968 was -300×10^{-10}.
1969, 1970, 1971 No time steps				UTC offset during 1969, 1970, 1971 was -300×10^{-10}.

(1) All steps are retardations in milliseconds unless otherwise noted.

REPORT 731-1

SURVEY OF USERS OF STANDARD-FREQUENCY AND TIME-SIGNAL EMISSIONS

(Question 1/7)

(1978–1982)

1. Introduction

During January-July 1975 the US National Bureau of Standards conducted a survey of users of its radio stations WWV and WWVH [NBS, 1975].

Questionnaires were distributed by a variety of means, including: existing NBS Time and Frequency Division mailing lists (1500); mailing lists made available to NBS by other organizations, such as the IEEE (9000), and US National Weather Service (list of 2600 ships), and a number of boating groups (11 000); direct reproduction in at least 10 publications (combined circulation in excess of 250 000); responses to requests for questionnaires stimulated by voice announcements on the WWV/WWVH broadcasts themselves; responses to requests arising from editorials or announcements about the survey appearing in at least 13 publications (combined circulation about 380 000); and by other miscellaneous methods.

All in all, by 1 May 1975, a total of 9359 completed questionnaires had been returned with some responses from every continent in the world.

It is perhaps worth noting that 23% of the returned questionnaires indicated that they "*officially*" represented more than their own personal use of the services. Most of these participants merely indicated that they were representing the interests of the company which employed them. In a few cases, actual numerical estimates of those officially represented were given. If one *assumes* that these numbers are representative of the entire 23% indicating "official" representation, then one obtains a figure many times greater than the 9359 number of returned questionnaires. However, in the analysis of the responses, each questionnaire was only counted as one reply.

In 1977 the Main Metrological Centre of the Time and Frequency Service of the U.S.S.R. carried out a survey by questionnaire among the users of standard frequency and time signals to collect information on the use by the existing radio stations of LF, MF and HF bands and on the requirements of the users with regard to accuracy and to the technical and information characteristics of signals.

In 1979-1980, in one of its periodic surveys, the National Physical Laboratory (NPL) conducted an inquiry of the users of MSF services, with specific reference to the HF emissions. A similar survey was carried out in Italy in the same period in order to learn the needs of users and in connection with the introduction of a time code via the broadcasting stations.

2. Summary of questionnaire results

2.1 *User classification*

In the survey conducted in the USA, each participant was asked to classify himself into one of 14 categories. In retrospect, it is now obvious that there were three important categories which were overlooked:

- private citizen,
- watchmaker/jeweller, and
- amateur radio operator.

Unfortunately, most of these have been grouped together under the heading of "other".

Figure 1 shows how the users classified themselves. It should be noted that several participants checked more than one category, and thus the sum of the classifications is greater than the number of responses.

2.2 *Relative use of the various broadcast frequencies*

As regards the USA survey, Fig. 2 shows that the broadcasts at 5, 10, and 15 MHz are the most used. This is predictable on the basis of three considerations:

- during the present low sunspot phase, propagation at these frequencies is more reliable;
- the greatest transmitted power from the radio stations is at these frequencies; and
- many commercial receivers receive only these frequencies.

Figure 3 shows the relative use of standard signal carrier frequencies of U.S.S.R. radio stations operating in the bands 2.5, 5, 10 and 15 MHz. Over 70% of standard signal users receive signals where the carrier frequencies are offset by ± 4 kHz from the standard values.

In the United Kingdom survey, only 21% of the total replies received indicated any use of the HF service. It was clear that within the United Kingdom many alternative sources of time/frequency reference were available, either from other HF stations or from the several LF broadcasts, e.g. MSF itself on 60 kHz, DCF77 and HBG.

The results of this most recent survey confirm that the MSF HF service has only a secondary role to play in the dissemination of a time and frequency reference within the United Kingdom and adjacent sea areas. The main burden for this purpose is now carried by MSF emissions on 60 kHz which provides greater accuracy and reliability, relative freedom from propagation effects and carries a time code designed for automatic date and time indication.

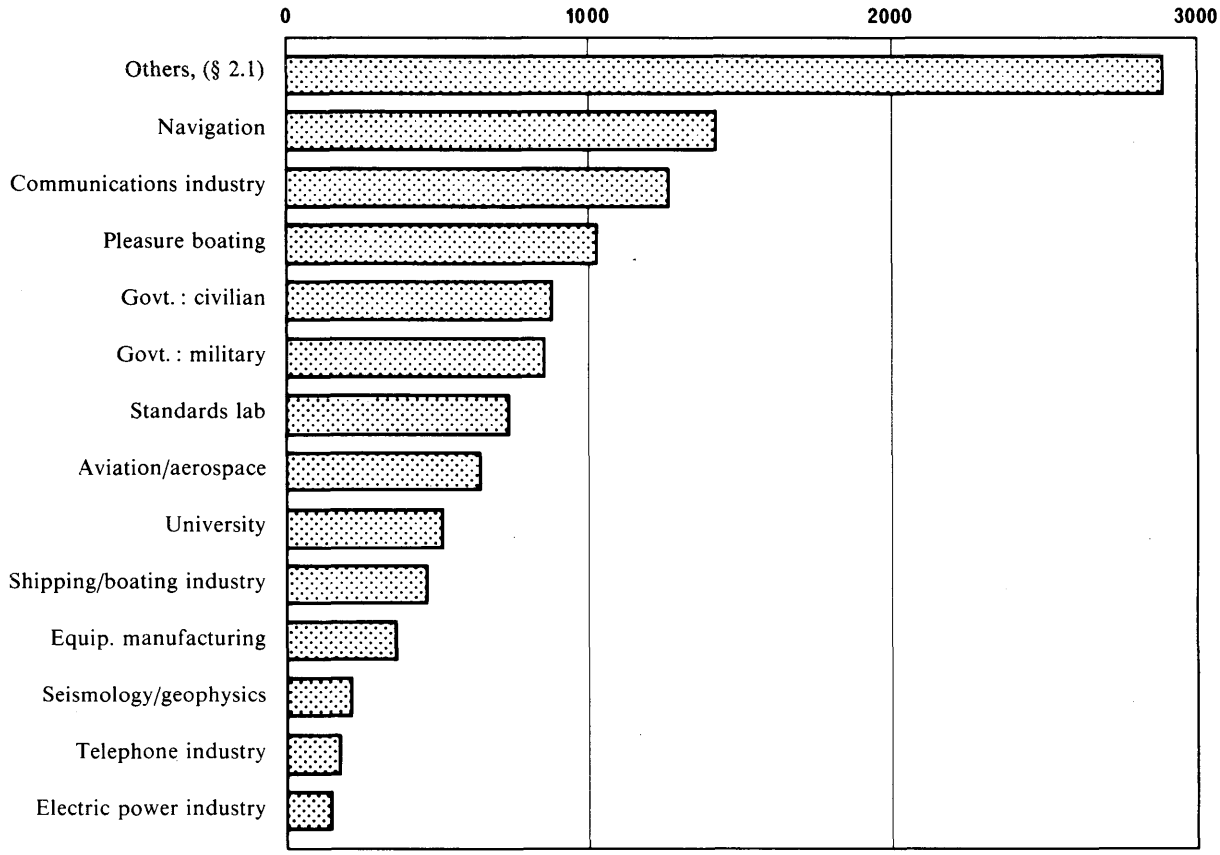


FIGURE 1 – *Number of responses for each user category according to USA survey*

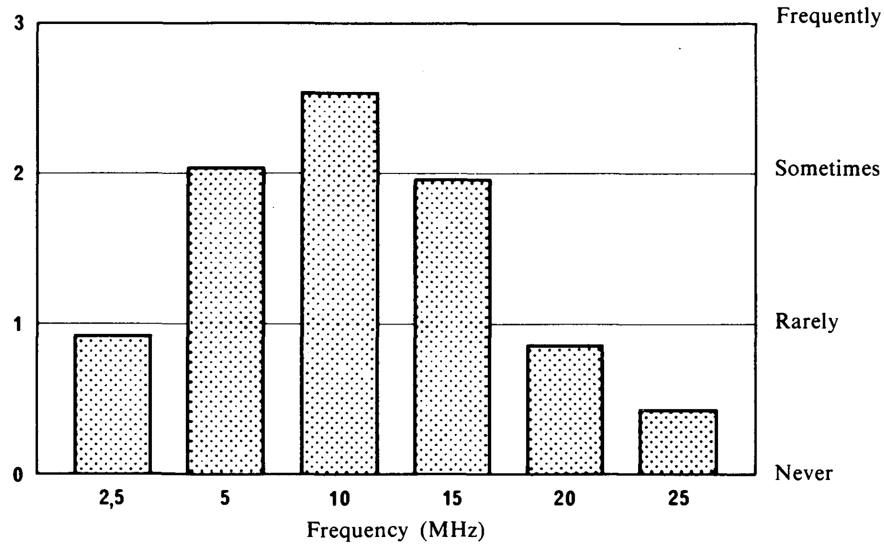


FIGURE 2 – *Use of the frequencies according to USA survey*

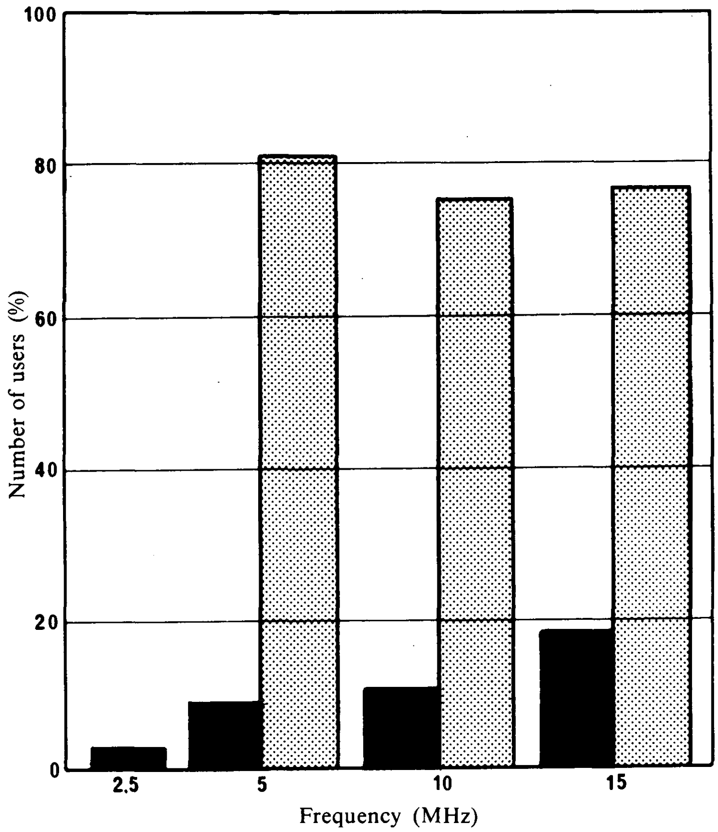
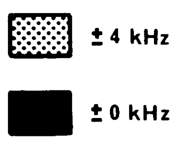


FIGURE 3 – *Use of frequencies according to U.S.S.R. survey*

(The list of the U.S.S.R. transmitters is contained in Report 267, Table I)



2.3 *Interference*

Users of the NBS services were asked to indicate how often they experience "harmful interference between NBS broadcasts and other time/frequency transmissions". Of the total responses to this question (approximately 8700) about 3% checked "frequently" and about 9% checked "sometimes". As expected, problems are much less severe within the US, although 14% of users in the Eastern Time Zone reported harmful interference either "frequently" or "sometimes". This compares with 19-25% for users giving their geographical locations as either the entire world or on all oceans. From user comments which were written in on many of the questionnaire forms, it is clear that conditions are particularly bad in the Eastern Atlantic, the Mediterranean area, and the Western Pacific, which is to be expected since WWV/WWVH are not the primary services in these areas. It is also apparent from some of the comments that at least some users interpreted "harmful interference" more broadly than just that resulting from other time/frequency broadcasts. There is no way to determine to what extent such misinterpretations might be influencing the results.

2.4 *Use of the various services by specific user categories*

For the USA survey, Table I displays the rating (on a zero-to-three-scale) for each of the 14 user categories and for each of the eight services provided by WWV and WWVH. Also shown on the matrix are the overall ratings and the sizes of each of the user categories. The zero-to-three numerical ratings within the matrix represent the consensus response for a given population (i.e., a specific user group) with respect to one of the eight WWV/WWVH services. The specific number is a weighted average of the individual responses to the question: "To what extent do you use the following information (followed by a list of the eight services)?", where the answers are weighted 3 (Frequently), 2 (Sometimes), 1 (Rarely), or 0 (Never). On the same 0-3 scale, the overall ratings given in the "Services" column provide a composite score for each service based on the responses of all users, irrespective of their particular user category. The most obvious features of the matrix are that voice time-of-day announcements are uniformly the most used aspect of the broadcasts and the DUT1 values are uniformly the least used. In fact, the highest use of the DUT1 values is still lower than the lowest use of any other aspect of the services for any category of user.

3. Voice time-of-day

It is perhaps interesting to note in the US experience that the categories of seismology, university, aviation, and pleasure boating return a high rating for voice time-of-day as the most used service of any of the user categories. On the other hand, standards labs and the electric power industry are relatively low in their use of this service. This is probably because standard frequency references are important to much of their work rather than time, and most of them use the WWVB (60 kHz) broadcasts for their calibration work rather than WWV or WWVH.

4. DUT1 values

At the time that the DUT1 values were proposed for inclusion into the UTC system of time dissemination by the CCIR, strong emphasis was placed on the need for real-time corrections to obtain the time scale UT1. Specifically, corrections allowing UT1 to be determined to 0.1 s which were available every minute of the broadcast were thought to be essential for navigation purposes. Because of this history, a very special effort was undertaken to sample the needs of navigators by the various mailing lists, publications and announcements which were mentioned above.

It is apparent from the matrix (Table I) that navigators, boaters and shippers display a particularly low use of DUT1. Similarly, in another survey question asking about the *importance* of the eight services, the navigation interests in DUT1 are as low as any. Indeed, it should be noted that a score of zero could be attained only if *every* respondent checked the "never" box, and it must be recognized that there will always be some "noise" or spurious responses to questions. Thus, the question arises as to whether or not a total score of 0.3 is as near to zero as one can measure with the questionnaire.

In an attempt to answer this question, it could be noted that the telephone industry, electric power industry, and standards labs probably have no real interest in DUT1 values, since they are not critically dependent on earth position. None the less, their responses are about the same as (actually slightly larger than) the navigation-related categories.

Unfortunately, the sample sizes are not great and some uncertainty remains. It is safe to say, however, that the DUT1 values represent the least important and used service provided by WWV and WWVH.

TABLE 1 — *Evaluation of broadcast services by various user categories (according to USA survey)*

(The numerical ratings are weighted averages on a 0-3 scale ranging from "never used" (0) to "frequently used" (3) (see § 2.4).)

Services (Overall Rating) \ User category (Number of responses)	Other (2870)	Navigation (1425)	Communications industry (1274)	Pleasure boating (1020)	Govt. civilian (894)	Govt. military (840)	Standards labs. (732)	Aviation/Aerospace (614)	University (489)	Shipping/Boating industry (463)	Equipment manufacturing (353)	Seismology/Geophysics (195)	Telephone industry (157)	Electric power industry (135)
Time of day: voice (2.80)	2.84	2.82	2.79	2.84	2.76	2.68	2.59	2.85	2.85	2.80	2.75	2.86	2.67	2.58
One-second ticks (1.99)	1.96	2.11	2.12	1.97	2.14	2.00	2.27	2.22	2.32	2.31	2.25	2.49	1.90	2.06
Standard frequency (1.88)	1.88	1.30	2.52	1.36	1.95	1.51	2.34	1.69	1.94	1.52	2.34	1.68	2.45	2.12
Propagation forecasts (1.54)	1.61	1.19	1.93	1.21	1.39	1.28	1.47	1.47	1.53	1.29	1.59	1.55	1.68	1.32
Weather (1.37)	1.27	1.86	1.41	2.00	1.13	1.07	1.16	1.52	1.30	1.92	1.27	1.48	1.18	1.14
Geoalerts (1.01)	1.08	0.87	1.23	0.93	0.93	0.87	0.97	1.01	1.24	0.79	1.04	1.68	1.03	0.83
Time-of-day: BCD (0.66)	0.56	0.83	0.79	0.63	0.81	0.85	0.76	0.89	0.80	0.98	0.74	1.10	0.64	0.77
DUT1 values (0.30)	0.26	0.27	0.41	0.25	0.36	0.38	0.48	0.41	0.47	0.25	0.40	0.46	0.31	0.40

Of course, some respondents did check "frequent" *use* of DUT1 values or rated it "very important". It is of interest to explore this further and see if there is some correlation with the principal use (the questionnaire contained 13 choices for "principal use") made of the broadcasts. Not surprising, "Astronomy" was high with 6% of these people rating DUT1 values as very important; and "Rocket/Satellite Tracking" was second at 5%. All others were 4% or less, with "Navigation/Position Location" at 2%. Thus, it can be concluded that what little use is made of the DUT1 values is mainly for space and astronomy, and they are not particularly used or needed for (terrestrial) navigation.

In the U.S.S.R., among all the users of standard signals to synchronize time scales, 60% need the UT1 time scale and therefore use UT1 – UTC information. 80% of the latter additionally use dUT1 information. In order to receive information on the differences between UT1 – UTC scales, more than 90% of users employ the position code while the Morse code is preferred by fewer than 10%. For this reason, in 1978 UT1 – UTC information broadcasts in Morse code were discontinued in the U.S.S.R.

5. Standard frequency

The results show that the standard frequencies provided by WWV/WWVH are the third most popular service offered by these stations. Table 5 suggests above-average dependence on the standard frequencies by the communications segment (which includes many amateur radio operators), standards labs, equipment manufacturers, and the telephone industry. Especially low use is indicated, as is reasonable, for the shipping/boating-related categories, where timekeeping is the more important aspect. Since propagation effects limit the useful frequency accuracy of most HF transmissions as received to about 1×10^{-7}, the responses to this survey do not include most applications requiring greater accuracy.

In the U.S.S.R., 75% of users employ the standard frequency and time signals emitted by radio stations for frequency measurements. The LF signals are the most popular in this respect. The measurement accuracy required by users can be divided into three classes: low (measurement uncertainty $\sigma > 10^{-7}$), medium ($10^{-7} \geqslant \sigma > 10^{-10}$) and high ($\sigma \leqslant 10^{-10}$) accuracy. The low and medium accuracy classes account for more than 90% of users.

6. Time signals

This service turned out to be the second most popular service on WWV/WWVH, being exceeded only by the voice time-of-day announcements. Greatest use was reported in the seismology/geophysics, university, shipping and boating (as distinct from pleasure boating), standards lab, and aviation/aerospace categories.

In the U.S.S.R., about 50% of the users of standard signals employ them to measure time. The degree of accuracy required by users can be divided into three classes as follows: low ($\Delta t > 0.1$ s), medium ($0.1 \text{ s} \geqslant \Delta t > 0.01$ ms) and high ($\Delta t \leqslant 10$ µs). The overwhelming majority of users (more than 90%) require an accuracy of 1 s to 0.1 ms. The most popular time signals are those emitted by HF radio stations RWM and RID.

7. BCD time codes

The interest in the BCD time code was a complete surprise. It might be supposed that this could be a confusion with the WWVB broadcast services at 60 kHz, but from several of the comments, there does seem to be a real interest in the code from WWV/WWVH. Most surprising of all, however, is the high interest in the BCD time code shown by seismologists and geophysicists. It was thought that this group was very dependent on WWVB and not WWV/WWVH.

In Italy the survey showed a marked interest in the complete time code that is provided, one particular requirement for general users being the day-of-the-week information.

8. Additional information on WWV/WWVH

8.1 *Marine weather information*

At regular intervals each hour, weather information is broadcast from radio stations WWV and WWVH. This weather information is supplied by the US National Weather Service, and its coverage areas include appropriate areas of the Atlantic and Pacific oceans. It was intended to be of main value to navigators on the oceans who also use the standard time broadcasts. From the matrix (Table 1), it is easy to see that this weather information is well received by its intended audience. The analysis revealed that 34% of the respondents who use WWV/WWVH for navigation consider the weather information to be "very important". At least for the navigators, this weather information is easily the third most important service supplied on the broadcasts.

8.2 *Propagation forecasts*

As would be expected, the "Communications Industry" category uses the propagation forecasts more than any of the other user categories. From the analysis, it is found that 35% of the amateur radio operators consider this information "very important". Indeed, amateur radio operators were easily the largest group numerically which found these forecasts to be "important" or "very important".

8.3 *Geoalerts*

It is easily seen from the Table 1 that the geoalerts are used primarily by seismologists and geophysicists.

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CCIR Documents

[1978-82]: 7/111 (United Kingdom); 7/130 (Italy).

REPORT 732-1

PROPOSED REDUCTION OF MUTUAL INTERFERENCE BETWEEN STANDARD-FREQUENCY AND TIME-SIGNAL EMISSIONS IN BANDS 6 AND 7

(Study Programme 1A/7)

(1978–1982)

1. Operational procedures

This Report is based partly on the conclusions of Interim Working Party 7/3 which was set up to consider means of reducing mutual interference in the standard-frequency and time-signal services. It distinguishes the following procedures to help alleviate the problems of mutual interference.

1.1 *Time sharing (time multiplexing)*

This provides a practical, if partial, remedy for mutual interference. It requires no change in receiving arrangements beyond a knowledge of the station schedules, if it is required to correct for propagation delay, and in an ideal situation could be applied world-wide to embrace a number of multiplexed transmissions, operating compatibly. Such a system was conceived some 20 years ago by the then Chairman of Study Group 7 as a means of alleviating the problems of mutual interference between WWV, then radiating from Beltsville, Maryland, and several European standard-frequency and time-signal (SFTS) transmitters.

Time-sharing continues to be applied in a geographically small area of Western Europe and applies to the transmissions of IAM, IBF and MSF on 5 MHz and FFH, MSF and OMA (modulation only) on 2.5 MHz. While accepting the usefulness of such local arrangements, this approach is not seen as the major solution to the present difficulties. Due to diurnal and seasonal variations in propagation it is not possible to guarantee continuity of reception on any one frequency and this must be considered a serious disadvantage of this system for some users. There is also the difficulty that the access time for the desired transmission is increased and problems may arise in identifying the signals of different stations.

An alternative approach to time multiplexing making use of a shorter cycle of alternation, can be envisaged in which, for example, six potentially interfering stations are each allocated successive and unique 10 second segments in each minute for their sole operation without interference from the other five. Such a system would, of course, require coordination between the participating stations but this should not be difficult to achieve since all stations adhere to UTC to within 1 ms.

An extension of the concept of time-sharing was also considered in which two potentially interfering stations would transmit carrier continuously but suppress, respectively, odd and even pulses, thereby enabling their time signals to interlace, but this appears to require somewhat exceptional conditions of continuity and stability of propagation to be effective.

1.2 *Audio frequency tone modulation*

This form of modulation, except to the limited extent necessary for station identification, is wasteful of valuable spectrum space and the aim should be its virtual elimination from the SFTS service.

1.3 *Frequency discrimination*

1.3.1 *Pulse sub-carrier*

At present most of the stations in bands 6 and 7 make use of A2X emission to transmit the time signals. Stations such as WWV, WWVH, JJY and others transmit seconds markers on seperate sub-carrier frequencies chosen in accordance with the formula:

$$f_{sc}(n) = 0.2n \qquad \text{kHz} \tag{1}$$

where n is an integer chosen to be $n = 5$ for WWV, $n = 6$ for WWVH and $n = 8$ for JJY.

The use of A2X emission for the time signals makes it relatively simple to separate potentially interfering signals on the same carrier frequency by means of suitable audio filters, although at the expense of increased delay in the receiver.

1.3.2 *Single-sideband (SSB) operation with full carrier*

The merits of SSB operation are evident in militating against the effects of interference while providing some spectrum economy and protection against fading. At the same time, it is understood that administrations might not wish to make the necessary capital investment in existing transmitting stations to convert to SSB operation when a finite term of, say, 15-20 years can be envisaged for the SFTS service in bands 6 and 7.

The same consideration applies to the introduction of more exotic systems of phase or frequency modulation which might allow several stations to co-exist with reduced mutual interference but only at the cost of additional complexity in both transmitters and receivers. To be acceptable, any modification of the existing network of SFTS stations must be simple to implement and require little or no modification of presently available equipment for radiation and reception.

1.3.3 *SSB with full and/or suppressed carrier-frequency offset operations*

This is seen as a hopeful method for the satisfactory co-existence of both present and possible future transmissions in the allocated MF and HF bands. It presupposes that the carrier frequencies are no longer confined to the values 2.5, 5, 10, 15, 20 and 25 MHz but instead may have, in addition to these, the values specified by the formula:

$$f(N) = (X + 4N) \qquad \text{kHz} \tag{2}$$

where X is 2500, 5000, 10 000, 15 000 and 20 000, and N may take the values 0 or ± 1 for $2500 \leqslant X \leqslant 20\,000$.

This technique of carrier offset is already applied successfully in the U.S.S.R. in the frequency range up to 15 MHz, with N chosen to be either 0 or $\pm$ 1. A plot of the disposition of SFTS stations within the Soviet Union is shown in Fig. 1 with the appropriate frequencies of operation (based on Report 267). Also shown are the locations of stations in other countries which operate simultaneously on at least 3 frequencies (i.e. ATA, BPV, LOL, MSF, WWV and WWVH) in the frequency range 2.5 to 15 MHz. The Soviet stations RWM and RID with offsets of plus and minus 4 kHz, respectively, are extremely widely used [Cherenkov, 1978] as shown in Report 731 by virtue of the high degree of protection they afford from disturbances by other SFTS stations operating at the centre of the allocated bands. These signals can be received in two ways: either as J2X signals by mixing with a local 5, 10 or 15 MHz carrier followed by linear or non-linear detection and filtering, or in the usual manner as A1X signals on carrier frequencies removed from the standard values.

In view of the considerable advantages of single-sideband operation in solving the problems of regional interference it is appropriate to recommend the consideration of the use of H2X (single-sideband, full carrier) and J2X (single-sideband, suppressed carrier) emissions only with the standard frequency carriers in the assigned bands. In order to simplify its receiver and enhance its noise immunity the upper ($f_{sc}+$) and lower ($f_{sc}-$) values of the sub-carrier frequencies could be chosen according to the following relations:

$$\left.\begin{aligned} f_{sc}+ &= 0.4\,(n + ½) \quad \text{kHz} \\ f_{sc}- &= 0.4\,(n + 1) \quad \text{kHz} \end{aligned}\right\} \tag{3}$$

For H2X emissions the proposed values of n are: n = 1, 2, ... 5 and for J2X emissions n = 6, 7, ... 11, e.g., n = 9 corresponds to an upper frequency offset of +3.8 kHz and a lower offset of −4 kHz (see equation (3)).

1.3.4 *Total bandwidth required for the SFTS service*

In order to embrace the modulation sidebands under the new system of carrier frequency allocation some extension in the total bandwidth available to the SFTS service is required.

At 2.5, 5 and 10 MHz the total bandwidth available should be ± 8 kHz to embrace three possible transmissions, corresponding to values of N of −1, 0 and +1. At present the so-called "guard bands" are at ± 5 kHz, except at 2.5 MHz in Region 1 where the frequency limits are only ± 2 kHz.

At 15 and 20 MHz the total bandwidth available should be ± 12 kHz, corresponding to values of N of −2, −1, 0, +1 and +2. In view of the remote possibility that 25 MHz will be re-activated as part of the SFTS service, it is further proposed that this frequency be relinquished for future operations of the SFTS service.

1.4 *Nearest neighbour concept*

The frequency plan described in the foregoing paragraphs would allow a number of SFTS emissions to co-exist with minimal mutual interference. How the plan should be implemented and the several frequencies available applied to the best advantage will depend on the relative geographical disposition of potentially interfering stations. It is advocated that when two stations are "nearest neighbours" and are separated by less than 3000 km, then it should be mandatory that there be a frequency difference of at least (±) 4 kHz between their respective carrier frequencies: the exact frequency disposition will depend also on the "next nearest neighbour" situation but basically it is a bilateral problem to be resolved between pairs of nearest stations.

By way of illustration, a possible implementation of the proposed frequency plan is considered by reference to Fig. 1. The relative offsets of the stations within the U.S.S.R. are accepted as the kernel of the plan and the appropriate values of N are indicated. Corresponding values of N for ATA, BPV, LOL, MSF, WWV and WWVH can be selected in conformity with the frequency plan to minimize the extent of mutual interference, although it should be emphasized that the examples below are not intended in any way to preempt the interests of administrations in arriving at suitable choices of N in bi-lateral or tri-lateral discussions.

Within Europe MSF, Rugby (N = 0) is at present offset from RWM, Moscow (N = −1), its nearest neighbour; the "next nearest" sources of interference are RCH/RIM, Tashkent, some 5000 km distant or RTA, Novosibirsk (on 10 MHz), even more distant. If necessary, MSF could operate with N = +1 to eliminate any residual danger of interference from the Soviet stations except for RID, Irkutsk in the most easterly region of the U.S.S.R. Looking at Fig. 1 it is apparent that it would be advisable, on the basis of these proposals, for ATA to operate with N = +1 or −1 to eliminate mutual interference with RCH/RIM, Tashkent.

Turning attention to the Western Pacific, it is evident that there is severe conflict between the transmissions of BPV, JJY and WWVH on 2.5, 5, 10 and 15 MHz. This could be much reduced if JJY were to operate with N = −1 bearing in mind that RID, Irkutsk has N = +1. An alternative would be for WWVH to accept N = +1; JJY, N = 0; and BPV, N = −1. A more thorough recasting of the world-wide operation of these "base" stations operating on at least two frequencies would be possible with some re-allocation of the N values within the U.S.S.R. From Fig. 1 it appears that an interchange of the N values for RTA and RID would be advantageous and would conform, moreover, with the "nearest neighbour" principle involving station RCH/RIM, Tashkent. Such a change would also allow a larger frequency difference to be adopted between BPV and JJY which are in relatively close proximity, with N = −1 for BPV and N = +1 for JJY. In the Americas station LOL is sufficiently remote from WWV and other transmitters that it could continue with N = 0 although the proposed system could also be exploited here by choosing N = ±1 for LOL.

It will be seen that the implementation of the proposed frequency plan is to a large extent self-determining and that once a value of N is selected for a given station it is not readily changed without affecting other parts of the SFTS network. Nevertheless, given as a starting point the frequency values adopted in the U.S.S.R., it is possible to devise a self-consistent and compatible network of SFTS stations with the minimum extent of mutual interference and with the least possible dislocation in the normal use of such stations.

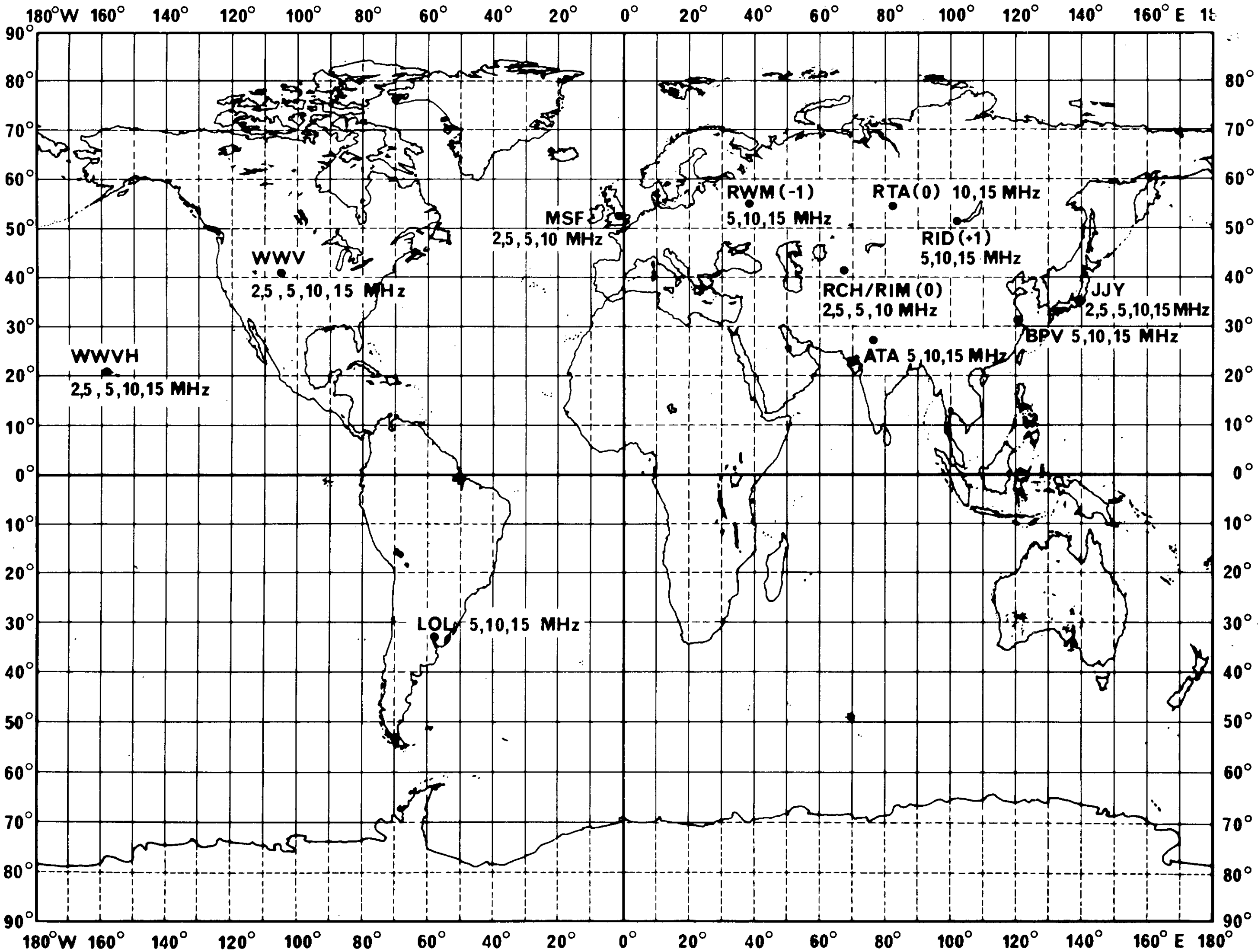
180°W 160° 140° 120° 100° 80° 60° 40° 20° 0° 20° 40° 60° 80° 100° 120° 140° 160° E 180°
90° 80° 70° 60° 50° 40° 30° 20° 10° 0° 10° 20° 30° 40° 50° 60° 70° 80° 90°
MSF
2,5, 5,10 MHz
RWM (-1)
5,10,15 MHz
RTA (0) 10,15 MHz
RID (+1)
5,10,15 MHz
WWV
2,5 , 5,10, 15 MHz
RCH/RIM (0)
2,5 , 5 ,10 MHz
JJY
2,5 , 5,10,15 MHz
BPV 5,10,15 MHz
ATA 5,10,15 MHz
WWVH
2,5 , 5,10,15 MHz
LOL 5,10,15 MHz

FIGURE 1

1.5 *Control of vertical and horizontal radiation pattern*

While it has been suggested that the main control of mutual interference should be achieved by the appropriate choice of relative frequency offset, this should not detract from the need to examine the spread of radiation in both the horizontal and vertical planes from the transmitter. In particular, in geographically small areas it may be necessary to confine the vertical polar diagram to angles greater than 30° elevation with a preponderance of high angle radiation. This is conveniently achieved by arrangements of horizontal dipoles and a relevant Report 301 of Study Group 10 gives the characteristics of such systems designed for broadcasting in tropical regions. Other information is also contained in the CCIR Handbook on Directional Antennas [ITU, 1966].

2. Administrative measures

2.1 It is proposed, also, that this Report be transmitted to the Chairman, Study Group 2, since the present allocated standard frequency bands are partially shared with the radio astronomy and space-research services.

2.2 Furthermore, although Report 731 has shown a strong and continuing need for the transmissions in bands 6 and 7 it is suggested that administrations periodically review the need for such services in view of the desirable savings in power and spectrum usage which would result from their curtailment.

Following the results of a survey of users of the MSF HF service carried out in 1979-1980 it has become clear that this service has only a limited part to play in the dissemination of a time and frequency reference within the UK and adjacent regions of Western Europe. Accordingly, it is the intention of the UK to cease transmission on all three frequencies of the MSF HF service towards the end of the present decade, probably in the first half of 1988.

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RECOMMENDATION 537

REDUCTION OF MUTUAL INTERFERENCE BETWEEN EMISSIONS OF THE STANDARD-FREQUENCY AND TIME-SIGNAL SERVICE ON THE ALLOCATED FREQUENCIES IN BANDS 6 AND 7

(Study Programme 1A/7)

(1978)

The CCIR,

CONSIDERING

(a) the provisions of Article 33, of the Radio Regulations;

(b) that mutual interference in the standard-frequency and time-signal service is the subject of continuing study;

(c) that additional standard-frequency and time-signal stations in bands 6 and 7 are likely to be required in areas of the world not yet adequately served;

(d) that the principal characteristics of the ionosphere may be satisfactorily modelled,

UNANIMOUSLY RECOMMENDS

1. that the provisions of Article 33 of the Radio Regulations should be applied with a view to improving coordination and the elimination of possible cases of interference;

2. that where mutual interference exists at present the IFRB, at the joint request of the relevant administrations, should carry out simulation studies to determine whether a compatible frequency/time sharing solution can be realized;

3. that, in pursuance of these studies, the full details of all standard-frequency and time-signal emissions, including the power fed to the antenna, the antenna configuration, orientation, height above ground, ground constants etc., should be made available to the IFRB.

REPORT 579-2

STATISTICAL WEIGHTS OF CLOCKS USED TO ESTABLISH A TIME SCALE – AVERAGING PROBLEMS

(Study Programme 1D/7)

(1974-1978-1982)

1. Uniformity

In most laboratories the local independent time scale is obtained from an ensemble of commercial caesium standards and is maintained uniform without reference to the calibrations by laboratory primary standards. To achieve a high uniformity, predicted rate corrections and weighting factors are applied to individual standards.

The simplest and most widespread rate prediction is the mean observed rate during a past interval of time (linear prediction) relative to the clock ensemble. However, it is theoretically justified for white noise frequency modulation only; in particular, it is not an optimum prediction for the flicker noise frequency modulation, which may be predominant in the problem of time scale evaluation. A near-optimum recursive prediction for a realistic model of frequency fluctuations was developed by the National Bureau of Standards [Allan and Grey, 1971; Allan *et al.*, 1973].

Refined methods of weighting are used by the National Bureau of Standards [Allan and Grey, 1971; Allan *et al.*, 1973] and the Commission Nationale de l'Heure in France. In some cases, a simpler weighting procedure is satisfactory: a clock is either considered with full "weight 1" or, in case of unsatisfactory performance, with "weight 0".

Clock averaging procedures which make use of different assumptions concerning clock behaviour and the concept of a uniform time scale are also used [Winkler *et al.*, 1970]. These methods employ iterative procedures with corrections applied which compensate for the contributions of those clocks which have excessively deviated from expected behaviour.

Research at the Physikalisch-Technische Bundesanstalt (PTB) and other laboratories has shown that the random model may not be sufficient to characterize fully long-term performance. Systematic frequency drifts and frequency jumps may occur. Effort has been devoted to the recognition of these non-random effects [Ganter, 1973]. They emphasize the need for precise calibrations of the clocks.

In the United Kingdom, an attempt is proposed to bring into operation a time scale combining the capabilities of several establishments, initially the National Physical Laboratory (NPL) and the Royal Greenwich Observatory (RGO). Such a system would be of a character intermediate between the two extreme cases of a central and a distributed system and would achieve the advantages of both with respect to availability and reliability. Centralization of the time scale computations, along with the appropriate improvements in the necessary links, would satisfy the accuracy requirements [Gibbs, 1980].

An improved method of time scale computation with weighted clock contributions [Imae, 1979; RRL, 1978] has been introduced by the Radio Research Laboratories (RRL) of Japan. By using a weighting factor for each clock which is derived from long term ($\tau \geqslant 10$ days) as well as short term ($\tau \leqslant 1$ day) variances, it is possible to improve the time scale stability in both areas, long term and short term. It has been demonstrated in a computer simulation that the time scale computation can be considerably improved if the bias of the clock variances is compensated before these variances are used for the determination of individual weighting factors [Yoshimura, 1980].

Using an ensemble of rubidium clocks, the Shanghai Observatory atomic time scale and the Shaanxi Observatory atomic time scale were established respectively in 1978 and 1979. The calibration references for the Shanghai Observatory atomic time scale are a caesium beam standard and three hydrogen masers and for the Shaanxi Observatory atomic time scale are two hydrogen masers. All atomic clocks used in these two observatories were developed and constructed in China [Chuang and Jair, 1980 and 1981; Shaanxi Observatory, 1979].

The atomic time scale of the National Institute of Metrology of China was established in 1980. This atomic time scale is based on an ensemble of four commercial caesium standards (HP-5061A) and is calibrated against two primary laboratory caesium beam standards (C_{s2} and C_{s3}). During more than one year of continuous operation the accuracy of TA(NIM) was determined as $1 \times 10^{-12}(1\sigma)$. The uniformity of TA(NIM) is $\sigma_y(\tau = 10 \text{ days}) \leqslant 1.0 \times 10^{-13}$ (this value was obtained by internal comparisons).

2. Accuracy

The above-mentioned methods may give rise to important frequency departure in the long term. Frequency corrections must be applied in order to maintain the agreement of the time scale unit with the second.

Stability of a time scale using the compensated weighting factors for the bias of the clock variances which correspond to the long-term and short-term stability proved to be about 2×10^{-13} for the averaging times of 10 to 300 days, with reference to TAI via Loran-C (9970-M) of four commercial caesium standards (C_{s2} and C_{s3}).

The atomic time scales of Shanghai and Shaanxi Observatories were compared with each other and with other atomic time scales in China via television links and portable clock and with UTC time scales abroad via satellite and LF (Loran-C) and VLF transmissions. The long-term instability over 30-day sampling time of the Shanghai Observatory atomic time scale is (3 to 4) $\times 10^{-13}$ relative to UTC(USNO) for a period of two years from 1978. The Shaanxi Observatory atomic time scale has a comparable long-term stability to that of the Shanghai Observatory.

One of the problems is to evaluate the frequency correction, when several calibrations of the time scale frequency with respect to the primary standards are available. Yoshimura [1972], Azoubib *et al.* [1977] derived formulae giving the weights of the calibrations for usual models of random noise in the time scales.

At the National Research Council of Canada, commercial caesium clocks were calibrated twice a week with CsIII [Mungall, 1971] until 28 December 1975. Since that date TA(NRC) has been derived, with a 0.97 ns/day gravitational correction, directly from the output of the primary standard of time and frequency, CsV. In two years of operation, TAI – TA(NRC) has deviated less than 1 µs from the linear projection made in July 1975 [Mungall and Costain, 1977]. However, the present time transfer to BIH via Loran C limits the short term stability observed to that of a high performance commercial standard. In 1979 three smaller primary standards CsVI A, B and C were put into continuous operation as clocks and fully evaluated. At the time of the evaluation, the frequencies of the CsVI standards were all within $\pm 1 \times 10^{-13}$ of CsV, with a mean frequency offset of $+6.5 \times 10^{-14}$. Routine reports of the CsVI clock readings to the BIH began in January 1980. NBS performs a complete evaluation of its primary standard approximately annually, and the results are used in a steering algorithm to control TA(NBS) [Allan *et al.*, 1975].

3. International Atomic Time (TAI)

Until August, 1973, TAI was a mean of 7 local independent atomic times. The weighting of these scales was discussed by Becker and Hubner [1973]; several weighting procedures were tested by these authors and also at the Bureau international de l'heure (BIH) [Granveaud and Guinot, 1972]. As a consequence of the difficulties in assigning weights to the time scales, the BIH began in June, 1973 to use directly data from individual clocks with a prediction and weighting procedure described in the BIH Annual Report for 1973. Since 1 January, 1977 a steering procedure has been applied in order to maintain the TAI time scale unit in conformity with the realizations of the SI second at sea level (see BIH Annual Report for 1977).

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RECOMMENDATION 375-2

STANDARD-FREQUENCY AND TIME-SIGNAL EMISSIONS IN ADDITIONAL FREQUENCY BANDS

(Question 2/7)

(1959–1963–1966–1982)

The CCIR,

CONSIDERING

(a) that for many purposes a world-wide time synchronization with an uncertainty of less than 1 ms is required;

(b) that precise intercontinental frequency comparisons have been achieved by the use of the frequency-stable emissions operating in band 4;

(c) that time comparisons with an uncertainty of about 1 μs are possible at distances greater than 2000 km by means of pulsed ground-wave signals;

(d) that line-of-sight transmissions in bands 8 and 9, and predominantly ground-wave signals in band 5, provide means of distributing time signals and standard frequencies;

(e) that precise continental and intercontinental frequency and time comparisons have been achieved by the use of satellite techniques;

(f) that new methods for time and frequency comparisons may be developed, using laser techniques,

UNANIMOUSLY RECOMMENDS

1. that the results and methods of measurements of phase instabilities over paths in bands 4 and 5, should be published;

2. that advantage be taken of pulse ground-wave navigation systems, for establishing intercontinental and possibly world-wide time synchronization;

3. that appropriate stations, existing in bands 5 and 6, should be employed as much as possible for distributing standard frequencies by precise control of their carrier frequencies;

4. that existing frequency-modulation sound-broadcasting stations and television stations in bands 8 and 9 should be employed as much as possible for distribution of standard frequency and time signals, which can be added to, or make use of, the existing modulation, (including sub-carrier modulation), without interference to the normal programme;

5. that satellite systems, not specifically devoted to the standard-frequency and time-signal service, should be designed to include, whenever possible, standard-frequency and time-signal information or to allow the transmission of time signals.

REPORT 518-3

TIME/FREQUENCY DISSEMINATION AND COORDINATION VIA SATELLITE

(Question 2/7)

(1971-1974-1978-1982)

1. Introduction

Present users of time and frequency (T/F) information have access to a variety of services and techniques for disseminating this information. These include: the well-known HF, LF and VLF broadcast services operated by many different administrations throughout the world; portable clock methods; the use of television transmission and radionavigation signals as T/F transfer standards; telephone-accessible services; and satellite techniques. Available accuracies may range all the way from the millisecond region down to the sub-microsecond region, depending on such factors as the particular techique used, the geographical locations involved, propagation conditions experienced, etc. (Reports 267, 271 and 363).

Although available services can satisfy many of the present user needs for T/F information, increasing numbers of measurement applications are developing that require, or can benefit from, T/F reference signals with improved accuracy, coverage, and reliability. For example, the rapid growth of technology as applied to such areas as precise navigation/position location, digital communications, scientific data monitoring, and space applications, has resulted in needs for time synchronization and intercomparisons over large geographical areas at the nanosecond or better level. Furthermore, an analysis of the long-term historical trends in timekeeping capabilities and the related application areas suggests strongly that the next 20 years will produce many more requirements for such time distribution levels.

While existing T/F services are undoubtedly capable of some further improvement, experience to date indicates that satellite techniques may offer the best chance for substantially improved dissemination and coordination services in the future. A number of different satellite techniques and systems are available for consideration, each with its own set of advantages and disadvantages for particular needs and applications.

Section 2 of this Report discusses some of the present and emerging needs for improved dissemination and coordination capabilities. Section 3 outlines some of the general advantages of using satellite-based techniques. In § 4 the most promising satellite alternatives are discussed and compared with respect to methods of use, present status, coverage, accuracy capabilities, user cost considerations, feasibility for on-site use, operational-versus-experimental status, and the most important advantages and disadvantages. In addition, a summary of experience to date and some indications of future plans for each technique or system are also included.

2. Some applications that can benefit from improved T/F time-transfer capabilities

Various laboratories throughout the world have already developed atomic frequency standards with well-documented uncertainty levels of about 1×10^{-13} and long-term stabilities of better than 1×10^{-14} (Report 364). Atomic time scales based on such reference standards show departures of less than 10 ns per day. If such time scale capabilities maintained within various national laboratories are to be of maximum usefulness in widespread T/F applications, techniques must be implemented for intercomparing the time scales at the subnanosecond level and disseminating corresponding reference signals to the user community.

Another potential beneficiary of improved T/F capabilities is the digital communications area. There is a strong trend towards synchronized, all-digital networks which, in some cases, are likely to be implemented using many atomic frequency standards to provide the necessary timing stabilities for maintaining bit-synchronism throughout the communiction networks. For example, a network operating at 1.5 Mbit/s and maintaining bit-synchronism at the 1 bit/day level requires frequency reference stable to 1×10^{-11}. As typical communication rates increase in the future, the T/F reference requirements also become more stringent. Other systems use satellite links in a time-division, multiple-access (TDMA) mode and require system time synchronization as good as 10 ns.

The general field of transportation, and, in particular, navigation/position location applications, are already generating requirements for improved timing at the 10 ns level, and in some cases, at the better-than-1 ns level. For example, extensive satellite navigation systems to provide positioning to a few metres by employing atomic frequency standards with 1×10^{-13} stabilities and timing capabilities of 10 ns are in the advanced planning stage. Navigation requirements for future planetary space probes imply a need for better-than-1 ns timing. Various specialized marine applications for precise position-location, such as dredging, pipe laying, cable laying, salvage operations, oil exploration, geophysics, and hydrography all require the use of precise timing, in some cases, of the order of 1 ns. Other needs for better T/F distribution are evolving with the continuing development of time-ordered air-traffic control systems and techniques. Further systems are likely to employ air-to-ground digital data links for integrated aircraft navigation, communications, separation, and traffic flow control.

Space applications [Cooper and Chi, 1979] are generating needs for expanded T/F dissemination capabilities while improved techniques for tracking satellites and for making geodetic measurements via satellites are developed and implemented. Satellites can already be tracked with a total uncertainty of only a few metres on a world-wide basis. Laser ranging systems are operating with uncertainties of only a few centimetres, implying that subnanosecond timing resolution could be achieved.

Some of the more demanding applications that are expected to develop during the 1980's in applied satellite geodesy will require timing at the 0.1 to 1 ns level.

A variety of scientific applications can benefit from better T/F capabilities. Significantly better relativity experiments may require the availability of frequency references stable to 1×10^{-16} over hours, while very long baseline interferometry (VLBI) work would be aided by the general availability of better than 1×10^{-14} frequency stabilities for periods up to one day. Similarly, measurements of earth strains and continental drift require 1 ps time stabilities over 1000 s. As a final example, the availability of better T/F reference signals should make possible the improved modelling of the troposphere and the ionosphere, which in turn could have favorable impact in many other applications where propagation uncertainties limit the results.

Many other applications which do not necessarily require state-of-the-art accuracy or precision can nevertheless benefit from improvements in other aspects of T/F dissemination service capabilities, such as wider coverage, more reliable reception, reduced interference, greater convenience of use by non-specialists, and lower cost requirements. Two examples are scientific data monitoring systems where data needs to be correlated from various dispersed sites and electric power networks that need T/F references for coordinating and controlling power flow within the network, for event timing, and for fault location and analysis.

Many of the specific requirements quoted here are operational requirements for time and frequency, where the numbers are chosen so that this error source will not be the limiting factor in the overall system error budget. It is perhaps worth noting also that it is generally desirable to keep the T/F technology capabilities a factor of 10 or so ahead of the operational requirements.

3. General advantages of satellite techniques

Present methods for distributing T/F information that are generally available to most users do not appear to have potential for satisfying the types of needs discussed above. HF, LF and VLF services are limited by propagation effects and, based on many years of accumulated experience, cannot reasonably be expected to offer much better time-transfer accuracy capabilities than are now achievable. Time transfers via television signals have been performed at the 10 ns level, but only within local areas where both timing sites are within line-of-sight in a common reception area of the same television station. Longer distance television comparisons using interconnected television networks show significant deterioration (to a few microseconds) due to the additional propagation path uncertainities. Portable-clock techniques can achieve much better results (50 ns) if special precautions are taken, but again do not appear to be practical solutions for more general problems.

Satellite-based methods for transferring T/F, on the other hand, appear to offer the potential to satisfy the future needs for higher accuracy and the other improvements noted previously. Uncertainties introduced by the signal propagation path are reduced considerably in most satellite techniques, since the Earth-to-satellite and/or satellite-to-Earth paths used are largely in free space with minimal perturbations from the ionosphere and troposphere. The use of higher frequencies, for example, greater than 1 GHz, such as is common in many satellite systems, also reduces ionospheric uncertainties in the total path delay. In the case of two-way satellite timing techniques, in which two sites exchange timing signals simultaneously (or nearly so) through the satellite, the propagation path delays, in principle, do not need to be determined and do not contribute directly to the uncertainty of the time transfer.

Satellites also offer significant advantages in coverage by virtue of their height above the Earth. A single satellite in the geostationary orbit, for example, can continuously broadcast or relay a timing signal to about one-third of the Earth's surface. Similarly, a single, polar-orbiting satellite in a lower-altitude orbit can provide total global coverage, though not continuously at a given point on the Earth. In general, reception reliability is very high for satellite signals anywhere in the coverage area, since propagation-medium disturbances are much reduced in importance compared to the case of terrestrial T/F signals.

Based on great variety of satellite experiments and evaluations performed using many different satellite systems, receiving equipment can be developed that is relatively inexpensive, highly automatic, and easy to use by non-specialists. To achieve the highest possible accuracies however, it may be necessary to use more expensive and more sophisticated equipment, requiring greater operating skills.

Satellite time transfer experiments have been performed successfully by a number of organizations throughout the world since 1962. Though no satellites dedicated exclusively for T/F applications are currently available, or are likely to be in the future, experimenters have been able to make effective use of satellite systems primarily designed for other functions. These include navigation, communication, television broadcast, meteorological, scientific, and experimental satellite systems. A tabular presentation of a number of these satellite experiments since 1962 is given in Annex I.

In recognition of these needs for improved services and the potential of satellite techniques for satisfying them, the World Administrative Radio Conference, Geneva, 1979, allocated the following frequency bands for T/F dissemination via satellites:

400.1 ± 0.025 MHz (Earth-to-space);
4202 ± 2 MHz (space-to-Earth);
6427 ± 2 MHz (Earth-to-space);
13.4 to 14 GHz (Earth-to-space);
20.2 to 21.2 GHz (space-to-Earth);
25.25 to 27 GHz (Earth-to-space);
30 to 31.3 GHz (space-to-Earth).

4. Satellite alternatives for improved T/F dissemination and coordination

In discussing the various satellite alternatives which appear potentially useful for improved T/F transfer in the future on an operational basis, frequent references will be made to one-way and two-way techniques. In this Report one-way operation implies that the user only employs receiving equipment for the reception of a transmission either originated or relayed by a satellite. One-way transmissions generally operate in a broadcast mode with the intent of serving a large number of users. They offer widespread service areas, good timing accuracies, simple methods and equipment for time recovery, and moderate user costs. Two-way operation implies that the users employ both transmitting and receiving equipment, normally in a point-to-point communications mode. Two-way techniques in general offer higher accuracy potential by virtue of being relatively independent of the propagation path connecting the user sites.

The various satellite alternatives are divided for convenience into three separate groups:

- those which have primary application for high-accuracy time transfer;
- those which appear most useful for general T/F dissemination to large numbers of users; and
- those systems/techniques which offer potential for both improved dissemination *and* improved high-accuracy T/F transfer.

For each alternative considered some more general information is first given, which describes the system or technique and its present status. Accompanying this is a summary, in Table I, giving some comparative information about each system or technique, including coverage, accuracy capability, some user cost considerations, a judgement about the feasibility of on-site use, and an indication of the experimental-versus-operational nature of the alternative. Table II summarizes some of the principal advantages and disadvantages of each of the alternatives considered. For each alternative a summary is also given of any experimental and/or operational experience to date along with some indication of future plans.

4.1 *Alternatives primarily for high-accuracy T/F transfer*

4.1.1 *Communication satellites*

The availability and use of communication channels provided by operational communication-satellite systems operated by many companies, nations and regional groups of nations are growing dramatically. For high-accuracy, point-to-point time comparisons two sites might for example, arrange to simultaneously exchange suitable timing signals through the satellite link. At each site the measurements consist of time differences between the transmitted and received time markers. Assuming that signal delays through the propagation medium, the satellite transponder, and the receiving/transmitting equipment are symmetrical, the time difference between the two sites can be computed simply from the measured time differences at each site without any knowledge of the satellite or user locations. Typically, measurements are conducted for periods of only 10 to 60 minutes at a time and once or twice per week. Other variations of the technique are also possible, not requiring the simultaneous exchange of signals. Currently available communication satellites operate either in the 4/6 GHz or the 11/12/14 GHz allocated bands. The user has considerable flexibility in selecting signal design and, in some cases, the channel bandwidth. With some systems entire 36 MHz wide transponder channels must be leased; in others, each channel can be subdivided. In digitally-oriented systems data bit rates of 56 kbit/s are often available as a "standard" channel, but bit rates of 1.5 Mbit/s and higher are often available.

In some situations (in the United States, for example) international comparison links via communication satellites may require a two-hop process with one link from the time laboratory to an INTELSAT terminal via domestic satellite and a second link from the INTELSAT terminal to the other country via the INTELSAT system. Since many commercial satellite systems are now in operation with proven technology, the implementation of operational timing links among major laboratories would be relatively straightforward.

Many domestic, regional, and international satellite common carriers are in operation and have communication channels available for lease. Earth stations are readily available from many sources either on a purchase or lease basis. Earth-station technology is developing rapidly, and there is a strong trend towards using smaller systems (antenna diameter of 5-10 m) located at the end point of use (e.g., the timing laboratory). The 4/6 GHz bands are being heavily used, resulting in some significant frequency coordination problems in certain areas. Some newer systems (e.g., INTELSAT-V, the US Satellite Business Systems (SBS), and Advanced WESTAR (US)) will operate in the 11/14 GHz bands to alleviate crowding and will make use of higher-speed TDMA techniques. Frequency re-use techniques are helping to create more available channels out of the same limited spectrum space. As satellite communications capacity and use increase, costs per channel are decreasing.

Experience in using communication satellites for precise time transfer extends back to 1962 when clocks at the US Naval Observatory (USNO), the National Physical Laboratory (NPL), United Kingdom, and the Royal Greenwich Observatory (RGO), United Kingdom, were compared to an accuracy of 1 μs using a two-way exchange of 5 μs pulses repeated at a 10 Hz rate. The experimental communication satellite Telstar was used [Steele *et al.*, 1964]. Nearly three years later the Relay satellite was used for similar time transfers between the USNO and the Radio Research Laboratories (RRL) Japan, achieving a stated accuracy of 0.1 μs [Markowitz *et al.*, 1966]. In these early experiments up-link and down-link frequencies were in the range of 1.7 to 6.4 GHz.

The US experimental communication satellite ATS-1 was used by several different organizations during 1974-1975 for two-way time transfer experiments using more complex signals in the form of pseudo-random noise (PRN) codes. Correlation detection of these PRN-coded transmissions resulted in very high accuracies and precisions during the time transfers. In the first series of experiments which were designed to have a master station in the western United States synchronize a slave station in the eastern United States, the US NASA organization was able to demonstrate an accuracy of 50 ns and a measurement resolution of better than 1 ns [Chi and Byron, 1975]. Also in 1975 similar time transfers using a sophisticated spread-spectrum, random-access communication system were made over intercontinental distances between RRL in Japan and the USNO and NASA in the USA with an accuracy of about 10 ns after applying relativistic corrections [Saburi *et al.*, 1976]. All the ATS-1 experiments made use of 4/6 GHz band. Similar time transfers at the 100 ns accuracy level have been performed on an operational basis among more than twenty stations since 1970 using the US Defense Communications System satellites. Time transfers use low-level PRN-coded signals which do not interfere with the normal communications function [Easton *et al.*, 1976].

Another group of two-way transfers has been accomplished during the 1976-1981 period using the 4/6 GHz band on the experimental European Symphonie series of satellites. Successful two-way time transfers with accuracies of about 50 ns or better and measurement precisions of a few nanoseconds have been reported between Raisting (Federal Republic of Germany) and Pleumeur-Boudou (France) [Brunet, 1979]; NRC (Canada), Pleumeur-Boudou (France), and LPTF (France) [Costain *et al.*, 1979]; NRC (Canada) and PTB (Federal Republic of Germany) via Raisting; Shanghai, Beijing, and Nanjing in China; Chinese Institute of Metrology (Nanjing) and PTB (Federal Republic of Germany); Shanghai and Shaanxi Observatories (China) and LPTF (France); and NPL (India) and PTB (Federal Republic of Germany) [Mathur *et al.*, 1980].

In the case of the NRC-LPTF comparisons regular time transfers have continued for more than three years since 1978. In February, 1980 PTB began participating in these regular comparisons via Symphonie. Since early 1979 these transatlantic time links have been used by the BIH instead of the Loran-C links. In most of these time transfers relatively simple signal formats featuring 1 pps signals were used. The main contributions to the overall time transfer uncertainties were usually related to difficulties in determining the exact delays through the satellite ground terminal equipment and uncertainties associated with the necessary timing links connecting the satellite receiving facilities and the timing laboratories. The introduction of a new 1 MHz modulation technique (modems devised by NRC) reduced the random uncertainty associated with the space link to a few tenths of a nanosecond. The addition of PTB to the comparisons permitted three separate pairs of measurements to be made each time and the resulting closure error Δ to be evaluated as an indication of the uncertainty. Using only 1 Hz modulation produced $\Delta = -42 \pm 8$ ns while the 1 MHz system resulted in $\Delta = -8 \pm 6$ ns.

The joint US/Canadian CTS/Hermes satellite provided an opportunity during 1978-79 for the USNO and NBS laboratories in the USA, and NRC (Canada) to experiment with some variations on the two-way transfers used previously [Costain *et al.*, 1979]. First, higher up-link and down-link frequencies, in the 12/14 GHz band, were used to advantage. Second, as in the technique mentioned above, 1 MHz signals were exchanged in part of the experiment in addition to the usual 1 pps. This resulted in an improved measurement precision of about 0.2 ns (1σ) and allowed accurate time comparisons to be made with only a few minutes, or even seconds, of actual measurements. Third, small on-site receiving terminals with dishes as small as 2.4 m in diameter were able to be used part of the time at two of the three sites. The UTC time scales were compared with an uncertainty of about 1×10^{-14}. Fourth, it was possible occasionally to link NBS with Pleumeur-Boudou (France) via a two-hop process by linking NBS and NRC via CTS/Hermes and then NRC and France via Symphonie. Measurements precisions for the two-hop mode were less than 10 ns (1σ).

The Istituto Elettrotecnico Nazionale (IEN) laboratory in Italy used the Sirio-1 experimental communication satellite in the 12/17 GHz band to evaluate still another variation of the two-way time transfer techique [Detoma and Leschiutta, 1980]. In this case the satellite motion was continuously accounted for so that only a single communication link needed to be used in a time-sharing mode between the two stations. The satellite motion effect on the time transfer accuracy was only a few nanoseconds for measurement times of up to 20 seconds. Measurement precisions were 1 to 5 ns.

Concerning future plans for use of communication satellites, the time transfers between Canada and Europe via Symphonie are continuing on a regular basis. NRC (Canada) also plans to conduct experiments using a domestic Canadian communications satellite that involve the use of very low power (1 W) CW timing signals added to a normal television transmission in a non-interfering way. Transmitting and receiving antennas will be 3 m in diameter.

4.1.2 *GPS (global positioning system)*

The GPS (also known as NAVSTAR) is being developed by the US Department of Defense as a high-accuracy, continuously available navigation/position-location system. [Milliken and Zoller, 1978]. The system is planned to include a total of 18 operating satellites, arranged in 3 orbital planes. The 18 satellites in 12-hour orbits will result in several being in view of any specific location at any time. Each satellite will contain atomic clocks (caesium, rubidium, and hydrogen devices are all being investigated) to generate extremely well characterized timing signals as part of the navigation message format. The system will be supported by an extensive network of monitoring stations and control stations which will provide updated timing corrections to the on-board atomic clocks. Although GPS system time will not necessarily track UTC precisely, its relationship to UTC will be accurately known at all times. The complex GPS signal format is transmitted to users on frequencies of 1575 and 1228 MHz and can be received with small omnidirectional antennas. Coded information is included giving clock corrections, ionospheric corrections, and satellite ephemeris data for calculating the one-way propagation delay. The GPS signal is designed in such a way that its navigation and time transfer potential can be made available at two different accuracy levels.

It should be noted that the US Department of Defense has not yet announced decisions which can have a major impact on the time transfer capabilities of GPS for general civilian users. Examples of questions which remain to be answered officially include:

- the extent to which access to the GPS timing information may be controlled for civilian users: and
- the extent, if any, to which the full timing accuracy of GPS may be intentionally deteriorated for civilian users.

Six GPS satellites are currently in orbit and are being evaluated. All carry rubidium standards and some also have caesium standards. Full system implementation (18 satellites) is projected for the mid-1980's. A variety of GPS navigation and timing receiver developments, intended for various applications, are in progress.

It may be possible to use the GPS timing signals in several different ways to perform high accuracy time transfers and comparisons. In the "normal" mode the transmitted signals are received at a user's site; decoded; corrected for GPS clock errors, ionospheric effects, and satellite ephemeris using encoded data in the transmission; and then compared with local clock outputs. The realizable accuracy will be strongly influenced by the specific correction information made available to the users.

In the "common-view" mode of use, the same GPS signal is received simultaneously at two (or more) sites [Allan and Weiss, 1980]. Since all of the clock errors and some of the ephemeris and the path correction uncertainties are common to each site's obervations, a degree of compensation for such uncertainties is realized and relatively good synchronization accuracy should be possible. A variation of this technique, involving the *sequential* observation of the *same* satellite with a time lag between, may also prove useful for intercontinental time transfers due to the extremely stable behaviour of the GPS satellite clocks over periods of many hours.

A number of organizations have obtained experience with the basic GPS technique, though not with the actual GPS signal format, through time transfer experiments using the Navigation Technology Satellites (NTS), NTS-1 and NTS-2 [Buisson *et al.*, 1976; Buisson *et al.*, 1978; Saburi *et al.*, 1979]. These satellites, designed to test equipment and techniques for later use with the GPS, carried small rubidium or caesium atomic standards and broadcasted timing signals in a one-way mode at 335 MHz.

NTS-1 has been used in the simultaneous-reception, common-view mode to compare clocks at the USNO and the Naval Research Laboratory in the USA to about 40 ns and at the RRL and NRLM laboratories in Tokyo to about 50 ns using data averaged over 1 to 2 months. International time comparisons via NTS-1 were conducted during the 1976-1979 period involving laboratories in the USA, the United Kingdom, Canada, France, the Federal Republic of Germany, Australia and Japan. Submicrosecond accuracies in the range of 300 to 700 ns were realized and, in some cases, substantial improvements in the measured results were obtained by correcting for ionospheric delays by applying the Bent model.

Initial test results obtained at the US Naval Observatory and the National Bureau of Standards using receivers of different design, showed that the GPS is capable of time transfers with a precision of better than 100 ns [Putkovich, 1980; Davis *et al.*, 1981]. One series of comparisons at these two laboratories during a 14 day period provided a comparison of their two UTC time scales with a precision of about 2×10^{-15}.

4.1.3 *LASSO (laser synchronization from geostationary orbit)*

The concept, as proposed to the European Space Agency (ESA) by the Bureau international de l'heure (BIH), employs a laser retroreflector mounted on a suitable geostationary satellite and laser-telescope-equipped ground stations which are to be synchronized [Serene and Albertinoli, 1979]. Each ground station arranges to transmit laser pulses to the spacecraft, detect the returned pulses, and measure the round-trip delay time. On the spacecraft the pulses received from the ground stations are also detected, and their times of arrival are measured in terms of a spacecraft clock in order to determine the difference in arrival times. These measured differences in the arrival time at the spacecraft are then combined with the measured round-trip delays from each ground station and the known time relationship of the emitted laser pulses to the local clock at each station to provide the time differences among the ground station clocks. Thereafter, the spacecraft timing data can be sent to the ground stations by normal telemetry channels and the ground stations can exchange their data via teletype or other terretrial links.

The LASSO project has been approved by the European Space Agency (ESA) as an experiment to be launched along with the Sirio-2 satellite in early 1982. The satellite will be located for a few months in geostationary orbit at 25° W longitude to enable some North and South American LASSO participation. After that, Sirio-2 will be moved to about 20° E longitude for its prime meteorological mission. A number of countries, including France, Spain, Brazil, India, the United States, the Netherlands, Italy, Federal

Republic of Germany, German Democratic Republic, and Austria, plan to participate in the LASSO experiment but, in most cases, the laser facilities are not co-located with the principal timing centres. There are no plans at this time for future *operational* use of the LASSO technique but it is anticipated that a standard LASSO spacecraft equipment package could be added to other future satellites-of-opportunity fairly easily and inexpensively.

4.1.4 *US space shuttle T/F transfer experiments*

The US NASA organization proposes to perform a time transfer experiment using one of the US space shuttle vehicles with the intent of demonstrating feasibility of 1 ns time transfers and 1×10^{-14} frequency comparisons on a global basis [Decher *et al.*, 1980]. The technique would include hydrogen maser clock systems on the spacecraft and on the ground, use of three separate microwave CW signals (two-way and one-way links) for Doppler cancellation and T/F transfer, and a laser link for calibration of the microwave links and comparisons of different techniques.

The initial experiment is being proposed for one of the low-altitude, orbiting space shuttle flights (perhaps in the mid-1980's) but has not yet been fully approved. If the technique is successfully demonstrated via the space shuttle, it may then be feasible to adapt the basic technique and equipment for later operational missions, presumably using higher orbits to allow a longer observation time for each pass over a participating ground station.

In 1984 the Federal Republic of Germany plans to conduct a time transfer experiment using a US space shuttle, featuring the use of dual-frequency microwave links and on-board atomic clocks [Starker and Rother, 1979].

4.1.5 *Use of 13-31 GHz allocations made by the WARC-79*

The World Administrative Radio Conference, 1979, made the following additional allocations for T/F transfer using satellites:

13.4-14.0 GHz (Earth-to-space);
20.2-21.2 GHz (space-to-Earth);
25.25-27.0 GHz (Earth-to-space);
30.0-31.3 GHz (space-to-Earth).

In each case the T/F allocations are secondary allocations, so that considerable coordination and sharing arrangements would need to be worked out with the primary services and other secondary services to assure that harmful interference is not caused to the other services. However, the wide bandwidth available may make such an effort worthwhile, particularly well into the future when extreme time transfer accuracies (< 1 ns) may be needed and technically feasible.

At present there has been no use of these frequencies for T/F transfer nor are any experiments in the definite planning stage. Cost-effective use will require further development of the technology needed in this frequency range.

4.1.6 *Simultaneous reception of ranging signals*

The proposed technique consists of the sumultaneous reception of ranging signals from appropriate satellite systems at two or more sites and comparing the received phase with local clock outputs. If such measurements are performed at the same time that the ranging signals are used to accurately determine the position of the satellite, the differential propagation path uncertainties can be very low, resulting in very accurate time comparisons of the two clocks.

In the specific case of the world-wide meteorological satellite system that includes two US GOES (Geostationary Operational Environmental Satellites) satellites, the European Meteosat satellite, and the Japanese GMS satellite, the use of this technique could permit a world-wide time coordination system on an operational basis. To link the three regions, stations would need to be established at suitable locations where at least two of the satellites can be observed during their respective ranging operations. For example, a station in Hawaii could link GMS and GOES/West, a continental US location could link the two GOES satellites, a Canary Islands station could receive Meteosat and GOES/East, and a station in India might be able to link Meteosat and GMS.

The particular meteorological satellite network cited, consisting of GOES, Meteosat and GMS satellites, is fully operational. In the case of the GOES satellites each satellite is ranged every four hours using a trilateration technique, thus providing frequent opportunities for accurate time transfers. Well-defined plans exist for maintaining this network operational well into the 1990's. Other satellite systems may also be available now or in the future that would be appropriate for this technique.

One experiment to evaluate such a technique was performed in 1970 by the United States NBS which used the ranging signals with the US LES-6 and Tacsat satellites to synchronize the clocks in North and South America [Hanson and Hamilton, 1971]. Although the low-resolution ranging measurements limited the synchronization accuracies achieved to a few tens of microseconds, the basic feasibility of the technique was established. Studies of this technique made in the Federal Republic of Germany indicate that the use of 2m dishes with the Meteosat ranging signals that are available every three hours should permit time synchronization accuracies of 30 ns [Nottarp *et al.*, 1979].

Planning is under way within the Federal Republic of Germany and the USA to perform experimental time synchronizations using the Meteosat and GOES satellites, respectively.

4.2 *Alternatives primarily for general T/F dissemination*

4.2.1 *Time signals from meteorological satellites*

Four geostationary satellites are currently operating to observe weather and environmental conditions on a world-wide basis: the two American GOES satellites located over the USA at 75° and 135° W longitude; the European Meteosat satellite located at 0° longitude; and the Japanese GMS satellite at 140° E longitude. The two GOES satellites are the only ones to include the time code capability described below, but, owing to their similarity with the other two, it might also be possible to include this capability in the European and Japanese spacecrafts at some point in the future. During normal operation of the GOES system a 100 bit/s data interrogation message is transmitted continuously from the GOES master control station at Wallops Island, Virginia, through the two operating US satellites to numerous data collection platforms. This data interrogation message is down-linked to the platforms on two frequencies near 468 MHz and contains an interleaved time code provided by and referenced to the US National Bureau of Standards [Hanson *et al.*, 1979]. The time code contains day-of-year, hour, minute, and second information as well as satellite position data that is updated each four minutes. Commercial receiving equipment is available which either simply decodes and displays the time-of-day information with an accuracy of ± 10 ms (± 1 ms if the user applies correction for his location on the earth to the received data) or which decodes the satellite position data as well, automatically computes the signal path delay, and adjusts the output 1 pps signal accordingly to be "on-time" to within approximately 50 μs. The timing signals from the satellites are derived from automatic frequency standards maintained by NBS at the Wallops Island facility [Beehler *et al.*, 1979].

The time code as described has been transmitted via the two US GOES satellites since 1975. As replacement satellites are added to the system, it is anticipated that all future US GOES satellites will continue to transmit this code. Extensive use of the GOES time code is being made in the western hemisphere for control and monitoring of events in electric power networks, correlation of recorded observations in seismic and other scientific data monitoring networks, synchronization of communication systems, phase measurements within electric power networks, and general clock calibrations.

4.2.2 *Use of 400.1 MHz transponders on satellites-of-opportunity*

The World Administrative Radio Conference for Space Telecommunications, Geneva, (1971) allocated the frequency of 400.1 ± 0.05 MHz for exclusive use for T/F dissemination by satellite. Many general timing needs for only modest accuracy levels could be efficiently satisfied by one-way time signal transmissions via a 400.1 MHz transponder added on to one or more satellites-of-opportunity. With the ± 25 kHz usable bandwidth allocated, there would be considerable flexibility in designing the timing signal. One could, of course, include voice announcements, ticks, tones, and time codes just as is done now on the HF services. On the other hand, it would also be possible to include some type of low-level, PRN code that could be optionally decoded at higher user cost to provide much higher accuracy, perhaps at the submicrosecond level. Since the satellite timing signal is inherently international in scope, one might also consider transmitting only a simple time code via the satellite transponder which could then be easily interfaced in the user's receiver to solid-state "talking chips" with digital voice storage to create locally the voice time announcement in any desired language. The development and implementation of such services might allow the gradual phasing out of many of the present terrestrial HF timing services and a potential solution to the current HF interference problems.

Although no experimentation in time dissemination using this specific frequency has taken place, the feasibility of providing such a satellite service for general T/F users has been shown previously. In August 1973, the National Bureau of Standards completed a two-year experimental one-way broadcast of a WWV type format via the ATS-3 satellite [Hanson and Hamilton, 1974]. Even with the relatively low 135 MHz space-to-Earth frequency used, time transfer accuracies of 25 µs were achieved for the one-way mode. Propagation delays could be computed to this level of accuracy by using a simple special-purpose slide rule developed for this purpose. The experiment successfully demonstrated that such results can be obtained consistently by relatively unskilled personnel after training of a few hours. As compared to using HF broadcasts, reception of the satellite signals proved far more reliable and required only simple receiving techniques and equipment of comparable cost and complexity. In spite of the fact that the ATS-3 time signals were experimental in nature and limited to two 15-minute periods per day, interest in the technique was evidenced by the thousands of requests for information which were received by the NBS.

At present there are no known plans for using the 400.1 MHz allocation.

4.2.3 *Special opportunities with communication satellites*

The direct approach of using leased channels on communication satellites to transmit timing signals has previously been discussed in connection with the high-accuracy, point-to-point alternatives, where the large available bandwidth is a necessity for highest performance. However, in special circumstances there may be other ways in which these versatile satellites can be used viably for general T/F dissemination. One suggestion that has been made is to use the VHF transponders on such satellites for time dissemination. These transponders are used mainly during initial orbit insertion manœuvres and thus may be available for other ancillary applications once the satellite is well established in its operational orbit.

Using such a transponder operating in a ranging mode on the Sirio-1 spacecraft, the Istituto Elettrotecnico Nazionale (IEN) disseminated a time code on the ranging sub-carriers. In spite of unfavourable reception conditions with *S/N* ratios of 0-3 dB and a baseband width of 1.5 kHz, the code could be received, using standard commercial decoders, with an accuracy of 1 ms. Averaging 60 measurements reduced this to about 0.1 ms. The decoding error rate was < 2%.

During 1977-79 India was able to take advantage of the availability of the Symphonie-I satellite to conduct time dissemination experiments. The types of information disseminated and the associated measured standard deviations included:

- a standard HF broadcast format similar to that of ATA, 50 ns;
- time code; and
- time signals on direct television broadcasts, 70 ns. In the television case an accuracy of 0.25 µs was confirmed.

In one specific case (India) an arrangement has been worked out for possible access by NPL to a portion of the communications spectrum on the Insat Indian national communications satellite for the specific purpose of time dissemination on an operational basis. A 10 kHz channel may be made available on the S-band frequency channel and planning is under way to provide a complete timing signal, including position information on the satellite for one-way path delay correction by users. The T/F service may become available by 1983.

4.3 *Alternatives useful for both high-accuracy and general dissemination*

4.3.1 *TRANSIT navigation system*

The US TRANSIT navigation system currently employs five operational, polar-orbiting satellites which continuously transmit navigation/timing signals on the dual frequencies of 150 and 400 MHz. Timing referenced to the US Naval Observatory can be extracted from fiducial timing markers transmitted each two minutes and by determining the propagation path delay from the satellite ephemeris information included in the TRANSIT signal format. Time is derived on the satellite from quartz crystal oscillators which are corrected as necessary from the ground monitoring stations to keep received time within ± 100 µs of UTC (USNO). Commercial receivers are available which can automatically average over selected Transit satellites and over a selected number of satellite passes. With a judicious use of satellite selection and averaging of satellite passes at a given location, general users can have access to a timing reference that normally remains with ± 10 µs of UTC (USNO).

The TRANSIT system is fully operational with five satellites and should continue to provide service for many more years. Support is provided by the US Navy which also publishes corrections relating the time of each Transit satellite to UTC (USNO).

Time comparison experiments conducted with an experimental improved Transit (Nova) satellite have indicated that accuracies of better than 100 ns are achievable [Rueger and Bates, 1978]. This improved performance, relative to the *operational* TRANSIT results, is due mainly to use of spread-spectrum, PRN-coded saellite signals and sophisticated receivers. One Nova satellite was launched in May, 1981 and a second is scheduled for 1982.

Since the TRANSIT system has been operating since 1965, a large amount of experience has been accumulated. One-way reception of the TRANSIT signals has been shown to provide a timing reference that generally remains within ± 20 µs of UTC(USNO), thus providing a highly useful T/F resource for general dissemination needs [Laidet, 1972; Beehler *et al.*, 1979].

In addition the improvements incorporated into the newer Nova series of Transit satellites may offer higher-accuracy (submicrosecond) capabilities in the future. Using an earlier experimental Nova satellite the Applied Physics Laboratory of Johns Hopkins University in the USA conducted extensive timing tests [Taylor, 1974]. The satellite had an on-board crystal clock and provided a pseudo-random noise (PRN) code at a 1.67 Mbit/s rate on a 400 MHz carrier. A 150 MHz carrier was also used to make corrections for ionospheric refraction effects. Two types of experiments have been performed. In the first type (regional clock synchronization), two sites observed the satellite transmissions simultaneously and were able to synchronize local clocks to within 50 ns. In the second type (global clock synchronization), synchronization of clocks located on different continents was of interest. For this mode of operation, uncertainties in the satellite position and instability of the satellite oscillator are expected to be two major limitations in time transfer capability. Experiments were performed by measuring the time of arrival of the PRN timing signals on one pass of the satellite, using this data to predict the time of arrival for the next satellite pass, and then comparing the predicted and measured results. It was concluded that the resulting synchronization errors using the global mode are less than 75 ns using 100-minute predictions. By using both carriers to determine ionospheric corrections, the error due to this source was estimated to be less than 30 ns.

An improved Nova satellite was launched in May, 1981 and another is scheduled for 1982. If at least one of these operates successfully, one or more additional Nova satellites are to be launched later. At present, there is no approved operational requirement for adding the PRN code to the operational TRANSIT system and it remains uncertain whether such improved signals (for timing) will be available on a long-term basis.

4.3.2 *TDRS (tracking and data relay satellite) system*

The TDRS system is being implemented to provide two-way relay of tracking and other types of data between NASA ground facilities and low-altitude orbiting satellites in the 1980's [Chi, 1979]. The system will include two operational geostationary satellites at 41° W and 171° W longitude and a dedicated spare in orbit with the master control centre at White Sands, New Mexico. With these locations the TDRS system could provide timing links to laboratories all the way from Japan and Australia through North America to and including all of Europe. While the TDRS system is mainly intended to communicate with orbiting spacecraft, some NASA tracking stations will also be in the system. The possibility may exist for timing organizations to also participate as users. In one possible high-accuracy, two-way mode, each timing user could have an S-band (approximately 2 GHz) transponder with suitable on-site auxiliary systems. A timing signal, consisting of an identified point in a PRN code sequence, could be transmitted at K-band from the master control station to the TDRS satellite and then to a timing user at S-band. This user could then measure the time of arrival in terms of his local clock, encode this information on to the TDRS signal, and return the signal to the control station via the satellite once again. The user could also generate a local timing signal and transmit it to the control station. Propagation delays can be accurately dealt with and time transfer accuracies of about 10 ns should be possible. For operational use one could envision a periodic sequence of measurements comparing each timing laboratory in turn with the master clock reference in New Mexico. Such regular comparisons could perhaps be scheduled and coordinated by NASA, the BIH, or some other interested organization.

Fixed-location users on the earth might also have the option to use the TDRS signals in a lower-accuracy, one-way mode by making suitable computations and corrections for path delay. There is some possibility that a time-of-day code may be added to the TDRS capabilities.

The TDRS system is approved as an operational system and will be implemented in 1982/1983 using leased communication capacity from a US commercial satellite operator. Prototype user timing equipment is being developed under NASA sponsorship. Timing experiments will be performed via the TDRS system using this prototype equipment during the next several years. It is not known at this time what, if any access, T/F users may have to the TDRS system.

4.3.3 *Television broadcast satellites*

Terrestrial time comparisons, both within local areas and over much longer distances, are conducted routinely in many countries by having two sites simultaneously observe a designated synchronization pulse within the normal television transmission format. When both sites are within common view of a single television transmitter, clock time differences can be measured to accuracies of approximately 100 ns or better, assuming the differential propagation path delay can also be determined. The method is also useful at larger distances where two different television transmitters can be observed that are interconnected in a television network. With the present trend towards developing television broadcast capabilities from dedicated satellites, it may become feasible to apply the same television time synchronization methods for the satellite television case [Kovačevič *et al.*, 1979]. The satellite television pulses can certainly be received over larger areas and measured against local clocks with high resolution (a few nanoseconds). The accuracy with which two clocks can be compared, however, depends on knowing the differential propagation delay. One interesting idea is to accurately range the television satellite via a few laser ranging stations and then use this information to compute the path delays. Another variation, suggested by the BIH, would use the LASSO technique to calibrate the emission time of the satellite television pulse, which would then be used to transfer time to individual users via one-way reception of the pulse. A third possibility would be for several timing centres to provide their own high-accuracy satellite position information by comparing reception times of selected television pulses. Still another approach for using television broadcasting satellites, in this case with emphasis more on general time dissemination, involves encoding time-of-day information into the television signal vertical blanking interval. It can then be received and decoded over wide reception areas with modest accuracy sufficient for many time keeping needs.

A number of experimental television broadcasting satellites are undergoing evaluation and, in a few cases, have also been used for T/F dissemination studies. In Japan preliminary frequency dissemination experiments have been made using the medium-scale broadcasting satellite for experimental purpose (BSE) which uses a down link of 12 GHz and an up link of 14 GHz. The measured short-term stability of the received television sub-carrier frequency was as good as in the terrestrial television broadcasting, for example, $\sigma_y(10\ \text{s}) = 3 \times 10^{-11}$. In order to establish the technique of the Doppler shift cancelling, the phase control servo including the satellite link, the pre-compensating frequency control using the measured values or using the orbital data of the satellite were tested. The amount of the residual Doppler shift at the control station can be reduced to the order of 1 part in 10^{12} or less by use of the first and the second methods. The method using the orbit data is expected to give a control capability of a few parts in 10^{11}. Thus, the maximum value of the Doppler shift at the farthermost place of the country, which is about 1500 km distant from the BSE transmitting station, is estimated to be $\pm 2 \times 10^{-10}$ without any correction [Ishida *et al.*, 1979; Saburi *et al.*, 1979].

As a result of further experiments using the BSE, an accuracy of frequency dissemination of 5×10^{-12} (1σ) was obtained at a point about 1000 km distant from the transmitting station when calculated correction based on the orbital data was applied to the measured value. As another result of those experiments, an accuracy of 0.2 µs (1σ)and a precision of 0.12 µs (1σ) were obtained in the time comparison, carried out for five months, between two caesium clocks, situated about 400 km apart from each other, via the television synchronizing pulse. Besides, in the experiment of standard time dissemination with the insertion of time code in vertical blanking interval, an accuracy of 10 µs was obtained all over the country, when the Doppler correction control was made at the transmitting station [Saburi *et al.*, 1980].

Experiments to evaluate the use of television broadcasting satellites for T/F dissemination are continuing in Japan and in Europe (via the OTS-2 satellite) and are planned in India (via the Apple and Insat satellites).

4.4 *Comparison of the alternatives*

Table I gives some additional comparative information on the alternatives, including coverage, accuracy capability, some user cost considerations, and indication of whether the alternative is feasible for on-site use as contrasted with the need for auxiliary timing links to off-site receiving facilities, and the status of the system or technique in terms of being available only experimentally or on a longer-term operational basis. Table II summarizes in concise form some of the principal advantages and disadvantages of the various satellite alternatives.

TABLE I – *Selected comparative information for satellite alternatives*

Satellite alternative	Coverage	Accuracy capability	User cost estimates (US dollars 1981)	Feasible for on-site use	Operational or experimental
1. Communication satellites	Regional or global (networks)	10 – 50 ns	$ 25 000 – $100 000 for onsite terminal. $500/hour for transponder time (TV channel)	Depends on specific satellite system and location. Expensive	Operational
2. GPS: Normal mode	Global ; continuous	Possibly ≈ 100 ns if not degraded	Present timing receiver > $ 50 000. Should decrease with development	Yes	6 satellites now in orbit. Full implementation sometime after 1985
Common-view mode	Mainly regional, but also intercontinental at reduced accuracy. Best results for up to a few thousand km.	Depends on specific geometry of link. Possibly ≈ 10 ns if not degraded	Relatively low cost	Yes	See above
3. LASSO	Europe, Africa, South America, eastern United States and Canada initially for a few months. Europe and Africa later	≈ 1 ns projected	Very expensive ; full laser stations ≈ $1 million. Usually requires auxiliary timing links to laser sites	Not in general. Requires laser station	Experimental during 1982. Could develop operational add-on package later
4. Space shuttle experiment	Depends on specific flight. Possibly covering ± 57° in latitude	< 1 ns (time) and 1×10^{-14} (frequency) projected	Requires 3-frequency microwave ground facility ; two-way links to shuttle. Expensive	Possibly, with further equipment development for later operational use	Proposed experiment ; no plans for operational system
5. Use of new 13 – 31 GHz allocations	Depends on satellite system used	Precision : 10 – 50 ps. Accuracy : limited by delay uncertainties	Expensive until further development	Probably	No present plans for operational or experimental use
6. Simultaneous reception of ranging signals	Depends on system. Could be regional or global for GOES/GMS/METEOSAT system	10 ns	< $ 30 000	Yes	GOES, GMS, and Meteosat satellites are operational

TABLE I – *(continued)*

Satellite alternative	Coverage	Accuracy capability	User cost estimates (US dollars 1981)	Feasible for on-site use	Operational or experimental
7. Meteorological satellites	Depends on system. Hemispheric for US GOES time code. Possible expansion to Europe and Japan	± 16 ms (uncorrected) ± 0.5 ms (corrected for mean path delay) ± 50 µs (fully corrected)	$ 2200 (1 ms accuracy) $ 4500 (50 µs accuracy) Antennas included	Yes	GOES satellite system is operational. Time code on US satellites since 1975
8. Use of 400.1 MHz allocation	Depends on satellite system used	Basic level : ≈ 1 ms Probably could achieve < 1 µs via PRN code	Basic level : < $ 500 PRN code : < $ 3000	Yes	Allocation exists but no known plans for use
9. VHF transponder or dedicated 10 KHz channel on communication satellite	Regional	≈ 1 µs possible. Could also disseminate less accurate codes or voice	Should be fairly low	Yes	India plans use of 10 KHz channel on INSAT in about 1983
10. Transit : 1981 Operational system	Global, including high latitudes, on an intermittent basis	≈ 30 µs (single satellite) ≈ 10 µs (satellite ensemble)	≈ $ 12 000 for fully automatic receiver and omni-directional antenna	Yes	Operational
Improved Transit (NOVA)	Same as above, except only two satellites are now planned initially	< 100 ns	$ 15 000 to $ 50 000 after initial receiver development	Yes	Experimental
11. TDRS : Two-way mode	Nearly world-wide, except for 30°-120° E longitude	Probably ≈ 10 ns	Not determined but probably > $ 25 000	Yes	Operational in 1982/1983
One-way mode	Same as above	≈ 1-10 µs	Not determined, but relatively inexpensive	Yes, in most cases	Same as above
12. Television broadcasting satellite : High-accuracy mode	Regional	Depends on quality of ephemeris data. Probably < 1 µs and possibly ≈ 100 ns	At present : ≈ $3300. Should be reduced significantly in production quantities	Yes. 1 m antennas may be usable	Experimental at present but many operational satellites are planned
General dissemination mode	Same as above	Depends on path correction capability. Possible time code for general use	Same as above. Less demand on users for handling path delays	Yes	Same as above

TABLE II – *Principal advantages and disadvantages of satellite alternatives*

Satellite alternative		Principal advantages	Principal disadvantages
1. Communication satellites		Technology and operational systems available now. Much accumulated experience. Long term continuity assured. Two-way technique provides high accuracy. Costs and required antenna size decreasing. High reliability regional and international coverage. On-site operation feasible in some cases. Large bandwidth may be available. Many governments already directly involved in operational systems	Present costs, though decreasing, are relatively high. Large antennas necessary in some cases – especially for INTELSAT links. User must have transmit capability. In some cases need auxiliary links to satellite facilities from T/F laboratories. Highest accuracy requires a difficult calibration of ground-station delays. High current demand for available channels
2. GPS:	Normal mode	May have high accuracy capability. World-wide, continuous coverage. Ample redundancy and system support. One-way technique. Long-term continuity of system. Strong receiver development effort likely if access and accuracy not unduly restricted. Small antennas feasible. On-site operation	May be restrictions on access and available accuracy for civilian users. Present receiver costs > $ 50 000. Complex signal format. One-way method requires path delay determination by users
	Common-view mode	Potentially lower receiver costs. High synchronization accuracy for distances of several thousand kilometers. Convenient on-site operation. Any ephemeris errors partly compensated for. Requires only knowledge of *differential* path delay.	For best results sites should be within ≈ 2000 km. Primarily for regional synchronization. May be restrictions on access and available accuracy for civilian users. Requires some coordination and scheduling among laboratories
3. LASSO		Potentially one of the most accurate alternatives. May allow < 1 ns time transfer. Synchronization requires only a few minutes. Standard LASSO packages could be added to other satellites in future	High user costs for equipment. Most laser sites not co-located with T/F laboratories. Laser operations subject to weather conditions. Experiments planned but no operational plans. Lack of laser experience. Possible safety hazards to aircraft
4. Space shuttle experiment		Potentially one of the most accurate alternatives. Use of multiple frequencies reduces uncertainties. Not weather sensitive. Uses H masers for stability. Allows direct frequency comparisons	Only a proposal at present; no plans for operational mode. Expensive, complex equipment required. Shuttle use for experiment limits observation time during each pass
5. Use of new 13 – 31 GHz allocations		Frequencies are internationally allocated for T/F use. Large bandwidths would permit measurement precisions of < 100 ps. Not restricted to a particular satellite system	Technology in this frequency range needs further development and cost reduction. Allocations are on a shared *secondary* basis. Probably not feasible for 5 to 10 years

TABLE II – *(continued)*

Satellite alternative	Principal advantages	Principal disadvantages
6. Simultaneous reception of ranging signals	Some suitable satellites are operational. High-accuracy potential. Potential for global coordination use. Relatively inexpensive equipment can be used on-site. Accurate ephemeris information simultaneous with time transfer. Convenient one-way technique	Must have access to satellite ephemeris information. Requires several special monitoring sites to link regional systems for global time transfer. User equipment must be developed
7. Meteorological satellites	Low user cost. Some commercial receivers already available. Continuous service available from geostationary satellites. Time code already operational on GOES satellites ; could be expanded to Meteosat and GMS using same equipment. GOES time code contains complete time-of-year information referenced to UTC. Relatively secure long-term continuity for prime satellite mission. On-site use	Coverage of present GOES time code limited to western hemisphere. Occasional time deviations of $>$ 100 μs possible with GOES. 468 MHz frequency used is not a specific T/F allocation. Secondary status of allocation may result in interference from land mobile service in some areas. Must have cooperation of non-T/F organizations
8. Use of 400.1 MHz allocation	Frequency is already internationally allocated for T/F use on a *primary* basis (with minor exceptions in some areas). Compatible with very inexpensive user equipment. Usable bandwidth could permit a dual-level service. Compatible with off-the-shelf satellite transponders. Could use 400.1 MHz transponder as add-on package to any satellite-of-opportunity. Service operating costs would be much lower than for current HF services. Could relieve HF interference problems. Flexibility of signal design. Could easily provide global, or a least international, coverage with multilanguage capability. On-site use	No present known plans for operational implementation. Need to identify appropriate satellites and develop cooperative arrangements. May be difficult to convince large numbers of users to convert to satellite service, even if technically superior. As replacement for HF services, would need long overlap period with both services to allow equipment amortization and user education
9. VHF transponder or dedicated 10 kHz channel on communication satellite	VHF transponders used mainly during orbit insertion and may be available later for T/F use. Convenient frequencies. Long-term continuity of primary satellite mission. Could be low cost. 10 kHz channel allows complete time information to be disseminated. India may implement operationally via INSAT. On-site use	Availability of transponders uncertain. Requires agreements and active cooperation with non-T/F organizations. Dedicated channels probably not generally available to T/F organizations, except in special situations. Limited accuracy capability with 10 kHz channel

TABLE II – *(continued)*

Satellite alternative		Principal advantages	Principal disadvantages
10. Transit	1981 Operational system	Fully operational, strongly supported with five satellites. Global coverage. Commercial receivers available. Time signals referenced to UTC. On-site use. Automatic receivers can average passes and select specific satellites for improved accuracy. Longterm Transit operation likely	Polar orbits result in timing signals being available only periodically at a given location. Time information has 30 min ambiguity. Receivers must handle Doppler shifts
	Improved Transit (Nova)	High accuracy possible with one-way technique. Global coverage, including high-latitude regions. Simple antennas ; on-site operation. Should provide improved performance with present receivers. Two Nova satellites scheduled for launch	NOVA improvements for time transfer still have only experimental status. Time signals available intermittently. Availability of most precise ephemeris information to general users may be restricted
11. TDRS :	Two-way mode	Coverage of nearly all major timing centres via two geostationary satellites. High potential accuracy capability ($\approx$ 10 ns). System fully approved. Has at least a 10 year projected life. In-orbit space	Two-way technique requires careful ground equipment calibration. Relatively high user costs. Access to TDRS would require NASA permission. Two laboratories can compare time only indirectly via a third station
	One-way mode	Access to TDRS much easier in one-way mode. Simpler, cheaper equipment. Wide coverage. May include a time code	Availability to non-NASA users not known. Limited accuracy capability. User costs uncertain at this time
12. Television broadcasting satellite :	High-accuracy mode	Some forms of user equipment for television timing measurements already developed. Many television satellites planned throughout the world. User equipment can be fairly simple with small antennas feasible. Accuracy can be excellent if satellite position is determined via auxiliary measurements at certain selected sites. Large signal-to-noise ratios and bandwidths available. On-site operation. Long-term continuity assured by primary satellite mission	Requires auxiliary facilities and techniques to determine satellite position and distribute this data to users for path corrections. Coverage confined to regions or, in some cases, individual countries
	General dissemination mode	Equipment already developed for using television synchronization pulses. Time code could be added to vertical interval. Small antennas, simple receivers and simple measurement techniques are feasible. Likely to be numerous, long-term television satellite systems in operation. On-site reception. Large S/N and bandwidth	Some knowledge of propagation path delays is needed. Coverage is mainly regional or to individual countries. Requires cooperation of non-T/F organizations for addition of vertical-interval time code

ANNEX I

SATELLITE TIME/FREQUENCY COMPARISONS

Year	Organizations and references	Satellite	Technique and description	Stated accuracy (A) or precision (P)
1962	USNO/USA, NPL/UK, RGO/UK [Steele *et al.*, 1964]	Telstar 6390 MHz	Two-way	1 µs (A) ; satellite link only 20 µs (A) ; total link
1965	USNO/USA, RRL/Japan [Markowitz *et al.*, 1966]	Relay-II 1723 MHz (up link) 4175 MHz (down link)	Two-way	0.1 µs (A) 0.01 µs (P)
1967	NBS/USA [Gatterer *et al.*, 1968]	ATS-1 136 MHz	One-way	10-60 µs (A)
1967	NBS/USA [Jespersen *et al.*, 1968]	ATS-1 149 MHz (up link) 136 MHz (down link)	Two-way	< 5 µs (A)
1968	NASA/USA [Laios, 1972]	GEOS-2 136 MHz	One-way ; spacecraft crystal clock	20 µs (A)
1969	CNES/France [Laidet, 1972]	Transit 400 MHz	One-way ; spacecraft crystal clocks	20 µs (A)
1970	NRL/USA [Murray *et al.*, 1971]	US Defense, Communications Satellite X band	Two-way	0.1-0.2 µs (A)
1970	NBS/USA [Hanson and Hamilton, 1971]	Tacsat/LES-6 sidetone ranging signals on 250 MHz carrier	One-way use of low-resolution ranging signals	40 µs (A)
1971	NASA/USA [Mazur, 1972]	ATS-3 6212 MHz (up link) 4119 MHz (down link)	Two-way	50-70 ns (A)
1971	NBS/USA [Hanson and Hamilton, 1974]	ATS-3 136 MHz	One-way transmission of WWV signals via satellite transponder	25 µs (A) 10 µs (P)
1974	APL/JHU/USA [Taylor, 1974]	Improved Transit 150 MHz 400 MHz	One-way ; spacecraft clock ; PRN-coded signal	< 75 ns (A) 10 ns (P)
1974	NASA/USA, FAA/USA [Chi and Byron, 1975]	ATS-1 6301 MHz (up link) 4178 MHz (down link)	Two-way ; PRN-coded signal	50 ns (A) 20 ns (P)
1975	NRL/USA, USNO/USA, RGO/UK, DNM/Australia	NTS-1 335 MHz	One-way ; spacecraft clock	< 500 ns (A) 50 ns (P)
1975	RRL/Japan, NASA/USA, USNO/USA [Saburi *et al.*, 1976]	ATS-1 6 GHz (up link) 4 GHz (down link)	Two-way with spread-spectrum, random-access communications system	10 ns (A) 1 ns (P)

ANNEX I – *(continued)*

Year	Organizations and references	Satellite	Technique and description	Stated accuracy (A) or precision (P)
1975	NBS/USA [Beehler *et al.*, 1979]	GOES 468 MHz	One-way	< 100 μs (A)
1976	CNES/France, LPTF/France, PTB/Federal Republic of Germany [Brunet, 1979]	Symphonie 6 GHz (up link) 4 GHz (down link)	Two-way	50 ns (A) < 10 ns (P)
1978	DNM/Australia, NRC/Canada, RGO/UK, BIH, IFAG/Federal Republic of Germany, NASA/USA, NBS/USA, NRL/USA, USNO/USA [Buisson *et al.*, 1978]	NTS-1 NTS-2 335 MHz 1580 MHz	One-way ; spacecraft clocks	< 1 μs (A)
1979	NRC/Canada, NBS/USA, USNO/USA, LPTF/France [Costain *et al.*, 1979]	CTS/Hermes Symphonie 4/6 GHz 12/14 GHz	Two-way	50 ns (A) 0.2 ns (P)
1979	NPL/India, PTB/Federal Republic of Germany [Mathur *et al.*, 1980]	Symphonie 4/6 GHz	Two-way	< 100 ns (A) < 10 ns (P)
1979	IEN/Italy [Detoma and Leschiutta, 1980]	Sirio-1 12/17 GHz	Two-way ; single, time-shared channel	50-100 ns (A) 1-5 ns (P)
1979	NIM/China, PTB/Federal Republic of Germany SO and CSAO/China, LPTF/France	Symphonie Symphonie	Two-way Two-way	< 80 ns (A) < 10 ns (P) < 100 ns (A) < 10 ns (P)
1980	USNO/USA [Putkovich, 1980] NBS/USA, USNO/USA [Davis *et al.*, 1981]	GPS GPS	One-way Common-view	< 100 ns (P) < 5 ns (P)
1980	RRL/Japan [Saburi *et al.*, 1980]	BSE	One-way	5×10^{-12} (1000 km) (A) 0.2 μs (A) 0.12 μs (P)
Since 1978 Since 1980	NRC/Canada LPTF/France, CNES/France PTB/Federal Republic of Germany	Symphonie Symphonie	Two-way Two-way	5 ns (P) (1) 5 ns (P) (1)

(1) Since April, 1980 precision has been improved to 0.5 ns by use of 1 MHz modulation.

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REPORT 735-1

IMPORTANCE OF STANDARD-FREQUENCY AND TIME-SIGNAL EMISSIONS IN BAND 5

(Study Programme 2B/7)

(1978-1982)

1. In band 5, a number of stations are emitting standard-frequency and time-signals on a continuous basis; some of these stations are radiating a time code with complete date information, such as the minute, hour, calendar day, day of the week, month and the year.

This kind of service is particularly well represented in Europe, where the emissions on band 5 are generally more used than the services on the bands allocated for the existing standard-frequency and time-signal emissions.

2. The segment of band 5 is particularly well suited for time-and-frequency distribution for the following reasons:

- the ground wave covers a wide range and is stronger than the sky wave up to distances of several hundred kilometres;
- the sky wave propagates via the ionospheric D layer and its propagation is stable especially in the daytime;
- the radiation efficiencies of the antennas in band 5 are considerably higher than the efficiencies that can be obtained in band 4 and relatively broad bandwidths can be secured.

As a consequence of these propagation and technical factors, the following features can be pointed out:

- for frequency comparisons, the phase time of the carrier is reproduced with good accuracy at the receiving station, e.g. with a standard deviation of less than 1 μs at a distance of 700 km during the day. At 300 km distance from the transmitting station the standard deviation of the recorded carrier phase time for the long-term average value has been found to be < 0.2 μs in the daytime. This allows a large geographic area to be supplied with standard frequencies with a relative uncertainty of less than 1×10^{-12} if appropriate averaging procedures are used. Secondary frequency standards, e.g. rubidium vapour standards can thus be locked, with suitable techniques, to these standard-frequency emissions, in order to improve their long-term frequency stability;
- for time comparisons, an uncertainty of less than 0.1 ms can be achieved during the day at distances of several hundred kilometres, using simple and inexpensive equipment. With some degradation of precision, slave clocks can be used at distances of up to 2000 km.

3. The following applications and classes of users have been identified as regards this kind of service on band 5:

3.1 *Standard frequency*

Industrial laboratories; scientific centres; time comparisons among time services of neighbouring countries; support of the time services of countries having no advanced technical facilities; control of the carrier frequency of transmitters used by various radio services; telecommunication networks (e.g. for synchronous or semi-synchronous digital networks); watch and chronometer calibration.

3.2 *Time signals*

Public clocks; speaking-clock services; public utilities such as television and broadcasting; postal services; railways and other means of transport including air traffic control; master clocks for industrial firms and public institutions.

Dating of events: traffic; geoscience (e.g. for seismic measurements and geoseismic investigations); medicine (for the chronology of medical examinations).

Common time reference for electronic data processing systems (e.g. processors) and for the process controllers in production plant.

Time reference for the dispatching of electrical energy, e.g. at time-dependent charges and studies on the dynamic behaviour of electric power network.

REPORT 271-6

STABILITY AND ACCURACY OF STANDARD FREQUENCY AND TIME SIGNALS IN VLF AND LF BANDS AS RECEIVED

(Question 3/7)

(1963-1966-1970-1971-1974-1978-1982)

The propagation time (phase delays) of VLF signals from a transmitter to locations thousands of kilometres distant varies little from day to day but has predominant diurnal and annual cycles created by ionospheric changes related to the solar zenith angle [Azuma, 1966; Iijima *et al.*, 1968; Decaux and Gabry, 1964]. Empirical and theoretical considerations have permitted accurate predictions of the propagation time which account not only for the diurnal and annual cycle, but also the sunspot number and the conductivity of the lower boundary of the wave guide supporting the VLF transmissions. The propagation time is sporadically altered by generally unpredictable sudden ionospheric disturbances (SID) which typically alter the ionosphere for 20 to 30 minutes and by polar cap absorption (PCA) events which alter the polar ionospheres for up to a week [Pierce, 1955; Reder *et al.*, 1964; Becker *et al.*, 1973a].

It has been observed that the phase shift accumulated during a 24-hour interval does not necessarily cancel, but can be $\pm 2\pi$ or a multiple thereof. The "cycle loss" can occur in several circumstances. For example, for great distances it will occur when the ratio of the amplitudes of the first to second order wave guide modes is less than unity at night and greater than unity during the day [Walker, 1967]. A second case may occur because of excessively large mode conversion at sunrise termination [Ries, 1967]. In addition, when the receiver is at a great distance (> 10 000 km) from the transmitter, it is possible that signals may be received along the long great circle path instead of the short great circle path for part of the day [Thompson *et al.*, 1963]. If the stability of the local frequency standard is sufficient, this situation is easily recognized and taken into account. Such effects have been observed for the signals of GBR, NBA and NPM in Australia, the signals of NBA and NPM in France and WWVL in the British Isles.

Other sources of variation include the cyclic variations at periods of 27, 29.53 and 14.765 days. The 27-day period is related to the average solar rotation rate and has been observed in ionospheric data [Ratcliff, 1960]. The 29.53 and 14.765-day periods are respectively related to the lunar synodic and semi-synodic tides and have been observed to exist in the lower atmosphere [Appleton and Beynon, 1949; Brady and Crombie, 1963; Rastogi, 1969; Chakravarty and Rastogi, 1970].

The effect of dispersion, which causes the phase and group velocities of VLF and LF waves to be different, must be considered in timing systems. At LF, appreciable dispersion occurs in the ground wave for propagation over ground of finite conductivity. At VLF, two sources of dispersion are important. The first occurs as a result of cut-off effects in the Earth-ionosphere wave guide [Crombie, 1966]. The second [Burgess, 1967] and less predictable source of dispersion is caused by interference between several wave-guide modes at night and thus causes spatially periodic variations in group velocity.

The time service provided by the transmitter HBG on 75 kHz located near Geneva (see Report 267, Table II) reaches a large part of Central Europe. Experiments have shown that the time signal of HBG can be received using simple receivers with an accuracy greater than ± 50 μs at medium distances (100-1000 km). The phase of the carrier is typically stable to better than ± 2 μs at the distance of 500 km during daylight hours.

The standard-frequency and time-signal transmitter DCF77 on 77.5 kHz, transmitting the official time signal and standard frequency of the Physikalisch-Technische Bundesanstalt (PTB) in the Federal Republic of Germany, is modulated in the following manner: at the beginning of each second, the carrier amplitude is reduced to about 25% of its normal amplitude, then, at the end of the second-markers, whose duration is 0.1 s or 0.2 s, the carrier amplitude is restored to its normal value.

Studies carried out at PTB and by some manufacturers working on this problem showed that simple oscillators can be more reliably synchronized with the residual carrier present as compared with zero carrier conditions during the period of the time markers.

In the modulation technique used by PTB the steepness of the falling edge is retained. The technique is as follows: at the beginning of each second, the transmitter drive is set to zero until the antenna amplitude has fallen to 25% of its maximum amplitude. The transmitter drive is then increased to retain 25% of carrier amplitude during the time marker.

Further study is required to determine whether the same reliability of oscillator synchronization can be achieved by means other than the retention of the residual carrier.

An investigation indicates [Becker *et al.*, 1973b] that the standard-frequency and time-signal transmitter DCF77 on 77.5 kHz can be well received in Central Europe and Scandinavia. During the day-time the carrier phase as received at 300 km distance from the location of the transmitter (Mainflingen near Darmstadt, Federal Republic of Germany) deviates only a few tenths of a microsecond from the average due to propagation changes. This results in a daily average relative frequency deviation of the carrier of 2.1×10^{-12} and in a weekly average deviation of 0.4×10^{-12} at a distance of 300 km. The time signals of DCF77 at noon were received with a spread of 37.5 μs as an average over three years [Becker, 1972; Becker and Hetzel, 1973].

A digital technique has been employed at the Free University, Brussels, to study the stability of the MSF 60 kHz time signals received at a distance of 420 km from the transmitter. The received pulse profile is sampled at 250 points, tests for quality are applied, and average values based on about 200 successive pulses are produced by a mini-computer.

The time of arrival may be taken as the time at which the signal envelope reaches a clearly defined percentage of the mean amplitude of the carrier (Am). Theoretical and experimental studies have shown that error is at a minimum at a characteristic point selected between 0.75 Am and 0.9 Am [Andrews *et al.*, 1970]. For the present study, the value chosen was 0.85 Am. In the case of the measurements carried out in the middle of the day – between 0900 and 1300 hours UTC – the standard deviation was usually between 5 and 10 μs. On the other hand, the fluctuations observed over long periods (several months) may attain 25 μs, taking account of the shape correction factor applied [Liévin *et al.*, 1975].

Experiments on the propagation of LF (40 kHz) signals at a distance of 400 km have been reported by Japan. The standard deviation of the daily phase fluctuations was found to be 1 μs in summer and 2 μs in winter; the seasonal variation in the phase of the signal as received at midday amounted to 3.3 μs.

The effect of sudden ionospheric disturbances (SID) in the D layer on the Loran-C timing and calibrating frequency was investigated in China by Shaanxi Astronomical Observatory (CSAO). During the period of the disturbance, because the sky-wave signals are enhanced and advanced and some of them mix with the sampled ground-wave signals, phase deviations of about 0.1-2 µs of the ground-wave signals occur [Miao and Yang, 1981].

Experimental evidence [Noonkester, 1972] indicates that VLF propagation time is subject to semi-synodic variations that would affect the dissemination of time and frequency information by VLF transmissions. The average amplitude of the lunar semi-synodic period was found to be 0.18 µs at midday and 0.52 µs at midnight for one north-south VLF path at 10.2 kHz. The maximum amplitude was found to be 1.3 µs during mid-winter months at midnight. Users of VLF transmissions for time and frequency information should be made aware of the known periodic components so that they may anticipate a certain error range.

As regards the long-term integration of the received phase, the accuracy which can be achieved will depend to a large extent on the complexity of the receiving equipment and measuring procedures. It has been reported [Leschiutta, 1968] that when using quartz oscillators at the receiving station the accumulated overall error for path lengths of 1000 to 5000 km is between 25 and 50 µs per year when receiving transmissions in bands 4 and 5. However, when the received phase is referred to an atomic standard and use is made of a receiver which can be calibrated and which does not lose the phase reference [Becker *et al.*, 1969] much improved results can be obtained. Thus, NSS received at a distance of 5000 km and recorded over a period in excess of 450 days shows variations relative to the mean phase of at most ± 10 µs and generally less than ± 3 µs. This latter figure is equivalent to a frequency uncertainty of about 1×10^{-13} over a year. Further improvements in the stability of the received phase can be obtained by forming a linear combination of the phase of two emissions at different frequencies to significantly reduce the major solar effects; the improvement is most noticeable when comparisons are made simultaneously for both directions of transmission over the same path at carrier frequencies not too far separated in band 4. Still greater accuracy in the phase reference can be obtained by the application of smoothing techniques based on the statistical character of the phase fluctuations [Becker *et al.*, 1969; Guetrot *et al.*, 1969] but these are effective only over limited periods where the statistical behaviour can be assumed representative of the process.

When Loran-C became available for precise time comparisons, the variations of propagation delays, and thus time comparison using VLF carrier phase, became easier to measure (for Loran-C phase values see United States Naval Observatory (USNO) Time Service Announcements, Series 4). Such measurements were made for several years over a path length of about 5000 km between North America and Europe. Three VLF transmissions (NAA, 17.8 kHz; GBR, 16 kHz; Omega-Trinidad, 12.0 kHz) were used. Typical results are given in Table I. In Table I, $\sigma_{\Delta t}(\tau)$ is the average change (divided by $\sqrt{2}$) of the measured time difference Δt, occurring during the time of measurement τ. This statistical processing technique is due to Kolmogorov [1941], Malakhov [1966a and b] and Allan [1966]. $\sigma_y(\tau)$ is the relative uncertainty of a frequency comparison in the measuring time τ.

TABLE I – *Typical fluctuations of propagation delays of VLF signals between North America and Europe*

τ (days)	$\sigma_{\Delta t}(\tau)$ (µs)	$\sigma_y(\tau)$ (10^{-12})
1	1.9	31
10	2.6	4.2
100	3.7	0.61
1000	5.3	0.09

Similarly, seasonal influences of $\sigma_{\Delta t}(\tau)$, as well as yearly and half-yearly correlations of the propagation fluctuations, were found. Due to the correlation between adjacent values, the possibility of improving the accuracy of measurement by means of averaging values is limited: in the most favourable case the measuring error is halved (from 2.2 µs to 1.1 µs) by averaging one hundred daily values instead of taking one daily value only.

In more recent experiments performed at NPL (India), long term integration results of the GBR carrier were confirmed indirectly with Loran-C measurements and directly via a geosynchronous satellite link. Over a period of one year an accuracy of a few parts in 10^{14} in frequency and 1-2 µs in time was achieved [Sen Gupta *et al.*, 1980; Mathur *et al.*, 1980].

For restoration of a VLF phase relationship, specific measuring techniques have been developed as well as a calibration technique to measure the time delay of the antenna and receiver [Becker *et al.*, 1973a; Becker, 1973]. This technique uses a test signal which is monitored by a parallel divider chain from which the time scale is generated. If this method is used to re-establish the lost phase relationship, an average error of 1.1 µs results if the break is short, and the values before and after the break are correlated. If the break is long (e.g. longer than 60 days), the measured values before and after the break are uncorrelated and an average error of 4.7 µs results.

Other techniques for cycle identification are available. The use of two coherent VLF signals for time transmission was first proposed in 1962 [Morgan, 1962], and demonstrated in 1966 [Chi and Witt, 1966; Fey and Looney, 1966]. It is a two-step time recovery technique. The phases of the VLF signals are used to determine the time difference between the clocks at the transmitting and receiving sites less than one cycle (fine time) and the phase difference between the received signal and the locally generated signal data of the two coherently transmitted signals are used to determine the carrier cycle of one of the received signals (coarse time). Experimental radio station WWVL of the United States National Bureau of Standards at Fort Collins, Colorado was used from 1964 to 1968 to conduct the feasibility test. The signal frequencies were 19.9 and 20 kHz. Larger frequency separations up to 700 Hz were tested. For frequency separation higher than 500 Hz, cycle identification was degraded due to the larger frequency dispersion effect of the propagation medium.

The Omega VLF navigation system is coming into operation. It uses multiple frequency VLF transmissions for the dissemination of time and frequency information. The advantages of this technique are well established [Swanson and Kugel, 1972]. These transmissions should be a useful source of frequency and precise time and should also enhance the status of VLF techniques for time and frequency. A total of eight stations providing continuous and redundant world-wide coverage is planned and is scheduled for global implementation. Each station derives its radiated phase from an ensemble of four caesium frequency standards, and transmits navigational frequencies on a time-shared basis every 10 seconds. The four navigational frequencies are 10.2, 11.05, 11⅓ and 13.6 kHz. Each station may also radiate one additional frequency in the 11⅓ to 13.6 kHz regions from which time or frequency information can be extracted. Report 267 lists these additional transmissions in Table III.

Development work on precise two-frequency timing has already taken place [Chi *et al.*, 1972]. Tests conducted in 1973 and 1974 using the 13.10 and 12.85 kHz signals transmitted for time transmission from the Omega station in North Dakota, showed reliable cycle identification for path lengths up to 7000 km [Chi and Wardrip, 1973 and 1974]. Further tests for path links up to 15 000 km using experimental transmissions from Omega stations, in North Dakota and Hawaii have been made.

The long range and phase stable VLF transmissions offer potential time reference signals for international time comparison to an accuracy of ± 1 µs.

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RECOMMENDATION 486-1 *

REFERENCE OF PRECISELY CONTROLLED FREQUENCY GENERATORS AND EMISSIONS TO THE INTERNATIONAL ATOMIC TIME SCALE

(Question 3/7)

(1974–1978)

The CCIR,

CONSIDERING

(a) that, for a user, data concerning the error of a standard-frequency and time-signal emission are of great importance;

(b) that the International Atomic Time scale (TAI) has considerable importance as a reference for time and frequency comparisons;

(c) that, in many cases, it is technically possible to adjust a radiated standard frequency so that the variations of phase with respect to TAI or Coordinated Universal Time (UTC) remain within a narrow tolerance $\pm \Delta t$, which is small compared to the period of the carrier frequency;

(d) that the TAI frequency and the UTC frequency are identical;

(e) that equipment is available which is capable of receiving several nearly synchronous emissions, thereby providing alternative operation in case of transmitter interruption;

(f) that there is a need for universally accepted reference frequencies for use in electronic systems;

(g) that there is an ever-increasing need for frequencies of high stability, particularly with regard to data transmission;

(h) that many new precisely controlled electronic systems (e.g. those controlled by atomic frequency generators) are now coming into use;

(j) that these systems can be better coordinated if they use a common frequency reference,

UNANIMOUSLY RECOMMENDS

1. that the UTC frequency should be used as the ultimate reference for standard-frequency emissions;

2. that data concerning the accuracy of the standard frequency, with reference to the UTC frequency, should be an average of the relative frequency difference over 10 days or more;

3. that the range $\pm \Delta t$ over which the phase of the standard frequency can vary with reference to UTC should be specified for each LF and VLF emission and the values published by the Administrations responsible for the standard time and frequency services;

4. that the UTC frequency should also be used as the ultimate reference for other electronic systems.

REPORT 270-3

OPTIMUM USE OF THE FREQUENCY SPECTRUM FOR HIGH-PRECISION TIME SIGNALS

(Study Programme 3A/7)

(1963–1966–1970–1978)

There is an increasing number of applications requiring the use of a very precise reference for time-signal synchronization. In an effort to achieve greater precision, it is desirable to make use of a suitable bandwidth up to the limits imposed by:

- the band allocated;
- the instabilities of the propagation;
- considerations of noise and interference.

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* The Director, CCIR is requested to bring this Recommendation to the attention of the CCITT.

Opportunities also exist for time dissemination and comparison by the use of signals which are transmitted for other purposes, such as VLF communication, broadcasting and television, or as aids to navigation. Use of these signals, when possible, conserves resources both of frequency-spectrum and of equipment and is therefore to be encouraged, but it is not considered further in this Report unless special features of the emissions make possible timing uncertainties significantly smaller than would normally be available within the same bandwidth.

The Loran-C navigation system, operating within the band 100 kHz ± 10 kHz, is in widespread use and yields timing uncertainties less than 1 μs over distances of up to 2000 km. The phase-encoded pulse modulation provides discrimination against signals received via the ionosphere and so makes possible measurements in which the ground-wave-propagated signal is dominant. The use of different modulation rates allows the operation of several separate transmitter chains within the same frequency band [Potts and Wieder, 1972].

At high frequencies, where long-distance propagation is wholly dependent upon the ionosphere, the precision with which the time signals can be received is limited by the characteristics of the propagation medium. The bandwidths in use have been largely determined by administrative rather than technical or scientific considerations. It may be noticed that many stations listed in Report 267 use an audio-frequency modulation as the time signal. This takes the form previously recommended by the CCIR and consists of n cycles of 200 n Hz audio modulation, leading to a pulse of constant length equal to 5 ms. The value of n can be varied conveniently to distinguish the various emissions.

Thus, WWV and several other stations have adopted a pulse wave form with $n = 5$, i.e., 5 cycles at 1000 Hz. For WWVH, $n = 6$ has been chosen, while JJY has adopted a pulse with $n = 8$. The use of this form of pulse does not make it possible to resolve one of the several components of a signal received via more than one path (multipath propagation). It is, however, reasonably economical in bandwidth. Disturbed propagation conditions produce easily recognizable distortions of the pulse wave form.

A method of signal dissemination which does not require the use of excessive bandwidth has been investigated for use in navigation [Casselmann and Tibbals, 1958] and timing [Morgan and Baltzer, 1964]. This method makes use of the interference between two closely-spaced phase coherent carrier frequencies to generate a coarse reference. When this coarse reference can be realized at the receiver with sufficient phase stability it serves to identify one particular cycle of the carrier frequencies and a precise time reference can then be obtained from observations of the carrier phase.

Early experiments using 19.9 and 20.0 kHz over a 1400 km path showed promise for cycle identification. Later experimental studies, including a technique for extracting time using conventional VLF receivers and giving results covering a period of months over a 2400 km path have been reported [Fey and Looney, 1966]. Further studies using several frequency separations and paths have been described [Raules and Burgess, 1967]. An experimental dual-frequency timing receiver has been constructed for use with the 20.0 and 19.9 kHz transmissions of WWVL [Chi and Witt, 1966]. The result of these various investigations suggested that a 100 Hz frequency difference between the carrier frequencies is too small to permit reliable daily cycle identification over arbitrary paths and in a further series of experiments a third carrier frequency was added to the WWVL emission to give frequency differences of 500 and 600 Hz. The results obtained under these conditions indicate that, with suitable averaging, cycle identification can be achieved at distances up to 8000 km. An analytical study using information theory techniques indicates that a multiple CW system may be optimum from the bandwidth conservation viewpoint [Jespersen, 1967]. Morgan [1967] has a useful bibliography on the general subject.

Theoretical studies have been made on a similar, very narrow bandwidth system at VLF [Egidi, 1969]. Two procedures have been investigated. The first uses a particular wave form, which can be interpreted as the product of two sinusoidal signals of the same amplitude, having frequencies in an integral ratio with a convenient phase relation. This procedure takes advantage of the timing index given by phase modulation of the radio frequency signal [Egidi and Oberto, 1964a and b] (not of the envelope). The second procedure uses periodic phase inversions of the carrier wave; the cases where inversions occur at zero phase and $\pi/2$ phase have been treated in detail [Egidi, 1968]. This reference also presents the results of calculations giving the relation between time discrimination and the bandwidth of the system.

A system using multiple carriers at VLF has also been proposed [CCIR, 1966-69] which enables the transmission of both 1 s and 10 ms time signals without interruption to the communication service. A theoretical description of the transmissions with three frequencies and of the receiving devices is given in the reference.

There is a limit to the timing accuracy which can be achieved by using two or more closely spaced signals. The limitation arises because the group delay T of the composite signal is given by

$$T = (\varphi_2 - \varphi_1)/2\pi(f_2 - f_1)$$

where φ_1 and φ_2 are the phase delays experienced by the two frequencies f_1 and f_2. The variation in the phase delays due to propagation can be expected to approach zero as $(f_2 - f_1)$ approaches zero. However the effect of additive noise is essentially independent of the frequency spacing. Under these conditions the standard deviation of the group delay σ_T is given by [Morgan and Baltzer, 1964]:

$$\sigma_T = (\sqrt{2}\sigma_\varphi)/2\pi(f_2 - f_1)$$

where $\sigma_\varphi = \sigma_{\varphi 1} = \sigma_{\varphi 2}$ is the standard deviation of the phase delays due to additive noise. As an example, if $\sigma_\varphi = 1$ μs and $f_1 = 20$ kHz while $f_2 = 20\,001$ Hz, $\sigma_T = 20\,000$ μs; whereas, if $f_2 = 20\,100$ Hz, $\sigma_T = 200$ μs. Thus, as the spacing of the frequencies decreases, the error due to uncorrelated phase fluctuations increases.

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REPORT 364-4

PERFORMANCE OF STANDARD-FREQUENCY GENERATORS

(Study Programme 3B/7)

(1966-1970-1974-1978-1982)

1. Introduction

In recent years, the results of a large number of studies have become available concerning the instability of standard-frequency generators. Theoretical treatments of the problem, definitions and experimental procedures for measurement have been widely investigated (see Report 580; specially for notations).

It has been shown [IEEE, 1966; NASA, 1964; Yasuda and Yoshimura, 1964] that the type of noise present in a standard-frequency generator may be classified by the form of the frequency (or phase) spectral density which it produces. Such densities are the Fourier transforms of the related auto-correlation functions and suitable mathematical techniques have been devised for operating on these functions [Blackman and Tukey, 1959; Davenport and Root, 1958]. The effect of the so-called "flicker noise" having a $1/f$ spectral variation is particularly important in the long-term operation of all forms of frequency standards and special studies have devoted to this aspect [NBS, 1974].

In both atomic sources and in quartz crystal oscillators, thermal and shot noise will contribute to the short-term instability and, depending upon the mechanism, will produce either a flat or f^2 variation in the frequency spectral density. The intended use of the standard-frequency generator will determine the importance of these effects relative to the instability produced by flicker noise and other frequency disturbances.

With the increasing availability and use of commercial atomic frequency standards to generate very stable time scales in a number of laboratories throughout the world, a large amount of stability performance data has been accumulated. One conclusion is that commercial caesium beam frequency standards occasionally demonstrate small, but significant systematic frequency shifts.

The appearance of these shifts shows that the fluctuation phenomena of these standards cannot be fully described by the stability measure $\sigma_y(\tau)$ in accordance with Kolmogorov [1941], Malakhov [1966], and Allan [1966]. Even if the value $\sigma_y(\tau)$ is available for every clock of a group, it may not be statistically meaningful to give the $\sigma_y(\tau)$ for the average of the group. This applies in particular to long time intervals (> 0.5 year). It is believed that this is due to the non-stationary behaviour of some clocks for time intervals which are an appreciable fraction of the clocks' lifetime.

In other words, this behaviour can be associated mathematically with statistical models but does not necessarily reflect an identified physical process.

2. Caesium beam frequency standards

As a typical example, systematic effects in commercial caesium standards have been investigated by the PTB [Becker and Hetzel, 1973] and the BIH [Guinot, 1974]. Typical long-term performance of commercial caesium standards in PTB laboratory consisted of a small relative frequency change of about -0.4×10^{-13} during the first 60 days of operation. After that the frequency remained comparatively constant (about $\pm 1 \times 10^{-13}$) for a time interval between 9 months and 3 years, after which the frequency decreased by several times 10^{-13} within a few weeks. Later on the frequency became more and more unstable. On the average more frequency decreases than increases have been observed. This typical negative frequency shift has not, however, been observed in some other laboratories [Winkler *et al.*, 1970].

The PTB has also developed procedures for periodically monitoring and readjusting the magnetic fields in commercial caesium standards. Such procedures appear to produce improved stability performance, especially during the first six months of a clock's life.

In view of the small long-term drifts mentioned above, which have been observed both in individual commercial caesium standards and in time scales based on these devices, the role played by the national laboratories primary reference standards assumes added importance.

At the present time, there are operating primary laboratory-type caesium beam frequency standards located at the PTB in the Federal Republic of Germany [Becker, 1976], NRC in Canada [Mungall *et al.*, 1976], and NBS in the United States [Wineland *et al.*, 1976]. These standards have been evaluated with respect to most parameters affecting their output frequency; i.e., experiments and theoretical studies have been performed which yield knowledge about the biases which cause the output frequency to differ from the unperturbed atomic resonance frequency. The accuracy which then results from an analysis of the data is within 1×10^{-13} for all three laboratory standards. International comparisons of the three devices, using TAI as a common reference, show agreements to within 2×10^{-13} peak-to-peak variation. The measurements also indicated (1976) that the TAI frequency was too high with respect to the definition of the second by about 1×10^{-12}. A step adjustment in TAI of 1×10^{-12} corrected this offset on 1 January 1977. The offset was due to the fact that TAI was constructed by the BIH in such a way as to maximize its uniformity, thus reasonably maintaining the rate adopted for TAI on 1 January 1969 on the basis of a limited number of contributing clocks. Other studies were made of the long-term stability of the TAI scale, constructed from commercial caesium standards, using primary standards as the reference. Over a period from 1969 to 1973, the PTB measurements showed the TAI frequency to have decreased on the average by about 1×10^{-13} each year [Becker, 1973]. Later measurements indicate that this drift has continued through 1977. A new caesium beam tube accuracy evaluation technique has been developed that is applicable to both laboratory and commercial type standards [Hellwig *et al.*, 1973].

Four long beam primary caesium clocks are now in operation at NRC. CsV, the first long beam primary clock, started operation in May 1975. Accuracy evaluations, performed at 6 to 12 month intervals, contribute negligible errors to the time scale, and have given consistent accuracy estimates of better than 1×10^{-13} [Mungall and Costain, 1977; Mungall, 1978]. Three new smaller clocks; CsVI A, B and C, constructed during 1977 and 1978 and used as secondary clocks during 1979, started operation as primary clocks early in December 1979. Their frequencies are within 1×10^{-13} of that of CsV, with a mean value of $+6.5 \times 10^{-14}$. Operating and evaluation procedures for all four clocks are similar. Routine reports to the BIH of the data from these new clocks commenced in January 1980.

The caesium beam time and frequency standard CS1 of the PTB has been in continuous operation as a primary clock since mid-1978, whereas it had until then only been switched on approximately every three months to monitor the frequency of PTB's atomic time scale generated by industrial caesium beam atomic clocks. The primary clock CS1 contributes directly to the formation of the International Atomic Time scale TAI [Becker, 1979]. The root mean square of the uncertainties caused by the various corrections yields for CS1, a relative uncertainty of 1×10^{-14} for frequency values averaged over 80 days [Becker, 1974; Becker, 1979]. The relative instability of the frequency standard averaged over 80 days is estimated at 6.4×10^{-15}.

Two Chinese laboratory-type caesium beam atomic primary time and frequency standards (Cs2 and Cs3) have been developed. The two beam tubes have an interaction length of 3.68 m. Identical oven-detector assemblies are installed at each end of the beam tube for beam reversal purposes. The beam optics are typical dipole systems, but one of them uses electromegnets and the other one permanent magnets. The accuracy and the instability of Cs2 and Cs3 were evaluated and measured several times from 1977 to 1980. The total uncertainties (root-mean-square) are 4.1×10^{-13} (1 σ) for Cs2 and 4.5×10^{-13} (1 σ) for Cs3, but in view of some limitations of operational conditions it is preferred to claim an accuracy of 8×10^{-13} (1 σ) for both standards.

An experimental passive caesium beam microwave resonator using optical pumping by a continuous single-mode tunable laser has been developed [Arditi and Picqué, 1980]. The difference in population between the hyperfine transition levels of the ground state of 133 Cs is produced by optical pumping with the GaAs laser at 852.1 nm; the microwave resonance, detected by the change in intensity of the fluorescence induced by the same laser, was used to synchronize an oscillator with an accuracy of a few parts in 10^{11}.

3. Hydrogen frequency standards

Work has been in progress to achieve, with hydrogen standards, accuracies commensurate with the excellent stabilities available in these devices. The principal limitation on the accuracy of the hydrogen maser has been the non-reproducibility of the wall shift [Vanier *et al.*, 1975]. To overcome this, it was proposed that a flexible bulb be used in a hydrogen maser to calibrate the wall shift within a single device by varying the collision rate in a known way [Brenner, 1969]. This technique was tested in conventional masers using both a flexible squeeze bottle [Brenner, 1970] and a flexible cone [Debely, 1970] as storage bulbs. The technique has been refined by using a flexible cone in the large storage box hydrogen maser [Uzgiris and Ramsey, 1970; Reinhardt, 1973] and by using a concertina bulb in a conventional maser [Peters, 1975]. Several ideas for future devices using the technique have also been proposed [Vanier *et al.*, 1975; Vessot *et al.*, 1971]. Among these is the zero wall shift maser [Vessot *et al.*, 1971] which is based on the discovery that the wall shift passes through zero at about 100 °C [Zitzewitz and Ramsey, 1971; Vessot and Levine, 1970] and which utilizes a flexible cone as a null detector. The accuracy achievable with the flexible bulb technique promises to be 1×10^{-14} or better [Peters, 1975; Reinhardt, 1973; Brenner, 1969]. Recent discoveries in hydrogen masers of an anomalous spin exchange shift and a magnetic inhomogeneity shift [Crampton and Wang, 1974] and the development of methods to correct for these shifts [Crampton and Wang, 1974; Reinhardt and Peters, 1975] lend some support to a potential achievement of 1×10^{-14} accuracy. Experiments have also been performed utilizing hydrogen in a conventional atomic beam device [Peters, 1972].

Cavity pulling is probably the most important cause for long-term (1 day and longer) instabilities in hydrogen masers. Cavity tuning schemes have been developed and used [Peters *et al.*, 1968; Vessot and Levine, 1970] as well as passively operating maser [Hellwig and Bell, 1972; Walls and Hellwig, 1976]. Recent results show that pairs of hydrogen masers which are autotuned against one another can maintain stabilities of 1 to 2×10^{-14} for up to 7 days [Petit *et al.*, 1975; Morris and Nakagiri, 1976]. The frequency of the masers at NRC measured against TAI, has decreased since 1971; the most accurate measurements, taken over the period 1975 to 1979, have shown a change of about 4×10^{-13} per year, with a total change over this period of 1.7×10^{-12} [Morris, 1978].

The time-keeping performance of a prototype small passive hydrogen maser developed at NBS [Walls, 1976] was recently compared to UTC (NBS). The measurements indicated a joint time-keeping stability of about 1.2 ns/day. The frequency stability of the small passive maser was estimated to be $\sigma_y(\tau) = 1.1 \times 10^{-14}$ for $\tau = 1$ to 8 days based on 32 consecutive days of data. Preliminary stability measurements indicate great potential for the passive masers as clocks. The small passive hydrogen masers will be contributors to the NBS time scale.

The metrological properties of two hydrogen masers have been studied in detail [Petit *et al.*, 1974]. A relative frequency stability of 3×10^{-13} for $\tau \approx 10^3$ s and of 2×10^{-14} for $\tau = 5$ days was obtained [Petit *et al.*, 1975]. The combined effect of the inhomogeneities of the static magnetic field and the microwave field was measured [Petit *et al.*, 1974]. The elimination of the mean dephasing by collision on the FEP 120 lining in the neighbourhood of 90 °C was verified [Petit *et al.*, 1975]. The theoretical estimate of the spin exchange frequency shift was confirmed experimentally [Desaintfuscien *et al.*, 1975]. It is very useful for the accurate determination of the residual frequency shifts recently revealed by Crampton [Crampton *et al.*, 1976].

An accuracy of 6×10^{-13} has been achieved on a hydrogen maser equipped with a storage bulb having two teflon-lined coaxial compartments [Petit *et al.*, 1980].

4. Performance of various devices

The particular type of frequency standard to serve as an optimum frequency reference in a given application depends, at least in part, on the measurement averaging time involved. Figure 1 presents some measured instability data as a function of measurement averaging time for several different types of frequency standards. Frequency drift has been removed from these plots. No attempt has been made to extend the stability plots to longer averaging times than shown because sufficient well-documented long-term data do not exist for most of the devices.

Figure 1 shows that quartz crystal oscillators and superconducting cavity (SCC) oscillators or rubidium masers show the best stability for short ($\tau < 1$ s) sampling times. The hydrogen maser and the superconducting cavity oscillator show a medium-term ($1 \text{ s} < \tau < 10\,000$ s) stability superior to any other standard available today. Representations of stability measures for several different atomic frequency standards which are currently available are shown in Fig. 2 in the time-domain and in Fig. 3 in the frequency-domain. The $S_y(f)$ curves are all normalized to $\upsilon_0 = 5$ MHz, $f_h = 10$ kHz except for the hydrogen maser for which $f_h = 10$ Hz. The quartz crystal controlled oscillator is a selected unit from the state-of-the-art units. The passive atomic frequency standards are used to demonstrate the effect of servo loop time constants ranging from 60 seconds to 300 ms. Caesium beam standards show presently the best long-term ($\tau > 10\,000$ s) stability. Rubidium and caesium gas cell standards are not superior in any region of averaging times; however, as shown in Table I, they offer a good combination of frequency stability, cost and size [Rovera *et al.*, 1976; Rovera and Beverini, 1977].

A frequency stability of 6×10^{-14} over 128 s was obtained with a quartz crystal, fitted with non-adhering electrodes, in the passive mode [Stein *et al.*, 1978; Besson and Peier, 1980].

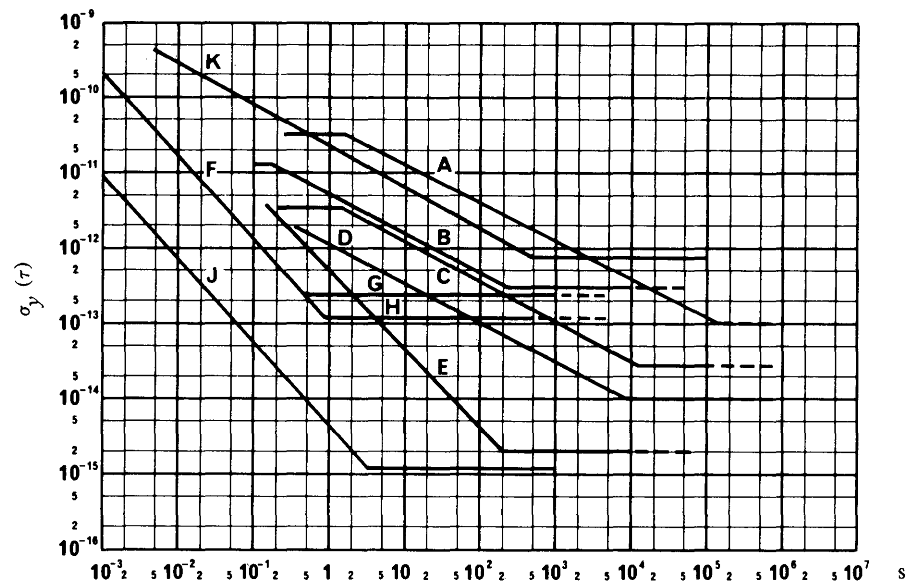

FIGURE 1 – *Typical measured instabilities of several tested types of standards*
The data are based on publications and specifications

A: commercial caesium beam
B: commercial Rb gas cell
C: high performance commercial caesium beam
D: laboratory caesium beam
E: H Maser ($f_h = 10$ Hz)
F: Rb Maser, quartz oscillator ($f_h = 1$ kHz)
G: Quartz crystal controlled oscillator
H: Rb Maser
J: Super Conducting Cavity oscillator ($f_h = 10$ kHz)
K: Cs Gas Cell

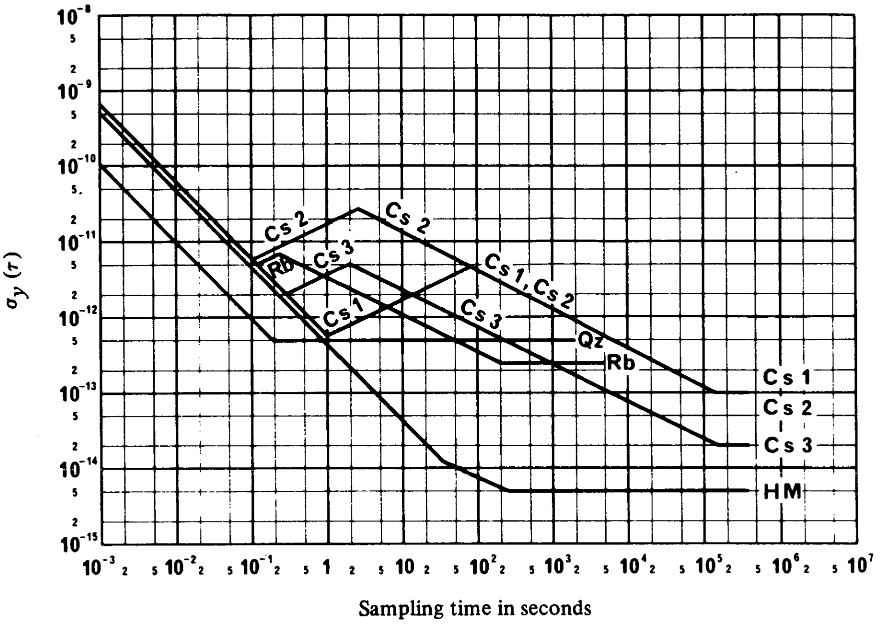

FIGURE 2 – *Frequency instability measures of typical atomic frequency standards and a selected quartz crystal controlled oscillator in the time domain*

OSC	Servo loop time const (s)	f_h (kHz)
Cs1 (Long time constant)	60	10
Cs2 (Short time constant)	2	10
Cs3 (High performance constant)	2	10
Rb	0.3	10
Qz	–	10
HM	–	0.01

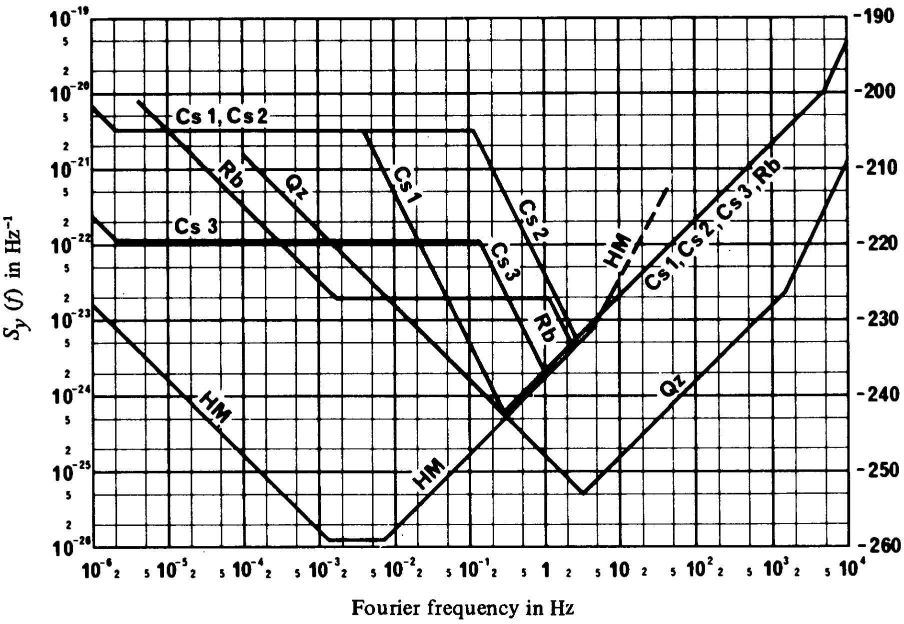

FIGURE 3 – *Frequency instability measures of typical atomic frequency standards and a selected quartz crystal controlled oscillator in the frequency domain*

OCS	f_h (Hz)
Cs1 (Long time constant)	10^4
Cs2 (Short time constant)	10^4
Cs3 (High performance constant)	10^4
Rb	10^4
Qz	10^4
HM	10

5. Superconducting-cavity stabilized oscillators

The superconducting cavity oscillator data perhaps merit special attention since this device is not yet as well known as other types of highly stable oscillator frequency standards. This oscillator concept has been recently developed and studied and has resulted in laboratory devices with demonstrated stability performance that exceeds that of any other known oscillator [Jimenez and Septier, 1973; Turneaure and Stein, 1975]. In fact, instabilities as low as 6×10^{-16} have been observed at averaging times of hundreds of seconds in one laboratory under particularly favourable conditions [Stein, 1975]. The super-conducting cavity oscillator appears adaptable to commercial design and would be the best oscillator for short or medium-term stabilities (averaging times of up to 1000 seconds). It could be of interest for special uses such as very long baseline interferometry and the production of highly stable microwaves and higher frequencies. It appears, however, unlikely that the superconducting cavity oscillator can become a very small and rugged device and it is equally unlikely that its environmental sensitivity can be reduced significantly.

6. Ion storage devices

A 5 MHz quartz oscillator has been controlled by the hyperfine resonance of 10^6 ions of mercury isotope 199, confined in a radio-frequency trap. The transition between hyperfine levels of the ground state roughly 40.5 GHz apart was observed through fluorescence, at 194 nm, of the 199 Hg^+ ions subjected to the optical pumping of a lamp emitting light with a resonance of 202 Hg^+. A frequency stability of the form $\sigma_y(\tau) = 3.6 \times 10^{-11} \tau^{-1/2}$ was obtained for: $10 \text{ s} < \tau < 3500 \text{ s}$ [Jardino *et al.*, 1980].

7. System applications

Table II combines stability data with operational data and other device characteristics. For each listed device in Table II, the data may be viewed as being compatible, i.e. realizable in the very same device. The values in Table II are choices of combinations which are presently available; however, other combinations are also possible. The values were chosen in view of a particular application: use of standards in aircraft and spacecraft.

Tables I and II and Fig. 1 illustrate that the choice of atomic frequency standards should be a matter of careful consideration of the technical alternatives, cost, size, etc., and actual requirements. For system applications using precision oscillators, it is important to first determine the required stability performance of the devices; secondly, to consider the environmental conditions under which the standard has to perform; and thirdly to determine the availability, size, weight, cost and turn-on characteristics of the standard. Occasionally, a system designer will find that a standard with all the characteristics needed does not exist on the market. In this case, the designer has two alternatives: either to adjust his system parameters to accommodate one of the available standards or to choose a combination of these standards to fulfill his need. The latter is an important aspect; suppose, for example, that a system requires very good long-term stability and clock performance, but at the same time high spectral purity; i.e., very good short-term stability. In addition, no cost, weight or size constraints are imposed. An optimum combination for this case could be a crystal oscillator paired with a caesium beam or hydrogen frequency standard. The systems concept as a solution to a design problem is a very powerful tool, and it can be realized technically at no sacrifice in the performance of the individual components of the system. The only actual restrictions may be physical size and cost.

The column "retrace to previous frequency" of Table II refers to the ability of the device to reproduce its previous frequency without readjustment after turnoff and cooling down.

TABLE I* – *Typical performances and practical physical characteristics of the major atomic frequency standards*

Frequency standard	Intrinsic reproducibility	Uncertainty	Stability			Volume (dm^3)	Instrument mass (kg)	Power demand (W)	Commercial availability	Estimated cost 1977 (x 1000 $)
			Short term(1s)	Flicker floor	Drift per year					
NH_3 maser	5×10^{-11}	5×10^{-11}	10^{-12}	10^{-12}	10^{-10}	50	50	50	No	40
H maser laboratory	10^{-12}	10^{-12}	5×10^{-13}	$2-5 \times 10^{-15}$	$<10^{-13}$	1000	250	100	No	250
H maser (small unit)	10^{-12}	10^{-12}	5×10^{-13}	5×10^{-15}		100	45	30	No	250
H maser (passive)	10^{-12}	10^{-12}	2×10^{-12}	$<2 \times 10^{-15}$	$<2 \times 10^{-13}$*	1000	250	100	No	250
87 Rb maser	(1)	(1)	10^{-13}	10^{-13}		30	30	50	No	100
Cs beam laboratory	10^{-13}	1×10^{-13}	10^{-12}	10^{-14}	$<10^{-13}$	2000	500	100	No	500
Cs beam(2) (commercial unit)	5×10^{-12}	7×10^{-12}	5×10^{-12}	5×10^{-14}	$<10^{-12}$	20	30	30	Yes	25
Rb cell (high performances)	(1)	(1)	7×10^{-12}	4×10^{-13}	10^{-10}	20	30	30	Yes	5–10
Rb cell (simplified)	(1)	(1)	10^{-11}	5×10^{-13}	10^{-9}	2	2	15	Yes	4
Super conducting cavity	(1)	(1)	10^{-14}	6×10^{-16}	(3)	2000	250	1000	No	100
127 I_2 stabilized laser (small)	10^{-11}	10^{-11}	10^{-11}	10^{-12}		30	40	50	No	200
CH_4 stabilized laser (small)	10^{-11}	10^{-11}	3×10^{-13}	3×10^{-14}		30	40	50	No	100
CO_2 stabilized laser	10^{-10}	10^{-10}	5×10^{-13}	10^{-13}		60	100	200	No	100

* Based on reference: Audoin and Vanier, [1976]

(1) The specification does not apply.

(2) "High performance unit"

(3) Not available.

TABLE II – *Selection of Available Devices. Other combinations of values are also available. The values were chosen in view of possible use in aircraft, and spacecraft environments*

Characteristic / Device	Rel. cost	Size(4) (dm³)	Mass (kg)	Power consumption (W)	Stability			Retrace to previous frequency(2)	Environment			
					One second	Floor	Drift (per day)		Temp. (K)	Accl. (g)	Barom. (mbar)	Mag. field (A/m)
Crystal	0.1	1	0.5	3	10^{-11}	10^{-11}	10^{-11}	10^{-10}	10^{-11}	10^{-9}	–	–
Rb (gas cell)	0.5	1	1.0	15	10^{-11}	10^{-12}	10^{-12} (1)	10^{-11}	10^{-11}	10^{-12} (3)	10^{-13}	8.10^{-6}
Caesium (tube)	1.0	10	20.0	30	10^{-11}	10^{-13}	10^{-14} (1)	10^{-12}	10^{-12}	10^{-13}	10^{-15}	8.10^{-7}
H (maser)	8.0	100	40.0	20	10^{-12}	10^{-14}	10^{-14} (1)	10^{-12}	10^{-13}	10^{-12} (3)	10^{-15}	8.10^{-7}

(1) These values have been observed with some units, but in most cases, the frequency drift can be expected to be smaller than this.

(2) Typical change without realignment.

(3) Estimation.

(4) Size refers to units without batteries.

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REPORT 580-1

CHARACTERIZATION OF FREQUENCY AND PHASE NOISE

(Study Programme 3B/7)

(1974-1978)

1. Introduction

Techniques to characterize and to measure the frequency and phase instabilities in frequency generators and received radio signals are of fundamental importance to users of frequency and time standards.

In 1964 a subcommittee on frequency stability was formed, within the Institute of Electrical and Electronic Engineers (IEEE) Standards Committee 14 and later (in 1966) in the Technical Committee on Frequency and Time within the Society of Instrumentation and Measurement (SIM), to prepare an IEEE standard on frequency stability. In 1969, this subcommittee completed a document proposing definitions for measures on frequency and phase stabilities. These recommended measures of stabilities in frequency generators have gained general acceptance among frequency and time users throughout the world. Some of the major manufacturers now specify stability characteristics of their standards in terms of these recommended measures.

Models of the instabilities may include both stationary and non-stationary random processes as well as systematic processes. Concerning the apparently random processes, considerable progress has been made [IEEE-NASA, 1964; IEEE, 1972] in characterizing these processes with reasonable statistical models. In contrast, the presence of systematic changes of frequencies such as drifts should not be modelled statistically, but should be described in some reasonable analytic way as measured with respect to an adequate reference standard, e.g., linear regression to determine a model for linear frequency drift. The separation between systematic and random parts however is not always easy or obvious. The systematic effects generally become predominant in the long term, and thus it is extremely important to specify them in order to give a full characterization of a signal's stability. This Report presents some methods of characterizing the random processes and as some important types of systematic processes.

Since then, additional significant work has been accomplished. For example, Baugh [1971] illustrated the properties of the Hadamard variance – a time-domain method of estimating discrete frequency modulation sidebands – particularly appropriate for Fourier frequencies less than about 10 Hz; a mathematical analysis of this technique has been made by Sauvage and Rutman [1973]; Rutman [1972] has suggested some alternative time-domain measures while still giving general support to the subcommittee's recommendations; De Prins *et al.* [1969] and De Prins and Cornelissen, [1971] have proposed alternatives for the measure of frequency stability in the frequency domain with specific emphasis on sample averages of discrete spectra. A National Bureau of Standards Monograph devotes Chapter 8 to the "Statistics of time and frequency data analysis" [Blair, 1974]. This chapter contains some measurement methods, and applications of both frequency-domain and time-domain measures of frequency/phase instabilities. It also describes methods of conversion among various time-domain measures of frequency stability, as well as conversion relationships from frequency-domain measures to time-domain measures and vice versa. The effect of a finite number of measurements on the accuracy with which the two-sample variance is determined has been specified [Lesage and Audoin, 1973, 1974 and 1976; Yoshimura, 1978]. Box-Jenkins-type models have been applied for the interpretation of frequency stability measurements [Barnes, 1976; Percival, 1976] and reviewed [Winkler, 1976].

Lindsey and Chie [1976] have recently generalized the r.m.s. fractional frequency deviation and the two-sample variance in the sense of providing a larger class of time-domain oscillator stability measures. They have developed measures which characterize the random time-domain phase stability and the frequency stability of an oscillator's signal by the use of Kolmogorov structure functions. These measures are connected to the frequency-domain stability measure $S_y(f)$ via the Mellin transform. In this theory, polynominal type drifts are included and some theoretical convergence problems due to power-law type spectra are alleviated. They also show the close relationship of these measures to the r.m.s. fractional deviation [Cutler and Searle, 1966] and to the two-sample variance [Allan, 1966]. And finally, they show that other members from the set of stability measures developed are important in specifying performance and writing system specifications for applications such as radar, communications, and tracking system engineering work.

Other forms of limited sample variances have been discussed [Baugh, 1971; Lesage and Audoin, 1975; Boileau and Picinbono, 1976] and a review of the classical and new approaches has been published [Rutman, 1977].

Frequency and phase instabilities may be characterized by random processes that can be represented statistically in either the Fourier frequency domain or in the time domain [Blackman and Tukey, 1959]. The instantaneous, normalized frequency departure $y(t)$ from the nominal frequency ν_0 is related to the instantaneous-phase fluctuation $\varphi(t)$ about the nominal phase $2\pi\nu_0 t$ by:

$$y(t) \equiv \frac{1}{2\pi\nu_0} \frac{d\varphi(t)}{dt} = \frac{\dot{\varphi}(t)}{2\pi\nu_0}, \tag{1}$$

$$\chi(t) = \frac{\varphi(t)}{2\pi\nu_0}$$

where $\chi(t)$ is the phase variation expressed in units of time.

2. Fourier frequency domain

In the Fourier frequency domain, frequency stability may be defined by several one-sided (the Fourier frequency ranges from 0 to ∞) spectral densities such as:

$$S_y(f) \text{ of } y(t),\ S_\varphi(f) \text{ of } \varphi(t),\ S_{\dot{\varphi}}(f) \text{ of } \dot{\varphi}(t),\ S_x(f) \text{ of } \chi(t), \text{ etc.}$$

These spectral densities are related by the equations:

$$S_y(f) = \frac{f^2}{\nu_0^2} S_\varphi(f) \tag{2}$$

$$S_{\dot{\varphi}}(f) = 4\pi^2 f^2 S_\varphi(f) \tag{3}$$

$$S_x(f) = \frac{1}{(2\pi\nu_0)^2} S_\varphi(f) \tag{4}$$

Power-law spectral densities are often employed as reasonable models of the random fluctuations in precision oscillators. In practice, it has been recognized that these random fluctuations are the sum of five independent noise processes and hence:

$$S_y(f) = \begin{cases} \sum_{\alpha=-2}^{+2} h_\alpha f^\alpha & \text{for } 0 < f < f_h \\ 0 & \text{for } f > f_h \end{cases} \tag{5}$$

where h_α's are constants, α's are integers, and f_h is the high frequency cut-off of a low pass filter. Equations 2, 3, and 4 are correct and consistent for stationary noises including phase noise. High frequency divergence is eliminated by the restrictions on f in Equation 5. The identification and characterization of the five noise processes are given in Table I, and shown in Fig. 1. In practice, only two or three noise processes are sufficient to describe the random frequency fluctuations in a specific oscillator; the others may be neglected.

3. Time-domain

Random frequency instability in the time-domain may be defined by several sample variances. The recommended measure is the two-sample standard deviation which is the square root of the two-sample zero dead-time variance $\sigma_y^2(\tau)$ [von Neumann *et al.*, 1941; Allan, 1966; Barnes *et al.*, 1971] defined as:

$$\sigma_y^2(\tau) = \left\langle \frac{(\bar{y}_{k+1} - \bar{y}_k)^2}{2} \right\rangle \tag{6}$$

where

$$\bar{y}_k = \frac{1}{\tau} \int_{t_k}^{t_k+\tau} y(t)\, dt = \frac{x_{k+1} - x_k}{\tau} \quad \text{and} \quad t_{k+1} = t_k + \tau \text{ (adjacent samples)}$$

< > denotes an infinite time average.

The x_k and x_{k+1} are time measurements made at t_k and t_{k+1} respectively where $t_{k+1} = t_k + \tau$, $k = 0, 1, 2, \ldots$, and τ is the fixed sampling time with zero dead time between measurements.

A plot of $\sigma_y(\tau)$ versus τ for a frequency standard typically shows a behaviour consisting of elements as shown in Fig. 1. The first part, with $\sigma_y(\tau) \sim \tau^{-1/2}$ (white frequency noise) and/or $\sigma_y(\tau) \sim \tau^{-1}$ (white or flicker phase noise) reflects the fundamental noise properties of the standard. In the case where $\sigma_y(\tau) \sim \tau^{-1}$, it is not possible to decide whether the oscillator is perturbed by white phase noise or by flicker phase noise unless additional measurements with different cutoff frequencies f_h are performed (see equation (8)). This is a limitation to the usefulness of $\sigma_y(\tau)$ when one wishes to study the nature of the existing noise sources in the oscillator. A frequency-domain analysis is more adequate for Fourier frequencies greater than about one hertz. This τ^{-1} and/or $\tau^{-1/2}$ law continues with increasing averaging time until the so-called flicker "floor" is reached, where $\sigma_y(\tau)$ is independent of the averaging time τ. This behaviour is found in almost all frequency standards; it depends on the particular frequency standard and is not fully understood in its physical basis. Examples of probable causes for the flicker "floor" are power supply voltage fluctuations, magnetic field fluctuations, changes in components of the standard, and microwave power changes. Finally the curve shows a deterioration of the stability with increasing averaging time. This occurs typically at times ranging from hours to days, depending on the particular kind of standard.

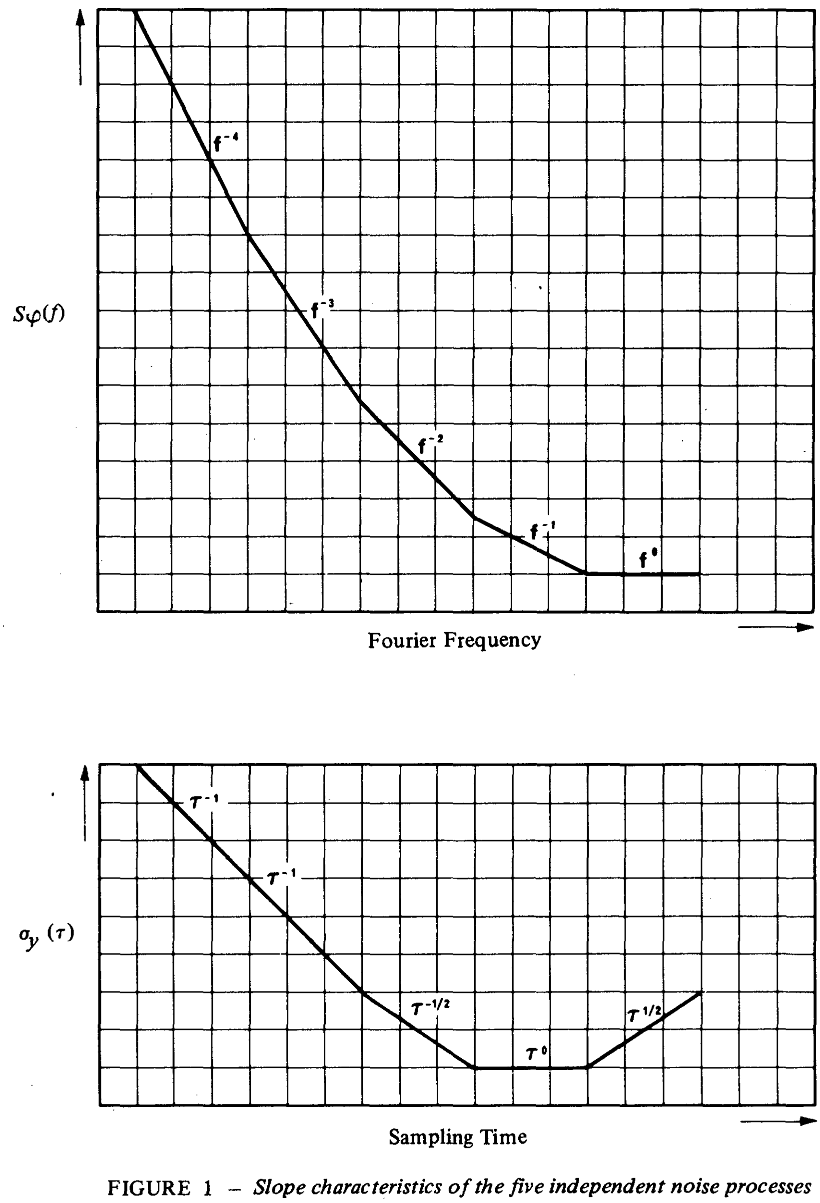

FIGURE 1 – *Slope characteristics of the five independent noise processes*

(leg scale)

4. Conversion between frequency and time domains

In general, if the spectral density of the normalized frequency fluctuations $S_y(f)$ is known, the two-sample variance can be computed [Barnes *et al.*, 1971; Rutman, 1972]:

$$\sigma_y^2(\tau) = 2 \int_0^{f_h} S_y(f) \frac{\sin^4 \pi\tau f}{(\pi\tau f)^2} \, \mathrm{d}f \tag{7}$$

Specifically, for the power law model given by equation (5), the time-domain measure also follows the power law as derived by Cutler from equations (5) and (7) *.

$$\begin{aligned} \sigma_y^2(\tau) = {} & h_{-2} \frac{(2\pi)^2}{6} \tau + h_{-1} \, 2 \log_e 2 + h_0 \frac{1}{2\tau} \\ & + h_1 \frac{1.038 + 3 \ln (2\pi f_h \tau)}{(2\pi)^2 \tau^2} + h_2 \frac{3 f_h}{(2\pi)^2 \tau^2} \end{aligned} \tag{8}$$

The values of h_α are characteristics of oscillator frequency noise. One may note for integer values (as often seems to be the case) that $\mu = -\alpha - 1$, for $-3 \lesssim \alpha \lesssim 1$, and $\mu \simeq -2$ for $\alpha \gtrsim 1$ where $\sigma_y^2(\tau) \sim \tau^\mu$.

These conversions have been verified experimentally [Brandenberger *et al.*, 1971] and by computation [Chi, 1977]. Table II gives the coefficients of the translation among the frequency stability measures from time domain to frequency domain and from frequency domain to time domain.

The slope characteristics of the five independent noise processes are plotted in the frequency and time domains in Fig. 1 (log log scale).

5. Measurement techniques

The spectral density of phase fluctuations $S_\varphi(f)$ may be approximately measured using a phase-locked loop and a low frequency wave analyzer [Meyer, 1970; Walls *et al.*, 1976]. A double-balanced mixer is used as the phase detector in a lightly coupled phase lock loop. The measuring system uses available state-of-the-art electronic components. The reference is also of a very high quality oscillator. For very low Fourier frequencies (well below 1 Hz), digital techniques have been used [Atkinson *et al.*, 1963; De Prins *et al.*, 1969; Babitch and Oliverio, 1974]. New methods of measuring time (phase) and frequency stabilities were introduced with picosecond time precision [Allan and Daams, 1975], and of measuring the Fourier frequencies of phase noise with 30 dB more sensitivity than previous state of the art [Walls *et al.*, 1976].

Several measurement systems using frequency counters are used to determine time-domain stability with or without measurement dead time [Allan, 1974; Allan and Daams, 1975]. A system without any counter has also been developed [Rutman, 1974; Rutman and Sauvage, 1974]. Frequency measurements without dead time can be made by sampling time intervals instead of measuring frequency directly. Problems encountered when dead time exists between adjacent frequency measurements have also been discussed and solutions recommended [Blair, 1974; Allan and Daams, 1975; Ricci and Peregrino, 1976]. Discrete spectra have been measured by Groslambert *et al.* [1974].

6. Confidence limits of time domain measurements

A method of data acquisition is to measure time variations x_j at intervals τ_0. Then $\sigma_y(\tau)$ can be estimated for any $\tau = n\tau_0$ (n is any positive integer) since one may use those x_j values for which j is equal to nk. An estimate for $\sigma_y(\tau)$ can be made from a data set with M measurements of $\bar{y}_j$ as follows:

$$\hat{\sigma}_y(n\tau_0) = \hat{\sigma}_y(\tau) \simeq \left| \frac{1}{2(M-1)} \sum_{j=1}^{M-1} (\bar{y}_{j+1} - \bar{y}_j)^2 \right|^{1/2} \tag{9}$$

* The factor 1.038 in the h_1 term is different from the value given in most previous publications.

or equivalent

$$\hat{\sigma}_y(\tau) \simeq \left| \frac{1}{2\tau^2(M-1)} \sum_{j=1}^{M-1} (x_{j+2} - 2x_{j+1} + x_j)^2 \right|^{1/2} \tag{10}$$

Thus, one can ascertain the dependence of $\sigma_y(\tau)$ as a function of τ from a single data set in a very simple way. For a given data set, M of course decreases as n increases.

To estimate the confidence interval or error bar for a Gaussian type of noise of a particular value $\sigma_y(\tau)$ obtained from a finite number of samples [Lesage and Audoin, 1973] have shown that:

$$\text{Confidence Interval } I_\alpha \simeq \sigma_y(\tau) \cdot \kappa_\alpha \cdot M^{-1/2} \text{ for } M > 10 \tag{11}$$

where:

M: total number of data points used in the estimate,

α: as defined in the previous section,

$\kappa_2 = \kappa_1 = 0.99$,

$\kappa_0 = 0.87$,

$\kappa_{-1} = 0.77$,

$\kappa_{-2} = 0.75$.

As an example of the Gaussian model with $M = 100$, $\alpha = -1$ (flicker frequency noise) and $\sigma_y(\tau = 1 \text{ second}) = 10^{-12}$, one may write:

$$I_\alpha \equiv \sigma_y(\tau) \cdot \kappa_\alpha \cdot M^{-\frac{1}{2}} = \sigma_y(\tau) \cdot (0.77) \cdot (100)^{-\frac{1}{2}} = \sigma_y(\tau) \cdot (0.077), \tag{12}$$

which gives:

$$\sigma_y(\tau = 1 \text{ second}) = (1 \pm 0.08) \times 10^{-12} \tag{13}$$

A modified estimation procedure including dead-time between pairs of measurements has also been developed [Yoshimura, 1978], showing the influence of frequency fluctuations auto-correlation.

7. Conclusion

The statistical methods for describing frequency and phase instability and the corresponding power law spectral density model described are sufficient for describing oscillator instability on the short term. Equation (7) shows that the spectral density can be unambiguously transformed into the time-domain measure. The inverse is not true in all cases since white and flicker phase noise cannot be distinguished in the time-domain without additional tests involving variation of the measurement system cutoff frequency f_h. For slow random fluctuations the time domain measure is a good spectrum estimator.

Non-random variations are not covered by the model described. These can be either periodic or monotonic. Periodic variations are to be analyzed by means of known methods of harmonic analysis. Monotonic variations are described by linear or higher order drift terms.

TABLE I – *The functional characteristics of five independent noise processes for frequency instability of oscillators*

Description of noise process	Slope characteristics of log log plot			
	Frequency-domain		Time-domain	
	$S_y(f)$	$S\varphi(f)$ ou $S_x(f)$	$\sigma^2(\tau)$	$\sigma(\tau)$
	α	$\beta \equiv \alpha - 2$	μ	$\mu/2$
Random walk of frequency	−2	−4	1	½
Flicker frequency	−1	−3	0	0
White frequency	0	−2	−1	−½
Flicker phase	1	−1	−2	−1
White phase	2	0	−2	−1

$$S_y(f) = h_\alpha f^\alpha \qquad \sigma^2(\tau) \sim |\tau|^\mu$$

$$S_\varphi(f) = \nu_0^2 h_\alpha f^{\alpha-2} = \nu_0^2 h_\alpha f^\beta \quad (\beta \equiv \alpha - 2) \qquad \sigma(\tau) \sim |\tau|^{\mu/2}$$

$$S_x(f) = \frac{1}{4\pi^2} h_\alpha f^{\alpha-2} = \frac{1}{4\pi^2} h_\alpha f^\beta$$

TABLE II – *Translation of frequency stability measures from spectral densities in frequency domain to variance in time domain and vice versa (For $2\pi f_h \tau \gg 1$)*

Description of noise process	$\sigma_y^2(\tau) =$	$S_y(f) =$	$S\varphi(f) =$
Random Walk Frequency	$A\,[f^2 S_y(f)]\,\tau^1$	$\frac{1}{A}\left[\tau^{-1}\sigma_y^2(\tau)\right]f^{-2}$	$\frac{\nu_0^2}{A}\left[\tau^{-1}\sigma_y^2(\tau)\right]f^{-4}$
Flicker Frequency	$B\,[f S_y(f)]\,\tau^0$	$\frac{1}{B}\left[\tau^{0}\sigma_y^2(\tau)\right]f^{-1}$	$\frac{\nu_0^2}{B}\left[\tau^{0}\sigma_y^2(\tau)\right]f^{-3}$
White Frequency	$C\,[f^0 S_y(f)]\,\tau^{-1}$	$\frac{1}{C}\left[\tau^{1}\sigma_y^2(\tau)\right]f^{0}$	$\frac{\nu_0^2}{C}\left[\tau^{1}\sigma_y^2(\tau)\right]f^{-2}$
Flicker Phase	$D\,[f^{-1} S_y(f)]\,\tau^{-2}$	$\frac{1}{D}\left[\tau^{2}\sigma_y^2(\tau)\right]f^{1}$	$\frac{\nu_0^2}{D}\left[\tau^{2}\sigma_y^2(\tau)\right]f^{-1}$
White Phase	$E\,[f^{-2} S_y(f)]\,\tau^{-2}$	$\frac{1}{E}\left[\tau^{2}\sigma_y^2(\tau)\right]f^{2}$	$\frac{\nu_0^2}{E}\left[\tau^{2}\sigma_y^2(\tau)\right]f^{0}$

$$A = \frac{4\pi^2}{6} \qquad D = \frac{1.038 + 3\log_e(2\pi f_h \tau)}{4\pi^2}$$

$$B = 2\log_e 2$$

$$C = 1/2 \qquad E = \frac{3 f_h}{4\pi^2}$$

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RECOMMENDATION 538 *

FREQUENCY AND PHASE STABILITY MEASURES

(Study Programme 3B/7)

(1978)

The CCIR,

CONSIDERING

(a) that there is a need for an adequate language with which to communicate the stability characteristics of standard frequency sources;

(b) that major laboratories, observatories, industries, and general users have already adopted some of the Recommendations of the Sub-Committee on Frequency Stability of the Technical Committee on Frequency and Time of the IEEE Society on Instrumentation and Measurement;

(c) that frequency stability measures should be based on sound theoretical principles, conveniently usable, and directly interpretable;

(d) that it is desirable to have frequency stability measures obtainable with simple instrumentation,

UNANIMOUSLY RECOMMENDS

1. that the random instabilities of standard frequency signals should be characterized by the statistical measures $S_y(f)$, $S_\varphi(f)_\sigma$ or $S_x(f)$, and $\sigma_y(\tau)$ as defined below:

1.1 the measure of the normalized frequency instabilities $y(t)$ in the frequency domain is $S_y(f)$; i.e. the one-sided spectral density $(0 < f < \infty)$ of the normalized frequency instabilities $y(t) = (\nu(t) - \nu_0)/\nu_0$, where $\nu(t)$ is the instantaneous carrier frequency, and ν_0 is the nominal frequency;

1.2 the measure of the phase instabilities $\varphi(t)$ in the frequency domain is $S_\varphi(f)$; i.e. the one-sided spectral density $(0 < f < \infty)$ of the phase instabilities $\varphi(t)$ at a Fourier frequency f;

1.3 the measuure of the phase instabilities expressed in time units (phase-time) $\chi(t)$ in the frequency domain is $S_x(f)$; i.e. the one-sided spectral density $(0 < f < \infty)$ of phase-time instabilities $\chi(t)$, where $\chi(t) = \varphi(t)/2\pi\nu_0$; $\chi(t)$ being related to $y(t)$ by $y(t) = \mathrm{d}\chi(t)/\mathrm{d}t$;

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* See Report 580 for more complete details.

1.4 the relationships of the above spectral densities are given below:

$$S_y(f) = \frac{f^2}{\nu_0^2} S_\varphi(f) = 4\pi^2 f^2 S_x(f) \tag{1}$$

The dimensions of $S_y(f)$, $S_\varphi(f)$ and $S_x(f)$ are respectively Hz^{-1}, Rad^2Hz^{-1} and s^2Hz^{-1};

1.5 the measure of the normalized frequency instabilities $y(t)$ in the time domain is the two-sample standard deviation, $\sigma_y(\tau)$, as defined in Annex I;

2. that, when stating statistical measures of frequency instability, non-random phenomena should be recognized, e.g.:

2.1 any observed time dependency of the statistical measures should be stated;

2.2 the method of measuring systematic behaviour should be specified (e.g. an estimate of the linear frequency drift was obtained from the coefficients of a linear least squares regression to M frequency measurements, each with a specified averaging or sample time τ and bandwidth f_h);

2.3 the environmental sensitivities should be stated (e.g. the dependence of frequency and/or phase on temperature, magnetic field, barometric pressure, etc.);

3. that, when stating a measure of frequency stability, all relevant measurement parameters should also be specified:

3.1 the method of measurements;

3.2 the characteristics of the reference signal;

3.3 the nominal signal frequency ν_0;

3.4 the measurement system bandwidth f_h and the corresponding low pass filter response;

3.5 the total measurement time or number of measurements M;

3.6 the calculation techniques (e.g. details of lag-windows when estimating power spectral densities from time domain data, or the assumption of the effect of dead-time in estimating the two-sample standard deviation $\sigma_y(\tau)$);

3.7 the confidence of the estimate;

4. that a graphic illustration or an analytic expression of the measures of the frequency instabilities should be provided and should include confidence intervals (i.e. $S_y(f)$, $S_\varphi(f)$ and $S_x(f)$ as a function of f and/or $\sigma_y(\tau)$ as a function of τ).

ANNEX I

DEFINITION OF THE TIME-DOMAIN MEASURE

The two-sample standard deviation * $\sigma_y(\tau)$ is defined as:

$$\sigma_y(\tau) = \left(\left\langle \frac{(\bar{Y}_{k+1} - \bar{Y}_k)^2}{2} \right\rangle \right)^{\frac{1}{2}} \tag{2}$$

where

$$\bar{Y}_k = \frac{1}{\tau} \int_{t_k}^{t_k + \tau} y(t) \, dt \tag{3}$$

τ is the averaging time with zero dead-time between successive measurements,

k is an index number such that $t_{k+1} = t_k + \tau$, and

$\langle \ \rangle$ denotes an infinite average.

For a finite number M of measurements of $\bar{Y}_k$, an estimate of the two-sample standard deviation is given by:

$$\hat{\sigma}_y(\tau) \simeq \left[\frac{1}{2(M-1)} \sum_{k=1}^{M-1} \left(\bar{Y}_{k+1} - \bar{Y}_k \right)^2 \right]^{\frac{1}{2}} \tag{4}$$

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* The square of the two-sample standard deviation is the two-sample variance (also known as pair variance or two-sample Allan variance).

RECOMMENDATION 582

TIME AND FREQUENCY REFERENCE SIGNAL DISSEMINATION AND COORDINATION USING SATELLITE METHODS

(Question 2/7)

(1982)

The CCIR,

CONSIDERING

(a) that applications for time and frequency reference signals in such areas as navigation, communications and space exploration require time and frequency services with improved coverage, accuracy, and reliability of reception;

(b) that substantial improvements in existing terrestrial time and frequency dissemination and coordination services are, in many cases, technically or economically impractical;

(c) that, because of such limitations, some HF services are being eliminated;

(d) that experiments performed to date using satellite-based techniques for time and frequency dissemination and synchronization have demonstrated significantly improved accuracy, precision, coverage, reliability, and operational convenience;

(e) that the number of satellite systems and vehicles that are potentially available to carry time and frequency signals is increasing rapidly;

(f) that a number of promising satellite systems or techniques for time and frequency dissemination and coordination, including LASSO, television broadcasting satellites, communication satellites, meteorological satellites, the Global Positioning System, and TRANSIT, will be available for evaluation during the next few years offering many opportunities for participation by time and frequency laboratories;

(g) that many time and frequency satellite experiments to date have indicated the advantages of having on-site satellite receiving capabilities at the time and frequency laboratories in order to eliminate the additional uncertainties introduced by auxiliary time-transfer links,

UNANIMOUSLY RECOMMENDS

1. that organizations interested in, or responsible for, time and frequency reference signal dissemination and coordination participate to the maximum extent possible in experiments to evaluate the relative merits of various satellite-based techniques for improved time and frequency transfer;

2. that time and frequency laboratories establish on-site satellite receiving (and transmitting, if appropriate) capabilities to the maximum extent possible;

3. that satellite-based techniques be given serious consideration in the development of any new time and frequency dissemination and/or coordination services.

REPORT 363-5

COMPARISON OF METHODS FOR THE TRANSFER AND DISSEMINATION OF TIME AND STANDARD FREQUENCIES

(Study Programme 3C/7)

(1966–1970–1974–1978–1982)

During recent years, time scale comparisons by means of Loran-C, portable clocks, and television signals have become important for the formation of International Atomic Time (TAI) at the Bureau international de l'heure (BIH). A variety of other time comparison methods has been investigated in many laboratories [Blair, 1973]. The differences between these methods in precision, coverage, operational convenience, cost and availability, have shown that no single system can satisfy all requirements.

1. Comparison using time and navigation signals in bands 4, 5, 6 and 7

These signals are in routine use for time comparisons [Bonanomi *et al.*, 1964; Beehler *et al.*, 1965; Morgan *et al.*, 1965; Blair *et al.*, 1967; Mungall *et al.*, 1969; Guinot, 1968 and 1969; Potts and Wieder, 1972].

With respect to phase comparisons in bands 4 and 5, it is suggested in Report 271 that the receivers should be calibrated as a precaution against displacement and phase loss, and that each laboratory should determine the best time of day for phase reading. Under these conditions, time scales can be compared to an accuracy of a few microseconds without introducing cumulative errors. Additional reduction of phase uncertainty can be achieved by means of appropriate smoothing techniques [Becker *et al.*, 1969; Guetrot *et al.*, 1969]. Since synchronization of the Loran-C Atlantic chains (August, 1968), a few European and American laboratories have been connected with an accuracy within 0.5 μs by the reception of Loran-C pulses. The results of these comparisons have enabled several studies to be made to determine the optimum method of forming a mean atomic time scale on a local or international basis [Guinot, 1968 and 1969; Barnes, 1967]. With Loran-C receivers, it has been possible to improve the BIH International Atomic Time Scale [Guinot, 1969].

The US National Bureau of Standards (NBS) has performed extensive statistical analyses on the Loran-C propagation paths connecting some major timing centres in the US, Canada and Europe. Up to eight years of clock comparison data via Loran-C were analyzed with special emphasis on examining for possible annual and seasonal fluctuations associated with variations in the propagation paths. One path in particular showed a statistically significant annual variation term with a peak-to-peak amplitude of about 1 μs. This level could induce corresponding normalized frequency fluctuations amounting to about 4×10^{-13} peak-to-peak. Some evidence of annual or seasonal terms was also suggested in some of the other links, and in the case of the PTB Loran-C link, two-year variations were observable.

Recent experiments with the satellite Symphonie allowed an independent estimate of the uncertainties in the transatlantic Loran-C link as well as in the link between the Federal Republic of Germany and France. In the transatlantic link random uncertainties of 150 ns (1 σ) superimposed on occasional systematic errors of $\pm$ 500 ns were observed. The Loran-C link between the Federal Republic of Germany and France showed a random uncertainty of 35 ns (1 σ).

Long-term stability of the time comparison between the UTC scale of the Radio Research Laboratories, Tokyo and that of the US Naval Observatory (USNO) via Loran-C emission from Iwo-Jima was examined for the period from 1969 to 1977 using the corresponding values via the portable clock of the USNO. The values of the long-term stability were as low as 0.3 μs (1 σ) for 1974 to 1977 mainly because of the improvement in the Loran-C monitoring system of the US Coast Guard and the USNO including the time transfer by satellites [Yasuda *et al.*, 1977].

The phase stability of several types of Loran-C receivers has been investigated in Japan by the Radio Research Laboratories and the Tokyo Astronomical Observatory. The analysis of four years of signal reception data from these two laboratories produced a standard deviation of less than 0.3 μs and indicated that the yearly mean could vary by as much as $\pm$ 0.3 μs, corresponding to a rate of about 1×10^{-14} for a year. The magnitude of the receiver delay instability is therefore not of great significance even in frequency comparisons among recent primary atomic standards.

The Radio Research Laboratories also carried out investigations concerning the effects of notch filters on the phase of the output signal of two types of Loran-C receivers, through the use of a signal simulator [Kobayashi *et al.*, 1978]. The receivers had notch filter bandwidths which varied from 1.7 to 4.3 kHz depending on frequency setting and receiver type. The results indicated maximum phase shifts of $\pm$ 60 ns and $\pm$ 120 ns respectively for phase tracking and visual type receivers.

The phase delay of a commercial Loran-C antenna was measured in Japan by the Tokyo Astronomical Observatory. A pair of antennas are used, one of them is used as a field generator and another is used as a field receiver. They are coupled by induction. The phase lag between them was measured and the result agreed well with a series LCR circuit model of the antenna. As the wavelength of a Loran-C signal is much longer than the scale of the antenna, the results can be extended to the radiation field and the method of this measurement will be useful for the precise and reliable clock comparison via Loran-C [Fujimoto and Fujiwara, 1981].

At Instituto y Observatorio de Marina, Spain, (OMSF), the control and interchange of data of the time scale is mainly made by means of the reception of Loran-C. Path delays are determined, when necessary, by means of portable clock trips. The dissemination of the time-scale is mainly performed in two ways: HF broadcast from OMSF's premises and portable clock trips whenever a higher precision is required.

A method of predicting the propagation delay in irregular terrain at 100 kHz was tested by Shaanxi Observatory in China. With this method the equivalent conductivity of the Earth can be evaluated by means of the measurement of the field strength of the ground wave. The uncertainty of prediction is about 0.5 μs for irregular terrain and has been confirmed by portable clock time transfer.

The results of time signal comparisons in bands 6 and 7 carried out in Italy [Leschiutta *et al.*, 1968] and Japan during the years 1961-1968, have been reported. When using a comparison system whose accuracy was ± 0.01 ms, the standard deviation for a single reception was found to vary from 0.01 ms at a distance of a few kilometres to about 0.5 ms at distances of about 18 000 km. For intermediate distances the standard deviation ranged from 0.015 ms at 500 km to 0.1 ms at 1000 km. Most signals were found to exhibit little seasonal variation except those from WWV and IAM when reception becomes poor in the northern hemisphere winter. Similar measurements of signals from HF stations JJY, RID, WWVH and VNG as received at Shanghai Observatory in China during 1976 resulted in standard deviations of daily values in the range 0.19-0.51 ms over path lengths ranging from 1700-8000 km.

Results were obtained in Japan during 1967-1971 making use of photographic integration of the received time-signal phase [Kobayashi *et al.*, 1977]. They indicate that HF single-mode signals propagating via the night-time E- or Es-layer are received at distances of 400 and 1100 km with a standard deviation of 6 μs on 2.5 MHz, and 14 μs on 5 MHz. The propagation time on 5 MHz at a distance of 400 km was found to vary by approximately 30 μs during the year owing to the seasonal changes in the E-layer critical frequency.

In addition, results of the measurements of propagation time of WWV and WWVH signals carried out at the Tokyo Astronomical Observatory during the years 1968-1976 have shown that the travel times for WWV and WWVH had seasonal variations, that in the case of WWV, both the yearly mean of the travel times and the amplitude of the seasonal variation had close correlation with Wolf's sunspot number, and that the values of the standard deviation for a single reception in both cases were almost constant ($\simeq$ 0.23 ms), regardless of the sunspot number and the season [Iijima *et al.*, 1978].

Nearly twenty years of Doppler observations of the standard frequency transmissions started in Japan in 1957 and carried out since then in several countries have produced information on the behaviour of frequency variations of the transmissions as received caused by various extraordinary variations of the ionosphere, as well as ordinary variations such as daily and seasonal ones [Ogawa, 1958; 1960]. The main causes of the extraordinary variations are solar flares [Davies *et al.*, 1962], solar eclipse [Ichinose and Ogawa, 1976], magnetic storm [Chan *et al.*, 1962], earthquake [Davies and Baker, 1965], typhoon [Tsutsui and Ogawa, 1973], severe thunderstorm [Georges, 1968], nuclear explosion [Baker and Davies, 1968] and the amount of frequency variations reaches to the order of 10^{-7} to 10^{-8}.

In practical applications the use of HF (band 7) time signals may be hindered by mutual interference. Delay variations due, for example, to receiver tuning and/or bandwidth switching, have to be taken into account.

2. Portable clocks

The comparison of time scales by using a transportable clock has come into general use. This is the most accurate method used for calibrating propagation time and instrument delay when required (for example, for the receivers of Loran-C or television signals). An improvement of this method consists in synchronization by flying clocks without landing [Besson and Cumer, 1969], in which case an accuracy of some tens of nanoseconds is possible.

By using a set of four clocks and comparison of these clocks during the trip, it was possible to measure relativistic effects in a global circumnavigation experiment [Hafele and Keating, 1972]. The uncertainty achieved with this method is less than 30 ns. Routine portable clock operations continue to play the role of a calibration service for time comparisons between time scales with an uncertainty of 0.1 to 0.2 μs [Winkler, 1972] depending on the interval between two calibrations. There is some evidence at the USNO that transporting a clock may alter its subsequent performance.

The NBS in the United States has developed a small, complete portable-clock package based on a compact commercial rubidium standard. The clock fits easily under an aeroplane seat, has sufficient battery capacity to make connection to the plane's power system unnecessary, and has demonstrated 0.1 μs time transfers over intercontinental travel time [Hellwig and Wainwright, 1975]. This performance has been achieved in part by modifications to the rubidium standard used to reduce its sensitivity to temperature, barometric pressure, and magnetic field variations.

Commercial high-performance caesium clocks can give accuracies of about 10 ns in journeys lasting up to 2 days.

Three experiments with portable clocks have been carried out by the National Institute of Metrology of China. The first two experiments were from 1 to 30 March 1979, between Beijing, Shanghai and Nanking. The last experiment was from 31 May to 26 June 1979, between the Nanking earth station in China and the Raisting earth station in the Federal Republic of Germany. In the portable clock experiment, the relativistic effect was calculated and considered. The uncertainties were 14, 28 and 73 ns respectively.

During 1980 and 1981 regular time comparisons were performed by portable clocks between PTB (Braunschweig) and Raisting (near Munich). Each time two caesium beam standards of different types were transported by car between the two locations, approximately 700 km apart. Measurements were carried out after the arrival at Raisting in the afternoon, before the departure in the morning of the next day. The uncertainties (1σ) of time comparisons were evaluated to 12 ns and to less than 5 ns for the two clocks respectively when the drift correction for the portable clocks was obtained by interpolation of relevant values before departure and after return. The uncertainties amounted to 21 ns and 7 ns for the two different clocks used when the drift correction was calculated by extrapolation of individual values before departure or after return.

OMSF, the Spanish organization responsible for time and frequency, has implemented a mobile laboratory with the purpose of extending, on a nationwide basis, its capabilities of frequency measurement and time comparison by means of portable clocks. The mobile laboratory has the capability of supporting the clock, or clocks, to be transported, along with the adequate measuring and control equipment, including a Loran-C receiver. Time and frequency measurements via the mobile laboratory have an estimated uncertainty of $\pm$ 0.1 μs and 1×10^{-11} respectively.

3. Television

Television signals are well adapted for the dissemination of time and frequency at several levels of accuracy, and for the comparison of time scales; among their advantages are:

- their widespread availability with good signal strength;
- their time structured nature and wide bandwidth in frequency allocations which already exist;
- the low price of receiving equipment;
- the predictability of their propagation.

Several methods have been developed for television time comparisons. The original method of Tolman *et al.* [1967] involves simultaneous time of arrival measurements of selected synchronization pulses. This system is in wide use in China [CCIR, 1974-78a], in Europe [Rovera, 1972; Allan *et al.*, 1970; Parcelier, 1976; Parcelier and Fréon, 1977; Becker and Enslin, 1972], in Japan [Saburi *et al.*, 1978] and in the United States of America [Allan *et al.*, 1972a; Davis *et al.*, 1971], where it is known as "Line-10".

Television synchronization pulses are used as common reference markers for many national, and sometimes international, time comparisons. A determination of the propagation delays has to be made by portable clocks or other suitable methods. For line-of-sight comparisons, using the same television transmitter, the uncertainty of a time difference measurement can be of the order of 10 ns.

Television signals from different transmitters can only be used for time or frequency comparisons if the delay introduced by the links between the transmitters remains effectively constant or may take only a small number of constant and distinguishable values. The uncertainty introduced by links which follow the same route is usually less than 1 μs but may reach several microseconds; much larger changes can be caused by the use of different routes through the linking network.

A method of measuring section by section for the determination of the total propagation delay has been employed by Beijing Observatory in China. This method only used simple apparatus and some general equipment. The results have been checked and compared with portable clocks or Loran-C timing, the systematic deviations of different methods being within 1 μs.

Variable and indefinitely large delays can be introduced by links containing satellites, or frame stores in which input and output are controlled by different clocks. These occur, for example, in frame synchronizers and in standards converters and their use is expected to increase. While this may limit the future usefulness of large television networks for time and frequency dissemination it may also simplify such use locally by permitting active and independent control of signal timing within a sub-network or after passage through a satellite link.

Improvements in the stability of measuring equipment for use with this method have been achieved in Japan by stabilizing the local oscillator frequency in the television set tuner and by using a fixed setting of the automatic gain control in the intermediate-frequency amplifier with controlling voltage as high as possible. Improved short-term and long-term stabilities of about 10 ns and 30 ns, respectively, have been obtained [Inouye and Nara, 1978; Fujiwara and Kato, 1978]. In addition, recent experiments have shown that significant improvement in the stability can be obtained by measuring the trailing edge of the synchronizing pulse rather than its leading edge. Thus, for purely differential measurements using the same synchronizing pulse, use of the trailing edge gives excellent results since the steeper trailing edge leads to better measurement precision [Saburi *et al.*, 1978].

It should be noted, however, that the time of occurrence of the *leading* edge of the pulse, with respect to a known time reference, is generally better controlled than that of the trailing edge. Thus, for time difference measurements between a local clock pulse and a particular synchronized television pulse, more accurate results may be obtained with the leading edge.

Several generations of receivers were specially built for daily comparison of the 15 clocks, in several laboratories in different parts of France, which contribute to TA(F) [Parcelier, 1976]. The measurements refer to a well-characterized pulse in a test line and are initiated automatically by the local clock. Tuning is adjusted for optimum shape of the received pulse, and automatic gain and level controls ensure that the results are unaffected by picture content. Simultaneous measurements over 30 minutes by two adjacent sets of equipment give a 1 σ dispersion of $\pm$ 5 ns about the mean; a precision of 40-50 ns is obtained in normal operation in a series of 15 or 30 consecutive measurements over distances of several hundred kilometres.

Two caesium clocks, one in Brittany and the other in Paris, were compared during one month through daily television measurements and six flying clock experiments [Parcelier and Fréon, 1977]. The standard deviation of the differences between the two methods of comparison over the period in question amounted to some 15 nanoseconds. A last flying clock experiment carried out 2½ months later gave a result 28 nanoseconds higher than that of the television experiment.

Clock comparisons by television signals on a routine basis and eight measurements by portable clock were made over seven years among three laboratories in Tokyo, all located within about 20 km of the television transmitter. The standard deviations of the difference between the two methods were about 50 ns. Receiver delay variations as determined by local calibrations have been taken into account.

A receiver developed in Switzerland measures the leading edge of a line synchronizing pulse and incorporates automatic frequency control and accurate stabilization of signal levels immediately before and after the edge. Measurements of signals from the same transmitter by co-sited receivers have shown 1 σ values below 1 ns for averaging times of 10 s and above, but for signals from different transmitters the 1 σ value rises from about 1 ns to 3 ns as the averaging time is increased from 50 s to 500 s [CCIR, 1974-78b].

A related method was reported by Lavanceau and Carroll, [1971] at the USNO. It involves stabilization of the colour sub-carrier in reference to a caesium beam frequency standard in the television studio. The line 10 synchronization pulse is also controlled and kept on time by referring to a "Table of Coincidences" (TOC) issued by USNO for use with the NTSC system, similar to the Loran-C TOC.

In contrast to a coherent TOC reference, as used in the weekly reports of the USNO (Time Service Announcements, Series 4), it has been proposed in Japan [Saburi *et al.*, 1978] to use the same TOC reference every day.

The NBS in the United States of America has developed and tested a method for time dissemination via television, by encoding data in particular lines of the television signal. First, lines 13 to 16, then line 1 and also line 21 were used. A 1 MHz reference signal was included in this system [Davis *et al.*, 1970; Howe, 1972].

Television systems used in Europe have nominal frame repetition rates of exactly 25 Hz and UTC seconds markers can in principle be inserted in a fixed position in the frame.

The national television network in Yugoslavia is used in this way to disseminate time and frequency originating from a caesium clock in the Belgrade studio. Seconds pulses on the UTC (YU) scale, with hour and minute markers are inserted in the second half of line 19, while line 332 carries a code which gives the hour, minute and second and indicates the origin and status of the timing information. The first half of both lines carries a stabilized 1 MHz burst [Kovačević, 1973 and 1977].

In the United Kingdom the line and frame synchronizing pulses transmitted by the British Broadcasting Corporation in band 9 are generally controlled by a rubidium standard. Their drift relative to UTC is usually only a few microseconds per day, but there are also programme dependent reversible time steps. Signals from a total of six transmitters serving many large centres of population and industry are monitored each working day with a precision of 0.1 µs. The measurements link the UTC scales maintained at the National Physical Laboratory (NPL) and the MSF/GBR transmitter site at Rugby, and supplement the Loran-C link between NPL and the Royal Greenwich Observatory [CCIR, 1974-78c].

Several methods have also been developed for using television transmissions as very stable frequency references. In the Federal Republic of Germany, precise frequency control has been extended to about 160 television transmitters at 82 locations operating in the frequency range 471.24 to 783.26 MHz. The transmitter frequencies are remotely controlled by a caesium standard that is adjusted relative to a central group of six commercial high performance caesium standards. The stations examined showed an average normalized frequency departure of 3×10^{-12}. The computed standard deviation is 3×10^{-11}. Signals received at distances of 46 to 125 km from the transmitter were found, over an interval of 30 s, to have phase fluctuations corresponding to frequency variations of about 1×10^{-11}, in the worst case.

In the German Democratic Republic the line and frame synchronizing pulses, transmitted by television are directly controlled by the national time and frequency service with an uncertainty of 6 ns and are used for frequency dissemination in the country and for time comparisons with the time services of neighbouring countries. The effect of reversible time steps greater than 200 ns due to changes in the delay time in the links of the television network can be eliminated by applying calculated corrections, leading to a reduction of the uncertainty of the time comparisons to less than 50 ns [Kalau, 1979 and 1980].

In France a television carrier at 182.25 MHz has been used as a common reference in frequency comparisons between hydrogen masers in two laboratories 16 km apart. Synthesizers driven by the masers were used to generate voice-frequency beats with the carrier, and phase comparisons of the beats were made via a telephone link. Resolutions obtained were $4 \times 10^{-11} \tau^{-1}$ for $1 \text{ s} < \tau < 300 \text{ s}$ and 6×10^{-14} for $\tau = 1$ hour [Gabry *et al.*, 1977].

In Japan and the United States, the frequency stability provided by the television colour sub-carrier has been demonstrated. This high stability results from the use of atomic frequency standards by television networks to generate the sub-carrier frequencies.

Frequency comparisons were performed between Tokyo and Mizusawa (Japan) [Saburi *et al.*, 1978]. The colour sub-carrier was phase-compared with a locally generated colour sub-carrier signal. The precision obtained was 6.5×10^{-12}, 4×10^{-12} and 2.2×10^{-12} for averaging times of 10, 30 and 60 minutes respectively.

Frequency comparisons were performed by the National Institute of Metrology of China in 1979. The results show that using the television colour sub-carrier over the range of 2000 km, the precision of frequency calibration is better than $\pm 5 \times 10^{-12}$ in 30 minutes. At the same time, similar results were obtained by Beijing and Shaanxi Observatories.

A quite simple method that uses directly the colour sub-carrier pulse was tested in Shanghai Observatory. The precision of frequency calibration is about 1 to 2×10^{-11} in 15 minutes.

Based on earlier demonstrations of the excellent long-term stability of the 3.58 MHz television colour sub-carrier transmissions from the major television networks in the United States [Davis *et al.*, 1971], the National Bureau of Standards has recently initiated an improved nationwide frequency calibration service. A user nearly anywhere in the United States can now easily and inexpensively calibrate his oscillator to an accuracy of a few parts in 10^{11} in about 15 minutes with respect to the primary frequency standard at the NBS. This accuracy is made possible by the high stability of the network atomic frequency standards generating the sub-carrier signals and by the availability of regular NBS measurements of the sub-carrier frequencies.

The user must first measure the frequency difference between his oscillator and one of the major television network sub-carriers during a time when he is receiving direct network programming. The necessary television sub-carrier signal can be obtained easily from a slightly modified colour television receiver. Several versions of suitable user equipment have been designed and constructed at the NBS [Davis, 1975]. In the simplest form, called the colour-bar comparator, the measurement is made by manually timing the period required for a coloured bar on the television screen to cycle through a changing colour sequence.

In a more sophisticated version of user equipment the frequency difference between the local oscillator and the network sub-carrier is automatically measured, computed, and displayed directly in parts in 10^{11} on the television screen. The entire automatic measurement requires about 15 minutes and provides a precision of 1×10^{-11}.

NBS has also developed a versatile microprocessor-based data-logging system that automates both the line-10 sync pulse comparison and the colour sub-carrier frequency comparison measurement capabilities into a single, relatively inexpensive package. Time comparisons to 10 ns and frequency comparisons to 1×10^{-12} (averaged over 1 day) are being routinely obtained from unattended, remote units located at several points within the US [Davis, 1976].

One of the major networks in the US now uses caesium standards to generate the 3.58 MHz colour sub-carrier frequencies which are then distributed nationwide. The caesium standard virtually eliminates any long-term drift in the sub-carrier frequency.

4. Intercontinental clock synchronization by VLBI

The fundamentals of VLBI have been described by Klemperer [1972] who presents an extensive list of references, as well as of the basic accuracies and limitations. Clark [1972] also considered the fundamentals and listed a number of current VLBI experimental programmes. Accuracies in frequency comparisons of 10^{-13} to 10^{-14} and in clock synchronization of the order of 1 ns are apparently possible, although it is not yet feasible to achieve these accuracies.

The 10 to 100 MHz bandwidths required for 1 to 10 ns resolution clock synchronization are achievable by the bandwidth synthesis techniques described by Hinteregger *et al.* [1972] and Rogers [1970].

Hydrogen maser stability is not required for clock synchronization; in fact, the prototype system demonstrations used rubidium oscillators. A series of three experiments have been conducted within the NASA stations between Madrid, Spain and Goldstone, California [Hurd, 1972]. Although the measurements demonstrated resolutions of 50 to 500 ns (1 σ), depending on the amount of data used, the accuracy of the clock differences obtained could only be verified to within about 10 µs.

If a sufficient amount of data is available and if a sufficiently large bandwidth can be obtained (50 MHz) then the VLBI synchronization method seems to be mainly limited in accuracy by difficulties in determination of the overall system delay and, in particular, in the atmospheric (ionospheric) delay.

5. Satellites

Experimental time comparisons over large distances via artificial satellites have been conducted successfully since 1962. Both one-way and two-way techniques are used with each offering certain advantages. In the one-way mode a user simply receives the timing signal which either originates from an on-board clock or is relayed to the user from another terrestrial location via a satellite transponder. Because the user is not required to transmit signals, simple equipment can be used and many users can be served simultaneously in a broadcast mode of operation. However, since the propagation path delay must be determined by calculation or calibration using some other technique, the one-way time transfers are generally characterized by larger uncertainties than for the two-way methods. Depending on the method and expense, accuracies from a few µs to a few ns can be obtained.

Two-way techniques involve the exchange of timing signals between two terrestrial sites, using a satellite transponder to relay the signals back and forth nearly simultaneously. More complex equipment is required since the user must also transmit, but lower uncertainties in the time transfers are generally possible as a result of being able to measure, and thus compensate for, the path delay directly. Two-way techniques offer the possibility of state-of-the-art time transfers to smaller numbers of sophisticated users requiring this level of performance. An example can be found in the numerous symphonie experiments.

More complete descriptions, comparisons and references pertaining to these and other satellite techniques or systems may be found in Report 518.

6. Other methods

Different time comparison methods can be combined. In the Federal Republic of Germany, television pulses have been used in conjunction with the LF standard-frequency and time-signal transmitter DCF77. The LF second marker allows identification of a television pulse. This pulse, in turn, is helpful in identifying a carrier cycle of DCF77 [Becker *et al.*, 1973]. Similarly, LF and VLF signals can be used if they are synchronously transmitted.

The use of power lines has been suggested as a means of synchronization. Tests at the PTB and in Italy have shown that the precision is usually from 0.25 to 0.5 ms for a distance of 200 km with the possibility of phase changes due to switching of lines [Becker and Enslin, 1973; Angelotti and Cordare, 1974]. Similar results were obtained in the US over even longer paths of greater than 2000 km [Allan *et al.*, 1972b].

Experiments have been made [Norton *et al.*, 1962] on the instability introduced by propagation over a 50 km line-of-sight microwave link. The deterioration of the transmitted wave phase stability due to propagation is usually less important than the inherent fluctuations in the signal due to the generator noise. For a measurement time interval of 1 s, the contribution of instability due to the propagation can be represented by a normalized standard error of about 3×10^{-12} which decreases to 1×10^{-14} as the averaging time is increased to 10^6 s.

In the U.S.S.R. two-way synchronization experiments were conducted over a 750 km Moscow-Kharkov path by observing 72 MHz signals reflected from meteor trails [Dudnik *et al.*, 1971; 1973]. With transmitted powers of 40 kW, 5620 successful synchronization measurements per hour were usable. After compensating for the measured path delays, synchronization accuracies in the 0.1-0.2 μs range were achieved. Possible non-uniformities of the equipment delays in the forward and return channels are considered to be the principal error sources at present.

Experiments were conducted in France during 1974 to determine how well two clocks separated by 6 km could be synchronized using a two-way exchange of laser pulses to compensate for the propagation delay. In one series of experiments the clock difference was determined within an uncertainty of 4 ns. By using better laser detectors over a 300 m path, the uncertainties were reduced to less than 1 ns [Sannier, 1974; Besson, 1974; Besson and Parcelier, 1974]. Further improvements have been made in the timing pulse control equipment, leading to a potential resolution of the overall transmission and reception system of 100 ps [Moreau, 1977].

A cooperative experiment between France and Spain was carried out in 1977, involving the comparison of the time-scales of Paris (OP) and San Fernando (OMSF) observatories by means of the over-flight of both observatories by an aircraft equipped with a retroreflector, a laser emitter and the necessary time-keeping equipment. The difference between UTC(OP) and UTC(OMSF) was determined to within 20 ns [Benavente *et al.*, 1979].

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REPORT 897

METHODS FOR SHORT RANGE PRECISION TIME TRANSFERS

(Study Programme 3C/7)

(1982)

There is a need for making comparisons between time scales maintained at separate locations within a range, typically less than 100 km. This Report deals with separate locations that are considered to be local in the sense that they share a common environmental or propagation medium. This includes sites within line-of-sight, within reach of coaxial cables or optical fibres, or within convenient reach by portable clocks.

A widely method of synchronization in frequency and comparing time scales (Report 363) is the common monitoring of a radio signal that both sites can receive; (i.e., Loran-C, television-line, television-carrier, HF, LF, VLF stabilized carriers, Omega) and comparing the differences observed between the external signal and an internally generated signal for each site. The simultaneous observation of signals from a satellite by independent ground receivers is one of the most promising examples [Taylor, 1974]. The method has the disadvantages that the propagation path difference must be calibrated.

For distances in which coaxial cable can join the sites, two-way propagation of signals provides a means of calibrating the path length and direct comparisons of working signals for frequency and time synchronization are directly measurable [Rueger and Bates, 1979].

For some distances, line-of-sight propagation patterns are an economical choice using radio waves, microwaves, or laser beams to provide signals to transfer in either one-way or reflected two-way propagation paths. The two-way approach permits control of variables resulting from the propagation path such as temperature, humidity, clouds, smoke, or rain, but is subject to multipath problems depending on the sending antenna and receiving antenna design parameters and location relative to obstructions or reflecting surfaces near the line-of-sight path.

Timing signals for synchronization purposes are characterized by the signal rise time, the bandwidth available and the stability of phase time delay as the signal passes through the propagation medium and measuring instruments.

It has been a common practice to calibrate differential propagation path lengths by carrying a precision clock between two sites assuming corrections can be made for the portable clock rate as determined from aging data, velocity and gravitational corrections [Allan and Ashby, 1979].

A range of capabilities for high quality performance realized by several methods is shown in Table I for a distance of about 100 km or less.

TABLE I – *Uncertainty of short range time transfer*

Method of time transfer		Uncertainty of time transfer	Utilization status	Calibration (1)
Portable clock	[Rogers *et al.*, 1977]	2 ns	Routine	
Television line	[Lavanceau and Shephard, 1978]	10 ns	Routine	X
Television carrier	[Lavanceau and Shephard, 1978]	0.1 ns	Routine	X
Microwave relay	[MacConnell *et al.*, 1977; Norton *et al.*, 1962]	2 ps 2-50 ps	Experimental	X (2)
Coaxial cable	[Rueger and Bates, 1979]	0.2 ns	Routine	X (2)
Loran-C	[Winkler, 1972]	0.1 μs	Routine	X
VLF (Omega)	[Cooper and Chi, 1979]	1.5 μs	Experimental	X
HF time signals		1 ms	Routine	X
Telephony 10 kHz		10-100 μs		X
Optical				
Optical fibres		10 μs	Experimental	X (2)
Laser	[Besson, 1970]	0.1 ns	Experimental	X
Geodimeter	[Levine, 1978; Faller and Faller, 1977]	2 ps	Experimental	
Satellite links				
GOES	[Beehler *et al.*, 1979]	1 μs	Routine	
Transit	[Laidet, 1972; Beehler *et al.*, 1979]	1-5 μs	Routine	
Transit improvement program	[Taylor, 1974; Rueger and Bates, 1979]	10 ns	Experimental	
Global positioning system	[Schuchman and Spilker, 1977]	10 ns	Design potential	
Radio broadcast	[CCIR, 1970-1974a]	6 μs	Routine	X
50-60 Hz power line	[CCIR, 1970-1974b and c]	0.25 ms	Routine	X

(1) Calibration of both the instruments and the installation is required to achieve the indicated uncertainty of time transfer. The methods indicated by an "X" require an independent propagation path calibration.

(2) No external calibration is required for two-way operation.

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REPORT 439-3

RELATIVISTIC EFFECTS IN A TERRESTRIAL COORDINATE TIME SYSTEM

(Study Programme 3C/7)

(1970-1974-1978-1982)

1. Introduction

Advances in the accuracy of time comparisons require the adoption of a set of conventions and a coordinate reference frame in order to account for relativistic effects in a self-consistent manner. Use of transponders or atomic clocks in satellites and jet aircraft will soon result in a network of time standards which are spread over the entire globe; the large distances involved also contribute to the need for well-defined procedures in accounting for relativistic effects in time comparisons. This Report proposes the adoption of local, geocentric reference frames to be used in these time comparisons.

The Consultative Committee for the Definition of the Second (CCDS) at its 9th session (23-25 September, 1980) recognized this need and proposed to the International Committee of Weights and Measures (CIPM):

- that TAI is a coordinate time scale defined at a geocentric datum line and having as its unit one SI second as obtained on the geoid in rotation and
- that, in consequence, in the present state of the art it may be extended with sufficient accuracy to any fixed or mobile point near the geoid by applying the corrections of the first order of general relativity, i.e. the corrections for differences in gravitational potential and velocity and for the rotation of the Earth.

The present Report is consistent with the CCDS proposal, but extends the proposed procedures to heights which include geostationary-satellite orbits. The following equations are accurate in representing clock rates to better than 1 part in 10^{14}.

When transferring time from point P to point Q, the process can be viewed either from a geocentric, earth-fixed, rotating reference frame, case R or from a geocentric, non-rotating, local inertia frame, case N.

2. Clock transport

2.1 *Case R*

When transferring time from point P to point Q by means of a portable clock, the coordinate time accumulated during transport is:

$$\Delta t = \int_P^Q \mathrm{d}s \left[1 - \frac{\Delta U(\vec{r})}{c^2} + \frac{v^2}{2c^2} \right] + \frac{2\omega}{c^2} A_E \qquad (1)$$

where c is the speed of light; ω is the angular velocity of rotation of the Earth; v is the velocity of the clock with respect to the ground; $\vec{r}$ is a vector whose origin is at the centre of the Earth and whose terminus moves with the clock from P to Q; A_E is the equatorial projection of the area swept out during the time transfer by the vector $\vec{r}$ as its terminus moves from P to Q; $\Delta U(\vec{r})$ is the potential difference between the location of the clock at $\vec{r}$ and the geoid as viewed from an earth-fixed coordinate system, with the convention that $\Delta U(\vec{r})$ is positive when the clock is above the geoid; and ds is the increment of proper time accumulated on the portable clock. The increment of proper time is the time accumulated on the portable standard clock as measured in the "rest frame" of the clock; that is, in the reference frame travelling with the clock. A_E is measured in an earth-fixed coordinate system. As the area A_E is swept, it is taken as positive when the projection of the path of the clock on the equatorial plane is eastward. When the height h of the clock is less than 24 km above the geoid, $\Delta U(\vec{r})$ may be approximated by gh, where g is the total acceleration due to gravity (including the rotational acceleration of the Earth) evaluated at the geoid. This approximation applies to all aerodynamic and earthbound transfers. When h is greater than 24 km, the potential difference $\Delta U(\vec{r})$ must be calculated to greater accuracy as follows:

$$\Delta U(\vec{r}) = -GM_e \left(\frac{1}{r} - \frac{1}{a_1} \right) - \frac{1}{2} \omega^2 (r^2 \sin^2 \theta - a_1^2) + \frac{J_2 GM_e}{2a_1} \left[1 + \left(\frac{a_1}{r} \right)^3 (3 \cos^2 \theta - 1) \right] \qquad (2)$$

where a_1 is the equatorial radius of the Earth; r is the magnitude of the vector $\vec{r}$; θ is the colatitude; GM_e is the product of the Earth's mass and the gravitational constant; and J_2 is the quadrupole moment coefficient of the Earth, $J_2 = +1.083 \times 10^{-3}$.

2.2 *Case N*

When transferring time from point P to point Q by means of a clock the coordinate time elapsed during the motion of the clock is:

$$\Delta t = \int_P^Q \mathrm{d}s \left[1 - \frac{U(\vec{r}) - U_g}{c^2} + \frac{v^2}{2c^2} \right] \qquad (3)$$

where $U(\vec{r})$ is the potential at the location of the clock and v is the velocity of the clock, both as viewed (in contrast to equation (1)) from a geocentric non-rotating reference frame, and U_g is the potential at the geoid, including the effect on the potential of the Earth's rotational motion. Note that $\Delta U(\vec{r}) \neq U(\vec{r}) - U_g$, since $U(\vec{r})$

does not include the effect of the Earth's rotation. This equation also applies to clocks in geostationary orbits but should not be used beyond a distance of about 50 000 km from the centre of the Earth.

3. Electromagnetic signals

3.1 *Case R*

From the viewpoint of a geocentric, earth-fixed, rotating frame, the coordinate time elapsed between emission and reception of an electromagnetic signal is:

$$\Delta t = \frac{1}{c} \int_P^Q \mathrm{d}\sigma \left[1 - \frac{\Delta U(\vec{r})}{c^2} \right] + \frac{2\omega}{c^2} A_E \tag{4}$$

where $\mathrm{d}\sigma$ is the increment of standard length, or proper length, along the transmission path; $\Delta U(\vec{r})$ is the potential at the point, $\vec{r}$, on the transmission path less the potential at the geoid (see equation (3)), as viewed from an earth-fixed coordinate system, and A_E is the area circumscribed by the equatorial projection of the triangle whose vertices are:

- at the centre of the Earth;
- at the point, P, of transmission of the signal;
- at the point, Q, of reception of the signal.

The area, A_E, is positive when the signal path has an eastward component. The second term amounts to about a nanosecond for an Earth-to-geostationary satellite-to-Earth trajectory. In the third term, $2\omega/c^2 = 1.6227 \times 10^{-6}$ ns/km^2; this term can contribute hundreds of nanoseconds for practical values of A_E. The increment of proper length, $\mathrm{d}\sigma$, can be taken as the length measured using standard rigid rods at rest in the rotating system; this is equivalent to measurement of length by taking $c/2$ times the time (normalized to vacuum) of a two-way electromagnetic signal sent from P to Q and back along the transmission path.

3.2 *Case N*

From the viewpoint of a geocentric non-rotating (local inertial) frame, the coordinate time elapsed between emission and reception of an electromagnetic signal is:

$$\Delta t = \frac{1}{c} \int_P^Q \mathrm{d}\sigma \left[1 - \frac{U(\vec{r}) - U_g}{c^2} \right] \tag{5}$$

where $U(\vec{r})$ and U_g are defined as in equation (3), and $\mathrm{d}\sigma$ is the increment of standard length, or proper length, along the transmission path. The quantities of $\mathrm{d}\sigma$ appearing in equation (4) and (5) differ slightly because the reference frames in which they are measured are rotating with respect to each other.

4. Examples

Due to relativistic effects, a clock at an elevated location will appear to be higher in frequency and will differ in normalized rate from TAI by:

$$\frac{\Delta U_T}{c^2}$$

where ΔU_T is the difference in the total potential (gravitational and the centrifugal potentials), and where c is the velocity of light. Near sea level this is given by:

$$\frac{g(\varphi) h}{c^2} \tag{6}$$

where $g(\varphi) = (9.780 + 0.052 \sin^2 \varphi)$ m/s^2, φ is the geographical latitude, and $g(\varphi)$ is the total acceleration at sea level (gravitational and centrifugal) and where h is distance above sea level. Equation (6) must be used in comparing primary sources of the SI second with TAI and with each other. For example, at latitude 40°, the rate of a clock will change by $+1.091 \times 10^{-13}$ for each kilometre above sea level.

If a clock is moving relative to the Earth's surface with the speed v which may have the component v_E in the direction to the East, the normalized difference of the frequency of the moving clock from that of a clock at rest at sea level is:

$$-\frac{1}{2}\frac{v^2}{c^2}+\frac{g(\varphi)h}{c^2}-\frac{1}{c^2}\cdot\omega\cdot r\cdot\cos\varphi\cdot v_E \tag{7}$$

ω is the angular rotational velocity of the Earth ($\omega = 7.992 \times 10^{-5}$ rad/s), r the distance of the clock from the centre of the Earth ($r = 6378.140$ km), c is the velocity of light ($c = 2.99792458 \times 10^5$ km/s) and φ the geographical latitude.

For example, if a clock is moving 270 m/s East at 40° latitude at an altitude of 9 km, the normalized difference of frequency of the moving clock relative to that of a clock at rest at sea level due to this effect is:

$$-4.06 \times 10^{-13} + 9.82 \times 10^{-13} - 1.071 \times 10^{-12} = -4.95 \times 10^{-13}$$

The choice of a coordinate frame is purely a discretionary one, but to define coordinate time, a specific choice must be made. It is recommended that for terrestial use a topocentric frame be chosen. In this frame, when a clock B is synchronized with a clock A (both clocks being stationary on the Earth) by a radio signal travelling from A to B, these two clocks differ in coordinate time by:

$$B - A = -\frac{\omega}{c^2}\int_P r^2\cos^2\varphi\,\mathrm{d}\lambda \tag{8}$$

where φ is the latitude, λ the longitude (the positive sense being toward East), and P is the path over which the radio signal travels from A to B. If the two clocks are synchronized by a portable clock, they will differ in coordinate time by:

$$B - A = \int_P \mathrm{d}t\left(\frac{\Delta U_T}{c^2}-\frac{v^2}{2c^2}\right)-\frac{\omega}{c^2}\int_P r^2\cos^2\varphi\,\mathrm{d}\lambda \tag{9}$$

where v is the portable clock's ground speed, and P is the portable clock's path from A to B.

This difference can also be as much as several tenths of a microsecond. It is recommended that equations (8) or (9) be used as correction equations for long-distance clock synchronization. Since equations (8) and (9) are path dependent, they must be taken into account in any self-consistent coordinate time system.

If a clock is transported from a point A to a point B and brought back to A on a different path at infinitely low speed at $h = 0$, its time will differ from that of a clock remaining in A by:

$$\Delta t = -\frac{2\omega A_E}{c^2} \tag{10}$$

where A_E is the area defined by the projection of the round trip path on to the plane of the Earth's equator. A_E is considered positive if the path is traversed in the clockwise sense viewed from the South Pole.

For example since:

$$2\omega/c^2 = 1.6227 \times 10^{-6}\ \text{ns/km}^2$$

the time of a clock carried eastward around the Earth at infinitely low speed at $h = 0$ at the equator will differ from a clock remaining at rest by -207.4 ns.

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REPORT 736-1

FREQUENCY SHARING BETWEEN THE TIME-SIGNAL SERVICE AND THE RADIOLOCATION SERVICE, THE FIXED-SATELLITE SERVICE AND THE FIXED AND MOBILE SERVICES NEAR 14, 21, 26 AND 31 GHz

(Study Programme 2A/7)

(1978-1982)

1. Introduction

This Report examines the problems of frequency sharing between a proposed satellite time dissemination system and the radiolocation service, the fixed-satellite service, and the fixed and mobile services in the vicinity of 14, 21, 26 and 31 GHz (see Table I). An evaluation is made of co-channel operation of a satellite time dissemination system, a radiolocation system, fixed-satellite communications equipment, and fixed and mobile terrestrial radio relay equipment. Typical parameters for the general classes of equipment have been assumed to allow completion of the analysis.

2. The satellite time dissemination system

Figure 1 illustrates a proposed satellite time dissemination system intended to provide a means for high-precision comparisons of time and frequency at widely separated points on the Earth. A pseudo-random noise (PRN) coded signal is transmitted from a ground transmitter to a spacecraft receiver. The spacecraft receiver decodes the transmitted signal and makes a comparison with a precision clock located onboard to determine the time of arrival referred to the spacecraft time standard. A spacecraft transmitter then uses a PRN modulated signal to relay data on the ephemeris and epoch of earth signal reception to the earth station. The earth receiver decodes this signal and a comparison can then be made between the spacecraft time standard and the ground clock. Two earth stations can be used with the spacecraft in such a way that stations one and two can compare clocks. The spacecraft clock can also be compared with a calibration time standard at an appropriate earth station in order to assess its accuracy. The radio frequency operating bands proposed for use by the satellite time dissemination system are listed in Table I. The operating characteristics are summarized in Table II. PRN coding is used to assure good S/N ratios with minimal interference power received by other stations sharing the bands.

3. Sharing with the radiolocation service

The radio frequency band proposed for timing dissemination up-link transmissions near 14 GHz must be shared with the radiolocation service. Typical operating characteristics for a radiolocation system which might operate in this portion of the spectrum are given in Table III. Interference between a timing dissemination system earth station and a radiolocation system can be prevented by coordination of siting, antenna orientation, antenna heights, etc., between the two installations. For example, if the two stations are separated by a distance (in kilometres):

$$d \leqslant \sqrt{17\,h_1} + \sqrt{17\,h_2}$$

where

h_1 : height of antenna 1, metres,

h_2 : height of antenna 2, metres,

they will be below each other's radio horizon and main beam coupling will not occur regardless of orientation. To illustrate this, if the two antennas are 15 m high, the two stations need only be separated by approximately 32 km to be below each other's radio horizon. Furthermore, the directivity of the timing dissemination system transmitting antenna can also be used to limit further the interference flux at the radiolocation system antenna site.

The Radio Regulations (RR 2540 to 2548) require that the effective isotropically radiated power transmitted in any direction towards the horizon by an earth station operating between 1 and 15 GHz shall not exceed:

$+40$ dBW in any 4 kHz band for $\theta \leq 0°$,

$+40 + 3\,\theta$ dBW in any 4 kHz band for $0° < \theta \leq 5°$,

where θ is the angle of elevation of the horizon viewed from the centre of radiation of the antenna of the earth station and measured in degrees as positive above the horizontal plane and negative below it. For the postulated system,

$$\text{e.i.r.p.} = P_t + G_t + B$$

$$= 20 + 53 - 48 = 25 \text{ dB(W/4 kHz) maximum,}$$

where:

P_t : transmitter power dBW,

G_t : transmitter antenna gain, dB,

B : bandwidth correction factor

$$10 \log \left(\frac{4 \times 10^3}{250 \times 10^6}\right)$$

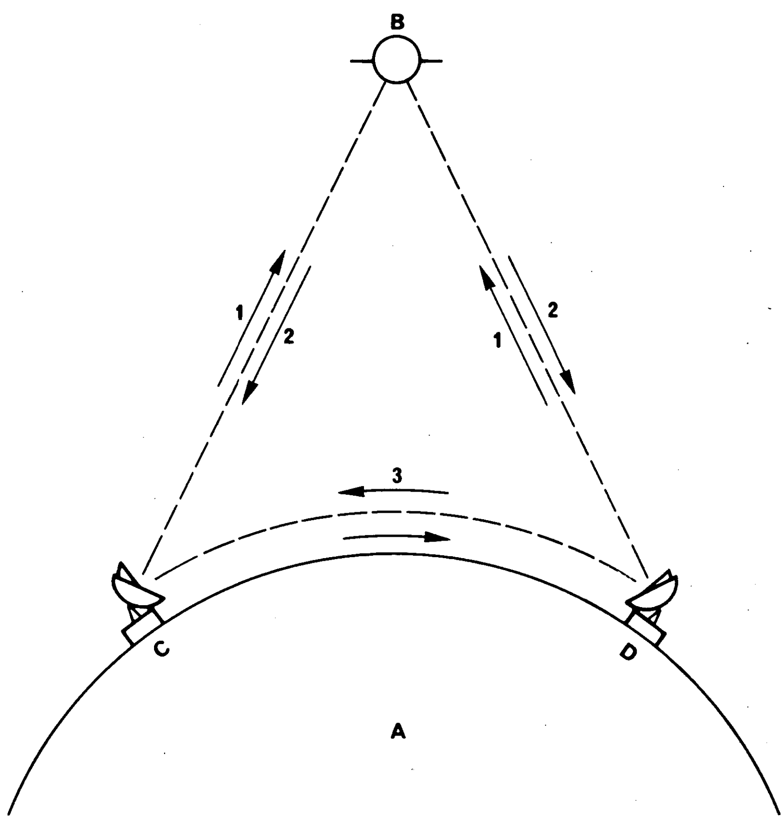


FIGURE 1 – *Satellite time dissemination system*

A Earth
B Time dissemination satellite
C Earth station number 1
D Earth station number 2
1 Earth-to-space link
2 Space-to-Earth link
3 Terrestrial path

TABLE I – *Proposed frequencies – satellite time dissemination system*

Proposed Centre Frequency Operating Band (GHz)	Proposed RF Bandwidth (GHz)	Other Allocations (Existing and Possible)	Operating Limitations (ITU Radio Regulations)
13.4-14.0 (up-link)	± 0.125 (0.25)	**Radiolocation** Earth Exploration Satellite (Active Sensor) Space Research (Earth-to-space)	e.i.r.p. +40dB(W/4 kHz) $\theta \leqslant 0°$ e.i.r.p. $(+40+3\theta)$ dB(W/4 kHz) $0° < \theta \leqslant 5°$ No limit on radiolocation
20.2-21.2 (down-link)	± 0.125 (0.25)	**Fixed satellite** (space-to-Earth) **Mobile satellite** (space-to-Earth)	No limit specified
25.27-27.5 (up-link)	± 0.6 (1.2)	**Fixed** **Mobile** EES (space-to-Earth)	e.i.r.p. $\leqslant +64$ dB(W/MHz) $\theta \leqslant 0°$ e.i.r.p. $\leqslant (+64 + 3\theta)$ dB(W/MHz) $0° < \theta \leqslant 5°$
30.0-31.3 (down-link)	± 0.6 (1.2)	**Fixed-satellite** (Earth-to-space) **Fixed** **Mobile** Space Research **Mobile satellite** (Earth-to-space)	Not yet specified

TABLE II – *Satellite time dissemination system – summary of characteristics*

Earth station	
Transmitter power	100W
Antenna gain (assumed)	53 dB
Type modulation	PRN code
Receiver noise temperature	1000 K (~6 dB NF)
Predetection bandwidth	250 MHz, 1.2 GHz
Post detection bandwidth	1 MHz
Processing gain	24 dB, 30.8 dB
Post detection *S*/*N* ratio	18 dB
Satellite	
Transmitter power	50W
Antenna gain	4 dB (over Earth angle)
Type modulation	PRN code
Receiver noise temperature	1000 K
Predetection bandwidth	250 MHz, 1.2 GHz
Post detection bandwidth	1 MHz
Processing gain	24 dB, 30.8 dB
Post detection *S*/*N* ratio	18 dB

TABLE III – *typical radiolocation system operating characteristics*

Peak pulse power	25 kW
Pulse width	32 ns
Pulse rise time	12 ns
PRF	15 kHz
Average power	12 W
Frequency (carrier)	~14 GHz
Receiver sensitivity	–85 dB (m)
Receiver noise figure	11 dB (T_s ~ 3400K)
Signal-to-noise ratio (required for operation)	12 dB
Receiver IF bandwidth	40 MHz
Antenna gain over isotropic	35 dB
Side lobes	25 dB below main lobe
Antenna tilt	0 deg.
Antenna scan rate	135 r.p.m.
Antenna pattern	10 deg. vertical beamwidth 0.34 deg. horizontal beamwidth

The emissions from the radiolocation system transmitter main beam may occasionally be directly coupled into the satellite receiver antenna when the timing dissemination satellite is in view and less than ten degrees above the radiolocation system horizon (due to assumed ten degrees vertical beamwidth). In this case the interference power density at the satellite receiver is:

$$D_r = P_t + G_t - B_t - 10 \log (4\pi R^2) + 10 \log \left(\frac{G_r \lambda^2}{4\pi}\right)$$

D_r: -179 dB(W/Hz)

where:

D_r: interference power density, dB(W/Hz),

P_t: average transmitter power, dBW,

G_t: transmitter antenna gain, dB,

B_t: transmitter bandwidth, dB (1 Hz),

R: distance between transmitter and receiver antennas, m (3709×10^3 m for a 1000 km satellite),

G_r: receiver antenna gain, dB,

λ: operating wavelength, m.

The estimated signal power density (given by the same relationship plus the processing gain, 24 dB) is -169 dB(W/Hz), thus yielding a carrier-to-interference ratio of 10 dB, in the worst case. This C/I ratio is adequate to protect the timing dissemination system during all operations.

4. Sharing with the fixed-satellite service (space-to-Earth)

The satellite time dissemination down link proposed in the vicinity of 21 GHz must share a band with fixed-satellite and mobile-satellite service down links (space-to-Earth). For sharing to be permissible in this band, the power flux-density at the Earth's surface must be less than the limits specified in the Radio Regulations (RR 2577 to 2585) (see Table I). Furthermore, the angular discrimination due to the directivity of the fixed-satellite antenna can be used to provide additional isolation by constraining satellite transmissions within a minimum angular separation from the fixed-satellite earth station antenna axis.

The power flux density at the fixed-satellite earth station is given by:

$$PFD = P_t + G_t - B_t - 10 \log (4\pi R^2)$$

$$= -145 \text{ dB(W/(m}^2 \text{ MHz))}$$

The interference criteria developed at the WARC-BS-77 specify a maximum single entry interference-to-carrier ratio of -35 dB for protection of fixed-satellite communication systems. Report 561 predicts a fixed-satellite down-link carrier PFD at the Earth's surface on the order of -124.0 dB(W/(m^2 MHz)). This value for PFD results in a carrier-to-interference ratio of 21 dB. The additional 14 dB of isolation required (assuming a 60 dB FSS antenna gain and ITU standard side lobe envelope) can be obtained by preventing transmission within 0.3 degree of the FSS earth station antenna axis. This angular separation is obtained from:

$$G = 32 - 25 \log \theta$$

where:

G = maximum antenna gain at an angle θ from the axis.

Thus:

$$(60 - 14) = 32 - 25 \log \theta$$

$$\theta = 0.3 \text{ degree}$$

The possibility exists that fixed-satellite earth stations with higher sensitivities than those described in Report 561 will be implemented. If for example, a fixed-satellite earth station had the following characteristics:

– earth station noise power referred to receive input:	–143.6 dB(W/MHz)
– wanted down-path carrier-to-noise ratio:	15 dB
– earth-station antenna gain:	65 dBi

the fixed-satellite pfd on the Earth's surface would be –146 dB(W/(m^2 · MHz)). This value is approximately the same as that of the time dissemination satellite system. In order to provide this sensitive fixed-satellite system with protection (i.e., a carrier-to-interference (C/I) ratio of 35 dB) the satellite time dissemination down link would be constrained from operation while it was within approximately 1.2° of the earth-station main beam.

A sensitive earth station of the type mentioned above would have a beamwidth on the order of 0.048°. Under the worst-case conditions, in which the time dissemination satellite control system failed but the satellite remained transmitting, the sensitive fixed-satellite earth station could receive main beam interference for about 1.7×10^{-7}% of the time or approximately 5 s a year. The longest possible occurrence of a single pass main beam coupling for this case is on the order of 0.4 s. Taking the entire 1.2° cone about the earth-station bore site into account a C/I of less than 35 dB could possibly occur for about 0.01% of the time until the failure of the time dissemination satellite was remedied.

5. Sharing with the fixed-satellite service (Earth-to-space)

The proposed satellite time dissemination system down link near 31 GHz would share a portion of a band allocated for fixed-satellite service up links. Interference between fixed-satellite service earth-station transmissions and time dissemination earth-station receivers can be prevented by coordination of station parameters, station locations, antenna orientations, etc. Interference between the satellite-borne time dissemination transmitter and the fixed satellite service spacecraft receiver is very unlikely because of the relatively low e.i.r.p. and relatively long distances involved. For example, the interference power flux density at the fixed-satellite receiver is given by:

$$\text{PFD}_\text{I} = P_t + G_t - B_t - 10 \log (4\pi R^2)$$

$$\leqslant 17 + 0 - 84 - 11 - 151 = -229 \text{ dB(W/(m}^2 \text{ Hz))}$$

Similarly, the carrier power flux density is:

$$\text{PFD}_\text{C} = P_t + G_t - B_t - 10 \log (4\pi R^2)$$

$$\leqslant 8.3 - 11 - 152 = -155 \text{ dB(W/(m}^2 \text{ Hz))}$$

(for e.i.r.p. density = 8.3 dB(W/Hz) and $R \simeq 41\,500$ km)

Thus the carrier-to-interference ratio would be approximately +74 dB.

6. Sharing with the fixed and mobile services

Sharing between the satellite time dissemination up link (~ 26 GHz) and the fixed and mobile services will be feasible if two requirements are fulfilled. The first is that the time dissemination transmitter e.i.r.p. fall within limits specified by the Radio Regulations (RR 2542). The second is that there be sufficient carrier-to-interference margin to preclude harmful interference to each other.

The requirement on e.i.r.p. density for earth stations operating above 15 GHz is:

$$64 \text{ dB(W/1 MHz) } \theta \leqslant 0°$$

$$64 + 3\,\theta \text{ dB(W/1 MHz) } 0° < \theta < 5°$$

The time dissemination earth station

$$\text{e.i.r.p.} \leqslant 20 + 71 + - 24 = 67 \text{ dB(W/MHz)}$$

Thus, if $\theta \geqslant 1.0°$, the first limitation is satisfied.

The second restriction, i.e., C/I margin, can be handled by coordination of station parameters (i.e., gain, power, etc.) siting, antenna height, antenna orientation, etc. As an example, if two stations sharing a band have antenna heights of 15 m, for

$$d \geq \sqrt{17 \times 15} + \sqrt{17 \times 15} \geq 32 \text{ km}$$

they are below each other's radio horizons.

Sharing near 31 GHz between the time dissemination down link and the fixed and mobile services will be determined by a trade-off between interference level and the percentage of operating time during which it occurs.

The interference power density in the receiver front end is:

$$P_I = E_T + G_r - L$$

where:

$$E_T = \text{transmitter e.i.r.p. density} = P_T + G_T - B_T$$
$$= 17 + 4 - 84 = -63 \text{ dB(W/Hz)}$$

L: propagation loss $= 92.5 + 20 \log f + 20 \log R$,

f: operating frequency, GHz,

R: distance, km.

For $R = 3709$ km ($L = 193.7$ dB) and $G_R = 60$ dBi, $P_I = -196.7$ dB(W/Hz).

From Report 686 for a relay network of 5 stations:

$$P_I = -196.2 + 10 \log \left(\frac{X}{1250}\right)$$

where:

X = allowable interference, psophometrically weighted, (pW0p)

Solving for $P_I = -196.7$ gives

$$X = 1114 \text{ pW0p}$$

or -59.5 dBm0p

According to Recommendation 357, this level of interference power can be withstood by an analog angle-modulated radio relay system for nearly 20% of the operating time. Report 684 which investigates low-orbit satellite visibility statisitics, shows that a single station would find a low orbit satellite within its main beam less than 1.0% of the time. Thus, the time dissemination system is capable of frequency sharing with fixed and mobile radio relay systems without causing harmful interference. Interference to time dissemination earth station receivers by fixed and mobile transmitters can be eliminated by coordination of station parameters, sites, antenna orientation, etc.

7. Conclusions

Sharing between a satellite time dissemination system and the radiolocation service near 14 GHz is feasible. Interference to radiolocation system operations by a time dissemination earth station can be prevented by coordination between the two installations. This effective isotropically radiated power of the time dissemination system earth stations should conform to the limitations of RR 2541. Radio-frequency energy emitted by radiolocation system transmitters will not interfere with time dissemination system operations.

Sharing between a time dissemination system down link and fixed-satellite service space-to-Earth links near 21 GHz is also feasible. The time dissemination spacecraft transmitter must comply with RR 2578, limiting the power flux density at the Earth's surface. Furthermore, the time dissemination satellite should be programmed to preclude transmission near 21 GHz when its position is within 0.3 degree of the principal axis of a fixed satellite earth-station receiver antenna operating near 21 GHz.

Sharing between a satellite time dissemination system down link and fixed-satellite up links near 31 GHz is feasible for the timing system parameters given in this Report. Coordination between fixed-satellite and time dissemination earth stations will be necessary to protect the time system from harmful interference.

Frequency sharing between a time dissemination system up link and fixed and mobile services near 26 GHz is feasible provided that the transmitter power is no more than 100 W when using an antenna of no more than 71 dB gain elevated at least one degree above the horizontal plane. Coordination of earth station and relay station installations will be required.

Sharing between a time dissemination system down link and fixed and mobile services near 31 GHz is feasible provided the satellite transmitter power is no greater than 50 W and the satellite antenna gain is no greater than 4 dB. PRN coding should be used to improve signal-to-noise ratios without increasing interference power levels.

REPORT 576-2

STANDARD-FREQUENCY DISSEMINATION VIA STABILIZED BROADCAST STATION CARRIERS

(Study Programme 4A/7)

(1974–1978–1982)

Many users of the standard-frequency and time-signal service emissions, particularly in the radio and electronic industries, require a frequency reference with only moderate precision. These users are often located in environments with severe electromagnetic interference which can seriously reduce the usefulness of standard frequencies and time signals in allocated and other bands. Moreover, there is a need for simple and inexpensive equipment to perform such frequency comparisons.

The requirements are met in Europe with a number of standard-frequency and time-signal services operating in band 5 and by the stabilization of broadcast station carriers: Allouis, 164 kHz; Donebach, 155 kHz; Droitwich, Westerglen, Burghead, 200 kHz (Westerglen and Burghead are phase-locked to Droitwich); Motala, 191 kHz and Milano I, 900 kHz. The carriers of these latter stations are derived from atomic frequency standards. For further details of some of these stations, see Report 267. (The carrier frequencies of the broadcasting stations in band 5 will be reduced by 2 kHz over the period 1 February 1986 to 1 February 1990; see Resolution No. 500 of the World Administrative Radio Conference, Geneva, 1979.)

Due to propagation characteristics in the LF band, depending on transmitter power, the primary service area can be very large (with a radius of the order of some hundreds of km). In this prime coverage area, frequency comparisons are possible with an uncertainty between 1×10^{-11} and 1×10^{-9}, provided that the measurement is performed during daylight hours and with a sufficiently long measurement interval.

Experiments have been carried out in the United States of America in band 6 with the stabilization of a broadcast station carrier at 650 kHz operating with 50 kW carrier power. A frequency comparison uncertainty of 1×10^{-10} was obtained at a distance of 800 km during daylight hours.

In the Federal Republic of Germany about 160 television transmitters are operating in band 9 with the carriers remotely controlled by the use of a standard frequency of 10 MHz supplied via the television programme distribution lines set up on radio-relay links. An average normalized carrier frequency departure of 3×10^{-12} was observed with a standard deviation of 3×10^{-11} (Report 363). By means of the stabilized carrier, frequency comparisons with an uncertainty of a few parts in 10^{10} are achievable in less than one minute.

The usefulness of stabilizing the carriers of broadcast stations is enhanced by the fact that existing frequency allocations and transmitters are used without degrading their primary purpose. In addition, these stations usually provide a field intensity large enough to ensure a good signal-to-noise ratio.

REPORT 577-2

DISSEMINATION OF TIME SIGNALS BY ADDITION OF PHASE MODULATION ON AMPLITUDE-MODULATED SOUND BROADCASTING TRANSMITTERS

(Study Programme 4B/7)

(1974–1978–1982)

Dissemination of time signals, with an accuracy meeting the requirements of many users, can be achieved without increasing the congestion in the bands allocated to standard-frequency and time-signal emissions, by use of existing transmitters designed for other services. In particular, it is possible to superimpose a phase modulation, simultaneously carrying second markers and date information (minute, hour, day, month, year) in coded form, on the conventional amplitude modulation of a sound broadcasting station.

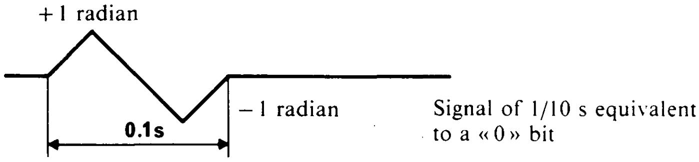
A suitable receiver can operate as a remotely controlled time display, the accuracy of which depends only on the accuracy of the time scale at the emission.

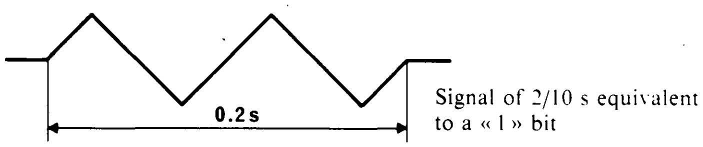
Experiments have been carried out on this technique in France, by modulating a sound broadcasting transmitter in band 5 (Allouis transmitter on 163.84 kHz * with a power of 2 MW).

The coded date information is transmitted by the "slow code" of one bit per second, the complete cycle taking one minute.

The code of the DCF77 transmitter is used with certain peculiarities incorporated (see Report 578 and the note ([48]) to Table II of Report 267).

The phase modulation model is given below:





The time signal obtained (on French territory) has an accuracy of 1 ms and a standard deviation of about 0.2 ms.

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* In compliance with Resolution No. 500 of the World Administrative Radio Conference, Geneva, 1979, the carrier frequency value of this transmitter shall be reduced to 162 kHz by 1 February, 1986.

RECOMMENDATION 583

TIME CODES *

(Question 7/7)

(1982)

The CCIR,

CONSIDERING

(a) that in many branches of science and technology there is a need of dating of events requiring the knowledge of the date (year, month, day) and clock time;

(b) that this time information can be transmitted in a coded form with a bit rate of one per second ("slow code") during about one minute;

(c) that such coded time transmissions require very small bandwidths resulting in an economic spectrum use and enabling a high reliability of the received time information;

(d) that "slow codes" are in widespread use and can be disseminated by normal AM broadcasting stations, without impairing the prime service by using a phase modulation of the carrier;

(e) that the time code first used by the standard-frequency and time-signal transmitter DCF77 is in use in several European countries and has shown a high utility;

(f) that it is desirable to use the same time code in large geographical areas;

(g) that in some areas of the world, e.g., in many developing countries, time codes are not yet introduced,

UNANIMOUSLY RECOMMENDS

1. that the introduction of such time codes should be encouraged;

2. that if in Region 1 such a time code is proposed by a time service, it should conform with one of the codes which has already found acceptance, (for example that in use by DCF77);

3. that if a time service of other Regions intends to introduce a time code, it should consider the advantages of adopting the practice as in Region 1.

REPORT 578-2

TIME CODES

(Question 7/7)

(1974-1978-1982)

Developments in recent years have emphasized the need for the transmission of more complete time information than is provided by the normal second and minute signals as part of the standard-frequency and time-signal services. Requirements for more complete coded time information, which may include the minute, hour and day of the year, arise in various fields – for example, in providing a common time base for geographically widespread monitoring systems making use of the unattended equipment. An increasing number of applications in science, industry and administration is expected.

Through a joint effort between the various user groups in the United States, a series of time codes was standardized and adopted. These codes became known as serial decimal (SD) time codes, binary coded decimal (BCD) time codes, and parallel grouped binary (PB) time codes [IRIG, 1970 and 1980; NASA/GSFC, 1970-81; NBS, 1979].

* Further information is given in Report 578.

The parallel grouped binary (PB) time code is designed to facilitate automatic data processing. Primary consideration is given to ground-to-satellite and satellite-to-satellite time transfer applications [Chi, 1979a and b]. For this reason, conventional time units were not always adopted although the concept of the International System (SI) of units is strictly followed.

The parallel grouped binary time code, as the name implies, consists of groups of binary numbers, each of which is designated a time unit. The groups of binary numbers are adopted (in preference to a single group) to accommodate not only the SI units of time but also the users' needs for different precisions and accuracies. The PB5 code which is shown in Fig. 1 illustrates this concept.

Figure 2 shows a typical BCD time code which consists of a time frame comprising a sequence of square waves or pulses. The sequence of pulses is so arranged in a time frame that their positions are used to designate a time unit. Within each time unit or sub-frame, a group of four pulses is used as a counter. The width of each pulse is used to designate a binary state. The four pulses in the sub-frame are given the binary weights of 1, 2, 4 and 8 to code a digit from 0 to 9. Each sub-frame is separated from the other by a sub-frame reference marker and each major frame is separated from the other by a frame reference marker at the end of each major frame.

Standard-frequency and time-signal station WWV was the first to add complete coded time information to its modulation schedule in 1960. Time codes were later extended to transmissions from stations WWVH and WWVB (60 kHz). The time codes on the high-frequency (HF) stations are radiated on a 100 Hz sub-carrier. For WWVB the carrier level is reduced by 10 dB for each binary digit.

An FSK time code is included on the 31st to 39th seconds pulses of CHU, giving the day, hour, minute and second. The FSK 300 baud system was chosen because of its proven utility in the transmission of commercial data, and the ready availability of commercial equipment. Under severe noise conditions, the decoding has proved much more reliable than equivalent amplitude modulated codes.

Starting with DCF77 in 1973 [Becker and Hetzel, 1973] a number of European stations transmitting standard frequencies and time signals in band 5, have added coded time information to their emissions.

Two approaches have been used, depending on the bandwidth available and on the degree of noise immunity in the decoder.

For maximum security the so-called "slow code" at a bit-rate of 1 Hz has been adopted, first by DCF77, then by MSF 60 kHz, the complete information thus extending over most of one minute.

This coding method is considered to have two essential advantages; the necessary bandwidth is small (less than 30 Hz) and the low transmission rate permits decoding by the use of simple recorders. These features are especially useful for remote and unattended stations. Receiving and decoding equipment for DCF has been described by [Hetzel and Rohbeck, 1974] and for MSF 60 kHz, by [Cross, 1976].

If a larger bandwidth is available at the transmitter, the so-called "fast code" can be employed in which the data rate is chosen to give complete information in about 0.5 s. Such a fast code is radiated by MSF 60 kHz and OMA 50 kHz.

A similar fast code is also broadcast in Italy by RAI on AM and FM networks, about 25 times a day.

The code formats in use generally can include information on the second, minute, hour, calendar day, day of the week, month, year, the modified Julian day and, in some cases, DUT1 and an indication if the radiated time differs from the zonal time.

A common feature of the services DCF77, MSF 60 kHz and Allouis 163.84 kHz, is the use of BCD codes; the same form of pulse width modulation is used, binary zeros being represented by 0.1 s-wide and binary ones by 0.2 s-wide second markers.

These codes are not all identical. Since September 1981, the second markers 17 and 18 of DCF77 indicate whether the broadcast time is UTC or UTC plus 1, 2 or 3 hours [Becker and Hetzel, 1981]. The French transmission Allouis 163.84 kHz has the same code as DCF77 with the additional information given on second 14, that the day is or is not a public holiday [Gabry, 1980] and Report 577.

Not all of these codes are considered to be in their final form, and the relevant information at any time should be requested from the responsible Authorities, listed in Annex I of the Report 267.

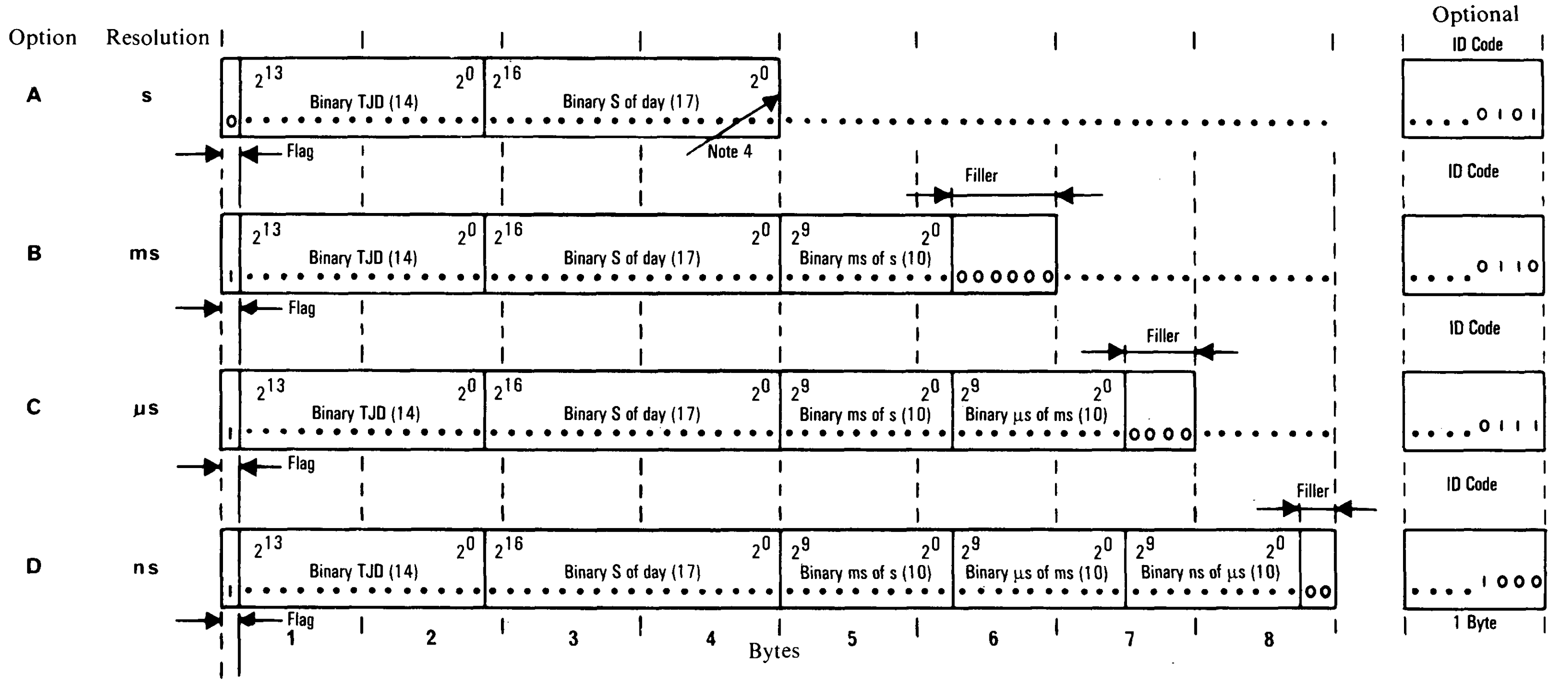


FIGURE 1 – *Parallel grouped binary time code PB5 and resolution options*

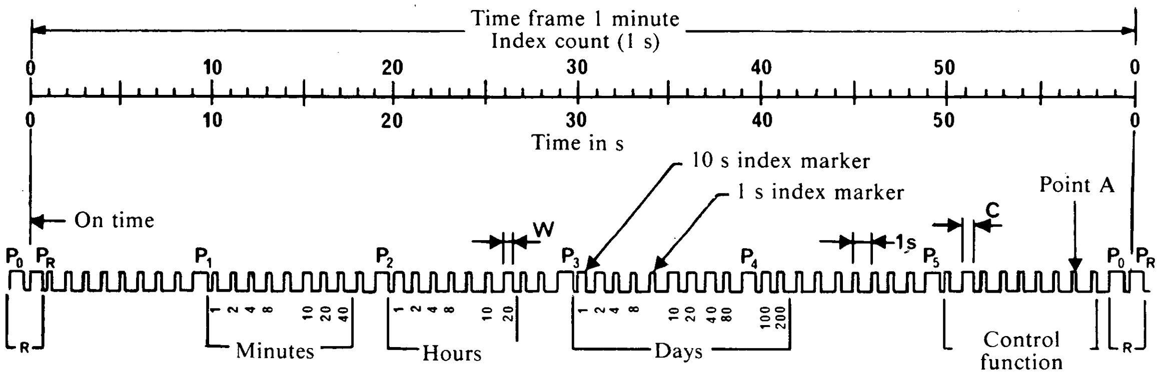
Note 1. – Dots represent bit positions.

Note 2. – The number in parenthesis represents bits in each group.

Note 3. – Filler bits may be added to the least significant sub-second group in option B, C, or D, as shown, to maintain integral byte boundaries.

Note 4. – The Truncated Julian Day, (TJD) and second-of-day groups are right-justified to this boundary ; the remaining groups are left-justified to this boundary.

TJD = MJD – 40000 (see Recommendation 457).



Time at point A = 21 : 10 57
= 21 hours 10 minutes 57 seconds on day 173

FIGURE 2 – *A typical BCD time code format*

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REPORT 737-1 *

RELIABILITY OF TIME AND FREQUENCY STANDARDS

(Question 8/7)

(1978-1982)

The reliability of a device is the mathematical probability that it will function within certain specifications until some time *t*. The traditional measure of reliability for electronic devices has been the "mean time before (or between) failure" (MTBF) statistic.

* The Director, CCIR, is requested to bring this Report to the attention of the CCITT.

The MTBF statistic is not useful to characterize the reliability of such devices as atomic clocks. The method would require many years in order for a sufficiently large number of clocks to fail. The use of atomic clocks solely for reliability tests would be too expensive. The MTBF statistic also ignores the time-dependent characteristic of atomic clock reliability; atomic clocks which have been in operation for one year appear to be more reliable than new ones.

Two characterizations of atomic clock reliability are the mean-life (ML) and the half-life (HL) [Percival and Winkler, 1975]. The mean-life statistic requires for its determination that all units of a test-set fail, and thus is very limited in usefulness for characterizing atomic clock reliability. However, if a failure-rate function can be hypothesized from available data, then the mean-life statistic may be estimated. The half-life statistic is more useful for characterizing atomic clock reliability. This statistic has a simple probabilistic interpretation: the probability that a clock will survive to a half-life time is 50%. An estimate of this time is available after one-half of a test set of clocks have failed.

The best statistic for calculating reliability factors is the probability that a clock, having survived a time t, will fail by time $t + \Delta t$. This conditional failure rate function may be defined as:

$$Z(t)\,\Delta t = -\left[\frac{N(t + \Delta t) - N(t)}{N(t)}\right],$$

where $N(t)$ represents the number of clocks expected to be operating at a time t and $N(0)$ represents the number of clocks initial on a given ensemble.

$Z(t)$ may be estimated to be:

$$Z(t) = -\left[\frac{\Delta N'(t)}{N'(t)\,\Delta t}\right]$$

where $N'(t)$ represents the number of clocks which were operating at time t and either failed in the interval t to $t + \Delta t$ or were still operating at time $t + \Delta t$, and $\Delta N' = N'(t + \Delta t) - N'(t)$.

$Z(t)$ may be modelled with rather simple functions for restricted regions of t.

$Z(t) = c$, where c is a constant, corresponds to the exponential probability law. It is used to describe such phenomena as electronic tube life, etc. It assumes purely random accidents as the causes for failures, which are thus independent of age.

$Z(t) = kt$, where k is a constant, assumes the conditional failure rate increases with time. This model seems to characterize the failure rate of commercial caesium beam clocks after they have been in operation for several years, but not over their entire life span. $k = 0.1$ approximately describes the failure rate of the caesium beam clocks in the US Naval Observatory clock ensemble of January, 1970. Most of these clocks were late production units already operating for more than one or two years. Table I shows the mean life and half-life for various models of $Z(t)$.

Table II gives an estimate for $Z(t)$ for a US Naval Observatory clock ensemble composed of two commercial models, some of which were early production units.

The reliability of a set of atomic clocks may be estimated from the conditional failure rate estimate for a single clock, based on the binomial distribution.

There should be a specified *design qualification* test for each Clock/Standard Type that establishes performance margins in environmental conditions equal to the extremes to be encountered in service. Also, the performance margin should be determined for the situation in which all limits are simultaneously encountered. The environmental tests should include, but not be limited to:

Temperature
Vibration
Shock
Alternating Magnetic Fields
Static Magnetic Fields
Conducted RFI
Radiated RFI
Atmospheric Pressure
Humidity

A measurement of the effect of environmental conditions on the rate of a commercial high performance caesium clock was carried out using a vacuum chamber designed for this purpose. The rate changes due to changes of temperature (per °C between 24 and 31 °C), absolute humidity (per gm^{-3} between 7 and 18 gm^{-3}), atmospheric pressure (per 100 mbar * between 673 and 1007 mbar) and geomagnetic field (per 100 mOe ** between −135 and 135 mOe) were less than $\pm 2 \times 10^{-14}$ with the estimated mean uncertainty of the order of 10^{-15}. These results for one caesium clock indicate that these environmental influences are not negligibly small and that the environmental conditions should be carefully controlled in keeping atomic clocks in operation as uniformly as possible [Iijima *et al.*, 1978].

It should be noted, however, that the specific values could not be generalized in the sense of sensitivity coefficients. They are not the same from clock to clock and are not even fixed for a particular clock since they depend on the range and speed of parameter changes.

Once these design limitations are established for a given design, *acceptance test levels* should be set, and it should be specified that each deliverable unit has been measured within these performance margins.

Prior to delivery to remove *workmanship* faults, each unit should be exposed to three axis random vibrations of at least two minutes duration on each axis. Following this, the unit should be exposed to five cycles of temperature extremes, dwelling at each extreme for at least four hours, and examined for one week's operation to establish that performance margins have not been degraded.

TABLE I – *Mean-life and half-life for various models of Z (t)*

(for *Z (t)* per year)

	$Z(t) = c$		$Z(t) = kt$
	$c = 0.1$	$c = 0.3$	$k = 0.1$
t_{HL} (years)	6.93	2.31	3.72
t_{ML} (years)	10.00	3.33	3.96

TABLE II – *Estimate of Z(t) based on a USNO clock ensemble*

(Probability, $Z(t)\,\Delta t$ for $\Delta t = 1$ year, that a clock will fail in the next year, given that it has already lasted *t* years)

t	$Z(t)\,\Delta t$ for $\Delta t = 1$ year
0.0	0.31 ± 0.03
0.5	0.24 ± 0.04
1.0	0.19 ± 0.04
1.5	0.20 ± 0.04
2.0	0.21 ± 0.05
2.5	0.20 ± 0.05
3.0	0.36 ± 0.07
3.5	0.46 ± 0.08
4.0	0.47 ± 0.11

* 100 mbar = 10^4 Pa.

** 100 mOe = 8 Am^{-1}.

In some applications of time and frequency standards, particularly in the field of communications, stringent requirements are placed on continuity of operation leading to the provision of multiple sources to guard against operational failures. A frequency averager which has been developed at the National Physical Laboratory is based on an extension of earlier work [McLeod and Wise, 1975]. This equipment produces an output frequency which is the weighted average of up to five input frequencies, the weighting factor for each source frequency being variable from 0 to 5 in unit steps. There is automatic compensation for any variation in the weighting factors and for the addition or removal of input frequencies. It thus constitutes a highly redundant system and in consequence would be an extremely reliable source for a communications channel. Moreover, the improvement in frequency stability of the averaged output as compared with any one input could be of significant benefit in some applications.

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REPORT 898 *

PERFORMANCE AND RELIABILITY OF REFERENCE CLOCKS

(Question 8/7 and Decision 29)

(1982)

1. Introduction

This Report is an answer to the questions asked by CCITT Study Group XVIII to CCIR Study Group 7 concerning the performance and reliability of reference clocks to be used in digital communications systems. It also offers some comments on CCITT Recommendation G.811 in view of its close relationship to the subjects of CCIR Decision 29.

Section 2 of this Report intends to ensure that the questions have been understood and answered correctly and develop as far as possible a common language in the field of timing and synchronization.

Section 3 contains the currently available data on the reliability of some types of clocks operating in services such as standard time and frequency, navigation and communications.

Section 4 refers to the Reports of the CCIR concerning the available measurement techniques required to relate a clock to the common reference time scale UTC.

Finally, § 5 identifies the subjects left for further study in view of the preliminary nature of this Report.

2. Terms and definitions concerning the characterization of clock performance

It appears that in some cases CCITT Study Group XVIII and CCIR Study Group 7 are using different terms to describe the same subjects. In order to facilitate the understanding of its texts, CCIR Study Group 7 has compiled a glossary in its Report 730 listing, defining and explaining most terms currently used in frequency and time measurements.

The long-term frequency departure of ± 1 part in 10^{11} allowed in Recommendation G.811 is about two orders of magnitude larger than the uncertainty of UTC, as determined by the Bureau international de l'heure. In the present context UTC is therefore a satisfactory approximation to an ideal clock.

For reasons of the general non-stationarity in the time interval errors (TIE) of actual clocks over longer periods of observation ($T > 10$ days), Study Group 7 has based most of its work on the concepts of frequency instability as the basic phenomenon.

* The Director, CCIR, is requested to bring this Report to the attention of the CCITT.

The TIE as mentioned in Recommendation G.811 may be interpreted as the integral of the normalized frequency departure computed over the time interval S. If we let t_0 be the starting time of the interval S, we have:

$$TIE = \chi(t_0 + S) - \chi(t_0) = \int_{t_0}^{t_0 + S} y(t)\mathrm{d}t \qquad (1)$$

using the notation of Report 580. The slope indicated as a dashed line in Fig. 1/G.811 thus represents the average frequency departure:

$$\bar{y}_0(t_0, S) = \frac{1}{S} \int_{t_0}^{t_0 + S} y(t)\mathrm{d}t \qquad (2)$$

Obviously, this departure is due to the *frequency instability* of the clock, whereas the long term average slope is due to the *error in initial frequency setting* of the clock relative to the nominal value. The error in initial frequency setting depends on the measurement techniques used to relate the clock to an external reference such as Loran-C or the national time and frequency services. The characteristics describing the performance of clocks and other properties such as size, weight, power, consumption, etc., are contained in Report 364. The random instabilities are described using the statistical measures recommended in Recommendation 538 and described in Report 580. In these texts, the sampling time, equivalent to the observation period (of S seconds) is designated by the lower case Greek letter τ.

The following estimate, based on computer simulations [Kartaschoff, 1979] of the statistical clock model, can be used to predict a probable time interval error of a clock adjusted and synchronized at $t = 0$ and left free running thereafter:

$$(TIE)_{est} = \frac{a}{2} t^2 + t \cdot \left(\sigma_{y_0}{}^2 + \sigma_y{}^2(\tau = t)\right)^{1/2} \qquad (3)$$

where a is the normalized linear frequency drift per unit of time (aging), σ_{y0} the error of the initial frequency setting and $\sigma_y(\tau)$ the two sample standard deviation describing the random frequency instability of the clock. It is assumed that the parameters characterizing the clock do not change with time and that the initial setting error and the subsequent random frequency fluctuations are statistically independent. As can be seen from the formula above, it is the initial frequency setting error which will be predominant in most cases.

3. Clock reliability

At the present stage, some initial data on the operational reliability can be presented for the following devices:

- caesium clocks,
- rubidium clocks,
- quartz crystal oscillators.

Other devices also listed in Report 364 are left aside for various reasons such as continuing research, very small population, lack of reliability data, etc., which at present limit their suitability for systems applications on a wide scale.

Based on the performance limits specified in CCITT Recommendation G.811, the failure criteria to be applied fall into two classes.

Crystal and rubidium clocks require initial frequency setting and subsequent frequency control from an external reference to compensate for the inherent frequency drift. Misadjustment and absence of control leading to the violation of the specification cannot be regarded as being failures of these devices.

Caesium clocks have a systematic uncertainty which is lower than the $\pm$ 1 part in 10^{11} limit specified by CCITT Recommendation G.811 and in general show negligible frequency drift. A violation of the limit can therefore be regarded as being a failure.

Except for this distinction other failures such as degradation or loss of output signal are common to all devices.

Report 737 shows that the estimation of the MTBF (mean time between (or before) failure) is difficult for devices such as caesium clocks. Only for a constant conditional failure rate $Z(t)$ the MTBF could be estimated to be equal to the half-life t_{HL}. Experience shows, however, that $Z(t)$ is not constant. For new devices, it decreases with time (early failures) then becomes constant and increases again later due to aging or end of life of some parts such as beam tubes or optical packages.

3.1 *Summary of reliability data*

A reliability survey by means of questionnaires sent to users and manufacturers in the participating countries via the delegates of the respective administrations was started in January 1981. The delegates also collected the completed questionnaires, checked and corrected them where necessary and forwarded them to the Chairman of Interim Working Party 7/5 for further processing. The results presented in this Report are based on data received until 10 August 1981. Up to this date reports have been received from the following countries: China, Federal Republic of Germany, France, Italy, Japan, Netherlands, Switzerland and the United Kingdom.

The total number of Reports received was 140 of which 130 were perfectly correct. Only 10 (7%) contained errors which made them partially or entirely worthless. They concerned rubidium (1) and crystal clocks (9).

52 reports were on caesium clocks, covering 135 units,
39 reports were on rubidium covering 78 units,
39 reports were on crystals covering 2665 units.

The survey covered 11 years from 1970 to 1980.

In the processing the following general procedure was used:

The sheets were grouped for each model using the manufacturers designation, for example: HP 5061A (Cs); R&S XSRM (Rb); B 5400 (Xtal), etc.

Manufacturers reports were kept separately from the users reports.

The following figures were defined and computed for each model:

ΣU: the sum over all units of the number of years of operation for each unit.

ΣF: total of failures observed for these units.

Then, the ratio $\Sigma U / \Sigma F = MTBF$ in years as an estimate assuming constant failure rate during the 11-year period of observation was computed.

Considering the limited population size and the spread in the data, conditional failure rate functions as defined in Report 737 cannot yet be estimated with less uncertainty than that of this simple MTBF estimate.

There is also a wide variance in the MTTR (mean time to repair a failed unit including shipping time) figures reported. The averages vary between 80 and 140 days and since there is a strong influence of the geographical location of the unit, the general average for Cs and Rb clocks of about 90 days MTTR is at best indicative. No MTTR figures are given for crystal clocks.

Tables I, II and III show the resulting MTBF estimates based on the data available today.

TABLE I – *Caesium clocks*

Model (year)	ΣU	ΣF	MTBF (years)	MTTR (days)	No. of units in survey
Users' report					
HP5061A (1968)	443	99	$4.47 \begin{smallmatrix} +0.31 \\ -0.25 \end{smallmatrix}$	80	71
OSA 3200 (1975/76)	69	24	$2.88 \begin{smallmatrix} +0.4 \\ -0.3 \end{smallmatrix}$	88	19
HP5061A – 004 (1973)	96	38	$2.53 \begin{smallmatrix} +0.31 \\ -0.25 \end{smallmatrix}$	85	21
HP5060A (1) (1965)	133	42	3.17	82	14
OSA 3000 (1976)	14	4	$3.5 \begin{smallmatrix} +0.9 \\ -0.6 \end{smallmatrix}$	80	6
Manufacturers' report (see comment)					
OSA 3000 (1976)	113	15	7.5	35	48
OSA 3200 (1975)	396	122	3.25	50	114

(1) Old model, no longer in production.

TABLE II – *Rubidium clocks*

Model (year)	Σ *U*	Σ *F*	MTBF (years)	MTTR (days)	No. of units in survey
HP5065A (1970)	119	18	6.61	140	16
FRT/FRK (1973)	83	18	4.61	90	17
XSRM (1972)	67	12	5.58	90	14
P 01 (1976)	44	41	1.08	–	20

TABLE III – *Crystal clocks*

Model	1st year	Σ *U*	Σ *F*	MTBF (years)	No. of units in survey	Notes
Users' report						
B5400	1974	23	0	>23	6	
B1250	1973	8	1	8	1	(1)
B1010	1965	926	25	37	132	(1)
HP104/105	1970	46	4	11.5	5	(2)
R&S XSC/D/S	1970	136	13	10.5	15	(2)
C60MCS	1972	223	1	200	52	
CP12MCS	1970	6316	33	191	1288	
MT	1975	834	13	64	139	
K	1975	1353	2	200	235	
Manufacturers' report						
OSA B5400	1974	1352	27	50	318	
OSA B1250	1970	214	3	71	20	(1)
HCD HCD50	1970	4383	104	42	587	

(1) Obsolete, no longer manufactured.

(2) Units combined in single survey because of high similarity of design and no apparent bias.

In Table I, 1 σ confidence margins are given for the MTBF estimates. These margins have been computed in the following way:

The data on the largest population (HP5061A, 71 units in the survey) were used. Adding the columns for each year, sequences of numbers of units in operation (ΣU_i) and of failures (ΣF_i) were obtained. Then a sequence of ratios:

$$Z_i = \frac{\sum F_i}{\sum U_i}$$

was computed for each year (1970 to 1980), as shown in Table IV below. Z_i is an estimate of the yearly failure rate in the mixed population of devices of various ages, this population growing as more new devices are put into service than old ones retired. A test has shown that these Z_i values are normally distributed. The median value is $Z_m = 0.230$ with a standard deviation of $\sigma_z \pm 0.043$. The probable relative error of the median is thus about $\pm$ 6%. The inverse $Z_m^{-1} = 4.35$ years is very close to the MTBF estimate of 4.47 years shown in Table I. The confidence margins indicated there have been computed using this 6% probable error estimate on the average failure rates of $1/4.47 = 0.233$.

The confidence margins of the other models have been computed by using the 6% error as a base, multiplied by the factor $\sqrt{N_0/N_i}$ where $N_0 = 71$ is the number of 5061A units and N_i the number of units of the other models. Data on the HP5060A are of historical interest only. No such estimates have yet been done on the data summarized in Tables II and III. For Table II the populations are too small and the units in Table III are quite diverse and some units have consistent very high MTBF.

Table V shows the distributions of failures among the various sub-assemblies of caesium clocks based on user and manufacturer reports. The data on the HP units are taken from Johnson *et al.* [1980]. M_i and Z_i are MTBF and yearly failure rate estimates for the sub-assemblies. These figures are to be taken with caution as there is no consideration included on the limited lifetime of some parts, especially the caesium beam tubes.

A comment is in order on the bias appearing between user and manufacturers reports, especially in Table I. We can be sure that the manufacturer has done his best in order to report real and correct figures. However, there are always some users who repair some minor faults in their own facilities without reporting these actions to the manufacturer. Thus, some bias is practically inevitable. Improvement of the feedback loop on failures and repairs would serve the interests of both manufacturers and users.

The data collected until now cover only a small fraction of the world population of precision clocks. No peak has been observed in the first year of operation of caesium clocks, i.e. the "early failures" seem to have been eliminated by the burn-in process performed by the manufacturers.

TABLE IV

Year	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980
ΣU_i	15	21	24	28	30	33	34	34	41	47	47
ΣF_i	2	4	8	5	7	8	4	11	5	3	10
Z_i	0.133	0.190	0.333	0.179	0.233	0.267	0.118	0.323	0.122	0.063	0.213

3.2 *Conclusions*

Although not yet complete, the survey on the reliability of precision clocks has yielded some interesting results. The MTBF estimates for caesium, rubidium and crystal clocks confirm the old rule that MTBF is inversely proportional to the complexity of the device. However, the most complex device also shows the highest frequency stability and might thus require less supervision and maintenance work (such as frequency adjustments) in the operation of a system.

TABLE V – *Caesium beam clocks*

$M_i = \sum U/F_i = Z_i^{-1}$

Model: HP5061A – OSA B3200 – HP5061A–004 – HP5060A – OSA 3000

Model	Atomic Resonator	Crystal Oscillator	Frequency conditioning circuits	Servo circuits	Output circuits	Internal power conditioning	Other parts	Σ U (Σ F)
Users' report								
HP5061A	48	3	13	22	2	9	14	443
M_i	9.23	148	34.1	20.1	222	49.2	31.6	
Z_i	0.1083	6.77×10^{-3}	0.0293	0.0497	4.51×10^{-3}	0.0203	0.0316	
F_i	43.2 %	2.7 %	11.7 %	19.8 %	1.8 %	8.1 %	12.6 %	(111)
OSA B3200	9	1	0	0	2	8	4	69
M_i	7.67	69	–	–	34.5	8.63	17.25	
Z_i	0.130	0.0145	0	0	0.0290	0.116	0.0580	
F_i	37.5 %	4.2 %	0	0	8.3 %	33.3 %	16.7 %	(24)
HP5061A–004	14	9	4	4	1	2	4	96
M_i	6.86	10.66	24.0	24.0	96	48	24	
Z_i	0.1458	0.0937	0.0417	0.0417	0.0104	0.0208	0.0104	
F_i	36.8 %	23.7 %	10.5 %	10.5 %	2.6 %	5.3 %	10.5 %	(38)
HP5060A	19	2	2	6	1	4	7	133
M_i	7.0	66.5	66.5	22.2	133	33.3	19.0	
Z_i	0.1429	0.0150	0.0150	0.0451	7.52×10^{-3}	0.0301	0.0526	
F_i	46.3 %	4.9 %	4.9 %	14.6 %	2.4 %	9.8 %	17.1 %	(91)
Manufacturers' report								
HP5061 (1) 5061–004 5062C	62 32 %	17 9 %	44 23 %	21 11 %	40 20 %	6 3 %	4 2 %	(194)
OSA 3200	18 15 %	10 8 %	12 10 %	5 4 %	5 4 %	64 53 %	1 1 %	114 (121)
OSA 3000	5 29 %	3 18 %	1 6 %	0 0	0 0	0 0	6 35 %	48 (17)

(1) Number of units not available.

Tables I and II also show the importance of production experience for reliability. Parts screening and burn-in have been successful measures for minimizing the so-called early failures. Some insidious hidden weaknesses may appear only after a few years of production and operation in the field. In view of this, the level of reliability attained with caesium beam standards is remarkable.

4. Measurement techniques

Measurements are the only means to assure conformity to the specifications. The current comparison methods for the transfer and dissemination of time signals and standard frequencies are reviewed in Reports 363 and 518.

Crystal, rubidium and caesium clocks all require checks to assure proper operation. Crystal and rubidium clocks require periodic calibration and readjustment of the frequency, but caesium clocks do not require such readjustments to meet the frequency tolerances of CCITT Recommendation G.811. Long-term comparison with another reference however constitutes a significant safety factor for detection of failure.

The main problem in the measurement of clock time over some distance is the uncertainty of transmission path delay. It usually determines the choice of the comparison method. The fact that transmission delays are not perfectly stable also raises the question whether synchronism in an extended system is feasible, necessary or desirable.

The digital communications system designer is faced with several choices. The clocks in the system may be referred to a single master clock which in turn is referred to UTC. An extended system may be subdivided into regions having each their master clock individually referred to UTC. These two varieties have been experimented in Canada with good success. In the first case, the network master was compared to the national frequency standard at the National Research Centre (NRC). In the second case, several master clocks were phase-locked to the signals of the Loran-C navigation system.

A most important design choice is the degree of reliance on the clocks, i.e. the time constant in the frequency control loop versus the quality of the clocks [Kartaschoff, 1980].

Comparison methods via satellite show great potential, especially for areas where other high stability time signals are not available (Report 518).

5. Subjects for further study of Interim Working Party 7/5

Confidence in reliability figures given in § 3 is expected to improve as additional data become available.

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REPORT 738-1

STANDARD-FREQUENCY GENERATORS IN THE SUBMILLIMETRE, INFRA-RED AND VISIBLE LIGHT REGIONS OF THE SPECTRUM

(Question 53/1)

(1978-1982)

1. Introduction

In January 1976 a new text on the use of the spectrum above 40 GHz, and in particular in the submillimetre, infra-red and visible light regions, was approved by correspondence and became Question 53/1 assigned to Study Group 1. At the same time the attention of all other Study Groups was drawn to the new Question.

Study Group 7 is directly concerned, because the telecommunication and detection systems which will be developed in these regions of the spectrum require ultrastable generators at these optical frequencies. Furthermore, as is already the case at lower frequencies, the international technical standards which will be defined to keep these systems in good working order will have a direct bearing on the quality of the standard-frequency sources to be used.

In view of these general remarks on the problems to be studied by the CCIR and the progress achieved in the measurement of optical frequencies *, Study Group 7, at its Interim Meeting in February 1976, decided to prepare a new Report on standard-frequency generators in the optical region.

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* In this Report the term "optical" is used to describe any frequency above about 300 GHz ($\lambda \lesssim 1$ millimetre). The term Terahertz (THz) will be widely employed: 1 THz = 10^{12} Hz.

This Report supplements Report 364, which deals with the performance of standard radio and microwave frequency generators. Report 580 discusses the parameters used to characterize the frequency and phase instability of standard-frequency generators.

2. Metrology of optical frequencies

The considerable progress made in this type of metrology over the past twelve years results from the development of techniques which permit:

(a) very effective stabilization of the frequency emitted by certain CW lasers;
(b) precise measurement of the absolute value of optical frequencies (up to 197 THz in 1977); the measurements are referred to the SI second.

This Report describes the main results obtained in these two fields; in view of the large volume of published material, generally only one recent reference is quoted for each laboratory and each topic considered.

While only a few laboratories are conducting absolute measurements of optical frequencies, numerous laboratories are engaged in determining the frequency instability of lasers by measuring, on a beat obtained between two lasers, the square root $\sigma_y(\tau)$ of a two-sample variance without dead-time (see Report 580). The typical values obtained for $\tau = 1$ second are given below; Fig. 1 shows the $\sigma_y(\tau)$ curves for the main stabilized lasers.

3. Frequency stabilization of lasers

Highly effective frequency stabilization methods had to be developed before the laser could be contemplated as a standard-frequency generator [Giacomo, 1970]. One of these methods, consisting of locking the laser frequency to a saturated absorption peak obtained by coincidence of the laser frequency with a molecular absorption frequency [Lee and Skolnick, 1967], has been widely used, in particular with CO_2 lasers (around 30 THz, λ = 10 μm) and He-Ne lasers (88 THz, λ = 3.39 μm; 474 THz, λ = 0.633 μm).

Generally speaking, the stabilities obtained are comparable with those of the conventional atomic standards * but no existing stabilized laser has an accuracy comparable with that of the primary caesium beam standard (10^{-13}).

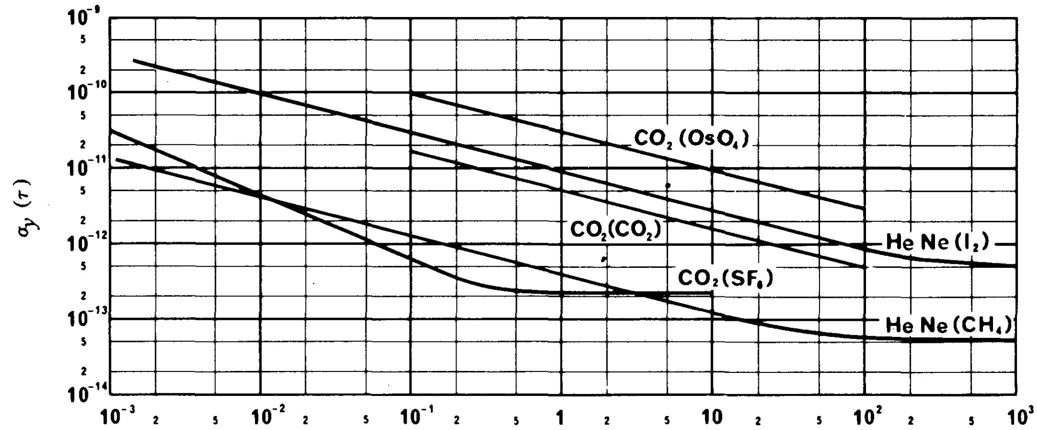

FIGURE 1 – *Typical frequency instability of the main stabilized gas lasers*

* See Fig. 1 of this Report, and Fig. 1 of Report 364.

3.1 *CO_2 lasers*

The stabilization of the CO_2 laser by saturated absorption in an external cell has been studied using SF_6 molecules [Clairon and Henry, 1974; Ouhayoun and Bordé, 1976; Gusev *et al.*, 1975] and OsO_4 molecules [Kompanets *et al.*, 1976] as reference. An instability of 3×10^{-13} for $\tau = 1$ s and a reproducibility of 3×10^{-11} were obtained with SF_6. With this technique, only a very small number of the laser lines can be stabilized in coincidence with a molecular absorption line.

Detailed theoretical and experimental studies of the heavy molecules SF_6 and OsO_4 which have metrological applications, have been carried out with the aid of a very high resolution spectrometer [Bordé *et al.*, 1980].

A technique using saturated fluorescence in the actual CO_2 molecule has been developed [Freed and Javan, 1970] and improved [Freed, 1975 and 1977]. Values of about 7×10^{-12} are obtained for $\tau = 1$ s and 2×10^{-10} for reproducibility. Despite its lower performance, this technique has been used in numerous laboratories owing to its ability to stabilize the frequency of any line of the CO_2 laser; there are over 100 lines between about 28 and 32 THz. In the same region of the spectrum the N_2O laser can be stabilized by means of a similar technique [Whitford *et al.*, 1976].

In addition to the usual lines of the $^{12}C^{16}O_2$ laser, many other lines can be obtained, either with other isotopes [Freed *et al.*, 1976] or by using higher energy levels [Siemsen and Whitford, 1977].

In view of its wide range of properties (power, stability, large number of lines), the CO_2 laser is a basic tool in virtually all infra-red frequency synthesis experiments.

3.2 *He-Ne lasers*

The stabilization of the He-Ne laser has been studied in many laboratories using methane (CH_4) or iodine (I_2) as reference molecules for the stabilization of the 88 THz line and the 474 THz (red) line respectively.

The He-Ne (CH_4) laser has an instability of 3×10^{-13} for $\tau = 1$ second and a reproducibility of about 10^{-11} [Barger and Hall, 1969; Hellwig *et al.*, 1972; Shimoda, 1973; Brillet *et al.*, 1974; Baird and Hanes, 1974; Bagaev and Chebotayev, 1975; Kramer *et al.*, 1975; Ohi and Akimoto, 1976].

The He-Ne (I_2) laser gives 10^{-11} for $\tau = 1$ s and about 2×10^{-11} for reproducibility [Hanes *et al.*, 1973; Helmcke and Bayer-Helms, 1974; Cérez *et al.*, 1974; Wallard, 1974; Bertinetto *et al.*, 1976; Shimoda and Tako, 1976; Tanaka *et al.*, 1977]. For 0.1 s $< \tau <$ 100 s, the stability of this laser has recently been improved by a factor of 10 [Cérez *et al.*, 1977]. The saturated absorption signals observed in an external absorption 127_{I_2} cell have also been applied to laser stabilization using an external optical modulator [Tanaka and Morinaga, 1979]; a 2×10^{-12} reproducibility has been reported using an external iodine cell [Cérez *et al.*, 1980].

Similar lasers have also been developed and studied at the International Bureau of Weights and Measures in connection with the metrology of length.

3.3 *Other lasers*

The ionized argon laser (582 THz; $\lambda = 0.514$ µm) has been stabilized by saturated absorption in iodine in an external cell ($\sigma_y(1 \text{ s}) \approx 10^{-13}$ [Camy *et al.*, 1976; Spieweck *et al.*, 1980] and by using a molecular iodine beam: $\sigma_y(1 \text{ s}) \approx 10^{-11}$, reproducibility 1.5×10^{-12} [Hackel *et al.*, 1976]

The He-Xe laser ($\lambda = 3.51$ µm) has been stabilized by saturated absorption in formaldehyde (H_2CO) with σ_y (100 s) $= 1 \times 10^{-14}$ [Ohtsu *et al.*, 1981] and the vacuum wavelength of this laser was measured to be 3 507 979.48 ± 0.39 pm [Tako *et al.*, 1980].

The stabilization of dye lasers is also being studied in several laboratories [Barger *et al.*, 1976; Man *et al.*, 1977]. The frequency tuning possibilities offered by these lasers mean that a reference molecule can be chosen for its metrological properties and not for the accidental coincidence between an absorption frequency and a laser frequency. In particular, they can be used to measure a visible frequency.

Molecular lasers with optical pumping by CO_2 laser enable hundreds of lines to be obtained in the far infra-red and are likely to have important applications in frequency metrology [Petersen *et al.*, 1975; Weiss and Kramer, 1976; Bava *et al.*, 1977a], particularly when their frequency has been effectively stabilized. The following instabilities have been obtained with free lasers: $\sigma_y(0.05 \text{ s}) \approx 2 \times 10^{-12}$ for the 70 µm line, $\sigma_y(0.05 \text{ s}) \approx 4 \times 10^{-12}$ for the 118 µm line of the CH_3OH laser [Plainchamp, 1979] and $\sigma_y(1 \text{ s}) \approx 1.8 \times 10^{-9}$ for the 394 µm line of the HCOOH laser [Godone *et al.*, 1978]. The Stark effect enhances the frequency tuning and modulation features of these lasers [Stein and Van de Stadt, 1977; Benedetti *et al.*, 1977] and also permits phase locking.

Frequency stabilization was also achieved with a PbSnTe diode laser on a methane line in the 7.7 µm band, and a stability of 4.3×10^{-11} over a duration of 15 s was obtained [Ohi, 1980].

Certain lasers with a sufficiently low frequency, such as the HCN 890 GHz laser, may be stabilized by locking on a harmonic of a standard radio frequency [Wells, 1973] with $\sigma_y(1 \text{ s}) \approx 10^{-12}$.

4. Measurement of optical frequencies

The development of non-linear diodes capable of generating harmonics and producing frequency beats in the optical region of the spectrum has extended the upper limit of directly measurable frequencies to about 200 THz (λ = 1.5 µm). Comparative studies have been published on the different diodes available [Pyée and Auvray, 1975; Knight and Woods, 1976]. Table I shows some important stages in the measurement of optical frequencies. Table II summarizes the main properties of point contact diodes which can be used as frequency multipliers in the infra-red.

An unknown optical frequency is measured by means of a heterodyne technique; the diode receives simultaneously the signal to be measured and an already measured frequency; because of its non-linearity, it generates a beat frequency which is low enough to be measured directly; the unknown frequency can thus be calculated.

As a result of the pioneer work carried out at MIT on the measurement of laser frequencies and on metal-insulating-metal (MIM) point contact diodes [Hocker *et al.*, 1967 and 1968], the introduction of laser chains has permitted the successive measurement of the frequency of HCN lasers (890 GHz), H_2O lasers (10 THz), CO_2 lasers (30 THz) and He-Ne (CH_4) lasers (88 THz), each measurement being based on the preceding one through a harmonic relation between the frequencies [Evenson *et al.*, 1973; Blaney *et al.*, 1977; Clairon *et al.*, 1980a].

The precision and accuracy of the measurement of an optical frequency are, in the most favourable case, restricted by the stabilities and accuracies of the two sources at the ends of the multiplication chain; for example, the primary caesium standard and the He-Ne (CH_4) laser for measurement at 88 THz.

TABLE I – *Main measurements of optical frequencies (non-exhaustive list showing progress since 1967)*

Year	Laser (λ in µm)	Frequency (in THz)	Precision (Normalized value)
1967	HCN (337)	0.890 759 5	$\pm 10^{-7}$
1968	H_2O (118)	2.527 954	
1969	D_2O (84)	3.557 143	$\pm 6 \times 10^{-7}$
1970	H_2O (28) CO_2 (10.6)	10.718 073 28.306 251	$\pm 2 \times 10^{-7}$ $\pm 9 \times 10^{-7}$
1972	HeNe (3.39)	88.376 245	$\pm 5 \times 10^{-7}$
1973	CO_2 (10.18) CO_2 (9.33) HeNe (CH_4) (3.39)	29.442 483 315 32.134 266 891 88.376 181 627	$\pm 9 \times 10^{-10}$ $\pm 8 \times 10^{-10}$ $\pm 6 \times 10^{-10}$
1974	CO (5.3)	56.168 515	$\pm 7 \times 10^{-8}$
1975	Xe (2.03)	147.915 850	$\pm 10^{-7}$
1977	Ne (1.52)	196.780 269	$\pm 1.3 \times 10^{-7}$
1980	HeNe (CH_4) (3.39)	88.376 181 618	$\pm 1.6 \times 10^{-10}$

TABLE II – *Main properties of point contact diodes usable as frequency multipliers in infrared*

Type of diode	Max. frequency reached by generation of harmonics	Corresponding order of multiplication and source	Highest order of multiplication	Highest frequency reached and corresponding source
Metal semiconductor (tungsten-silicon)	3.56 THz D_2O laser	4 HCN laser	23	1.58 THz DCN laser
Schottky (As-Ga type *n*)	2.52 THz CH_3OH laser	33 microwave source	33	2.52 THz CH_3OH laser
Metal-Insulator-Metal (tungsten-nickel)	88.4 THz (1) He-Ne laser	3 CO_2 laser	12	10.7 THz H_2O laser
Josephson (2) (niobium-niobium)	3.8 THz H_2O laser	401 microwave source	825	0.89 THz HCN laser

(1) A frequency around 200 THz may be attained by adding frequencies without harmonic generation.

(2) Operates at the temperature of liquid helium.

The use of optical-pumping lasers as transfer oscillators has raised the initial precision of measurements at 88 THz from 6×10^{-10} to about 3×10^{-11} to 10^{-10}.

Towards the higher frequencies, a line of the 148 THz Xe laser and a 197 THz Ne line have been measured using a MIM diode by frequency additions and beats without harmonic generation [Evenson *et al.*, 1977]. Non-linear crystals have had to be used to reach the visible domain.

Furthermore, the numerous lines of the CO_2 laser, using two such lasers with a MIM diode, are convenient for the synthesis of a very narrow frequency "comb" between the microwave region and about 100 THz, so that any frequency in this region may be measured in relation to the lines of the CO_2 laser which is taken as a secondary standard [Petersen *et al.*, 1975].

Attempts have been made to measure the absolute value of the frequency of various OsO_4 transitions in the neighbourhood of 28 THz [Clairon *et al.*, 1980b].

A number of laboratories are engaged in the study of one or other of the main problems described above (improved accuracy, measurement of increasingly high frequencies, easier synthesis of the infra-red frequencies). As examples of this, we may point to the in-depth study of frequency multiplication chains between 5 MHz and the far infra-red [Bava *et al.*, 1977b]; the use of Schottky diodes [Fetterman *et al.*, 1974; Pyée and Auvray, 1975]; the use of Josephson junctions [McDonald *et al.*, 1972; Blaney and Knight, 1974; Lourtioz *et al.*, 1977]; the development of thin-layer MIM diodes [Davis *et al.*, 1977]; the proposal of an original method of measuring the red line of the He-Ne laser by mixing infra-red radiation frequencies in a gas [Chebotayev *et al.*, 1976].

In conclusion, we should remember that though stabilized lasers constitute excellent secondary frequency standards, their use as clocks will depend on the development of new devices capable of generating second-pulses conveniently from frequencies in the terahertz range.

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QUESTIONS AND STUDY PROGRAMMES, RESOLUTIONS, OPINIONS AND DECISIONS

QUESTION 1/7

STANDARD-FREQUENCY AND TIME-SIGNAL EMISSIONS

(1948-1951-1953-1956-1963)

The CCIR,

CONSIDERING

(a) that the World Administrative Radio Conference, Geneva, 1979, called for coordination of the establishment and operation of a standard-frequency and time-signal service on a world-wide basis;

(b) that a number of stations are now regularly emitting standard frequencies and time signals in the bands allocated by this Conference;

(c) that some areas of the world are not yet adequately served;

(d) that the use of more stations than are technically necessary would diminish the utility of the service by producing harmful interference,

UNANIMOUSLY DECIDES that the following question should be studied:

1. what measures can be recommended for increasing the effectiveness of the existing standard-frequency and time-signal service in the bands allocated by this Conference;

2. what measures can be recommended for the reduction of mutual interference between standard-frequency and time-signal stations operating on the same frequency and whose service areas overlap?

Note. – See Recommendations 374, 376, 457, 458, 460, 485, 535, 536, Reports 267, 731, 896, Resolution 14 and Opinions 26, 28, 71.

STUDY PROGRAMME 1A-1/7

IMPROVEMENTS IN THE EFFECTIVENESS OF THE STANDARD-FREQUENCY AND TIME-SIGNAL SERVICE

(1965-1970)

The CCIR,

CONSIDERING

(a) that Question 1/7 and Recommendation 374 call for information on methods for improving the usefulness of the existing standard-frequency and time-signal service;

(b) that standard-frequency stations are operated simultaneously on the same carrier frequency,

UNANIMOUSLY DECIDES that the following studies should be carried out:

1. an investigation of the possibilities of reducing mutual interference between emissions in the standard-frequency and time-signal service by:

1.1 shortening the programme of continuous tone modulation and of announcements;

1.2 use of a modulation which gives the required information and accuracy with minimum bandwidth;

1.3 staggering the emitted frequencies in the allocated bands and using a convenient type of modulation;

1.4 a convenient coordinated time-sharing of frequencies for those areas where there is mutual interference;

1.5 avoiding unmodulated carrier emissions, not strictly necessary for the operation of the service;

2. collection of information on how standard-frequency emissions in bands 6 and 7 may be coordinated with emissions in other bands to give the best overall world-wide service.

Note. – See Recommendation 537 and Report 732.

STUDY PROGRAMME 1B-1/7

SINGLE-SIDEBAND OPERATION FOR THE STANDARD-FREQUENCY AND TIME-SIGNAL SERVICES

(1965-1970)

The CCIR,

CONSIDERING

the measures taken by the ITU urging Administrations to accelerate the conversion of their double-sideband systems, in the frequency bands below 30 MHz, to single-sideband systems, to reduce congestion in these bands,

UNANIMOUSLY DECIDES that the following studies should be carried out:

the improvements that may be obtained in the distribution and use of standard-frequency and time-signal emissions by the use of single-sideband operation, with full carrier, particularly in the 2.5, 5, 10, 15, 20 and 25 MHz bands.

Note. – See Report 732.

STUDY PROGRAMME 1D-1/7

STATISTICAL WEIGHT OF CLOCKS USED TO ESTABLISH A TIME SCALE – AVERAGING PROBLEMS

(1970-1974)

The CCIR,

CONSIDERING

(a) that atomic time scales are often obtained by establishing the individual time-scale averages of a large number of clocks or groups of clocks remotely located from each other;

(b) that for many applications it is important that a time scale should be as uniform as possible;

(c) that in addition, the sub-division of the time scales should be made in agreement with the accepted value of the second,

UNANIMOUSLY DECIDES that the following studies should be carried out:

1. the averaging procedures to be recommended, including the determination of the statistical weight assigned to clocks or groups of clocks used in establishing the time scale.

It should be recognized that the intrinsic accuracy and stability of such clocks may differ, that commercial-type clocks, as well as laboratory models, must be considered and that the clock readings are ascertained with varying degrees of accuracy by those dealing with averaging problems;

2. the procedures to be recommended in cases where the number and/or accuracy and stability of the clocks, used to establish a time scale, changes.

Note. – See Report 579.

QUESTION 2/7

STANDARD-FREQUENCY AND TIME-SIGNAL EMISSIONS IN ADDITIONAL FREQUENCY BANDS

(1956-1963)

The CCIR,

CONSIDERING

(a) that in certain regions, particularly in industrial centres, it is not always possible to obtain an adequate ratio of the wanted signal to the noise level with the existing standard-frequency and time-signal service;

(b) that the bands allocated for standard-frequency and time-signal emissions are more useful for long-distance distribution than for local distribution;

(c) that a better service is needed in certain areas and this service may be given by use of frequencies in band 8 and higher;

(d) that high-accuracy frequency and time comparisons between distribution centres can be made using frequencies in bands 4 and 5,

UNANIMOUSLY DECIDES that the following question should be studied:

what can be recommended for the distribution of standard frequencies and time signals above 30 MHz and below approximately 100 kHz?

Note. – See Recommendations 375, 582, Report 518 and Opinions 27, 72.

STUDY PROGRAMME 2A-2/7

STANDARD FREQUENCY AND TIME SIGNALS FROM SATELLITES

(1963-1970-1982)

The CCIR,

CONSIDERING

(a) that continuing advances in science and technology have increased the requirements for accuracy and service range of standard-frequency and time-signal emissions;

(b) that the work of several CCIR Study Groups describes radiocommunication systems making use of satellites that give extensive coverage and satisfactory stability of signals over the Earth's surface;

(c) that satellite techniques provide the basis for existing and future standard-frequency and time-signal comparison and dissemination systems;

(d) that a number of satellite services (e.g., for navigation, meteorology, geosciences, television) may be used additionally for the comparison and distribution of standard frequency and time-signals,

UNANIMOUSLY DECIDES that the following studies should be carried out:

1. the technical factors and quantitative measures to be considered in recommending frequencies and in determining the transmitting, modulating and receiving techniques, which are important to the development of standard-frequency and time-signal emissions from satellites.

2. the technical and operational requirements to be considered in incorporating standard-frequency and time-signal emissions or retransmissions in host satellites.

Note. – See Reports 518, 736 and Decision 28.

STUDY PROGRAMME 2B/7

OPERATIONAL METHODS FOR STANDARD-FREQUENCY AND TIME-SIGNAL EMISSIONS IN THE VLF AND LF BANDS

(1976)

The CCIR,

CONSIDERING

that the usefulness of the standard-frequency and time-signal emissions in the VLF and LF bands depends upon the operational characteristics of the transmitters and upon the modulation methods and formats used, UNANIMOUSLY DECIDES that the following studies should be carried out:

the technical and operational methods for transmitters and antennas, the modulation methods and signal formats to be recommended for the dissemination of standard frequencies and time signals using frequencies below about 100 kHz.

Note. – See Report 735.

QUESTION 3/7

STABILITY OF STANDARD-FREQUENCY AND TIME-SIGNAL EMISSIONS AS RECEIVED

(1956-1959-1963)

The CCIR,

CONSIDERING

(a) that the standard-frequency and time-signal emissions as received are less stable than at the source, owing to phenomena occurring in the propagation of radio waves, e.g. the Doppler effect, diurnal variation and multipath interference;

(b) that errors, which occur during propagation, depend on the geographical location of both the transmitter and receiver, as well as on the nature and condition of the medium, and generally differ in different regions of the radio spectrum;

(c) that special techniques of standard-frequency and time-signal emissions may improve the accuracy with which they can be received;

(d) that the accuracy with which standard-frequency and time-signal emissions can be received may depend upon the design of the receiving equipment,

UNANIMOUSLY DECIDES that the following question should be studied:

1. what are the causes of the reduction in the stability and accuracy of the standard frequencies and time signals as received by the users;

2. what is the magnitude in statistical terms of the instability introduced by these causes;

3. what are the most suitable techniques for transmitting and receiving standard frequencies and time signals to obtain the best results in the reception of:

– standard frequencies and time signals as used by those requiring moderate accuracy;
– standard frequencies and time signals as used by those requiring the maximum possible accuracy?

Note. – See Recommendation 486, Report 271 and Decision 29.

STUDY PROGRAMME 3A-1/7

OPTIMUM USE OF THE FREQUENCY SPECTRUM FOR HIGH-PRECISION TIME SIGNALS

(1959-1970)

The CCIR,

CONSIDERING

(a) that higher precision in the radio distribution of time signals necessitates, with present techniques, the use of an increased bandwidth;

(b) that newly developed techniques may, nevertheless, effect a considerable economy for a given precision;

(c) the effects of noise of all types on system performance,

UNANIMOUSLY DECIDES that the following studies should be carried out:

1. an investigation of the relationship between bandwidth required and precision obtainable at present for various signal-to-noise ratios encountered in practice;

2. an investigation of narrow-band techniques to generate and broadcast high-precision time markers;

3. an investigation of the characteristics of the radio paths involved that limit the accuracy of time signals as received, and how these radio-path parameters affect the choice of an optimum method.

Note. – See Report 270.

STUDY PROGRAMME 3B/7

INSTABILITY OF STANDARD-FREQUENCY GENERATORS

(1965)

The CCIR,

CONSIDERING

that the employment of high-quality frequency standards in a wide range of applications has given rise to a need to specify, in convenient and precise terms, the various forms of frequency and phase instability which limit performance in relation to the increasingly stringent requirements,

UNANIMOUSLY DECIDES that the following studies should be carried out:

1. how may the various forms of frequency and phase instability inherent in a standard-frequency generator be qualitatively described;

2. how may the limitations of precision imposed by various forms of frequency and phase instability in a standard-frequency generator be quantitatively expressed?

Note. – See Recommendation 538 and Reports 364, 580.

STUDY PROGRAMME 3C-3/7

COMPARISON OF DIFFERENT METHODS FOR THE TRANSFER AND DISSEMINATION OF TIME SIGNALS AND STANDARD FREQUENCIES

(1978)

The CCIR,

CONSIDERING

(a) that according to Recommendation 460 standard frequencies and time signals are to be coordinated;

(b) that comparisons of standard frequency and time signals distributed by various methods yield important information on the capabilities of these methods,

UNANIMOUSLY DECIDES that the following studies should be carried out:

1. comparisons of standard frequencies and time signals distributed by various methods;

2. analysis of the observed differences and fluctuations in order to determine the capabilities of the various methods.

Note. – See Reports 363, 439 and 897.

STUDY PROGRAMME 3D-2/7

METHODS FOR RELIABLE VERY LOW FREQUENCY PHASE COMPARISONS

(1970-1978)

The CCIR,

CONSIDERING

(a) that it is often necessary to produce a mean value based on the time scales of distant clocks or groups of clocks and that, for this purpose, extensive use is made of very low frequency (VLF) phase comparisons;

(b) that, in comparisons of VLF phase, the risk exists at present that the phase continuity as received may be lost from time to time, and that each loss of the phase continuity may cause error which cannot be considered negligible;

(c) that the use of calibrated measuring devices is an essential prerequisite for a thorough study of the problems of VLF propagation;

(d) that it is advisable to measure VLF phase values at the most favourable time of the day from the standpoint of the reliability of the received signal phase,

UNANIMOUSLY DECIDES that the following studies should be carried out:

1. how to promote the development and application of apparatus which allows for calibration for VLF phase comparisons;

2. investigation of the propagation behaviour at VLF in order to determine the most favourable reception conditions for daily phase comparisons.

QUESTION 4-1/7

DISSEMINATION OF STANDARD FREQUENCIES AND TIME SIGNALS

(1965-1970)

The CCIR,

CONSIDERING

(a) the need for increased accuracy of standard frequency and time signals;

(b) that the present standard-frequency and time-signal emissions, as received, are degraded in accuracy due to effects in the propagation of the radio waves, such as diurnal variations and the Doppler effect,

UNANIMOUSLY DECIDES that the following question should be studied:

what additional techniques can be employed for improving the accuracy of disseminated standard frequencies and time signals?

Note. – See Report 736.

STUDY PROGRAMME 4A/7

DISSEMINATION OF STANDARD FREQUENCIES BY CARRIER-FREQUENCY STABILIZATION OF BROADCASTING EMISSIONS

(1966-1970)

The CCIR,

CONSIDERING

(a) the need for investigation of additional techniques for the dissemination of standard frequencies and time signals;

(b) that broadcasting of standard-frequency signals is carried out in some countries by stations in the broadcasting bands;

(c) that certain advantages may be obtained by the technique of stabilizing the carrier frequencies of broadcasting stations, namely:

– the possibility of providing good ground-wave coverage, free of Doppler-effect errors, at centres of population and industry;
– the rapid comparison of frequencies at receiving locations by the use of such sufficiently high carrier frequencies; and
– the use of relatively simple receiving equipment,

UNANIMOUSLY DECIDES that the following studies should be carried out:

1. determination of the accuracy and stability of received signals from such broadcasts;

2. investigation of the influence of the location of transmitting stations on convenience of use and on propagation characteristics of signals;

3. determination of the desirability of establishing a service of this nature;

4. investigation of the relative merits of amplitude and frequency modulation as related to the dissemination of time signals and of the use of the broadcasting bands for the dissemination of standard frequencies by carrier-frequency stabilization.

Note. – See Report 576.

STUDY PROGRAMME 4B/7

DISSEMINATION OF TIME SIGNALS BY ADDITION OF PHASE MODULATION ON AMPLITUDE-MODULATED SOUND BROADCASTING TRANSMITTERS

(1974)

The CCIR,

CONSIDERING

(a) the need for wide dissemination of time signals, without increasing the number of transmitters operating on frequencies allocated to the standard-frequency and time-signal services;

(b) the desirability of investigating additional techniques for disseminating time signals;

(c) Recommendation I.3 adopted by the International Union of Radio Science (URSI) at its XVIIth General Assembly, Warsaw, 1972;

(d) the wide geographical coverage of amplitude-modulated sound-broadcasting transmitters in bands 5 and 6,

UNANIMOUSLY DECIDES that the following studies should be carried out:

1. the possibility of superimposing time signals by phase modulation of the carrier of a conventional amplitude-modulated sound-broadcasting transmitter without disturbance to listeners of the broadcast programme;

2. the possibility of implementation of such techniques on amplitude-modulated sound-broadcasting transmitters in bands 5 and 6.

Note. – See Report 577.

QUESTION 5-1/7

REQUIREMENTS FOR HIGH PRECISION TIME TRANSFER

(1978)

The CCIR,

CONSIDERING

(a) that there is a growing need for world-wide time transfers to be effected to accuracies that exceed those currently available;

(b) that such refinements may be achieved economically by utilizing the inherent timing capabilities of systems with other primary objectives,

UNANIMOUSLY DECIDES that the following question should be studied:

what techniques can be developed, independently or in conjunction with existing world-wide or intercontinental systems, to meet the requirements that can be foreseen for achieving higher accuracy in time transfers?

STUDY PROGRAMME 5A/7

REQUIREMENT FOR HIGH PRECISION TIME

(1976)

The CCIR,

CONSIDERING

(a) that time transfer is continuously available in many areas with a day-to-day standard deviation of 100 ns by means of LORAN-C;

(b) that time comparisons effected by two-way satellite links have been reported with uncertainties of 10 to 50 ns;

(c) that with refinements of satellite techniques and with laser techniques a further reduction in the uncertainty by a factor of ten appears to be possible;

(d) that such refinements are costly and their development should be guided by requirements,

UNANIMOUSLY DECIDES that the following studies should be carried out:

the present and projected requirements for high precision time for various applications such as: navigation systems, high-speed data networks, very long baseline radio interferometry (VLBI).

QUESTION 7/7

TIME CODES

(1974)

The CCIR,

CONSIDERING

(a) the need to provide a complete and unambiguous time reference for a variety of scientific and industrial applications;

(b) that a number of stations now transmit time codes giving, at least, minute, hour and day of year information;

(c) that it is very desirable that such codes be compatible with each other and with commonly available commercial equipment,

UNANIMOUSLY DECIDES that the following questions should be studied:

1. what formats can be recommended for the transmission of time code information;

2. what modulation characteristics will best ensure reliable decoding under conditions of noise and interfering signals?

Note. – See Recommendation 583 and Report 578.

STUDY PROGRAMME 7A/7

CHARACTERISTICS OF TIME CODES

(1978)

The CCIR,

CONSIDERING

(a) that coded DUT1 information is necessary in some time signal emissions in order to ensure immediate availability of UT1;

(b) that a number of standard-frequency and time-signal transmitters now emit time codes giving minute, hour and the date, and that it is desirable that such codes should be compatible with each other and with commonly available commercial equipment;

(c) that details are not readily available on the various timing codes which have been developed for system applications, and that unnecessary proliferation is undesirable,

UNANIMOUSLY DECIDES that the following studies should be carried out:

1. the most convenient methods for the dissemination of DUT1;

2. the most suitable types and formats of coded time information in standard-frequency and time-signal emissions;

3. the compilation and publication of an index of timing codes, with information about sources of full details, and an assessment to facilitate the selection of codes best suited to particular system applications.

QUESTION 8/7

RELIABILITY OF TIME AND FREQUENCY STANDARDS

(1976)

The CCIR,

CONSIDERING

that for many applications the reliability of time and frequency standards is of great importance,

UNANIMOUSLY DECIDES that the following question should be studied:

1. what criteria should be used for the meaningful expression of the reliability of clocks and frequency standards;

2. how reliable in operation are the existing time and frequency standards;

3. what steps can be taken to increase the reliability of time and frequency standards?

Note. – See Reports 737, 898 and Decision 29.

RESOLUTION 14-3

STANDARD-FREQUENCY AND TIME-SIGNAL EMISSIONS

(Question 1/7)

(1963–1966–1970–1974)

The CCIR,

CONSIDERING

the provisions of Article 33 of the Radio Regulations,

UNANIMOUSLY DECIDES

1. that, whenever an assignment to a station operating standard-frequency emission is put into service, the administration concerned shall notify this assignment to the IFRB, in accordance with the provisions of Article 12 of the Radio Regulations; however, no notice should be submitted to the IFRB until experimental investigations and coordination have been completed, in accordance with Article 33, of the Radio Regulations;

2. that, in addition, each administration should send all pertinent information on standard-frequency stations (such as frequency stability, changes in the phase of time pulses, changes in transmission schedule) to the Chairman, Study Group 7, and to the Directors, CCIR and BIH, for official publication within the shortest possible time;

3. that Study Group 7 should cooperate with the International Astronomical Union (IAU), the International Union of Radio Science (URSI), the International Union of Geodesy and Geophysics (IUGG), the International Union of Pure and Applied Physics (IUPAP) and the Bureau international de l'heure (BIH).

OPINION 26-2

STUDIES AND EXPERIMENTS CONCERNED WITH TIME-SIGNAL EMISSIONS

(Question 1/7)

(1966–1970–1974)

The CCIR,

CONSIDERING

(a) that the standard-frequency and time-signal emissions are used in many fields of pure and applied science;

(b) that Study Group 7 frequently needs the advice of the scientific unions and organizations,

IS UNANIMOUSLY OF THE OPINION

1. that the General Conference of Weights and Measures (CGPM), the Bureau international de l'heure (BIH), the International Union of Radio Science (URSI), the International Astronomical Union (IAU), the International Union of Geodesy and Geophysics (IUGG), and the International Union of Pure and Applied Physics (IUPAP) should be asked to cooperate with CCIR Study Group 7;

2. that the Chairman, Study Group 7, should communicate with the Director, BIH, and with the Chairmen of the appropriate Commissions of URSI, the IAU, the IUGG, the CGPM and the IUPAP, and that the Director, CCIR, should be informed.

OPINION 27

STANDARD-FREQUENCY AND TIME-SIGNAL EMISSIONS IN ADDITIONAL FREQUENCY BANDS

(Question 2/7)

(1966)

The CCIR,

CONSIDERING

(a) that in certain areas, particularly in industrial centres, it is not always possible to obtain an adequate signal-to-noise ratio with the existing standard-frequency and time-signal service;

(b) that a better service is needed in certain areas and this service may be given by use of frequencies in band 8 and higher,

IS UNANIMOUSLY OF THE OPINION

that each administration should, as far as possible, provide for the distribution of standard frequencies and time signals, on a local basis, two bands 100 kHz wide in bands 8 and 9 respectively, the centre frequencies of which should be whole multiples of 5 MHz.

OPINION 28

SPECIAL MONITORING CAMPAIGNS BY THE IFRB WITH A VIEW TO CLEARING THE BANDS ALLOCATED EXCLUSIVELY TO THE STANDARD-FREQUENCY SERVICE

(1966)

The CCIR,

CONSIDERING

(a) the results of the special monitoring campaigns organized by the IFRB, with a view to clearing the bands allocated exclusively to the standard-frequency service;

(b) the need for achieving a more complete clearance of those bands;

(c) the difficulty experienced by the IFRB in identifying stations not belonging to the standard-frequency service, but operating in the standard-frequency bands,

IS UNANIMOUSLY OF THE OPINION

1. that the IFRB should be asked to increase, as far as practicable, the number of special monitoring programmes per year, covering the bands allocated exclusively to the standard-frequency service;

2. that the IFRB should urge administrations of countries where direction-finding facilities are available to take bearings with a view to determining the position of the stations observed.

OPINION 70

THE UTC SYSTEM AND THE ROLE OF THE BUREAU INTERNATIONAL DE L'HEURE

(1982)

The CCIR,

CONSIDERING

(a) that the Coordinated Universal Time (UTC) system is now the accepted time reference for nearly all scientific and technical purposes throughout the world;

(b) that the operation of the UTC system is dependent on the support of the Bureau international de l'heure (BIH) which provides the essential basis for UTC in the form of International Atomic Time (TAI) together with the necessary relations to astronomical time;

(c) that active and fruitful cooperation between CCIR Study Group 7, and the BIH has existed for many years; and

(d) that the BIH derives its support from a number of organizations, both national and international,

IS UNANIMOUSLY OF THE OPINION

1. that the Director, CCIR, should convey to the Director, BIH, his sincere appreciation of the degree of cooperation provided by the BIH in furtherance of the UTC system;

2. that all administrations should be made aware of the need to support the activities of the BIH in respect of the formation and maintenance of TAI and UTC; and

3. that a similar statement should be communicated to the International Council of Scientific Unions (ICSU) and also to the bodies most immediately concerned, including the General Conference of Weights and Measures (CGPM), the International Astronomical Union (IAU), the International Union of Radio Science (URSI), the International Union of Geodesy and Geophysics (IUGG), the International Union of Pure and Applied Physics (IUPAP) and to the President of the Paris Observatory.

OPINION 71 *

DOCUMENTATION OF TIME TRANSMISSIONS

(Question 1/7)

(1982)

The CCIR,

CONSIDERING

(a) that the transmitted time signals have been kept within various accuracy limits by the introduction of steps or changes in the rate over the past twenty-five years;

(b) that each administration furnishes current information concerning adjustments to frequency and time signals in accordance with Article 33, No. 2771 of the Radio Regulations and CCIR Resolution 14;

(c) that there have been different values of the steps and changes of the rates in the different countries during the period 1955 to 1972, and that the relevant details are not readily available;

(d) that these data will be necessary for the analysis of long-term phenomena,

IS UNANIMOUSLY OF THE OPINION

that all administrations operating a standard-frequency time-signal service should document the details of adjustments to frequencies and time scales in the period 1955 to 1972 and specifically should publish the amount and date of time steps and rate changes in their emissions and also communicate the data to the Bureau international de l'heure.

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* The Director, CCIR, is requested to transmit this Opinion to the authorities responsible for standard-frequency and time-signal services listed in Report 267.

OPINION 72 *

TIME DISSEMINATION USING METEOROLOGICAL SATELLITES

(Question 2/7)

(1982)

The CCIR,

CONSIDERING

(a) that needs are growing in many application areas, such as geodesy, geophysics, international time coordination, and many other types of coordinated scientific observations for reference time signals that are available world-wide on a highly reliable basis;

(b) that an accurate time code referenced to UTC has been successfully disseminated from two United States GOES meteorological satellites since 1975 and is finding increasing acceptance and use within the western hemisphere;

(c) that the European Meteosat satellites and the Japanese GMS satellites are part of the same world-wide meteorological satellite system as the United States GOES satellites and have similar data formats, including apporopriate code bits reserved for possible time code use;

(d) that inexpensive receivers could be used in common with the GOES, Meteosat, and GMS satellites with little or no modification;

(e) that time and frequency organizations in Europe and Japan have expressed interest in implementing time codes on the Meteosat and GMS satellites,

IS UNANIMOUSLY OF THE OPINION

1. that the addition of a time code compatible with the GOES satellites to Meteosat and GMS satellites would provide a valuable world-wide time and frequency dissemination service useful in many applications and requiring no significant modifications to the satellite signal formats, space hardware, or ground equipment;

2. that the World Meteorological Organization should be asked to distribute this Opinion to its national organizations in appropriate countries;

3. that the European Space Agency should be asked to distribute this Opinion to appropriate organizations within Europe that are interested in the METEOSAT program.

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* The Director, CCIR, is requested to bring this Opinion to the attention of the International Union of Geodesy and Geophysics (IUGG) and CCIR Study Group 2.

DECISION 28

WORLD-WIDE TIME DISSEMINATION BY MEANS OF SATELLITES

(Question 2/7)

(1978)

CCIR Study Group 7,

CONSIDERING

(a) that the performance of present standard frequency generators with relative uncertainties of 10^{-13} and of the associated time scales which vary only by about 10 ns per day, exceed available time dissemination capabilities;

(b) that modern technology, for example, in electronic navigation and high-speed digital communication systems, is relying more and more on precise time and frequency;

(c) that various satellite time transfer experiments have demonstrated a potential capability for time transfers with a precision of a few nanoseconds and an accuracy of about 50 ns;

(d) that satellite techniques have also demonstrated capabilities for dissemination of time at more modest accuracy levels with better coverage, reliability, and accuracy than present systems, while requiring only simple receiving methods and equipment;

(e) that the inherent wide coverage capabilities of satellite timing signals make regional and international coordination of satellite timing services highly desirable,

DECIDES

1. that an Interim Working Party 7/4 be set up to study the requirements, technical alternatives and opportunities, and methods of coordination for an international time dissemination service by means of satellites. The study will include:

1.1 possibilities for improved time comparison and coordination among laboratories which provide or require the most precise timing signals obtainable;

1.2 possibilities for the widespread distribution by satellite of timing signals to meet the requirements of general users;

2. that the conclusions of its work should be reported to Study Group 7 as soon as possible and before the XVIth Plenary Assembly of the CCIR;

3. that the work of this Interim Working Party shall be carried out as far as possible by correspondence.

Note. – The Administrations of the countries shown in Annex I have already indicated their intention and desire to participate in the work of Interim Working Party 7/4:

ANNEX I

List of participants in IWP 7/4:

Chairman: Mr. Roger Beehler
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Canada
China (People's Republic of)
United States of America
France
India
Italy
Japan
United Kingdom
Switzerland
Yugoslavia (Socialist Federal Republic of)
European Space Agency
Bureau international de l'heure

DECISION 29-1

PERFORMANCE AND RELIABILITY OF FREQUENCY STANDARDS AND REFERENCE CLOCKS

(Questions 3/7 and 8/7)

(1978–1981)

CCIR Study Group 7,

CONSIDERING

(a) that there is an increasing use of accurate standard-frequency generators in communication networks;

(b) that Study Group XVIII of the CCITT has requested advice and information from Study Group 7 on the particular subject of the performance, i.e. accuracy and stability, and the reliability of frequency standards and reference clocks, as well as the relevant measurement techniques,

DECIDES

1. that an Interim Working Party 7/5 be continued to study further:

1.1 the reliability of reference clocks,

1.2 the performance of such clocks,

1.3 measurement techniques for determining the performance of clocks;

2. that an Interim Report of its work be made to Study Group 7 before the Interim Meeting of the 1982-86 study period;

3. that the work of this Interim Working Party shall be carried out as far as possible by correspondence.

The Administrations of the countries shown in Annex I have already indicated their intention and desire to participate in the work of Interim Working Party 7/5.

ANNEX I

List of participants in IWP 7/5:

Chairman: Dr. Peter Kartaschoff
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ALPHABETICAL INDEX OF KEY WORDS AND TERMS OF VOLUME VII

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