INTERNATIONAL TELECOMMUNICATION UNION

CCIR

INTERNATIONAL
RADIO CONSULTATIVE
COMMITTEE

RECOMMENDATIONS AND REPORTS OF THE CCIR, 1986

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

XVIth PLENARY ASSEMBLY
DUBROVNIK, 1986

VOLUME VII

STANDARD FREQUENCIES AND TIME SIGNALS

Geneva, 1986

CCIR

1. The International Radio Consultative Committee (CCIR) is the permanent organ of the International Telecommunication Union responsible under the International Telecommunication Convention "... to study technical and operating questions relating specifically to radiocommunications without limit of frequency range, and to issue recommendations on them..." (International Telecommunication Convention, Nairobi 1982, First Part, Chapter I, Art. 11, No. 83).

2. The objectives of the CCIR are in particular:

a) to provide the technical bases for use by administrative radio conferences and radiocommunication services for efficient utilization of the radio-frequency spectrum and the geostationary-satellite orbit, bearing in mind the needs of the various radio services;

b) to recommend performance standards for radio systems and technical arrangements which assure their effective and compatible interworking in international telecommunications;

c) to collect, exchange, analyze and disseminate technical information resulting from studies by the CCIR, and other information available, for the development, planning and operation of radio systems, including any necessary special measures required to facilitate the use of such information in developing countries.

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

(Dubrovnik, 1986)

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.
VOLUMES 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-1	Land mobile service. Amateur service. Amateur-satellite service.
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VOLUME VIII-3	Mobile satellite services (aeronautical, land, maritime, mobile and radiodetermination). Aeronautical mobile service.
VOLUME IX-1	Fixed service using radio-relay systems.
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VOLUMES X/XI-3	Sound and television recording.
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 XVIth 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 1986 edition, unless otherwise noted; i.e., only the basic number is shown.

Printed in Italy

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

Volumes I to XIV, XVIth Plenary Assembly, contain all the valid texts of the CCIR and succeed those of the XVth Plenary Assembly, Geneva, 1982.

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.

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(1) Published separately.

1.3 *Reports (cont.)*

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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.

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43	X/XI-2	60	XI-1	72	X-1 + XI-1

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)

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* Report 737 has been incorporated in Report 898.

** Became new Study Programme 10B/7.

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NUMERICAL INDEX OF TEXTS

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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.

1982-1986-1990	*Chairman:*	J. McA. STEELE (United Kingdom)
	Vice-Chairman:	S. LESCHIUTTA (Italy)

INTRODUCTION BY THE CHAIRMAN, STUDY GROUP 7

1. General

At its Final Meeting (Geneva, 1985), the Study Group gave consideration to the order and presentation of its texts. It was decided that these should be grouped in three main chapters which would bring out the principal sub-divisions of the documentation and provide the reader with a more orderly sequence of information. Following Report 730 devoted to the glossary of terms in use by Study Group 7, the various Reports and Recommendations are now assembled under the headings of:

- the specification of the standard-frequency and time-signal service;
- the methods available for the dissemination and comparison of signals; and
- the characteristics of standard-frequency sources and their use for time scale formation.

The remaining texts including Questions, Study Programmes, Resolutions and Opinions are given at the end of the Volume. It will be convenient in this Introduction to follow the broad lines of demarcation adopted for the Study Group documentation as a whole.

2. Specification of the standard-frequency and time-signal service

2.1 *System of Coordinated Universal Time (UTC)*

It is a tribute to the original concept and design of the UTC system embodied in Recommendation 460 that no significant modification has been found necessary in recent years. In the period following the introduction of the system in 1972 the Earth behaved with great regularity and leap seconds were applied consistently on the last day of December of each year to compensate for the difference in rate between astronomical time derived from the Earth's rotation and the atomic reference. However, from about 1979 onwards, the Earth displayed less predictable behaviour and the provision in Recommendation 460 which allows leap seconds to be applied on the last day of June was first exercised in 1981 and thereafter in successive years until 1985, with the exception of 1984 when no leap second was required, the Earth's rate of rotation having increased appreciably as compared with its performance in the immediate past years.

In its 15 or so years of operation, the UTC system with its concomitant leap seconds has gained widespread acceptance and the need to accommodate the seconds adjustment in any operational system of time-keeping is now well understood. It is, perhaps, unfortunate that in the case of some navigational transmissions it is not possible to accept the loss of coherence which would arise through the introduction of a leap second, especially where the stations are widely distributed either on Earth or in space. Omega and the Global Positioning System (GPS) are two particular examples where no leap seconds are applied but where, nevertheless, the difference between UTC and the current navigational system time frame is always made available. In the case of Omega, the relevant difference is given in Report 267 for a defined epoch. In the same Report it is made clear that the Loran-C network, while it suffers no temporal change on the introduction of a leap second, does register the effect of such a change by a redefinition of the "times-of-coincidence" issued by the United States Naval Observatory.

Prior to the introduction of the UTC system, various methods of adjustment were in use for emitted time signals. It is important that the details of such changes should continue to be available for archival purposes. Initially they were to have been included in Report 896 on the subject of the documentation of such changes but it was agreed at the Interim Meeting, in line with Opinion 71, that it was more appropriate that such information be deposited with the Bureau international de l'heure (BIH) and with the World Data Centres, A, B and C. The Administrations of France, the Federal Republic of Germany, Japan, the United Kingdom and the United States of America have already lodged the pertinent details with the BIH.

2.2 *Bureau international de l'heure (BIH)*

Some of the functions of the BIH in overseeing the operation of the UTC system have already been mentioned: the central role of the Bureau in relation to UTC is acknowledged in Opinion 70 which emphasizes the need to support the activities of the BIH in the formation and maintenance of the atomic time scales. The need for such support will be no less in the future now that the functions of the BIH have been separated into two parts: one concerned with atomic time at the Bureau international des poids et mesures (BIPM), Sèvres, France, and the other devoted to studies of the rotation of the Earth which remains at the Paris Observatory. It is proposed that the CCIR will be represented on a Working Group having the oversight of International Atomic Time (TAI) which will become effective when all the concerned scientific unions have given their assent to the new arrangements. The responsibility for TAI will then fall within the competence of the Comité international des poids et mesures (CIPM). In respect of UTC, an additional input will still be required from Earth rotation observations in deciding upon the incidence of leap seconds.

3. Time and frequency dissemination and comparison

3.1 *Allocated bands*

The present status of the stations operating in the allocated (terrestrial) bands, i.e., at centre frequencies of 20 kHz, 2.5, 5, 10, 15, 20 and 25 MHz, is given in Table I of Report 267. There is no use of the lowest (20 kHz) nor, since 1977, of the highest (25 MHz) frequency by any administration. A number of changes in the available services have taken place in recent years and it is notable, despite the development of other methods of dissemination, that the number of additions to the Table exceeds the deletions. The transmission of FFH (Paris) on 2.5 MHz was discontinued in May, 1982: conversely an additional transmission on this frequency, limited to daylight hours, has been added to the programme of BPM (Pusheng). RCH (Tashkent) previously limited to 2.5 MHz has added 5 and 10 MHz to its emissions while in the Far East the Republic of Korea has introduced a new station, HLA (Taedok) operating on 5 MHz for a total of 7 hours each working day. These additional services undoubtedly increase the potential for mutual interference (Recommendation 537) and effect the possible remedies which are addressed in Report 732. The situation has been improved somewhat by the decision of the WARC-79 which enabled the frequencies of 4, 8 and 16 MHz to be used for time and frequency dissemination in Region 3 and it is gratifying to see that 8 MHz has been added to the JJY emissions on 2.5, 5, 10 and 15 MHz.

3.2 *Additional frequency bands*

Recommendation 375 encourages the use of existing services in bands 4, 5, 6, 8 and 9 for the dissemination of a time and frequency reference. Tables II to V of Report 267 list the characteristics of such stations embracing navigational communication and broadcasting transmitters, the latter being specifically the subject of Report 576, in addition to a number of dedicated time and frequency stations. In respect of most of the powerful VLF sources a cautionary footnote has been added drawing attention to the widespread use of minimum shift keying (MSK) which results in the loss of phase coherence. This can be recovered but only at the expense of additional processing in a suitable receiver.

The spectrum available for time and frequency dissemination is necessarily limited and Report 270 emphasizes the need for its optimum use for high-precision time transfer. Several stations are now exploiting phase modulation as a means of achieving greater precision combined with enhanced resistance to interference. As described in Report 577, the Allouis (162 kHz) transmitter makes use of triangular phase modulation of amplitude $\pm$ 1 rad in an interval of 0.1 s to realize both a time reference and also a time code distribution, the phase modulation being applied simultaneously with the normal amplitude modulation of sound broadcasting. In the USSR, phase modulation has also been studied on station RBU (66 2/3 kHz) using narrow-band signals at sub-carrier frequencies of 100 and 312.5 Hz and a phase excursion of 0.7 rad, to identify second and minute markers. An alternative technique making use of phase modulation by a pseudorandom (PR) sequence has been the subject of experiments on DCF77 (77.5 kHz) since 1983. Initial results indicate that the time obtained by correlation of the PR sequence is more reproducible than that derived from amplitude-modulated seconds marker.

3.3 *High precision time transfer*

With the increasing ability to make high precision ($\leqslant$ 1 ns) time comparisons by various means, there is a need to determine the limitations set by instrumental instability and propagation variations and this is recognized in a new Study Programme 5B/7. An associated problem lies in determining the delays arising in the antennas used to launch high-precision signals and a first report has been provided on this subject (Report 1017). The existing Report 897 on short-range high-precision time transfer has been extended to include the results obtained by means of cables, including optical fibres, as well as line-of-sight links using laser transmitters.

3.4 *Methods for the transfer and dissemination of time and standard frequencies*

Following discussion at the Interim Meeting, it was agreed that the original text of Report 363 on comparison of methods for transfer and dissemination had become unwieldy and it was appropriate to assign to a Special Rapporteur the task of reviewing its contents and seeking to identify those areas of the Report which might be better considered in more detail in a separate context, either as part of an existing Report or forming the basis of a new text. The Study Group was fortunate in having the services of Dr. G. M. R. Winkler (United States of America) for this work which, following review at the Final Meeting, now constitutes the revised version of Report 363. This is now essentially a comparative document, contrasting many different methods of time transfer and dissemination, the details of which are embodied in separate texts, e.g. satellite time transfer in Report 518.

One consequence of this revision was that television methods for transfer and dissemination emerged as a subject sufficiently large and important to be treated in a separate new Report 1016.

3.5 *Time codes*

The emission of a time code continues to be a valuable feature in a number of services operating both in the allocated bands and in the additional bands. Details of the coding formats in use are given in Report 578: there is no unique code common to all time and frequency services although Recommendation 583 does advise that only a limited set of codes should be used and any new system should conform to one of the codes already in use. At the Final Meeting, note was taken also of the Recommendation on time code formats issued in June, 1985 by the Consultative Committee for Space Data Systems (CCSDS). The Recommendation establishes a common basic format for time code data for use by seven member space agencies.

4. Characterization of sources and time scale formation

The performance of standard-frequency sources and the methods available to characterize it are concepts basic to the work of Study Group 7. The Final Meeting adopted a new and more logical structure for the enabling texts in this area: a new Question 10/7 was approved on the performance of frequency and time standards and appended to this is the new Study Programme 10B/7 the "Time scale algorithms and statistical problems" (previously Study Programme 1D-1/7 of which only the title has been changed) and a new Study Programme 10A/7 on the performance and characterization of frequency and time standards. Minor corrections have been made to a number of related Reports including Report 364 on the performance of standard-frequency generators, Report 439 on relativistic effects, Report 579 on time scale algorithms and Report 580 on frequency and phase noise. New results for the frequencies of standards in the sub-millimetre and visible regions of the spectrum are incorporated in Report 738.

5. Interim Working Parties

After operating energetically and successfully throughout two study periods, Interim Working Parties IWP 7/4 and IWP 7/5 had substantially discharged their allotted tasks and therefore concluded their activities at the Final Meeting. In consequence, Decisions 28 and 29 are now cancelled. The Study Group recorded its grateful thanks to the respective Chairmen, Mr. R. E. Beehler (United States of America) and Dr. P. Kartaschoff (Switzerland) for their sustained efforts and application during nearly 8 years in pursuing these important studies. Thanks are also due to the members of both Working Parties and their administrations for contributing to the success of the work.

5.1 *IWP 7/4*

This Working Party was established with broad terms of reference to consider the requirements, technical possibilities and methods for achieving a world-wide dissemination of a time reference by means of satellites. As is customary, the IWP functioned largely by correspondence, in the process accumulating a considerable literature. However, progress was also assisted by additional face-to-face discussions during Interim and Final Meetings in 1980, 1981 and 1983.

Having assembled extensive background information on satellite methods including experimental results and comparative estimates of the advantages and disadvantages of various systems, IWP 7/4 prepared suitable summaries for inclusion in a revised version of the Study Group's basic satellite document, Report 518. This omnibus Report also includes material relevant to the satellite sector from other Reports and particularly from Report 363 already mentioned in § 3.4 and it was part of the activity of the IWP to keep this comprenhensive satellite document up to date by appropriate revisions at each Interim and Final Meeting. Other Study Group texts emanating directly from the work of IWP 7/4 include Recommendation 582 which exhorts administrations to consider the benefits of satellite-based techniques in planning future services of time dissemination and also Opinion 72 directed to the advantages of combining time and time-code dissemination with the operation of meteorological satellites in geostationary orbit. The Working Party was also responsible for generating the Study Group contribution to the Conference Preparatory Meeting (CPM, 1984) for the WARC ORB-85 on the use of the geostationary orbit.

Given the number and variety of both existing and projected satellite systems for improved time dissemination and transfer, it is not surprising that IWP 7/4 was not able to recommend a single system or technique as the preferred choice. However, the IWP was still able to serve a valuable function in providing objective information on the most promising systems, encouraging member administrations to give high priority to the development of new satellite time-transfer technology and operational services and advising on opportunities for the time and frequency community to influence the development of specific satellite systems which might serve its needs. Some of these activities of IWP 7/4 will continue to have a beneficial effect in the work which is to be undertaken on the preparation of a handbook on satellite time and frequency dissemination (see § 6).

5.2 *IWP 7/5*

It will be recalled that IWP 7/5 was established initially in response to a request from CCITT Study Group XVIII for advice and information on the subject of the reference clocks which provide synchronization in digital networks, and specifically on their reliability, their instability and on the measurement techniques to determine that instability. In seeking to respond to the question of the reliability of frequency standards and clocks, the Working Party conducted a comprehensive, world-wide survey embracing both atomic and non-atomic devices. This was a most valuable exercise, ably supported by the members of the IWP, and the results are now presented in several tables in Report 898 which can be regarded as a complete response to the original Study Group XVIII questions. The Report also incorporates the previous Report 737 on the reliability of time and frequency standards and the latter now disappears.

It is very satisfactory to record that the reliability data obtained and analysed by IWP 7/5 have now been included in an Annex to CCITT Recommendation G.811. This Recommendation also specifies the timing to be associated with the nodes terminating international links in the form of the permissible time interval error (TIE) for the reference clocks for various observation periods. It is one of the features of Report 898 that it reinterprets the TIE in terms familiar to Study Group 7 as the integral of the normalized frequency departure.

The contacts between Study Group 7 and CCITT Study Group XVIII continue to be very useful to both sides and it is gratifying that Dr. Kartaschoff has kindly agreed to act as a Special Rapporteur in furthering the relations between the two Study Groups.

6. Decision 65: Handbook on the Use of Satellite Time and Frequency Dissemination

The terms of reference of Study Group 7 include the use of satellite systems in achieving standard-frequency and time-signal dissemination on a world-wide basis and by their very nature satellites may overcome many of the limitations of equivalent ground-based systems of time and frequency distribution. The studies carried out by IWP 7/4 have demonstrated the technical possibilities in the satellite field based on the operational experience with a number of systems of time dissemination or comparison making use of satellites in the geostationary orbit. The potential for a future world-wide service is unquestioned, taking account especially of the deployment of the Global Positioning System (GPS) which will be effective in the next study period.

On the basis of these considerations, the Study Group agreed at the Final Meeting that the time was opportune to set up an *ad hoc* Working Group with the task of preparing a handbook on satellite-based services of time and frequency dissemination. The text will draw initially on the documents of Study Group 7 and especially on Report 518 and the collected papers of IWP 7/4: it will also draw upon the relevant documents from other Study Groups and extensive open literature on satellite systems for position determination. It is encouraging to record that, pursuant to the circulation of the Decision to administrations, the following have indicated their wish to participate in the Working Party: Canada, France, India, Japan, the United Kingdom, Socialist Federal Repubic of Yugoslavia and the Bureau international de l'heure.

SECTION 7A: GLOSSARY

Report

REPORT 730-1 *

GLOSSARY

(1978-1986)

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)

* This Report should be brought to the attention of the CMV.

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.

In many contexts the expression "stability" instead of "instability" is used and is acceptable.

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".)

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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.

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.

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.

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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.

1.10 **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.

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" (frequently abbreviated to "phase"). 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.

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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.

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.

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.

3.9 **Universal Time (UT)**, *Temps universel (UT), Tiempo Universal (UT)*

Universal Time (UT) is the general designation of time scales based on the rotation of the Earth.

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.)

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, Instánte*

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 (JD)**, *Date julienne (DJ), Fecha juliana (FJ)*

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 (DJM), Fecha modificada del calendario Juliano (FMCJ)*

Julian Date less 2 400 000.5 days.

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

(See Time scales in synchronism).

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SECTION 7B: SPECIFICATIONS FOR THE STANDARD-FREQUENCY AND TIME-SIGNAL SERVICES

Recommendations and Reports

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,
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 International Maritime Organization (IMO), 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 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.

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 460-4

STANDARD-FREQUENCY AND TIME-SIGNAL EMISSIONS

(Question 1/7)

(1970–1974–1978–1982–1986)

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 International Maritime Organization (IMO), 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 IMO, 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)

Universal Time (UT) is the general designation of time scales based on the rotation of the Earth.

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 unsure 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 (see Note).

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

Note. – 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.

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. 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.

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 and UT2 − UTC.

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.

$$\text{DUT1} = (n \times 0.1)\ \text{s}$$

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.

$$\text{DUT1} = -(m \times 0.1)\ \text{s}$$

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:

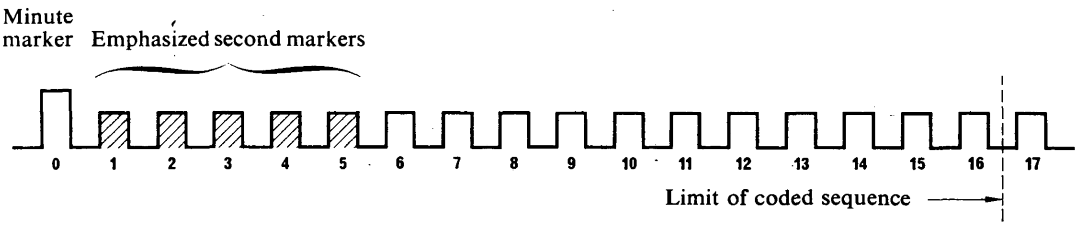

FIGURE 1

DUT1 = +0·5 s

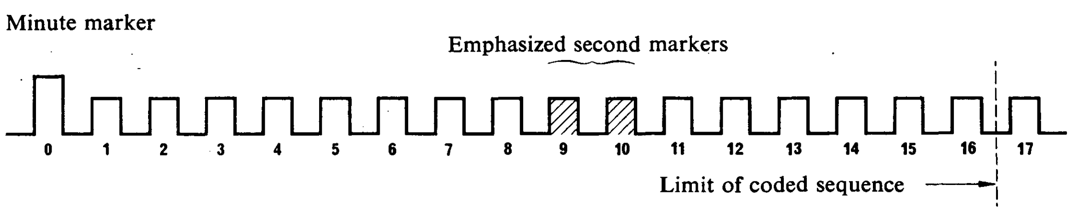

FIGURE 2

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:

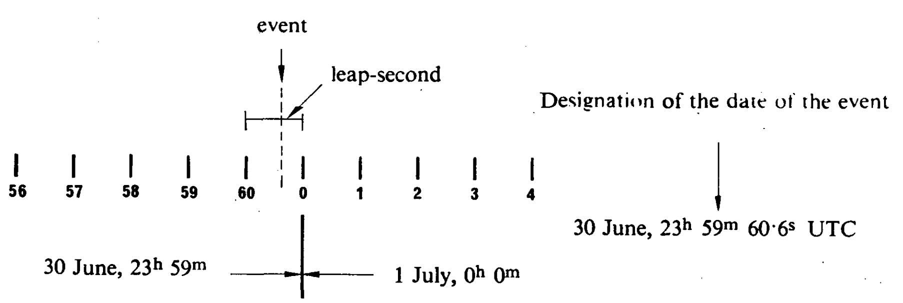

FIGURE 3 – *Positive leap-second*

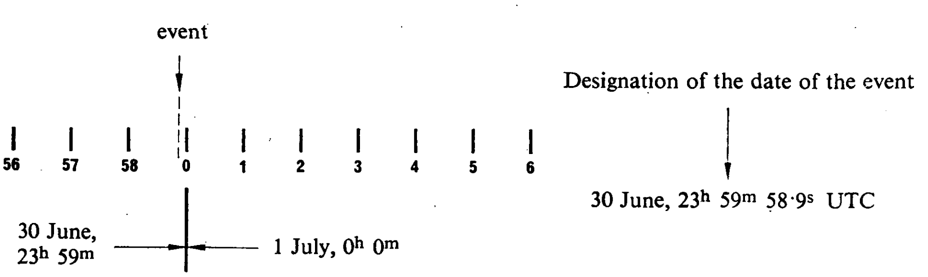

FIGURE 4 – *Negative leap-second*

RECOMMENDATION 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 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,

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

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.

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;

(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 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;

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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 International Maritime Organization (IMO) and the World Meteorological Organization (WMO).

(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 International Maritime Organization (IMO), 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.

SECTION 7C: SYSTEMS FOR DISSEMINATION AND COMPARISON

Recommendations and Reports

REPORT 267-6

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)

(1956-1959-1963-1966-1970-1974-1978-1982-1986)

The characteristics of stations appearing in the following tables are valid as of 1 November, 1985. 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 November 1985*

Station			Type of antenna(s)	Carrier power (kW)	Number of simul-taneous trans-missions	Period of operation		Standard frequencies used		Duration of emission		Uncertainty of frequency and time intervals (parts in 10^{12}) (1)	Method of DUT1 indication
Call sign	Approximate location	Latitude Longitude				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	24 (2)	5, 10, 15	1, 1000	continuous	4/15	± 10	
BPM (3)	Pucheng, China	35° 00′ N 109° 31′ E	Omni-directional	10-20	2	7	24 (4)	2.5, 5, 10, 15	1, 1000	20/30 (UTC) 4/30 (UT1)	nil	± 10	Direct emission of UT1 time signal
HLA	Taedok Science Town, Republic of Korea	36° 23′ N 127° 22′ E	Vertical (conical monopole)	2	1	5	7	5	1	continuous	nil	± 10	CCIR code by double pulse
IAM (5)	Roma, Italy	41° 47′ N 12° 27′ E	Vertical λ/4	1	1	6	2	5	1	continuous	nil	± 10	CCIR code by double pulse
IBF (5)	Torino, Italy	45° 02′ N 07° 46′ E	Vertical λ/4	5	1	7	2¾	5	1	continuous	nil	± 10	CCIR code by double pulse
JJY (5)	Sanwa, Sashima, Ibaraki, Japan	36° 11′ N 139° 51′ E	(6)	2	5	7	24 (7)	2.5, 5, 8, 10, 15	1 (8) 1000 (9)	continuous	30/60	± 10	CCIR code by lengthening
LOL (5)	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 (5)	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

TABLE I *(continued)*

Station			Type of antenna(s)	Carrier power (kW)	Number of simultaneous transmissions	Period of operation		Standard frequencies used		Duration of emission		Uncertainty of frequency and time intervals (parts in 10^{12}) (1)	Method of DUT1 indication
Call sign	Approximate location	Latitude Longitude				Days/ week	Hours/ day	Carrier (MHz)	Modulation (Hz)	Time signal (min)	Audio-modulation (min)		
OMA (5)	Praha, Czechoslovak S.R.	50° 07′ N 14° 35′ E	T	1	1	7	24	2.5	1, 1000 (10)	15/30	4/15	± 1000	
RCH (5)	Tachkent, USSR	41° 19′ N 69° 15′ E	Horizontal dipole	1	2	7	21	2.5, 5, 10	1, 10	40/60	nil	± 50	CCIR code by double pulse, additional information dUT1 (11)
RID (5)	Irkutsk, USSR	52° 26′ N 104° 02′ E	Horizontal dipole	1 1 1	3	7	24	5.004 10.004 15.004	1, 10	40/60	nil	± 50	CCIR code by double pulse, additional information dUT1 (11)
RIM (5)	Tachkent, USSR	41° 19′ N 69° 15′ E	Horizontal dipole	1	1	7	20½	5, 10	1, 10	39/60	nil	± 50	CCIR code by double pulse, additional information dUT1
RTA (5)	Novosibirsk, USSR	55° 04′ N 82° 58′ E	Horizontal dipole	5	1	7	20½	10, 15	1, 10	40/60	nil	± 50	CCIR code by double pulse, additional information dUT1 (11)
RWM (5)	Moskva, USSR	55° 48′ N 38° 18′ E	Horizontal dipole	5 5 8	3	7	24	4.996 9.996 14.996	1, 10	40/60	nil	± 50	CCIR code by double pulse, additional information dUT1 (11)

TABLE I *(continued)*

Station			Type of antenna(s)	Carrier power (kW)	Number of simul-taneous trans-missions	Period of operation		Standard frequencies used		Duration of emission		Uncertainty of frequency and time intervals (parts in 10^{12}) (1)	Method of DUT1 indication
Call sign	Approximate location	Latitude Longitude				Days/ week	Hours/ day	Carrier (MHz)	Modulation (Hz)	Time signal (min)	Audio-modulation (min)		
WWV (5)	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 (12)	1, 440, 500, 600	continuous (13)	continuous (14)	± 10	CCIR code by double pulse, additional information on UT1 corrections
WWVH (5)	Kekaha, Kauai, Hawaii, USA	21° 59′ N 159° 46′ W	Vertical λ/2 dipole arrays	2.5-10	4	7	24	2.5, 5, 10, 15 (12)	1, 440, 500, 600	continuous (13)	continuous (14)	± 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 (5)	Olifantsfon-tein, Republic of South Africa	24° 58′ S 28° 14′ E	Vertical monopole	4	1	7	24 (15)	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) 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.

(2) 5 MHz: 1800-0900 h UTC; 10 MHz: 24 hours; 15 MHz: 0900-1800 h UTC.

(3) Call sign in Morse and language.

(4) 15 MHz: 0000-1400 h UTC; 5 MHz: from 1400-2400 h UTC; 10 MHz, continuous.

(5) 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.

(6) Vertical $\lambda/4$ for 2.5 MHz, horizontal $\lambda/2$ dipole for 5 and 8 MHz, and vertical $\lambda/2$ dipoles for 10 and 15 MHz.

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

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

(9) 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.

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

(11) 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 multipes of 0.02 s. 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 s × 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 s × q.

(12) 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.

(13) 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.

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

(15) 2.5 MHz: from 1800-0400 h UTC; 5 MHz: continuous.

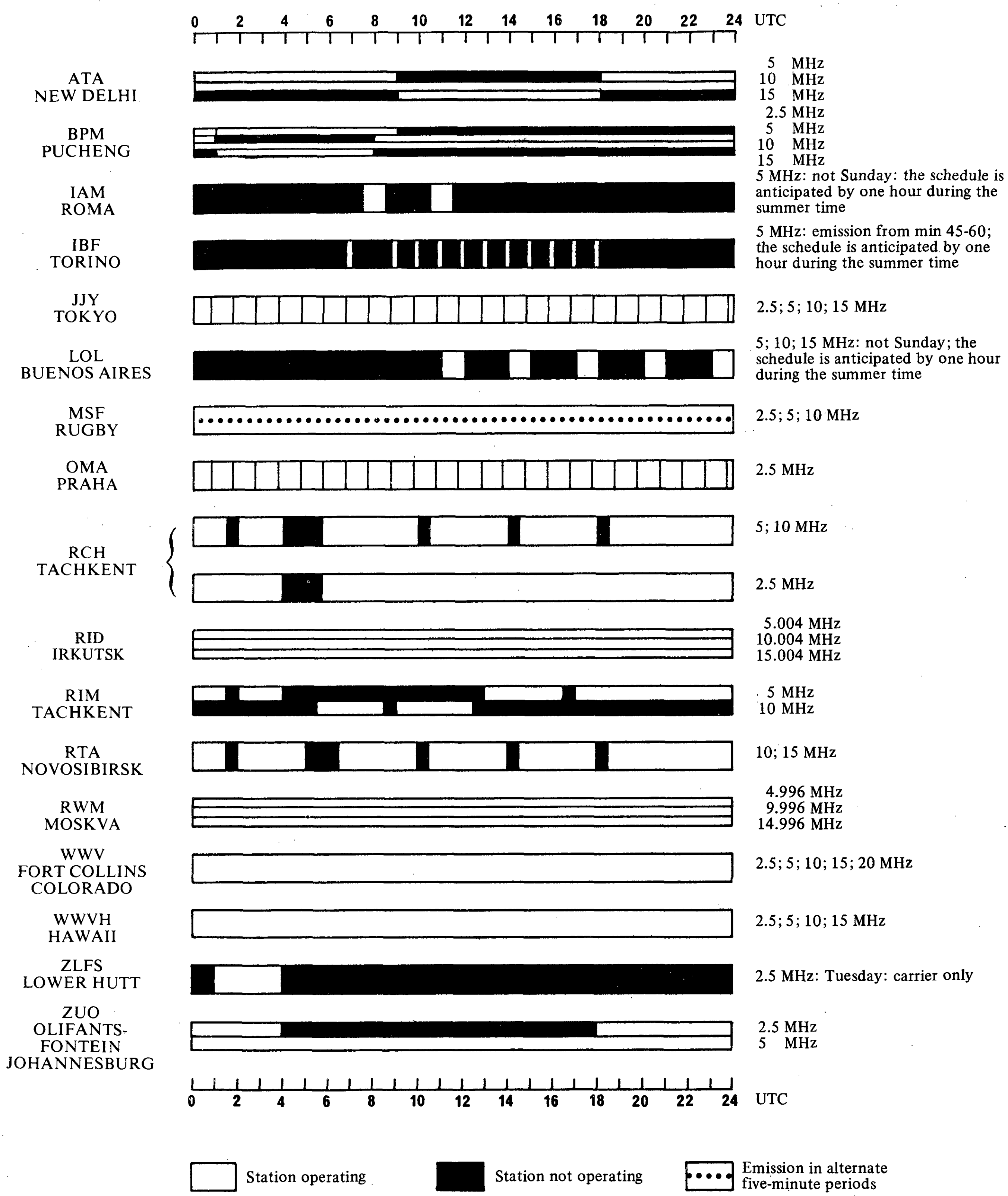
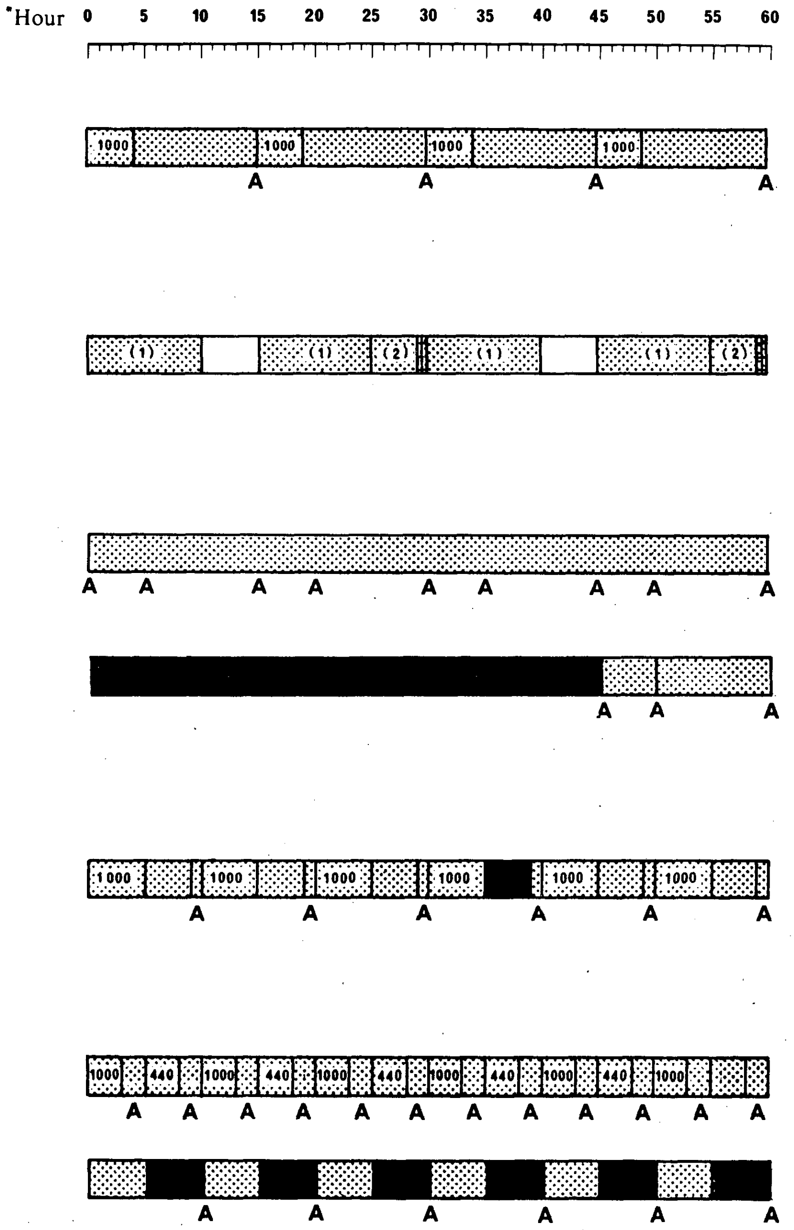


FIGURE 1 – *Daily emission schedule*



Min.

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 10 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 20 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.

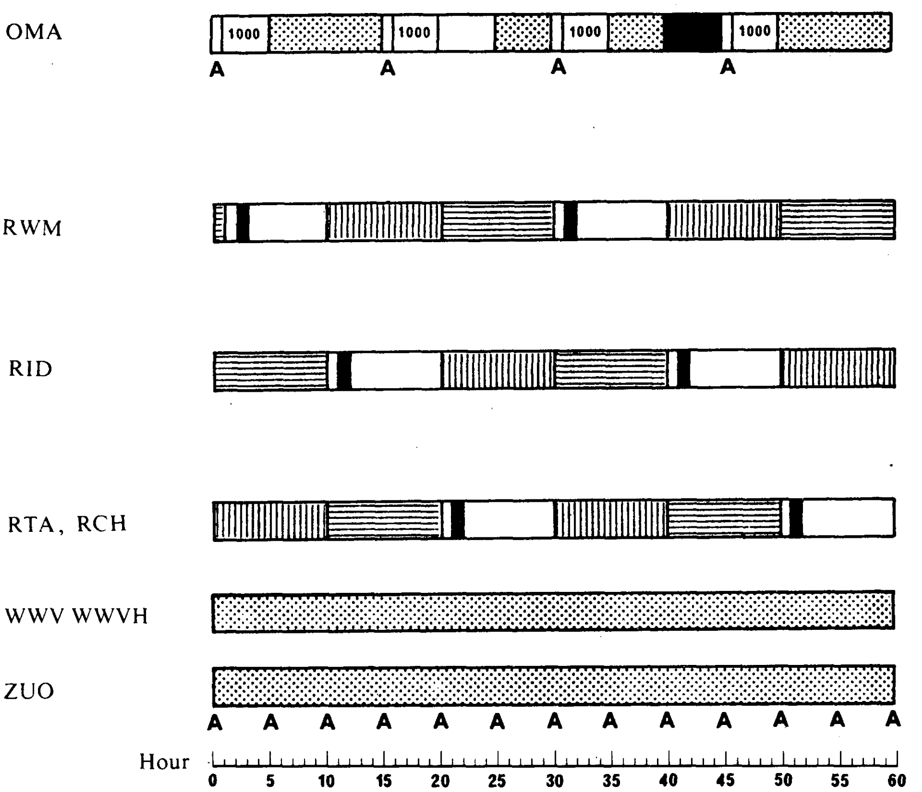
IAM — Pulse of 5 cycles of 1000 Hz tone: minute pulse of 20 cycles of 1000 Hz tone. Call sign and time (UTC) in Morse and voice identification.

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 4th, 9th, 14th, 19th, 24th, 29th, 34th, 39th, 44th, 49th, 54th and 59th minutes.

See Note.

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

Min.

FIGURE 2 – *Hourly modulation schedule*

Note. – 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.

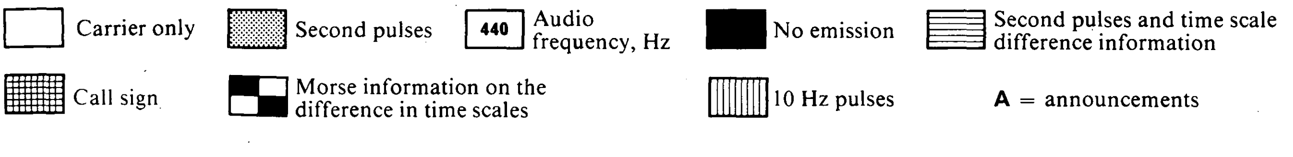


TABLE II – *Characteristics of standard-frequency and time-signal emissions in additional bands, valid as of 1 November 1985*

Station			Type of antenna(s)	Carrier power (kW)	Number of simul-taneous trans-missions	Period of operation		Standard frequencies used		Duration of emission		Uncertainty of frequency and time intervals (parts in 10^{12}) (1)	Method of DUT1 indication
Call sign	Approximate location	Latitude Longitude				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	162	1 (2)	continuous	A3E broadcast continu-ously	± 2	No DUT1 transmission
CHU (3)	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	153	nil	nil	A3E broadcast continu-ously	± 2	
DCF77 (3)	Mainflingen, F.R. of Germany	50° 01′ N 09° 00′ E	Omni-directional	20 (5)	1	7	24	77.5	1	contin-uous (6)	contin-uous (7)	± 0.5	No DUT1 transmission
	Droitwich, United Kingdom	52° 16′ N 02° 09′ W	T	400	1	7	22	200 (8) (9)	nil	nil	A3E broadcast continu-ously	± 20	
	Westerglen, United Kingdom	55° 58′ N 03° 50′ W	T	50	1	7	22	200 (8) (9)	nil	nil	A3E broadcast continu-ously	± 20	
	Burghead, United Kingdom	57° 42′ N 03° 28′ W	T	50	1	7	22	200 (8) (9)	nil	nil	A3E broadcast continu-ously	± 20	
GBR (3) (10)	Rugby, United Kingdom	52° 22′ N 01° 11′ W	Omni-directional	750 60 (5)	1	7	22 (11)	15.95 16.00	1 (12)	4 × 5 (13) per day	nil	± 2	CCIR code by double pulse
HBG (14)	Prangins, Switzerland	46° 24′ N 06° 15′ E	Omni-directional	20	1	7	24	75	1 (15)	continuous	nil	± 1	No DUT1 transmission

TABLE II *(continued)*

Station			Type of antenna(s)	Carrier power (kW)	Number of simul-taneous trans-missions	Period of operation		Standard frequencies used		Duration of emission		Uncertainty of frequency and time intervals (parts in 10^{12}) (1)	Method of DUT1 indication
Call sign	Approximate location	Latitude Longitude				Days/ week	Hours/ day	Carrier (kHz)	Modulation (Hz)	Time signal (min)	Audio-modulation (min)		
JJF-2 (3) JG2AS	Sanwa, Sashima, Ibaraki, Japan	36° 11′ N 139° 51′ E	Omni-directional	10	1	7	24 (16)	40	1 (17)	continuous (18)	nil	± 10	
MSF	Rugby, United Kingdom	52° 22′ N 01° 11′ W	Omni-directional	25 (5)	1	7	24 (19)	60	1 (20)	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	A3E broadcast continu-ously	± 2	
NAA (3) (21) (22)	Cutler, Maine, USA	44° 39′ N 67° 17′ W	Omni-directional	1000 (5)	1	7	24 (23)	24.0 (24)	nil	nil	nil	± 10	
NCA (3) (21) (22)	Aguada, Puerto Rico	18° 21′ N 67° 11′ W	Omni-directional	100 (25)	1	7	24	28.5	nil	nil	nil	± 10	
NTD (3) (21) (22)	Yosami, Japan	34° 58′ N 137° 01′ E	Omni-directional	50 (5)	1	7	24 (26)	17.4	nil	nil	nil	± 10	
NLK (3) (21) (22)	Jim Creek, Washington, USA	48° 12′ N 121° 55′ W	Omni-directional	125 (5)	1	7	24 (27)	24.8	nil	nil	nil	± 10	
NPM (3) (21) (22)	Lualualei, Hawaii, USA	21° 25′ N 158° 09′ W	Omni-directional	600 (5)	1	7	24 (28)	23.4	nil	nil	nil	± 10	
NSS (3) (21) (22)	Annapolis, Maryland, USA	38° 59′ N 76° 27′ W	Omni-directional	400 (5)	1	7	24 (29)	21.4	nil	nil	nil	± 10	

TABLE II *(continued)*

Station			Type of antenna(s)	Carrier power (kW)	Number of simul-taneous trans-missions	Period of operation		Standard frequencies used		Duration of emission		Uncertainty of frequency and time intervals (parts in 10^{12}) (1)	Method of DUT1 indication
Call sign	Approximate location	Latitude Longitude				Days/ week	Hours/ day	Carrier (kHz)	Modulation (Hz)	Time signal (min)	Audio-modulation (min)		
NWC (3) (21) (22)	North West Cape, Australia	21° 49′ S 114° 10′ E	Omni-directional	1000 (5)	1	7	24 (30)	22.3	nil	nil	nil	± 10	
OMA	Podebrady, Czechoslovak S.R.	50° 08′ N 15° 08′ E	T	5	1	7	24	50	1 (12)	23 hours per day (31)	nil	± 1000	No DUT1 transmission
RBU (3)	Moskva, USSR	55° 48′ N 38° 18′ E	Omni-directional	10	1	7	24	$66\frac{2}{3}$	1, 10	6/60 (32)	nil	± 5	CCIR code by double pulse (33)
RTZ (3)	Irkutsk, USSR	52° 26′ N 104° 02′ E	Omni-directional	10	1	7	23	50	1, 10	6/60	nil	± 5	CCIR code by double pulse (33)
RW-166	Irkutsk, USSR	52° 18′ N 104° 18′ E	Omni-directional	40	1	7	23	200		nil	A3E broadcast continu-ously	± 5	
RW-76	Novosibirsk, USSR	55° 04′ N 82° 58′ E	Omni-directional	150	1	7	22	272		nil	A3E broadcast continu-ously	± 5	
SAJ	Stockholm, Sweden	59° 15′ N 18° 06′ E	Omni-directional	0.02 (e.r.p.)	1	3 (34)	2 (35)	150 000	nil	10 (36)		± 2	
UNW3	Molodechno, USSR	54° 26′ N 26° 48′ E	Omni-directional	–	1	7	2	25.5 25.1 25.0 23.0 20.5	1, 10, 40 (37)	40 min twice per day (38)	nil	± 10	

TABLE II *(continued)*

Station			Type of antenna(s)	Carrier power (kW)	Number of simultaneous transmissions	Period of operation		Standard frequencies used		Duration of emission		Uncertainty of frequency and time intervals (parts in 10^{12}) (1)	Method of DUT1 indication
Call sign	Approximate location	Latitude Longitude				Days/ week	Hours/ day	Carrier (kHz)	Modulation (Hz)	Time signal (min)	Audio-modulation (min)		
UPD8	Arkhangelsk, USSR	64° 24′ N 41° 32′ E	Omni-directional	–	1	7	2	25.5 25.1 25.0 23.0 20.5	1, 10, 40 (37)	40 min twice per day (39)	nil	± 10	
UQC3	Khabarovsk, USSR	48° 30′ N 134° 51′ E	Omni-directional	300	1	7	2	25.0 25.1 25.5 23.0 20.5	1, 10, 40 (37)	40 min 3 times per day (40)	nil	± 10	
USB2	Frunze, USSR	43° 04′ N 73° 39′ E	Omni-directional	–	1	7	3	25.5 25.1 25.0 23.0 20.5	1, 10, 40 (37)	40 min 3 times per day (41)	nil	± 10	
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 (37)	40 min 3 times per day (42)	nil	± 10	
VNG (3)	Lyndhurst, Victoria, Australia	38° 03′ S 145° 16′ E	Omni-directional	10	2	7	24 (43)	4500 7500 12 000	1, 1000 (44)	continuous	nil	± 100	CCIR code by 45 cycles of 900 Hz immediately following the normal second markers
WWVB (3)	Fort Collins, Colorado, USA	40° 40′ N 105° 03′ W	Top-loaded vertical	13 (5)	1	7	24	60	1 (45)	continuous	nil	± 10	No CCIR code

TABLE II *(continued)*

Station			Type of antenna(s)	Carrier power (kW)	Number of simul-taneous trans-missions	Period of operation		Standard frequencies used		Duration of emission		Uncertainty of frequency and time intervals (parts in 10^{12}) (1)	Method of DUT1 indication
Call sign	Approximate location	Latitude Longitude				Days/ week	Hours/ day	Carrier (kHz)	Modulation (Hz)	Time signal (min)	Audio-modulation (min)		
Y3S	Nauen, German Democratic Republic	52° 39′ N 12° 55′ E	Omni-directional	5	1	7	24	4525	nil	continuous (46)	continuous	(8)	CCIR code by split pulses
ZUO (47)	Olifantsfon-tein, Republic of South Africa	24° 58′ S 28° 14′ E	Omni-directional	0.08	1	7	24	100 000	1	continuous	nil	± 10	CCIR code by lengthening
	Motala, Sweden	58° 26′ N 14° 59′ E	Omni-directional	300	1	7	17	191 (9)	nil	21 s once per day (48)	A3E broadcast continu-ously	± 50 (8)	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 6840	(49)	10	(50)	± 100	CCIR code by double pulse

Notes to Table II:

(1) 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.

(2) 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 the current day is a public holiday (Christmas, 14 July, etc.).

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

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

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

(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 0.2 s 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) No coherence between carrier frequency and time signals.

(9) The carrier frequency of these stations will be reduced by 2 kHz on 1 February 1988 in accordance with Resolution No. 500 of the World Administrative Radio Conference, Geneva, 1979.

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

(11) Maintenance period from 1000 to 1400 h UTC each Tuesday.

(12) A1A telegraphy signals.

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

(14) Coordinated time signals.

(15) 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.

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

(17) 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.

(18) In absence of telegraphic traffic.

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

(20) 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.

(21) MSK (minimum shift keying) in use: a phase-stable carrier can be recovered after suitable multiplication and mixing in the receiver.

(22) 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.

(23) From 1200 to 2000 h UTC each Sunday while NSS is off the air (until 15 July).

(24) As of 23 January 1984, until further notice.

(25) Became operational on 14 August 1984, 74 kW.

(26) 2300 to 0900 h UTC just first Thursday-Friday, 2300 to 0700 h UTC all other Thursday-Fridays. Half power 2200 to 0200 h UTC each Monday and Friday.

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

Notes to Table II (continued):

([28]) 2.5 MHz: 0000-1000 h UTC; 5 MHz: 0900-0100 h UTC; 10 MHz: continuous; 15 MHz: 0100-0900 h UTC.

([29]) Off the air until 2100 h UT on 15 July, except for fourteen hours each Sunday to cover the period when NAA is off the air.

([30]) From 0000 to 0800 h, usually each Monday.

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

([32]) Possible experimental transmission offering continuous time signals.

([33]) 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 0.02 s. 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 s × 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 s × q.

([34]) Each Monday, Wednesday and Friday.

([35]) From 0930 to 1130 h UTC. When Summer Time, add one hour to the instants given.

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

([37]) 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.

([38]) From 0736 to 1817 h and 1936 to 2017 h UTC from 1 October to 31 March.
From 0736 to 1817 h and 2036 to 2117 h UTC from 1 April to 30 September.

([39]) From 0836 to 0917 h and 1136 to 1217 h UTC.

([40]) From 0036 to 0117 h, 0636 to 0717 h and 1736 to 1817 h UTC from 1 October to 31 March.
From 0136 to 0217 h, 0536 to 0617 h and 1736 to 1813 h UTC from 1 April to 30 September.

([41]) From 0436 to 0517 h, 0936 to 1017 h and 2136 to 2217 h UTC from 1 October to 31 March.
From 0436 to 0517 h, 1036 to 1117 h and 2236 to 2317 h UTC from 1 April to 30 September.

([42]) From 0536 to 0617 h, 1336 to 1417 h and 1836 to 1917 h UTC from 1 October to 31 March.
From 0636 to 0717 h, 1336 to 1417 h and 1837 to 1917 h UTC from 1 April to 30 September.

([43]) 4500 kHz, from 0945 to 2130 h UTC, 12 000 kHz, from 2145 to 0930 h UTC, 7500 kHz, continuous service, with a technical interruption from 2230 to 2245 h UTC.

([44]) 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.

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

([46]) 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.

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

([48]) A3E time signals of 0.1 s duration between 11 h 58 min 55 s and 11 h 59 min 16 s UTC. The minute marker is of 0.5 s duration. When Summer Time, add one hour to the instants given.

([49]) 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.

([50]) Minutes 00 to 10, 12 008 kHz, A2A.
15 to 25, 12 008 kHz, J3E.
30 to 40, 6 840 kHz, A2A.
45 to 55, 6 840 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 November 1983*

Station			Type of antenna(s)	Carrier power (kW)	Number of simul-taneous trans-missions	Period of operation		Standard frequencies used		Duration of emission		Uncertainty of frequency and time intervals (parts in 10^{12}) (1)
Call sign	Approximate location	Latitude Longitude				Days/ week	Hours/ day	Carrier (kHz)	Pulse repetition (μs)	Time signal	Audio-modulation	
Loran-C (2) (7980-Z, 9960-Y)	Carolina Beach, NC, USA	34° 03.8′ N 77° 54.8′ W	Omni-directional	550 (3)	1	7	24	100	99 600 79 800 (4)	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	79 800 (4)	continuous (5)	nil	± 1
Loran-C (2) (5930-Y, 7930-W)	Cape Race, Newfoundland	46° 46.5′ N 53° 10.5′ W	Omni-directional	1500 (3)	1	7	24	100	79 300 59 300 (4)	continuous (5)	nil	± 1
Loran-C (8970-Z)	Gordon Lake, Ontario, Canada	46° 24.5′ N 83° 52.0′ W	Omni-directional	1000 (3)	1	7	24	100	89 700	continuous (5)	nil	± 1
Loran-C (2) (5930-X, 9960-X)	Nantucket Island, USA	41° 15.2′ N 69° 58.6′ W	Omni-directional	275 (3)	1	7	24	100	59 300 (4) 99 600	continuous (5)	nil	± 1
Loran-C (2) (8970-M, 9960-Z)	Dana, Indiana, USA	39° 51.1′ N 87° 29.2′ W	Omni-directional	400 (3)	1	7	24	100	89 700 (4) 99 600	continuous (5)	nil	± 1
Loran-C (2) (7930-X, 9980-W)	Angissog, Greenland	59° 59.3′ N 45° 10.5′ W	Omni-directional	760 (3)	1	7	24	100	79 300 (4)	continuous (5)	nil	± 1

TABLE III *(continued)*

Station			Type of antenna(s)	Carrier power (kW)	Number of simultaneous transmissions	Period of operation		Standard frequencies used		Duration of emission		Uncertainty of frequency and time intervals (parts in 10^{12}) (1)
Call sign	Approximate location	Latitude Longitude				Days/ week	Hours/ day	Carrier (kHz)	Pulse repetition (μs)	Time signal	Audio-modulation	
Loran-C (2) (7970-M, 9980-X)	Ejde, Faeroe Is.	62° 18.0′ N 7° 04.4′ W	Omni-directional	325 (3)	1	7	24	100	79 300 79 700 (4)	continuous (5)	nil	± 1
Loran-C (7970-W)	Sylt, F.R. of Germany	54° 48.5′ N 8° 17.6′ E	Omni-directional	325 (3)	1	7	24	100	79 700 (4)	continuous (5)	nil	± 1
Loran-C (7970-X)	Boe, Norway	68° 38.1′ N 14° 27.8′ E	Omni-directional	165 (3)	1	7	24	100	79 700 (4)	continuous (5)	nil	± 1
Loran-C (2) (7970-Y, 7930-W, 9980-M)	Sandur, Iceland	64° 54.4′ N 23° 55.4′ W	Omni-directional	1500 (3)	1	7	24	100	79 300 (4)	continuous (5)	nil	± 1
Loran-C (7970-Z)	Jan Mayen, Norway	70° 54.9′ N 8° 44.0′ W	Omni-directional	165 (3)	1	7	24	100	79 700 (4)	continuous (5)	nil	± 1
Loran-C (5930-Z, 7930-M)	Fox Harbour, Canada	52° 22.6′ N 55° 42.5′ W	Omni-directional	800 (3)	1	7	24	100	59 300	continuous (5)	nil	± 1
Loran-C (7990-M)	Sellia Marina, Italy	38° 52.3′ N 16° 43.1′ E	Omni-directional	165 (3)	1	7	24	100	79 900 (4)	continuous (5)	nil	± 1
Loran-C (7990-X)	Lampedusa, Italy	35° 31.3′ N 12° 31.5′ E	Omni-directional	325 (3)	1	7	24	100	79 900 (4)	continuous (5)	nil	± 1
Loran-C (7990-Y)	Kargabarun, Turkey	40° 58.3′ N 27° 52.0′ E	Omni-directional	165 (3)	1	7	24	100	79 900 (4)	continuous (5)	nil	± 1

TABLE III *(continued)*

Station			Type of antenna(s)	Carrier power (kW)	Number of simul-taneous trans-missions	Period of operation		Standard frequencies used		Duration of emission		Uncertainty of frequency and time intervals (parts in 10^{12}) (1)
Call sign	Approximate location	Latitude Longitude				Days/ week	Hours/ day	Carrier (kHz)	Pulse repetition (µs)	Time signal	Audio-modulation	
Loran-C (7990-Z)	Estartit, Spain	42° 03.6′ N 3° 12.3′ E	Omni-directional	165 (3)	1	7	24	100	79 900 (4)	continuous (5)	nil	± 1
Loran-C (4990-M)	Johnston Is.	16° 44.7′ N 169° 30.5′ W	Omni-directional	275 (3)	1	7	24	100	49 900 (4)	continuous (5)	nil	± 1
Loran-C (4990-X)	Upolu Point, Hawaii, USA	20° 14.8′ N 155° 53.1′ W	Omni-directional	275 (3)	1	7	24	100	49 900 (4)	continuous (5)	nil	± 1
Loran-C (4990-Y)	Kuré, Hawaii, USA	28° 23.7′ N 178° 17.5′ W	Omni-directional	275 (3)	1	7	24	100	49 900 (4)	continuous (5)	nil	± 1
Loran-C (9970-M)	Iwo Jima, Japan	24° 48.1′ N 141° 19.5′ E	Omni-directional	1800 (3)	1	7	24	100	99 700 (4)	continuous (5)	nil	± 1
Loran-C (9970-W)	Marcus Is., Japan	24° 17.1′ N 153° 58.9′ E	Omni-directional	1800 (3)	1	7	24	100	99 700 (4)	continuous (5)	nil	± 1
Loran-C (9970-X)	Hokkaido, Japan	42° 44.6′ N 143° 43.2′ E	Omni-directional	1000 (3)	1	7	24	100	99 700 (4)	continuous (5)	nil	± 1
Loran-C (9970-Y)	Gesashi, Okinawa, Japan	26° 36.4′ N 128° 08.9′ E	Omni-directional	1000 (3)	1	7	24	100	99 700 (4)	continuous (5)	nil	± 1
Loran-C (9970-Z)	Yap, Caroline Is.	9° 32.8′ N 138° 09.9′ E	Omni-directional	1000 (3)	1	7	24	100	99 700 (4)	continuous (5)	nil	± 1

TABLE III *(continued)*

Station			Type of antenna(s)	Carrier power (kW)	Number of simultaneous transmissions	Period of operation		Standard frequencies used		Duration of emission		Uncertainty of frequency and time intervals (parts in 10^{12}) (1)
Call sign	Approximate location	Latitude Longitude				Days/ week	Hours/ day	Carrier (kHz)	Pulse repetition (μs)	Time signal	Audio-modulation	
Loran-C (9990-M)	St. Paul, Pribiloff Is., Alaska	59° 09.2′ N 170° 15.0′ W	Omni-directional	275 (3)	1	7	24	100	99 900 (4)	continuous (5)	nil	± 1
Loran-C (9990-X)	Attu, Alaska	52° 49.7′ N 173° 10.8′ E	Omni-directional	275 (3)	1	7	24	100	99 900 (4)	continuous (5)	nil	± 1
Loran-C (2) (9960-M, 8970-X)	Seneca, NY, USA	42° 42.8′ N 76° 49.6′ W	Omni-directional	800 (3)	1	7	24	100	99 600 (4) 89 700 (4)	continuous (5)	nil	± 1
Loran-C (2) (9960-W, 5930-M)	Caribou, ME, USA	46° 48.5′ N 67° 55.6′ W	Omni-directional	350 (3)	1	7	24	100	59 300 (4) 99 600 (4)	continuous (5)	nil	± 1
Loran-C (2) (8970-W, 7980-M)	Malone, FL, USA	30° 59.6′ N 85° 10.2′ W	Omni-directional	800 (3)	1	7	24	100	89 700 (4) 79 800 (4)	continuous (5)	nil	± 1
Loran-C (8970-Y)	Baudette, MN, USA	48° 36.8′ N 94° 33.3′ W	Omni-directional	800 (3)	1	7	24	100	89 700 (4)	continuous (5)	nil	± 1
Loran-C (7980-W)	Grangeville, LA, USA	30° 43.6′ N 90° 49.7′ W	Omni-directional	800 (3)	1	7	24	100	79 800 (4)	continuous (5)	nil	± 1
Loran-C (7980-X)	Raymondville, TX, USA	26° 31.9′ N 97° 50.0′ W	Omni-directional	400 (3)	1	7	24	100	79 800 (4)	continuous (5)	nil	± 1

TABLE III *(continued)*

Station			Type of antenna(s)	Carrier power (kW)	Number of simul-taneous trans-missions	Period of operation		Standard frequencies used		Duration of emission		Uncertainty of frequency and time intervals (parts in 10^{12}) (1)
Call sign	Approximate location	Latitude Longitude				Days/ week	Hours/ day	Carrier (kHz)	Pulse repetition (µs)	Time signal	Audio-modulation	
Loran-C (9990-Y)	Pt. Clarence, Alaska	65° 14.7′ N 166° 53.2′ W	Omni-directional	1000 (3)	1	7	24	100	99 900 (4)	continuous (5)	nil	± 1
Loran-C (2) (9990-Z, 7960-X)	Narrow Cape, Alaska	57° 26.3′ N 152° 22.2′ W	Omni-directional	400 (3)	1	7	24	100	99 900 79 600 (4)	continuous (5)	nil	± 1
Loran-C (7960-M)	Tok, Alaska	63° 19.7′ N 142° 48.5′ W	Omni-directional	540 (3)	1	7	24	100	79 600 (4)	continuous (5)	nil	± 1
Loran-C (2) (7960-Y, 5990-X)	Shoal Cove, Alaska	55° 26.4′ N 131° 15.3′ W	Omni-directional	540 (3)	1	7	24	100	79 600 59 900 (4)	continuous (5)	nil	± 1
Loran-C (5990-M)	Williams Lake, BC, Canada	51° 58.0′ N 122° 22.0′ W	Omni-directional	400 (3)	1	7	24	100	59 900 (4)	continuous (5)	nil	± 1
Loran-C (2) (5990-Y, 9940-W)	George, Washington, USA	47° 03.8′ N 119° 44.7′ W	Omni-directional	1600 (3)	1	7	24	100	59 900 99 400 (4)	continuous (5)	nil	± 1
Loran-C (9940-M)	Fallon, Nevada, USA	39° 33.1′ N 118° 49.9′ W	Omni-directional	400 (3)	1	7	24	100	99 400 (4)	continuous (5)	nil	± 1
Loran-C (9940-X)	Middletown, California, USA	38° 46.9′ N 122° 29.7′ W	Omni-directional	400 (3)	1	7	24	100	99 400 (4)	continuous (5)	nil	± 1

TABLE III *(continued)*

Station			Type of antenna(s)	Carrier power (kW)	Number of simul-taneous trans-missions	Period of operation		Standard frequencies used		Duration of emission		Uncertainty of frequency and time intervals (parts in 10^{12}) (1)
Call sign	Approximate location	Latitude Longitude				Days/ week	Hours/ day	Carrier (kHz)	Pulse repetition (μs)	Time signal	Audio-modulation	
Loran-C (9940-Y)	Searchlight, Nevada, USA	35° 19.3′ N 114° 48.3′ W	Omni-directional	540 (3)	1	7	24	100	99 400 (4)	continuous (5)	nil	± 1
Loran-C (5990-Z)	Port Hardy, BC, Canada	50° 36.5′ N 127° 21.5′ W	Omni-directional	400 (3)	1	7	24	100	59 900 (4)	continuous	nil	± 1
RNS-E(A)	Briansk, USSR	53° 13′ N 34° 24′ E	Omni-directional	800 (3)	1	7 (6)	10 (7)	100	80 000 (8)	continuous	nil	± 5
RNS-E(D)	Syzran, USSR	53° 11′ N 49° 46′ E	Omni-directional	800 (3)	1	6 (6)	10 (7)	100	80 000 (8)	(9)	nil	± 5
RNS-W(A)	Aleksandrovsk, Sakhalinsky	50° 56′ N 142° 38′ E	Omni-directional	400 (3)	1	7 (1)	12 (10)	100	50 000 (8)	continuous	nil	± 5
Omega Ω/N	Aldra, Norway	66° 25′ N 13° 08′ E	Omni-directional	10 (11)	1	7	24	11.05-F 10.2-A (12) 11⅓-C 13.6-B	nil	(12)	nil	± 5
Omega Ω/ND	Lamoure, North Dakota, USA	46° 22′ N 98° 20′ W	Omni-directional	10 (11)	1	7	24	11.05-A 10.2-D (12) 11⅓-F 13.6-E	nil	(12)	nil	± 1

TABLE III *(continued)*

Station			Type of antenna(s)	Carrier power (kW)	Number of simultaneous transmissions	Period of operation		Standard frequencies used		Duration of emission		Uncertainty of frequency and time intervals (parts in 10^{12}) ([1])
Call sign	Approximate location	Latitude Longitude				Days/ week	Hours/ day	Carrier (kHz)	Pulse repetition (μs)	Time signal	Audio-modulation	
Omega Ω/H	Haiku, Hawaii, USA	21° 24′ N 157° 50′ W	Omni-directional	10 ([11])	1	7	24	11.05-H 10.2-C ([12]) 11⅓-E 13.6-D	nil	([12])	nil	± 1
Omega Ω/J	Tsushima Is., Japan	34° 37′ N 129° 27′ E	Omni-directional	10 ([11])	1	7	24	11.05-E 10.2-H ([12]) 11⅓-B 13.6-A	nil	([12])	nil	± 1
Omega Ω/L	Monrovia, Liberia	06° 18′ N 10° 40′ W	Omni-directional	10 ([11])	1	7	24	11.05-G 10.2-B ([12]) 11⅓-D 13.6-C	nil	([12])	nil	± 1
Omega Ω/LR	La Reunion	20° 58′ S 55° 17′ E	Omni-directional	10 ([11])	1	7	24	11.05-B 10.2-E ([12]) 11⅓-G 13.6-F	nil	([12])	nil	± 1
Omega Ω/A	Golfo Nuevo, Argentina	43° 03′ S 65° 11′ W	Omni-directional	10 ([11])	1	7	24	11.05-C 10.2-F ([12]) 11⅓-H 13.6-G	nil	([12])	nil	± 1

Notes to Table III:

(1) No transmission on the 20th or 21st of each month.

(2) Dual-rated stations.

(3) Peak radiated power.

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

(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) No transmission on the 10th and 11th of each month.

(7) From 0400 to 1000 h and 1400 to 1800 h UTC.

(8) 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.

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

(10) From 2300 to 2400 h and 0000 to 1100 h UTC.

(11) Figures give the estimated radiated power.

(12) See Table IV.

TABLE IV – *OMEGA signal format*

Time (s)	0–1	1–2	2–3	3–4	4–5	5–6	6–7	7–8	8–9	9–10

Segment	A	B	C	D	E	F	G	H
Duration	0.9	1.0	1.1	1.2	1.1	0.9	1.2	1.0
kHz:								
10.2	Norway	Liberia	Hawaii	North Dakota	La Reunion	Argentina	Australia	Japan
$11^1/_3$	Australia	Japan	Norway	Liberia	Hawaii	North Dakota	La Reunion	Argentina
13.6	Japan	Norway	Liberia	Hawaii	North Dakota	La Reunion	Argentina	Australia
11.05	North Dakota	La Reunion	Argentina	Australia	Japan	Norway	Liberia	Hawaii

Note 1. – Segment A does not begin at 0.0 s UTC. Time of segments changes with leap-seconds. Segment A begins at second 47.0 in January 1986.

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 11⅓ kHz transmitted by all the stations, the stations transmit "unique frequencies". These stations and their frequencies/segments are given in Table V.

* 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	(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.

ANNEX I

AUTHORITIES RESPONSIBLE FOR STATIONS APPEARING IN TABLES I AND II

Station	*Authority*
Allouis	Centre National d'Études des Télécommunications Département FRE 196, rue de Paris 92220 Bagneux, France
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.
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
GBR	National Physical Laboratory Electrical Science Division Teddington, Middlesex TW11 OLW United Kingdom
HBG	Service horaire HBG Observatoire cantonal CH-2000 – Neuchâtel, Switzerland
HLA	Korea Standards Research Institute P.O. Box 3 Taejon, Ch'ungnam 300-31 Republic of Korea
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	Standards and Measurements Division The Radio Research Laboratories Ministry of Posts and Telecommunications Nukui-Kitamachi, 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'URSS Moscou, USSR 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

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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.

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 $\pm$ 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 271-7

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

(Question 3/7)

(1963-1966-1970-1971-1974-1978-1982-1986)

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 $\pm$ 50 μs at medium distances (100-1000 km). The phase of the carrier is typically stable to better than $\pm$ 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.

In addition to the amplitude modulation with second markers, the carrier frequency of DCF77 has been, since 1983, phase-modulated with pseudo-random noise to achieve greater precision and improved protection against disturbances in the transmission of time signals. The pseudo-random phase noise corresponds to a binary random sequence which is phase synchronous with respect to the carrier and to the second markers. First results [Hetzel, 1984] indicate that, at a distance of 300 km from the transmitter, the time signals obtained by correlation are less disturbed than those obtained from the slope of the demodulated second markers. In summer, the dispersion of the zero crossings is, during the day, less than half the period of the carrier (<6.5 μs).

An investigation [Becker *et al.*, 1973b] has shown 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].

Studies on a new form of time-signal modulation have been carried out in the USSR to improve the synchronization reliability of generators using the carrier frequency of station RBU (66 2/3 kHz) as a reference.

Compared with previous signals, the duration of the pause has been reduced to 5 ms and the frequency of the pause repetition increased to 10 Hz. Marker and coding pulses with a duration of 80 ms are used for the identification of the second and minute markers. The pulses are obtained by narrow-band phase modulation with an index of 698 of two sub-carriers off-set by 100 Hz and 312.5 Hz. This has increased the protection band [Cherenkov, 1984a] to 50 Hz, which now makes it possible to synchronize signal generators with an equivalent passband of the automatic phase control circuit of up to 20 Hz. The phase jitter of the output signal of the synchronized generator (or the signal at a receiver output with the same passband), due to the phase modulation of the carrier wave, does not exceed 20 ns.

The use of phase modulation made it possible to use the full transmitter power and yielded higher power levels for both marker and information bits, equal to 0.735 and 0.215 respectively, relative to the maximum power of the unmodulated emission [Cherenkov, 1984b].

The generation of the information and marker bits on the sub-carrier frequencies, increases the capacity of the information that can be transmitted by frequency or phase modulation of the sub-carrier during the other 80 ms intervals, which are not currently used. The increased repetition frequency (10 Hz) of the time markers makes for more accurate determination of their time position by averaging over a larger number of results for the same measurement interval.

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 on $\sigma_{\Delta t}(\tau)$, 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 of 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 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 are a useful source of frequency and precise time and should also enhance the status of VLF techniques for obtaining these items. A total of eight stations provides continuous and redundant world-wide coverage. 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 s. The four navigational frequencies are 10.2, 11.05, 11⅓ and 13.6 kHz. Each station also radiates one additional frequency in the range 11.8 to 13.1 kHz 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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REPORT 363-6

METHODS FOR THE TRANSFER AND DISSEMINATION OF TIME AND STANDARD FREQUENCIES

(Study Programme 3C/7)

(1966-1970-1974-1978-1982-1986)

1. Introduction

In time-transfer and standard-frequency dissemination, new methods have come into use which are particularly suited for the comparison of atomic clocks within an international coordinated timing system. These applications, however, go far beyond the more traditional use of a standard-frequency and time-signal service (SF and TSS) which existed when atomic clocks were first introduced into widespread use. Compared to a capability for millisecond timing which is typically required by the vast majority of the SF and TSS users, the utilization of atomic standards requires measurement uncertainties which should be as small as possible. The best performance obtained so far in long distance comparison has been a measurement uncertainty approaching 1 ns.

This Report reviews the general principles involved and gives an overview of the various characteristics and experience gained with the experimental and operational use of these methods.

2. Background

2.1 *Requirements for operational coordinated timing*

In contrast to the need for immediate access to a reliable source of time, which is typically required by the large majority of users of an SF and TSS, the measurements needed for international coordinated timing require a very precise means of time transfer which is only occasionally used. Instrumental cost is of lesser concern as precision or repeatability of measurements is the primary goal. For such reasons, many methods have been employed even though they could not be used in operational systems in the conventional sense. As examples, one may cite the global positioning system (GPS) which was used for time transfer long before it became accepted, as an operational navigation system. Another example would be the use of very long baseline interferometry (VLBI) for time comparisons or the "common view" technique which can be used with any source of timed or untimed signals.

2.2 *Correction for relativity effects for highest precision time transfer*

Report 439 discusses the principles and gives formulae for relativistic corrections which have to be applied in all cases where the accuracy required is of the order of 100 ns or better.

2.3 *Bandwidth and signal-to-noise ratio in high-precision time transfer*

Low uncertainty mesurements of time of arrival require a commensurately large bandwidth. This is due to two reasons: the rise time must be minimized to reduce trigger uncertainty and secondly, the variations of group delay through the circuits must be minimized. These changes could represent a small percentage of the group delay itself. Therefore, pre-detection bandwidth should be as large as is practicable. The signal-to-noise ratio available only dictates the integration time (post-detection bandwidth) necessary to make a measurement with a given uncertainty. In practice, this has led to the increased importance of spread-spectrum techniques for timed systems. A distinction must also be made between the bandwidth required for a given information flow and the effective bandwidth of the signal used. In the case of the GPS, the effective bandwidth of the C/A code is 1 MHz, while the actual information transfer (the navigation message) takes place at the modest rate of 50 Bd. However, the timing itself is done by using the fast transitions of the spread-spectrum modulation and therefore benefits from the full available bandwidth of the code. For Loran-C, which is an LF navigation system widely used for timing, the effective bandwidth of the signal is 20 kHz (the signal is pulsed) and there is no transmission of information. In this case, the uncertainty of timing is a few tenths of a microsecond (1% of 50 μs is 0.5 μs, again demonstrating the rule of thumb that uncertainty is limited to about 1% of the reciprocal of the effective bandwidth). For a general discussion on spread-spectrum techniques see [Dixon, 1976]. Added advantages of the use of spread-spectrum techniques are a substantial reduction in the susceptibility to interference for reception in urban areas (television harmonics can be a serious problem) and a reduced variability of circuit path delay due to changes in the bandwidth occupancy of the signal. This latter effect is a major source of error in normal HF standard frequency and time signal service reception. On the other hand, the large bandwidth can also create problems if dispersion or multipath is present in the channel.

2.4 *One-way versus two-way time transfer*

The one-way method, i.e. reception only, can be used with high precision if the path delay can be either assumed to be fixed (in which case it needs to be measured only once), or if the delay can be determined in some other way. This explains the intrinsic feasibility of using electronic navigation systems for timing because such systems have been designed to provide position information i.e. path delay, as an essential feature. In these systems, the user does not have to transmit which is an additional burden for two-way systems. On the other hand, by a near-simultaneous two-way exchange of signals, the path delay can easily be determined, assuming reciprocity. This assumption, however, has to be tested before a two-way method of time transfer can be used with confidence. In principle, the two-way method offers the lowest uncertainty.

2.5 *Effects of the choice of frequency (VLF – optical frequency)*

While the lower frequencies up to, and including, HF have been the backbone of time transfers in the past, all very high-precision methods require that the influence of the ionosphere be kept as small as possible which is the reason why the bands from VHF and upwards are increasingly used. However, with increasing frequency and the consequent decreasing influence of the ionosphere, tropospheric effects soon become an important factor. Water vapour, in particular, turns out to be more of a problem than expected because of rapid and irregular variations in the line-of-sight water vapour content as measured by various means. This constitutes a powerful argument in favour of optical frequencies (lasers) for extremely high-precision time transfer. (For details, see also Report 271.)

2.6 *Satellite links versus terrestrial microwave links*

The great advantage of satellite links is the large available bandwidth and line-of-sight connections at frequencies where the ionospheric influences can be minimized. The disadvantage is that the path delay is very large in comparison to terrestrial microwave links and must be continuously determined. Optical fibre link technology can be expected to replace microwave links and to find extensive use during the present decade. It remains to be seen to what extent highest-precision timing can be obtained via long distance fibre link cables. The state-of-the-art in highest-precision time transfer at this time is entirely dependent on satellite technology using communications and navigation satellite systems.

2.7 *Remote computer controlled time measurements using common view and multiple timing sources*

The low price of mini- and microcomputers has introduced yet another dimension into long distance time intercomparison and measurement techniques. Remote and completely automated time stations have been introduced which perform regular measurements of common view signals, or of all timed signals available at the site. A central computer collects the data, filters the measurements and correlates them with measurements obtained elsewhere. The result is then sent back to the station for local print-out and use. Several such systems have been reported by the USNO [Wheeler, 1983] and by NBS [Allan and Weiss, 1980; Stein *et al.*, 1983]. One NBS system utilized an NBS-design GPS receiver while another is based on the reception of either Loran-C or WWVB broadcasts. The USNO system used only high-grade commercial equipment such as automatic Loran-C receivers or commercial GPS time transfer units. Such systems can be tailored to the particular needs of the remote site [Wheeler, 1983]. In cases where a GPS receiver is installed at the remote site, uncertainties of the order of 10 ns and precision of a few nanoseconds have been reported [Allan *et al.*, 1985].

3. **Overview of utilized time and frequency transfer methods**

3.1 *Comparison using signals in bands 4 to 7 and via portable clocks*

Methods using bands 4 to 7 signals and portable clocks, have been in routine use for over twenty years but must now be considered as declining in importance with the following exceptions:

- VLF: in remote areas, frequency-stabilized transmissions from the Omega navigation network and also from certain high-power communications stations can serve as inexpensive phase references. They are actually used for air navigation in small aircraft. The timing capability has been documented by Guinot [1968 and 1969] (see also Report 271);
- frequency-stabilized LF transmissions, such as WWVB, DCF 77, HBG, MSF, and others, are still used by a large number of time-code receivers which are automatically kept synchronized with millisecond accuracies. Phase tracking has largely ceased due to problems with cycle ambiguity and interference between some of these stations;
- Loran-C has permitted the introduction of completely automatic receivers which eliminate the cycle identification problem. Loran-C is still widely available and remains the best routine comparison method for purposes where uncertainties of a few tenths of a microsecond due to, among other effects, seasonal variations [De Jong, 1984] are acceptable and where ground-wave coverage exists (most of the Northern Hemisphere); see [Potts and Wieder, 1972] and Report 271;
- the HF, SF and TS service remains the main source of time for ships, radio amateurs and other users who appreciate the very low cost and who are satisfied with uncertainties of a few milliseconds [Ogawa, 1958]; see also [Iijima *et al.*, 1978];
- portable clocks which have demonstrated a capability of tens of nanoseconds in round-the-world experiments [Hafele and Keating, 1972] are likely to be used less in the future due to the advent of high-precision satellite methods such as GPS or commercial wide-band channel satellite links.

3.2 *Television*

Television is a timed electronic system and as such can be used for time comparisons. Due to the existence of different systems such as the NTSC, PAL, SECAM, etc. and to the difficulties of establishing the exact path delay for each intercomparison, particularly over large distances, the method has found its greatest application in the simultaneous reception of a transmitter within its local coverage area. A novel and more promising method is the reception of satellite television programmes if the satellite position can be obtained elsewhere, with sufficient precision e.g. from the operating authorities. Extended tests have been conducted between stations in Austria, the Netherlands, the United Kingdom and the Federal Republic of Germany [De Jong, 1984]. In the United States of America, the widespread use of frame synchronizers has effectively terminated the long distance use of television for timing because these devices store a complete frame and release it for transmission with time reference to the local clock. For more detailed information within its local coverage area, see Reports 1016 and 897.

3.3 *Intercontinental clock synchronization by VLBI*

The fundamentals of VLBI have been described by Klemperer [1972], who gives 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 experimental VLBI programmes. Accuracies in frequency comparisons of 10^{-13} to 10^{-14} and in clock synchronization of the order of 1 ns are apparently possible.

The 10-100 MHz bandwidths required for clock synchronization to a resolution of 1-10 ns are achievable by the bandwidth synthesis techniques described by Hinteregger *et al.* [1972] and Rogers [1970].

In principle, hydrogen maser stability is not required for clock synchronization; in fact, prototype system demonstrations used rubidium oscillators. A series of three experiments have been conducted between the NASA stations at Madrid (Spain) and Goldstone (California) [Hurd, 1972]. Although measurements demonstrated a resolution of 50-500 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.

3.4 *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 satellite experiments.

More complete descriptions, comparisons and references pertaining to these and other satellite techniques or systems may be found in Report 518.

3.5 *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 Physikalisch-Technische Bundesanstalt (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.*, 1972].

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 USSR 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].

TABLE I – *Comparison of time transfer methods*
(Status as of 1985)

System/Method	Coverage	Equipment cost (in thousands of US $)	Performance	Notes
Omega (VLF)	World-wide	5-25	2 μs/jour	Frequency reference
Loran-C (LF)	Regional, Northern Hemisphere	3 1 10	1 μs 100 ns-2 μs (¹) 100 ns (¹)	Automatic, time code Manual Automatic
HF Time signal	World-wide	0.2	1 ms	Operator training
GOES	America	4	50 μs	Automatic, code
TRANSIT	World-wide	14	10-25 μs	Automatic, code
GPS	World-wide	25	10 ns	Automatic, code
Communication satellite	Point to point	100	1 ns	Two-way, transmit/receive

(¹) Excluding sky wave and overland paths.

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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 518-4

TIME/FREQUENCY DISSEMINATION AND COORDINATION VIA SATELLITE

(Question 2/7)

(1971-1974-1978-1982-1986)

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 technique 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 inmany 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;
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.

TABLE I – *Selected comparative information for satellite alternatives*

Satellite alternative	Coverage	Accuracy capability	User cost estimates (US dollars 1981)	Feasible for on-site use	Satellite system – operational or experimental
1. Communication satellites	Regional or global (networks)	< 10 ns	\$ 25 000-\$ 100 000 for on-site terminal + transponder time	Depends on specific satellite system and location	Operational
2. GPS: Normal mode	Global; continuous	Possibly ≈ 100 ns if not degraded	Present timing receiver > \$ 25 000. Should decrease with development	Yes	6 satellites now in orbit. Full implementation sometime after 1987
Common-view mode	Intercontinental	Depends on specific geometry of link. Possibly ≈ 10 ns if not degraded	> \$ 25 000	Yes	See above
3. LASSO	Europe, Africa. Depends on satellite location	< 1 ns projected	Very expensive: full laser stations ≈ \$ 1 million. Usually requires auxiliary timing links to laser sites	Not in general. Requires laser station	Possibly 1986 (METEOSAT-P2). Could develop operational add-on package later with internal resolution of < 10 ps
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: < 1 ns Accuracy: limited by delay uncertainties	Expensive until further development	Probably	No present plans for operational or experimental use
6. Simultaneous reception of ranging signals	Regional	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	Satellite system – 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)	$ 3500 (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 planned use of 10 kHz channel on INSAT in about 1984
10. TRANSIT 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 in orbit	< 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 1984
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 (OTS-2) or global	Depends on quality of ephemeris data. 300 ns and possibly < 50 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 operation systems	Present costs, though decreasing, are reletively 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	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	Timing accuracy for civilian users may be degraded to 250 ns (two-sigma). Present receiver costs > $ 25 000. 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	Usable for regional and intercontinental distances. May be restrictions on access and available accuracy for civilian users. Requires some coordination and scheduling among labaratories
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. No operational plans. Lack of laser experience
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. 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 at 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 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. Long-term 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 in orbit	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 generally 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

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.

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 1976-1982 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 continued for four years from June, 1978 to July, 1982. In February, 1980 the PTB began participating in these regular comparisons via Symphonie. 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 pulse/s 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 pulse/s signals. 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 measurement time. 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 technique [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.

At the NRC in Ottawa, experiments on two-way time transfer via commercial 6/4 GHz geostationary satellites have been carried out using pairs of low power CW signals. Two experimental satellite ground stations with 3 m antennas and 1 W power have been installed at ground level 100 m from the Time Laboratory, with triax cables connecting directly with the laboratory [Costain *et al*,, 1982].

In 1983, signals of $f_0 \pm 0.5$ MHz were transmitted through the Anik-A3 satellites, and the 1 MHz frequency was recovered directly [Costain *et al.*, 1983]. The r.m.s. deviation of the measurements was 0.4 ns. The experiments showed that time transfer using CW signals or PRN code is practical with low-cost terminals.

One of the NRC 6/4 GHz 3 m terminals has been converted for operation in the 14/12 GHz band, and a PRN code modem recommended by Interim Working Party 7/4 has been acquired. An experimental network using a 14/12 GHz geostationary satellite for two-way time transfer between NRC, USNO and NBS is being implemented. This should provide a valuable check on the GPS time transfer method now in operation.

The Radio Research Laboratories in Japan (RRL) are developing a domestic accurate time-comparison system which uses the Japanese geostationary communication satellite CS (medium capacity communication satellite for experimental purpose), spread spectrum random access (SSRA) equipment and 30/20 GHz earth stations such as the Kashima main station and two small mobile stations. Two-way time transfer experiments were carried out in 1981 and 1982 between the main station and a small station placed at the headquarters and between two small stations, both of which were located at the same site. In each case, time fluctuation of about 1 ns and a frequency stability of less than 1×10^{-13} for averaging times of 100-200 min were obtained. The accuracies of the experiments were estimated at about 13 ns for the time comparison between the main station and the headquarters using as a reference a two-way time transfer through a terrestrial microwave link, and about 0.74 ns for that between a two-way time transfer experiment using two small earth stations at the same site with a common clock. The time delay of each station was measured by inserting a pulse-modulated signal into each of the up-link and down-link paths of the station and detecting it at the other end of the path for comparison with the input pulse. For the main station, the delay was estimated with about 7.7 ns of accuracy (capability) while for the small stations it was estimated with about 3.6 ns of accuracy [Imae *et al.*, 1983] (see Table III).

TABLE III – *Measurement results of the delays at the two small stations*

		Time delay (ns)
1 m antenna diameter station up-link delay	(U_1)	329.6
1 m antenna diameter station down-link delay	(D_1)	372.0
2 m antenna diameter station up-link delay	(U_2)	361.3
2 m antenna diameter station down-link delay	(D_2)	401.0
$K = (U_1 - D_1) - (U_2 - D_2)$	(K_1)	−2.7
K by the common clock method	(K_2)	−6.3
$K_1 - K_2$		3.6

Intercontinental time transfer experiments were performed in the summer, 1983 in cooperation between the USCO, COMSAT, Technical University of Berlin and DFVLR (Federal Republic of Germany) using Intelsat-V communication channels between stations in Washington, DC, and Oberpfaffenhofen (Federal Republic of Germany).

At the earth station, the time signal was inserted as a pseudo-random noise (PRN) sequence with a 2 MHz chip-rate at the intermediate frequency (IF) interface into the communication link and retransmitted at the receiving end. Time transfer accuracy is measured by correlation detection of the original PRN sequence with its received replica.

With earth stations of G/T values of 20 dB(K^{-1}) and 26 dB(K^{-1}) (corresponding to antenna diameters of 2.2 m and 4.5 m) and transmitter powers as low as 170 mW and 80 mW, respectively, reliable time transfer experiments were performed resulting in an r.m.s. time jitter of less than 1 ns. With the chosen link characteristics, the time transfer signal which is spread over a 2 MHz bandwidth is received at a signal-to-noise ratio of −9 dB, well below the thermal noise level.

4.1.2 *GPS (global positioning system)*

The GPS (also known as NAVSTAR) was developed by the US Department of Defense as a high-accuracy, continuously available navigation/position-location system [Milliken and Zoller, 1978]. The system was planned to include a total of 18 operating satellites, arranged in 6 orbital planes. The 18 satellites in 12-hour orbits would result in several being in view of any specific location at any time. Each satellite contains atomic clocks (caesium, rubidium, and hydrogen devices were investigated) to generate extremely well characterized timing signals as part of the navigation message format. The system is supported by an extensive network of monitoring stations and control stations which provides 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 including 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.

In 1985, the United States Department of Defense announced that the GPS C/A code, including the time and satellite position data, would continue to be made available to civilian users and that no user fees would be charged. Furthermore, it was stated that the two-sigma time and position uncertainties available to the civilian users will be no greater than 250 ns (relative to GPS time), 100 m (horizontal position) and 156 m (vertical position).

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-1980s. 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 observations, a degree of compensation for such uncertainties is realized and relatively good synchronization accuracy is possible. It has now been shown by extensive GPS time and frequency comparisons conducted by many different laboratories on a global basis that time comparisons with precisions of less than 10 ns and frequency comparisons with uncertainties of less than 1×10^{-14} can be achieved on essentially an operational basis [Allan *et al.*, 1985]. 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.

Since the GPS comparisons have proved to be from 10-100 times better than the corresponding Loran-C data, certain inconsistencies and errors as large as 1 μs have been detected and eliminated in the process of formulating TAI and UTC. The GPS results have been compared with portable clock data in some cases and the agreement has normally been within the combined uncertainties (a few tens of nanoseconds) of the techniques used. In the case of the primary laboratory caesium standards, such as those operated by NBS, NRC and PTB, the GPS common-view comparisons now permit these devices to be compared with uncertainty contributions of less than one part in 10^{14} from the comparison process itself. A number of specific comparisons of time scales and primary frequency standards using GPS are given in references [Allan *et al.*, 1985; USNO, 1985].

A number of laboratories have reported their specific experiences using the GPS technique. Some of these results are summarized in the remainder of this section.

The United States Naval Observatory (USNO), using a commercially available GPS receiver, has monitored GPS transmissions since November, 1979. GPS data obtained by this unit extends from 10 October, 1980 (MJD – 44 522) in machine readable form. Ths most current data is available in real-time through the USNO Automated Data Service and is published in USNO Time Service Announcement, Series 4. Since 1 December, 1982, GPS System Time has been maintained within 1 μs of UTC(USNO), and transmitted corrections allow synchronization to within 100 ns of UTC(USNO).

The United States National Bureau of Standards has developed its own version of a GPS timing receiver, primarily intended for use in the common-view mode of reception. The internal receiver satellites are at the 1 ns level and satellite signal stabilities are routinely observed at the 5 ns level for 15 s averages [Davis *et al.*, 1981a].

Routine time comparisons, conducted at the USNO and NBS over many months using these 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.*, 1981b]. 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}.

An intercontinental frequency comparison between the space agency of the Federal Republic of Germany (DFVLR) and the USNO in Washington, DC, using an experimental receiver, showed an accuracy of 2×10^{-14} during a measurement period of 12 days [Starker *et al.*, 1982].

Using an experimental Naval Research Laboratory GPS timing receiver, it was possible to compare hydrogen masers located in the United States of America and France [Wardrip *et al.*, 1983]. The Jet Propulsion Laboratory in the United States of America uses the GPS to coordinate time and frequency between three hydrogen maser clocks located approximately equidistantly around the Earth. By using GPS timing receivers, the hydrogen maser clocks can be characterized in near real-time to within 50 ns in time offset and 1×10^{-15} in frequency offset [Clements *et al.*, 1984].

The GPS time transfer system was introduced at the Tokyo Astronomical Observatory (TAO) in 1982 [Fujimoto *et al.*, 1983] and regular measurements with world-wide cooperation are being conducted. The transpacific common-view link between TAO and USNO [Allan and Weiss, 1980; Klepczynski, 1982; Allan *et al.*, 1985] was checked by three portable clock experiments and the two techniques agreed to within the experimental errors [Aoki *et al.*, 1984]. The precision of the GPS time transfer of this link was evaluated to be 4×10^{-13} over an averaging time of 1 day and 3×10^{-14} over an averaging time of 10 days.

The Radio Research Laboratories (RRL) (Japan) have made international time comparison since August, 1984, using two GPS time transfer receivers, one of which was developed by RRL and the other independently by a Japanese electrical firm. The receivers have a precision of 6-20 ns for time comparison and the receiver delays were measured with an accuracy of 15 ns by using a GPS signal simulator [Yoshimura *et al.*, 1986; Imae *et al.*, 1986].

The United States National Bureau of Standards initiated in 1983 a new calibration service based on the GPS common-view technique. NBS provides at each user's site a completely automated, turn-key GPS receiving system, including receiver, system controller, data storage and analysis capabilities, telephone access, and personnel training and system support. The receiver which is located at the user's facility communicates its data automatically to an NBS computer which stores the raw data, determines which data elements are suitable for time transfer calculations and provides an optimally filtered value for the time and frequency of the user's clock with respect to the NBS automic time scales. The user is given an account on one of the NBS computers through which he may access both the raw data and the results of the NBS analysis.

The increasing use of the GPS common-view technique has been aided by several developments. Many laboratories routinely make their GPS comparison data generally available by recording the results in the GE Mark 3 Information System. This exchange of data is amplified by an agreement to use a "standardized" data format. Also, to assist laboratories in determining when to make GPS measurements that are simultaneous with those of other selected laboratories, NBS regularly generates and distributes such scheduling information based on certain geographical ragions. The number of sources of suitable GPS timing receivers seems to be increasing significantly. While some laboratories continue to develop their own versions, several different commercial products are also available.

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 the ground stations which are to be synchronized are equipped with laser telescopes [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 terrestrial links.

Although the LASSO concept has not yet been tested, a LASSO instrument package is scheduled to be launched on the METEOSAT-P2 spacecraft in 1986. It is anticipated that a standard LASSO spacecraft equipment package could be added easily and inexpensively to future satellites of opportunity.

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 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.

The Federal Republic of Germany plans to conduct a time transfer experiment using a United States 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 in 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.

The world-wide meteorological satellite system that includes the GOES satellites, the European METEOSAT satellites, and the Japanese GMS satellites, offers some opportunities for use of this technique for regional time comparisons. Although the GOES satellite system does not currently include suitable ranging signals., the GMS and METEOSAT systems do use a trilateration ranging technique that includes the transmission of suitable microwave ranging signals several times each day. Other satellite systems may also be available now or in the future which are well suited for this time transfer technique.

One experiment to evaluate such a technique was performed in 1970 by the United States NBS which used ranging signals with the US LES-6 and Tacsat satellites to synchronize clocks in North and South America [Hanson and Hamilton, 1971]. Although the low-resolution of the 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 2 m dishes with the Meteosat ranging signals that are available every three hours should permit time synchronization accuracies of 30 ns [Nottarp *et al.*, 1979].

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 automatically computes the signal path delay, and adjusts the output 1 pulse/s signal accordingly to be "on-time" to within approximately 50 µs. The timing signals from the satellites are derived from atomic 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. Experience during this period indicates that:

– the time code as transmitted can be maintained indefinitely within 10 µs of UTC(NBS); and

– the time code as received (when corrected for path delay) generally shows variations of a few tens of microseconds over a day and < 100 µs over all longer periods, except for occasional larger variations due to poor-quality satellite orbital elements used to generate position predictions [Beehler, 1982].

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.

The Istituto Elettrotecnico Nazionale (IEN) used such a transponder on the experimental telecommunication satellite Sirio-1, with its VHF-transponder operating at 136 MHz [Detoma *et al.*, 1981]. The experiment included also the use of the SHF transponder operating at an up-link frequency of 17 GHz and a down-link frequency of 14 GHz. The tests were performed using a coded time signal [Detoma *et al.*, 1983]. The bandwidth available in both cases (VHF and SHF) was of a few kilohertz. The standard deviation in the VHF-experiment was 1.5 ms and in the SHF experiment 30 μs.

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 (approx. 2 GHz) 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.

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 satellite signals and sophisticated receivers. Two improved TRANSIT (Nova) satellites are currently in orbit.

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.

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 (18-26 GHz) 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 in the process of being fully implemented, but no experiments have been performed as yet to evaluate the system's capabilities for time transfer. It is not known at this time what access, if any, T/F users may have in the future 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 [Kovačević *et al.*, 1979 and 1981]. 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 to determine the satellite position very accurately via a two-way method applied by a minimum of three ground transmitting stations [Kovačević *et al.*, 1981; Hartl *et al.*, 1983]. 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 a technique for cancelling Doppler shift, tests were made using a phase control servo included in the satellite link or a pre-compensating frequency control using measured values of the orbital data of the satellite. 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 a 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. In an experiment of standard time dissemination which used a time code inserted in the 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].

During recent years beginning in 1980, a time comparison experiment involving VSL, NPL, IEN, DFVLR, TUG and PTB, has been carried out in Europe using the television signals relayed on 11.682 GHz by the European experimental communication satellite OTS-2, and ending in late 1983. During a period of one week in October, 1983, it was possible to compare time and frequency transfer measurements via OTS-2 and NAVSTAR/GPS between IEN and TUG. The difference of the relative frequency differences obtained by the measurements using OTS-2 and GPS was below 3×10^{-14} and the standard deviation of both types of measurements was below 20 ns [Kirchner *et al.*, 1985].

The OTS-2 measurements have demonstrated that it will be possible to establish high-quality links for time and frequency comparisons using direct-television-broadcasting satellites. For high-accuracy time comparisons it will of course be necessary to calibrate the delays of the receiving equipment [De Jong *et al.*, 1981; De Jong and Kaarls, 1983].

For short distances between the partipating laboratories, standard orbit determination procedures as used for communication satellites, will be sufficient for the computation of the propagation delays. For long baselines, the position of the satellite has to be determined as accurately as possible and this may be done by precise range measurements carried out by the time-keeping laboratories themselves, as demonstrated by measurements such as conducted in Graz which achieved a quality comparable to that of SHF-tracking stations [Kirchner *et al.*, 1984].

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.

ANNEX I

SATELLITE TIME/FREQUENCY COMPARISONS

Year	Organization 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 side-tone ranging signals on 250 MHz carrier	One-way 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	Organization 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/People's Republic of China, PTB/Federal Republic of Germany	Symphonie	Two-way	< 80 ns (A) < 10 ns (P)
	SO and CSAO/People's Republic of China, LPTF/France	Symphonie	Two-way	< 100 ns (A) < 10 ns (P)
Since 1980	NBS/USA, USNO/USA, BIH/France, LPTF/France, PTB/Federal Republic of Germany, NRL/USA, VSL/Netherlands, TUG/Austria, TAO/Japan, JPL/USA, RRL/Japan	GPS	Common-view	< 100 ns (A) 10-30 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)
1978-1982	NRC/Canada, LPTF/France, CNES/France	Symphonie	Two-way	0.5 ns (P)
1980-1982	PTB/Federal Republic of Germany	Symphonie	Two-way	0.5 ns (P)

ANNEX I *(continued)*

Year	Organization and references	Satellite	Technique and description	Stated accuracy (A) or precision (P)
Since 1981	RRL/Japan [Imae *et al.*, 1983]	CS 30/20 GHz	Two-way, 1.3 m-2 m antenna with SSRA Two-way, 1 m-2 m antenna with SSRA	1 ns (P) 13 ns (A) 1 ns (P) 13 ns (A)
1982	VSL/Netherlands, NPL/UK, IEN/Italy, DFVLR, PTB/Federal Republic of Germany, TUG/Austria [De Jong *et al.*, 1981; De Jong and Kaarls, 1983]	OTS-2	One-way	300 ns (A) 20 ns (P)
1983	USNO/USA, COMSAT/USA, DFVLR/Federal Republic of Germany	Intelsat-V	Two-way	300-500 ps (P)

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REPORT 576-3

STANDARD-FREQUENCY DISSEMINATION VIA STABILIZED BROADCAST STATION CARRIERS

(Study Programme 4A/7)

(1974-1978-1982-1986)

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, 162 kHz; Donebach, 153 kHz; Droitwich, Westerglen, Burghead, 200 kHz ~~(see Note 1)~~; Motala, 189 kHz and Milan 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.

Due to the propagation characteristics in the LF band and 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 period.

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 circuits 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.

In the USSR, standard frequencies are transmitted via stabilized carriers of the sound-broadcasting stations RV-166 (Irkutsk) – 200 kHz (see Note 1) with a carrier power of 40 kW, and RV-76 (Novosibirsk) – 272 kHz ~~(see Note 2)~~, which use class of emission A3EGN (double sideband, single channel, amplitude-modulated with sound of broadcasting quality (monophonic)).

The emitted signals have a frequency uncertainty of 5×10^{-12}.

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.

Note 1. – 198 kHz after 1 February, 1988 (see Resolution No. 500 of the World Administrative Radio Conference, Geneva, 1979).

Note 2. – 270 kHz after 1 February, 1990 (see Resolution No. 500 of the World Administrative Radio Conference, Geneva, 1979).

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.

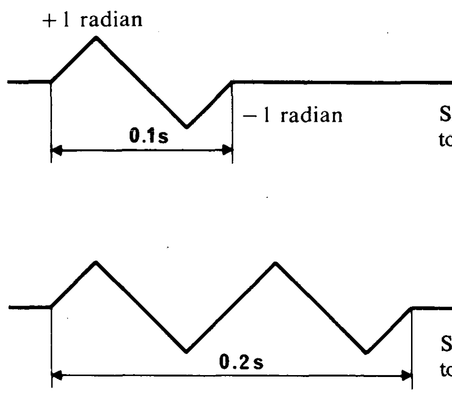
A suitable receiver can operate as a remotely controlled time display, the accuracy of which depends only on the accuracy of the time scale at the emission.

Experiments have been carried out on this technique in France, by modulating a sound broadcasting transmitter in band 5 (Allouis transmitter on 162 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 (2) to Table II of Report 267).

The phase modulation model is given below:



Signal of 1/10 s equivalent to a «0» bit

Signal of 2/10 s equivalent to a «1» bit

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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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;

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* Further information is given in Report 578.

(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].

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.

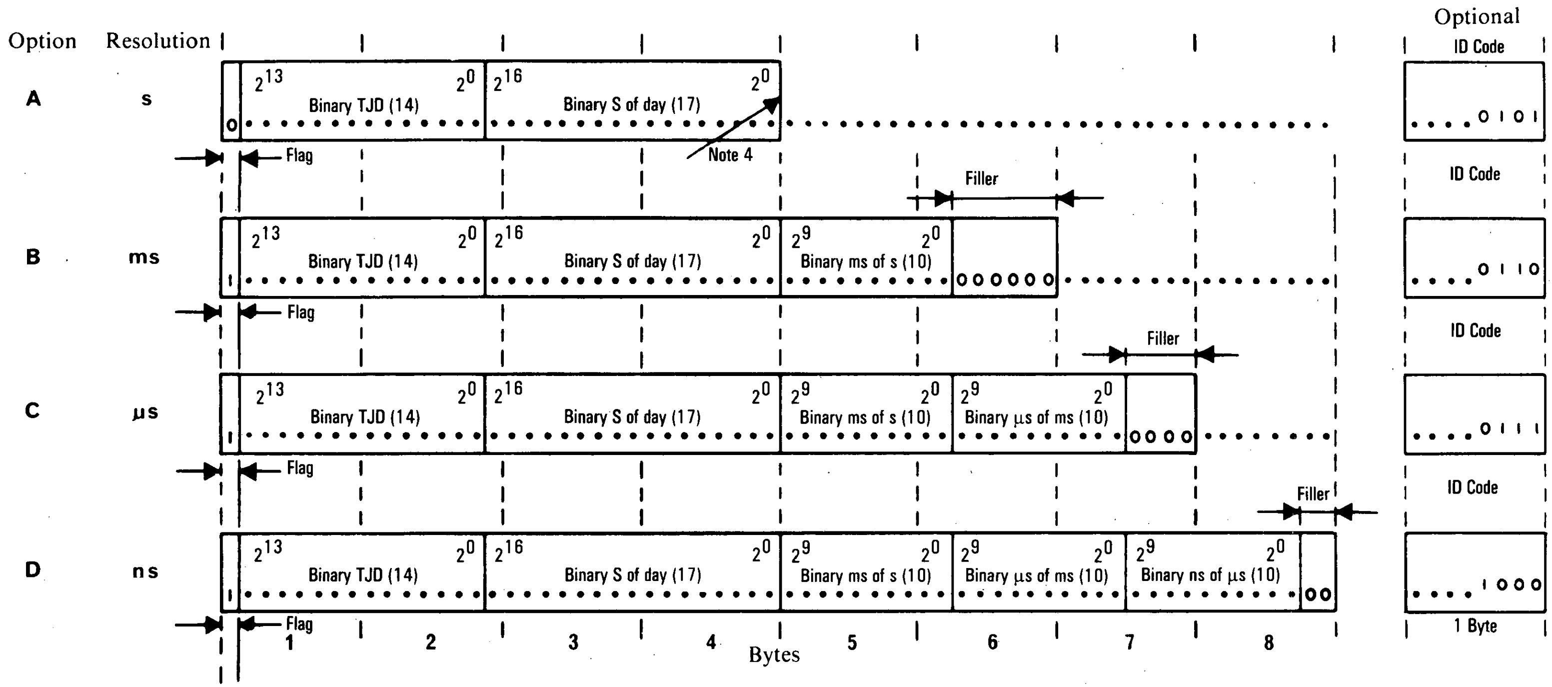

FIGURE 1 – *Parallel grouped binary time code PB5 and resolution options*

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).

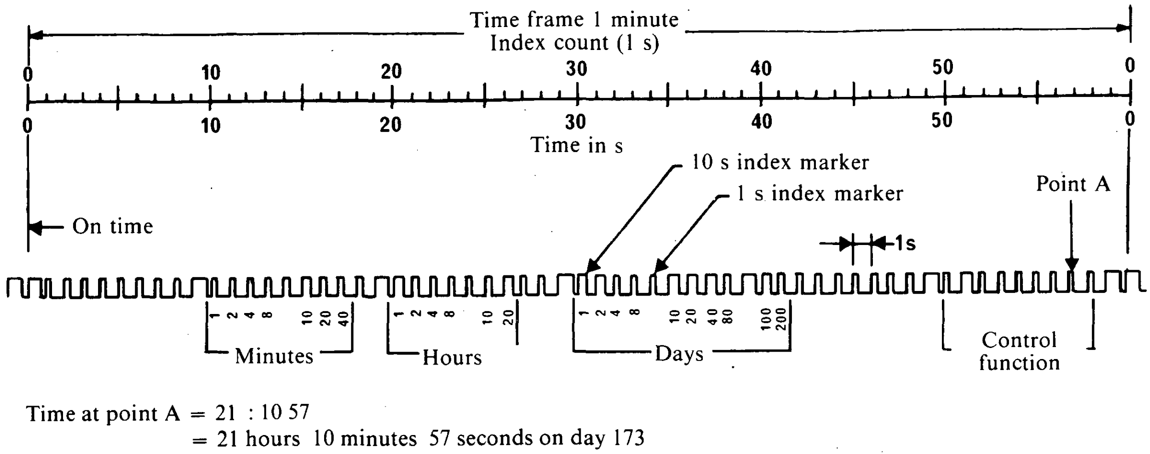

FIGURE 2 – *A typical BCD time code format*

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 decoders. 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 transmitted 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 transmitted time differs from the zonal time.

A common feature of the services DCF77, MSF 60 kHz and Allouis 162 kHz, is the use of BCD codes; the same form of pulse width modulation is used, binary zeros being represented by 0.1 s markers and binary ones by 0.2 s 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 162 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.

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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 USSR 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.

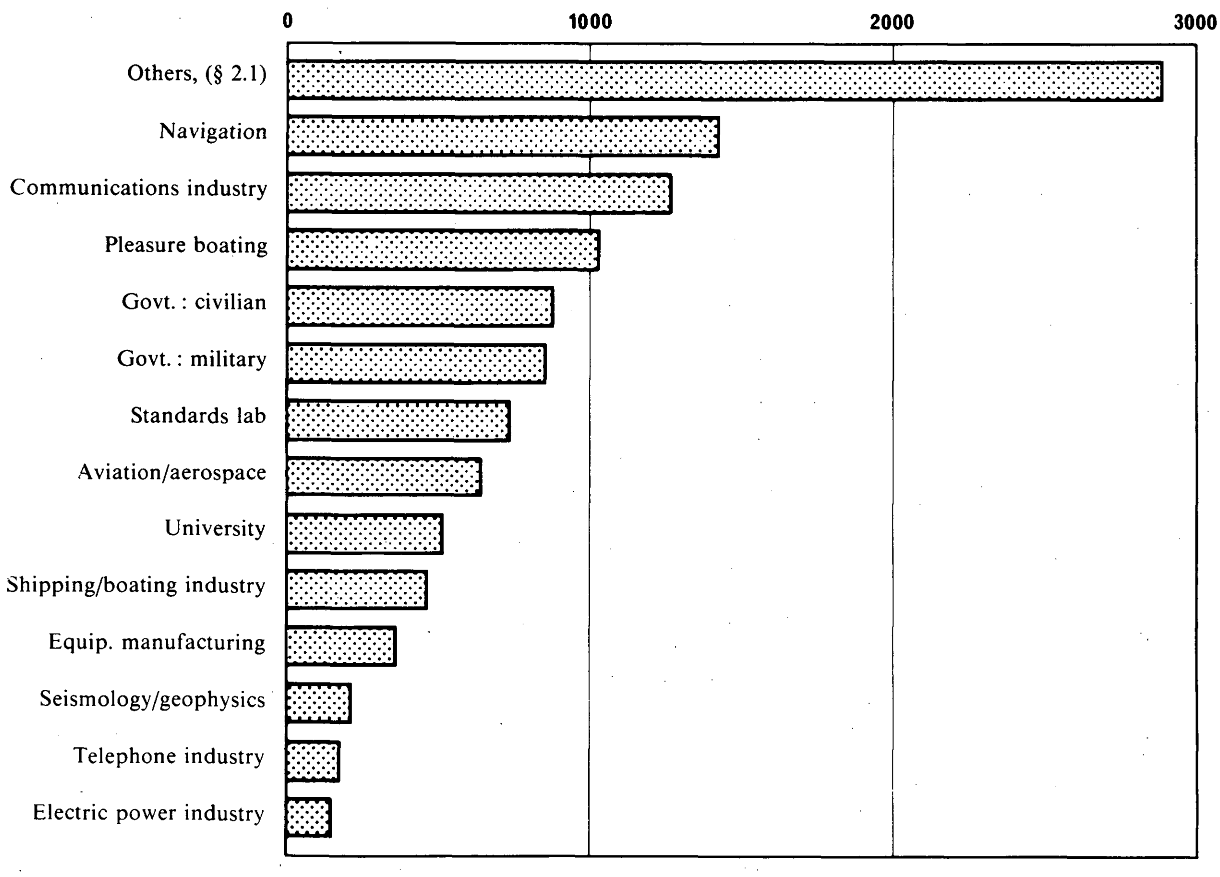


FIGURE 1 – *Number of responses for each user category according to USA survey*

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.

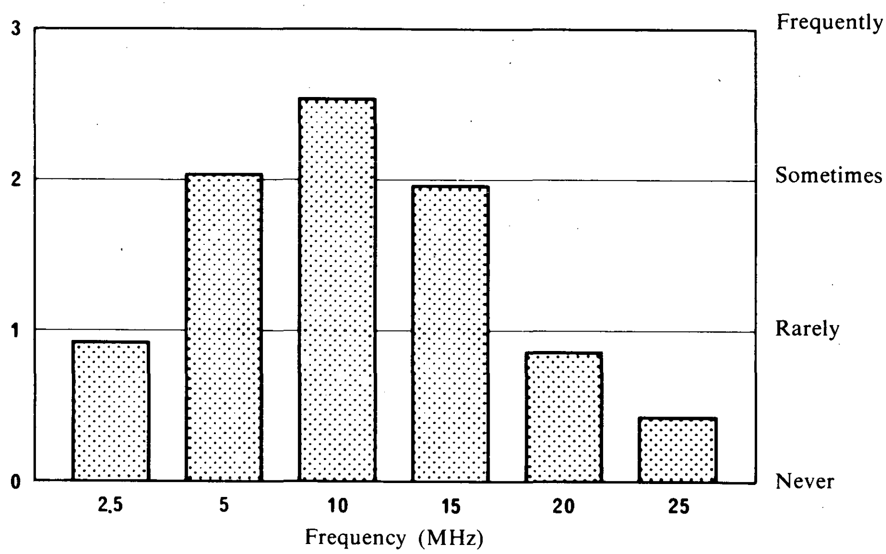


FIGURE 2 – *Use of the frequencies according to USA survey*

Figure 3 shows the relative use of standard signal carrier frequencies of USSR 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.

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.

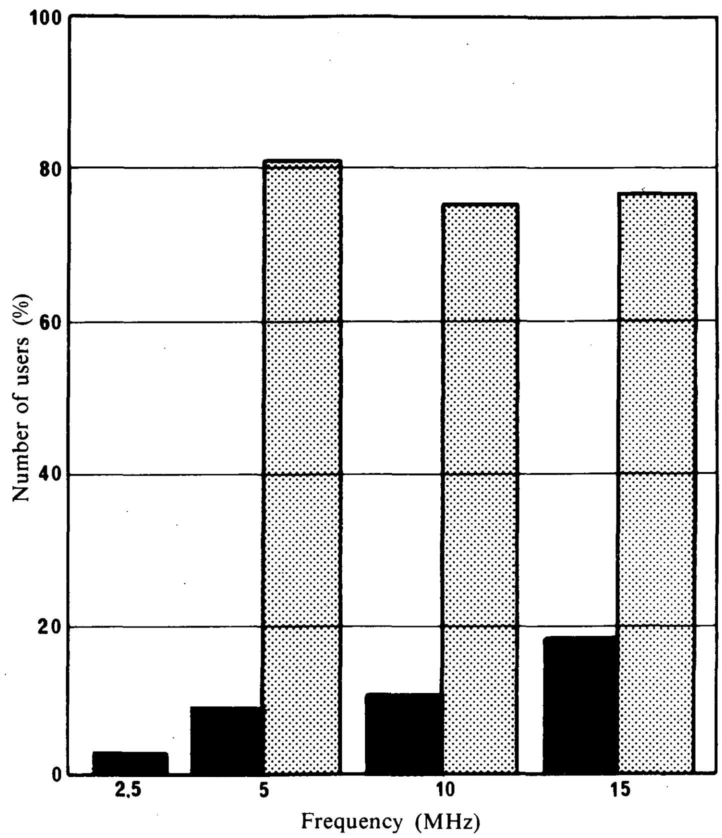
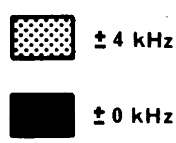


FIGURE 3 – *Use of frequencies according to USSR survey*

(The list of the USSR transmitters is contained
in Report 267, Table I)



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.

TABLE I — *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

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.

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 USSR, 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 USSR.

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 I 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 USSR, 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 USSR, 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 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).

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 732-2

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

(Study Programme 1A/7)

(1978–1982–1986)

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. In an ideal situation time sharing 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, 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.

An alternative form of time-sharing is to offset by an appropriate amount the emissions of the second pulses; such a procedure is followed by the station BPM in the People's Republic of China, for the UTC pulses.

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 USSR 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, BPM, 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:

$$\left.\begin{aligned} f_{sc}+ &= 0.4\,(n + \tfrac{1}{2}) \quad \text{kHz} \\ f_{sc}- &= 0.4\,(n + 1) \quad \text{kHz} \end{aligned}\right\} \qquad (3)$$

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 $\pm$ 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 $\pm$ 5 kHz, except at 2.5 MHz in Region 1 where the frequency limits are only $\pm$ 2 kHz.

At 15 and 20 MHz the total bandwidth available should be $\pm$ 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.

1.3.5 *Use of the new allocated frequencies*

By decision of the World Administrative Radio Conference (Geneva, 1979) standard frequencies and time signals can be transmitted in three bands at 4, 8 and 16 MHz, in Region 3. This decision could alleviate the mutual interference problem on the other frequencies in Region 3. Station JJY in Japan has started operation on 8 MHz.

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 $\pm$ 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 USSR are accepted as the kernel of the plan and the appropriate values of N are indicated. Corresponding values of N for ATA, BPM, 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.

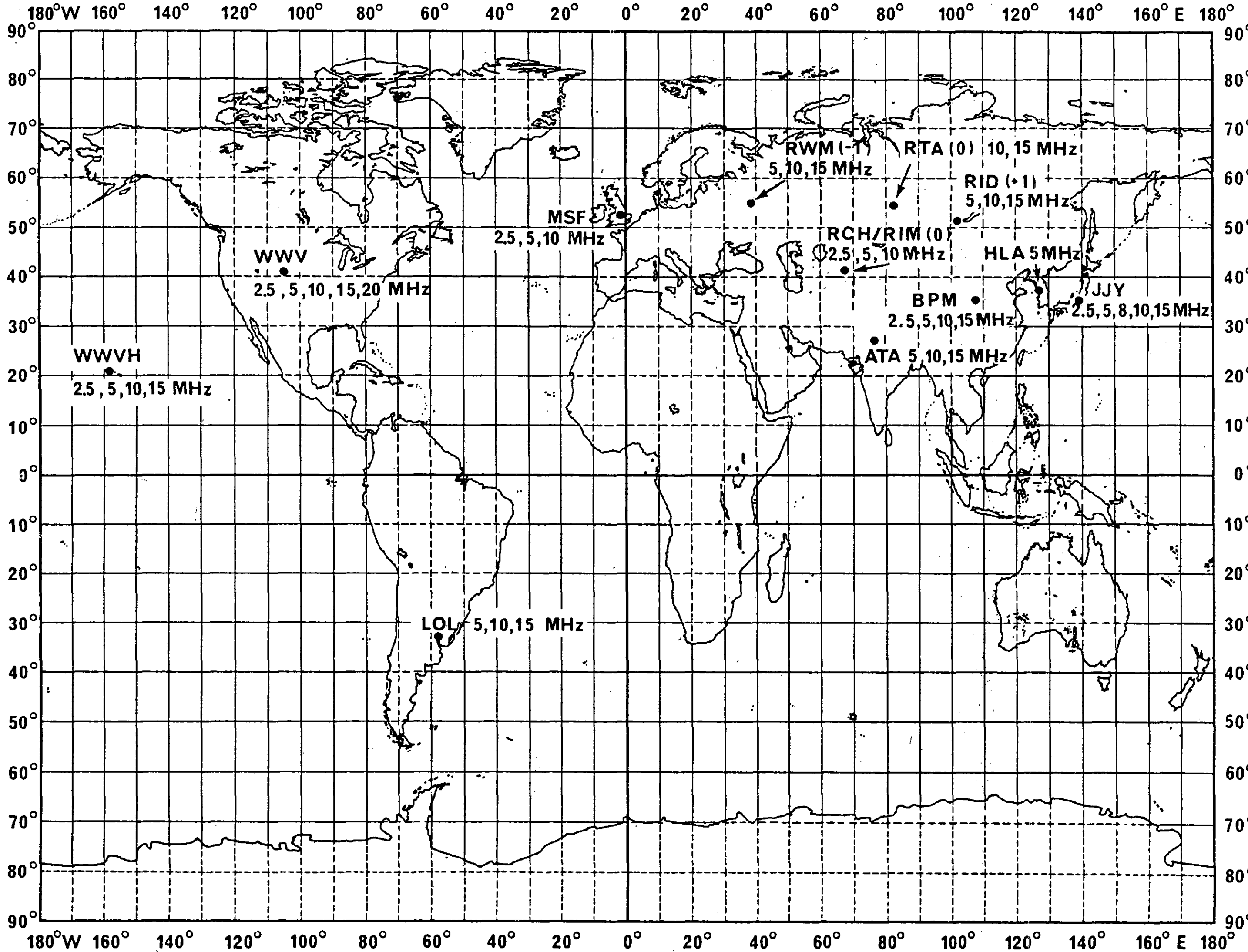

FIGURE 1 – *Carrier frequency offsets of standard-frequency and time-signal stations*

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 USSR. 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 BPM, 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 BPM, $N = -1$. 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 USSR. 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 BPM and JJY which are in relatively close proximity, with $N = -1$ for BPM 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 $N = \pm 1$ 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 USSR, 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.

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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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 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 $\theta \leqslant 0°$,

$+40 + 3\,\theta$ dBW in any 4 kHz band for $0° < \theta \leqslant 5°$,

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

$$10 \log \left(\frac{4 \times 10^3}{250 \times 10^6}\right)$$

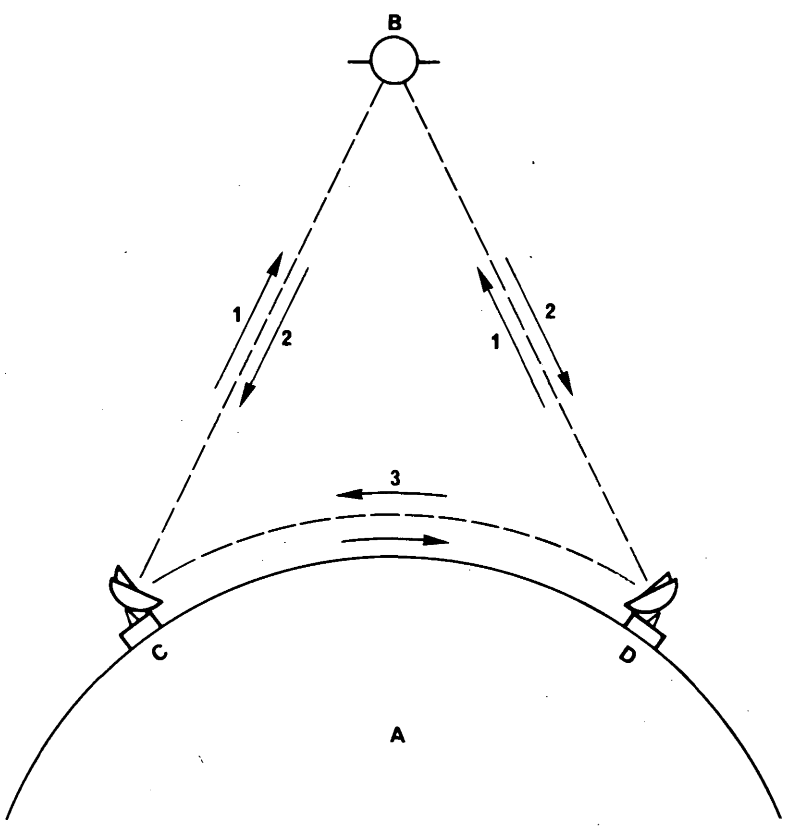

FIGURE 1 – *Satellite time dissemination system*

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+3θ) 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 +3θ) 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:

$$\text{PFD}_\text{C} = P_t + G_t - B_t - 10 \log (4\pi R^2)$$
$$\leqslant 8.3 - 11 - 152 = -155 \text{ dB(W/(m}^2\text{ Hz))}$$
$$\text{(for e.i.r.p. density} = 8.3 \text{ dB(W/Hz) and } R \simeq 41\,500 \text{ km)}$$

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 ($\sim$ 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

$$d \geqslant \sqrt{17 \times 15} + \sqrt{17 \times 15} \geqslant 32 \text{ km}$$

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

$$X = 1114 \text{ pW0p}$$
$$\text{or } -59.5 \text{ dBm0p}$$

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 896-1

DOCUMENTATION OF CHANGES IN TRANSMITTED TIME SIGNALS

(Question 1/7)

(1982–1986)

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) have been reported for 1956-1971 [CCIR, 1978-82]. Corrections to UTC have been made since 1972.

3. JJY time signals

Time and frequency steps by JJY of the Radio Research Laboratories (RRL), Japan, have been reported in [CCIR, 1982-86]. From January 1955 to August 1961, the time and frequency of JJY were maintained to be nearly in agreement with UT2 which was determined by the Tokyo Astronomical Observatory (TAO). The UTC system has been introduced since 1 September 1961.

4. Prior to the introduction of the present UTC system (according to Recommendation 460), various methods of time-signal adjustments have been in use. The details of these adjustments should remain accessible for archival purposes. The Administrations of the Federal Republic of Germany, France, Japan, the United Kingdom and the United States of America have sent this information to the Bureau international de l'heure (BIH) which, following the suggestion expressed in Opinion 71, has agreed to keep such information on record. Additionally, the respective World Data Centres would also be possible sources for this information.

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REPORT 897-1

METHODS FOR SHORT RANGE PRECISION TIME TRANSFERS

(Study Programme 3C/7)

(1982-1986)

1. Introduction

There is a need for comparisons between time scales maintained at separate locations within a short range of each other, 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 environment of propagation medium. This includes sites within line-of-sight, within reach of coaxial cables or optical fibres, or within convenient reach by portable clocks.

2. Common view method

A widely used method of synchronization in frequency and time (see 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); 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] although the method has the disadvantage that the propagation path difference must be calibrated.

3. Cable including optical fibres

For those distances in which coaxial cable can be used to join the sites, two-way propagation of signals provides a means of calibrating the path length and direct comparison of signals for frequency and time synchronization [Rueger and Bates, 1979].

Time comparison using telephone lines is one simple and inexpensive method. Experiments were carried out by the Radio Research Laboratories (RRL), Japan, using an acoustic coupler on local and 800 km long-distance telephone circuits. Measurements of reception time and round-trip time were made for different carrier frequencies used for the call and answer-modes of the couplers, and the results were averaged. An accuracy of within ± 0.1 ms was obtained for both the local and long-distance circuits [CCIR, 1982-86]. This method can only be applied if the two paths are equal as in some administrations, routing of calls takes place asymmetrically. In the United States of America, for example, long-distance calls are often split with one way sent via a satellite and the other via a terrestrial link. This is done to reduce the overall round-trip delay. If the delay measured when satellites are used is less than 100 ms or greater than 500 ms, then the probability is high that identical routing took place and the method described for delay compensation is applicable.

An experimental T/F transfer link using fibre optics at 850 nm and 100 MHz modulation was tested at the Jet Propulsion Laboratory. Over a 3-km path, a stability of 3×10^{-15} at 100 s and 1×10^{-16} at 1000 s was attained. The link operated by continuously measuring the round-trip delay in a single fibre and correcting the input phase to compensate for the variations in the delay, thus achieving constant phase at the receiving end. A single-mode fibre system at 1300 nm, which is expected to give improved performance, is being installed at Goldstone, California, USA, to link two deep-space network antennas [Lutes, 1982].

At the Technical University, Graz, a multi-mode fibre optic T/F distribution system for distances up to several hundred metres has been developed and built with off-the-shelf components. The system is comparable both in price and performance with standard equipment used in time-keeping laboratories. The jitter (output versus input, standard deviation of 100 samples) is well below 50 ps and the temperature-induced changes of the propagation delay of the transmitter and receiver are below 30 and 50 ps/°C respectively. The signal delay variations of the cables used are between 5 and 17 ps/°C for cables of 100 m length [Kirchner and Ressler, 1984].

4. Line-of-sight links

For some distances, line-of-sight propagation links using radiowaves including microwaves or laser beams, are an economical choice for transferring signals on either a one-way or reflected two-way propagation path. 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 and receiving antenna design parameters and location relative to obstructions or reflecting surfaces near the line-of-sight path.

A horizontal two-way time comparison link in air using the University of Maryland's user ranging and time transfer equipment has been established between the Goddard optical research facility (GORF) 1.2 m telescope and the Time Services Division of the United States Naval Observatory (USNO). The bent path has a one-way distance of 26 km. Two optical corner reflectors at the USNO, identical to those placed on the Moon during the Apollo programme, reflect the laser pulses back to the GORF. Light pulses of 100 ps duration and an energy of several hundred microjoules from a neodymium-YAG laser, frequency doubled to a wavelength of 532 nm (green), are sent at a rate of 10 pulses per second. The detection at the USNO is by means of an avalanche photodiode and the timing is accomplished by a computing counter and a computer with respect to a 10 pulses per second pulse train from the master clock. The standard deviation for 100 comparisons is typically 200-400 ps. The corresponding standard deviation of the mean is 20-40 ps. The calibration accuracy, at present, is 1-2 ns, established with a portable clock [Alley *et al.*, 1982].

In 1982, similar techniques were used in time comparison experiments via laser pulses between the two sections of the Shanghai Observatory, Zi-Ka-Wei and Zo-Se, separated by 25.2 km. Time fluctuations of clock difference between two sections were about ± 8.0 ns (r.m.s.) for single measurement and about ± 1.3 ns for the average value of two minute measurements respectively [Yang *et al*, 1983].

5. General remarks

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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[1970-74]: **a.** 7/2 (Japan); **b.** 7/57 (Germany (Federal Republic of)); **c.** 7/82 (Italy).

[1982-86]: 7/2 (Japan).

REPORT 1016

TELEVISION METHODS FOR THE TRANSFER AND DISSEMINATION OF TIME AND FREQUENCY

(Study Programme 3C/7)

(1986)

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 the 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 the People's Republic of 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.*, 1972; 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 10 ns or less.

Television signals from different transmitters can only be used for time or frequency comparisons only if the delay introduced by the links between the transmitters either remains constant or is restricted to a small number of constant and distinguishable values. It is also necessary that no frame synchronizer is used. Such frame synchronizers store a complete picture frame in digital form and release the frame in synchronism with a local clock. The uncertainty introduced by links between transmitters is usually less than 1 μs if they follow the same route, 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 delays, section by section, to determine the total propagation delay has been employed by the Beijing Observatory in the People's Republic of China. This method used only simple apparatus and standard equipment. The results have been checked and compared with portable clocks and Loran-C timing; the systematic deviations of different methods were 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.

Experiments with portable clocks indicated that the accuracy of a technique using television line 6 synchronization pulse for seven years on a routine basis by Shaanxi, Shanghai and Beijing Observatories achieved 2 μs or better, and a daily frequency calibration precision of about $(2 - 20) \times 10^{-13}$ over a distance of 2000 km.

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 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; CCIR, 1974-78b]. 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 ± 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.

In the USSR, experiments have been carried out with insertion of seconds marker pulses in the sixth line of the video signal, with the possibility of remote control relative to UTC (S). In addition, a time code has also been inserted [Borisockin and Fedoton, 1982].

Two caesium clocks, one in Brittany and the other in Paris, were compared during one month through daily television measurements and six portable 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 ns. A last portable clock experiment carried out 2½ months later gave a result 28 ns 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, 1974-78c].

A related method was reported by Lavanceau and Carroll, [1971] at the USNO. It involves stabilization of the colour sub-carrier by reference to a caesium beam frequency standard in the television studio. The line 10 synchronization pulse is also controlled and maintained in synchronism by referring to a "Table of coincidences" (TOC) issued by the 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 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]. Belgrade Television has carried these signals in its two programmes for the entire duration of the studio broadcasts since 1975.

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 several 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 [CCIR, 1974-78d].

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].

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 the People's Republic 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.

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[1974-78]: **a.** 7/137 (China (People's Republic of)); **b.** 7/6 (Japan); **c.** 7/125 (Switzerland); **d.** 7/106 (United Kingdom).

REPORT 1017

CHARACTERIZATION OF SIGNAL DELAYS IN ANTENNAS

(Question 9/7)

(1986)

1. Introduction

As greater resolution in time transfer becomes possible by the use of improved time and frequency generators with better short-term stabilities, the means of calibrating and measuring circuit delays between the standards to be compared may become a dominating source of error. Included in the intervening circuits are the delay contributions from the antennas used to emit and receive electromagnetic waves propagated over the path separating the precision time time generators. This Report addresses the related work in the published literature and is an initial attempt to present the state of the art in the present technology. Since means of performing these calibrations have not been standardized between administrations, it is appropriate to address guidelines for consideration that may lead to the adoption of acceptable procedures for these measurements.

2. Background

Time signal generators now exist with the potential for maintaining time scales with deviations of less than 1 ns for periods of hours to days. Electronic circuit delays can be measured and calibrated within a laboratory environment at the hundreds of femtoseconds (fs) level. Susceptibility of these circuits to environmental change, such as temperature, magnetic fields, and acceleration can be measured and provision made to sense and compensate or to allow for these perturbing effects. Antennas can be considered a subset of the possible electric circuits that can be serially connected. They may, however, require a more sophisticated treatment for measurement and calibration.

Large antennas used to emit Loran-C signals take 60 or more microseconds for the energy to build up the radiation fields at 100 kHz [Fujimoto and Fujiwara, 1981]. Likewise, the small inductive loop antennas used to receive these signals have delays associated with the build-up of the received signal. Signals such as used in Omega at 11-15 kHz, take tens of milliseconds to build up [Watt, 1967].

To a lesser degree, antennas used in satellites to emit 150 MHz and 400 MHz signals have delays of the order of 25 to 50 ns. Since these delays depend on factors such as bandwidth, frequency, physical length and directivity, time signals derived from a common time scale can develop time offsets, or delays that are the dominant errors in time transfers.

3. Measurements

Experiments have been performed to measure antenna signal delays by a substitution process. A section of cable comparable in length to the far field radiation distance, $2D^2/\lambda$, for electrically small antennas is selected and the total phase delay determined. The cable is divided into two parts; one part feeding a signal to one antenna; the other receiving the signal from another similar antenna. The total phase delay of this combination is determined. The difference between the two delay measurements, less the calculable propagation delay in the air dielectric medium between the two antenna phase centres, represents twice the delay associated with a single antenna.

For a situation where the antenna is of very large aperture, it may not be possible to have two nearly identical antennas sufficiently separated for the above measurement. Here the delay measurement can be made between two smaller nearly identical antennas, and then compared to the delay when one of the small antennas is replaced by the large antenna. Measurements of this kind have been carried out by the Jet Propulsion Laboratory, Pasadena, California [Otoshi, 1975; Cha *et al.*, 1978; Otoshi *et al.*, 1985].

In experiments with space probes, small variations in the delay of microwave signals have been measured in order to obtain data on planetary atmospheres and the distribution of gaseous matter in space. This work has led to investigations of the effect of discontinuities on the group delay in microwave transmission lines [Beatty and Otoshi, 1975] and has also led to the development of a set of group delay standards [Otoshi and Beatty, 1976] for 15, 30 and 60 ns. These delay standards have been calibrated at 2113, 2295 and 8415 MHz to ± 0.1 ns.

4. Conclusions

For antennas serving for the dissemination of precision time signals, calibration of the signal delay represents a new parameter or characteristic, not normally specified or calculated in the initial design of a service antenna. Prior experimenters have performed substitution measurements to determine empirically antenna delay, but have not provided either an organized format or a common set of data across the radio spectrum. Families of antennas used for field-strength measurements are well developed and could represent a set of antenna designs suitably adaptable for standardization of this parameter.

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SECTION 7D: CHARACTERIZATION OF SOURCES AND TIME SCALES FORMATION

Recommendations and Reports

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 measure of the phase instabilities expressed in time units (phase-time) $x(t)$ in the frequency domain is $S_x(f)$; i.e. the one-sided spectral density ($0 < f < \infty$) of phase-time instabilities $x(t)$, where $x(t) = \varphi(t)/2\pi\nu_0$; $x(t)$ being related to $y(t)$ by $y(t) = \mathrm{d}x(t)/\mathrm{d}t$;

1.4 the relationships of the above spectral densities are given below:

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

The dimensions of $S_y(f)$, $S_\varphi(f)$ and $S_x(f)$ are respectively Hz^{-1}, $\mathrm{Rad}^2\mathrm{Hz}^{-1}$ and $\mathrm{s}^2\mathrm{Hz}^{-1}$;

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.);

* See Report 580 for more complete details.

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:

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

where

$$\bar{y}_k = \frac{1}{\tau} \int_{t_k}^{t_k+\tau} y(t)\, \mathrm{d}t \tag{3}$$

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

$< >$ 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:

$$\hat{\sigma}_y(\tau) \simeq \left[\frac{1}{2(M-1)} \sum_{k=1}^{M-1} \left(\bar{y}_{k+1} - \bar{y}_k\right)^2\right]^{\frac{1}{2}} \tag{4}$$

REPORT 364-5

PERFORMANCE OF STANDARD-FREQUENCY GENERATORS

(Study Programme 3B/7)

(1966-1970-1974-1978-1982-1986)

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).

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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).

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]. A $1/f^2$ spectrum has also been shown to be important in frequency generators [Jones and Tryon, 1983].

In both atomic sources and in quartz crystal oscillators, thermal and shot noise will contribute to the short-term instability and, depending on 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.

Alternatively, it has been shown that the majority of these frequency steps can be modelled as a random walk frequency modulation process, and $\sigma_y(\tau)$ can be used to identify the $\tau^{1/2}$ process and its magnitude [Percival, 1976; Barnes *et al.*, 1982; Jones and Tryon, 1983].

2. Caesium beam frequency standards

Systematic effects in commercial caesium beam frequency standards have been investigated by several laboratories (PTB [Becker and Hetzel, 1973], BIH [Guinot, 1974], the USNO [Winkler *et al.*, 1970]). There is no evidence that commercial caesium standards exhibit unidirectional frequency drift as a group at the 10^{-14} level. Procedures have been developed [Becker and Hetzel, 1973] for periodically monitoring and adjusting the magnetic fields in these commercial standards. These procedures appear to produce improved stability performance, particularly during the first six months of a clock's life. A caesium beam tube accuracy evaluation technique has been developed that is applicable to both laboratory and commercial type standards [Hellwig *et al.*, 1973].

Laboratory-type primary caesium beam frequency standards are located at the PTB in the Federal Republic of Germany [Becker, 1976]; the NRC in Canada [Mungall *et al.*, 1976], the NBS in the United States of America [Wineland *et al.*, 1976]; VNIIFTRI, USSR [Iljin *et al.*, 1976] NRLM and RRL, Japan [Nakadan and Koga, 1985]; Nakagiri *et al.*, 1984]; NIM, the People's Republic of China. 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 continued through 1977.

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. [Mungall *et al.*, 1980, 1981; Mungall and Costain, 1983]. These clocks have an accuracy limit of about

1.5×10^{-13}, and require more frequent accuracy evaluations in order to maintain this limit. Systematic corrections for the magnetic field reversal effect and the cavity phase difference tend to be less stable than for CsV, but the re-evaluations, performed when necessary, have maintained agreement with CsV to better than 1×10^{-13}. The long-term frequency instability of all four clocks is approximately 1×10^{-14} for periods of about 24 hours and has attained values of several parts in 10^{15} over periods of several weeks or months. Routine reports to the BIH from these clocks commenced in January, 1980.

The difference between the time scales TA(NRC) and TA(PTB) has remained constant within $\pm$ 1.2 μs for the period 1977-1983. The frequencies of the primary standards NRC CsV and PTB Cs1, from which the respective time scales are directly derived, have agreed to 3×10^{-14} on a yearly average.

The Millman effect in the caesium beam clock has been re-examined both theoretically and experimentally. It has been shown that the effect does not exist for $\Delta M_F = 0$ transitions. When such transitions are used to determine the static magnetic field intensity in the clock, the resulting uncertainty on the clock frequency is less than 2×10^{-14} [Vanier *et al.*, 1984].

A new method for the determination of the caesium atom velocity distribution, based on the variation of the Ramsey pattern height with the RF interrogation power, has been implemented. The method leads to the determination of the second order Doppler shift with an uncertainty less than 10^{-14} [Boulanger *et al.*, 1984].

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}.

The NBS has used a series of laboratory-type primary caesium standards for its basic frequency reference since 1960. The current versions, designated NBS-6 and NBS-4, feature interaction regions of up to 3.6 m, reversible beams, and other characteristics designed to permit the thorough re-evaluation of accuracy limits on a regular basis. The yearly accuracy evaluations consistently produce uncertainties of less than 1×10^{-13} [Wineland *et al.*, 1976].

In the People's Republic of China, two laboratory-type 3.8 m caesium primary standards with reversible beams, Cs2 and Cs3, were evaluated and measured several times between 1977 and 1980. The total uncertainties (root mean square) are 4.1 and 4.5×10^{-13} but because of some limitations in operational conditions, it is preferred to claim an accuracy of 8×10^{-13} for both standards.

The USSR state time and frequency standard has two primary caesium standards (MTs-1 and MTs-2) of length 63 and 100 cm respectively. MTs-1 has been operational since 1975 [Iljin *et al.*, 1976] and MTs-2 has been operational since 1980 [Abashev *et al.*, 1980]. Recent improvements in these standards yield accuracies of 1×10^{-13} with frequencies uncertainty of 1.5×10^{-13} for MTs-1 and 1×10^{-13} for MTs-2. The agreement in frequency between the two is 1.5×10^{-13} [Elkin *et al.*, 1983].

The laboratory-type caesium beam standard of the NRLM has been in operation since 1976. Its accuracy was estimated as 2.2×10^{-13} [Nakadan and Koga, 1985]. During the experiments, an improved method of measuring the Zeeman shift was proposed utilizing a pair of sigma-transitions with the same absolute value of quantum number [Koga, 1984]. The RRL laboratory-type caesium beam standard Cs1 featured a hexapole magnet focusing system and a 55 cm Ramsey cavity using a coaxial line-to-waveguide transducer inside the magnetic shield [Kobayashi *et al.*, 1978]. The RRL has been reporting the data of the accuracy evaluation to the BIH. The total uncertainty is 1.1×10^{-13} [Nakagiri *et al.*, 1984].

Optical pumping with a single mode tunable laser and detection of the microwave resonance by means of the fluorescence induced by the same laser were incorporated in an experimental standard [Arditi and Picque, 1980]. An oscillator was synchronized with this device to produce an accuracy of a few parts in 10^{11}.

Theoretical work on the problems of optical pumping of caesium standards has been carried out. Shifts in frequency caused by the light was studied [Brillet, 1981; De Clercq and Cérez, 1983]. Efficient usage of all the hyperfine levels under certain conditions of optical pumping was studied [Avila *et al.*, 1985]. A small laboratory version of the optically pumped caesium standard has been constructed. Preliminary results show that the instability is $\sigma_y(\tau) = 1 \times 10^{-11} \tau^{-1/2}$. A large laboratory model is being built [Derbyshire *et al.*, 1985].

3. Hydrogen frequency standards

For the range of averaging times up to about 10^5 s, the performance of active masers is much better than that of caesium devices. A passive maser can produce better frequency stability performance than a caesium device for averaging times between 1000 and 100 000 s [Walls and Persson, 1984]. Hydrogen masers are not primary standards because of the uncontrolled wall shift [Vanier *et al.*, 1975; Vanier and Larouche, 1978].

Work on the reduction or measurement of the wall shift to improve the accuracy of the maser has been carried out at a number of laboratories. 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, showed a change of about 4×10^{-13} per year, with the total change over this period of 1.7×10^{-12} [Morris, 1978]. However, this effect has not been confirmed by all laboratories. Use of a variable volume storage bulb [Brenner, 1969 and 1970; Debely 1970; Uzgiris and Ramsey, 1970; Reinhardt, 1973; Vanier *et al.*, 1975; Vessot *et al.*, 1971], selecting the operating temperature to be at the point where the wall shift is zero (approximately 100 °C) [Vessot *et al.*, 1971; Zitzewitz and Ramsey, 1971; Vessot and Levine, 1970] are possibilities that have been considered. Discovery of an anomalous spin exchange shift and a magnetic inhomogeneity shift [Crampton and Wang, 1974] and development of means 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. The metrological properties of two hydrogen masers were 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 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 revealed by Crampton *et al.*, [1976]. An accuracy of 6×10^{-13} was achieved on a hydrogen maser equipped with a storage bulb having two teflon-lined compartments [Petit *et al.*, 1980].

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 in active masers [Peters *et al.*, 1968; Vessot and Levine, 1970] as well as passively operating masers [Hellwig and Bell, 1972; Walls and Hellwig, 1976]. Pairs of masers which are auto-tuned 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 time-keeping performance of a prototype small passive hydrogen maser developed at the NBS [Walls and Hellwig, 1976] was evaluated against UTC (NBS). The measurement indicated a joint time-keeping stability of about 1.2 ns/day.

The frequency instability of the small passive maser was measured to be $\sigma_y(\tau) = 1.4 \times 10^{-12} \tau^{-1/2}$ for τ up to one day and $5 \times 10^{-15} \tau^{-1/2}$ for a τ of 16 days based on 64 consecutive days of data. No drift versus the NBS caesium ensemble was found to within an uncertainty of $\pm 3 \times 10^{-16}$/day. There was also non evidence of flicker [Walls and Persson, 1984]. Preliminary stability measurements indicate great potential for the maser as a clock. A small passive hydrogen maser now contributes to the NBS time scale. This work demonstrated that the wall shift is constant to within an uncertainty of 3×10^{-16} per day, averaged over 64 days, and that the cavity drift can also be controlled to that level.

The amplitude noise of hydrogen and rubidium masers was analyzed experimentally [Lesage *et al.*, 1980]. The ultimate frequency stability of passively operated hydrogen masers, which depends chiefly on freedom from amplitude noise, was determined [Lesage *et al.*, 1979]. The effect on frequency stability of an electronic reaction enhancing the quality factor of a hydrogen maser cavity was studied both theoretically and experimentally [Tetu *et al.*, 1981]. It was shown that the frequency stability of actively operated compact hydrogen masers should be slightly better than for passively operated masers [Audoin *et al.*, 1981].

An evaluation programme [NASA, 1983] to determine the characteristics of masers of two different types was completed at the Jet Propulsion Laboratory, under the supervision of NASA. The magnetic sensitivity of the masers was measured as 8 to 30×10^{-10}/T, the temperature sensitivity as 7.5 to 15×10^{-15}/K and the pressure sensitivity as 1.5 to 3×10^{-15}/kPa. The frequency instability was 2.0×10^{-14} at 10 s, 9 to 21×10^{-16} at 4000 s and 7 to 8×10^{-15} at 10^6 s. The frequency drift of the masers was 5 to 10×10^{-15} per day. Later VLG-11 masers delivered to the USNO have used improved methods of optical lapping of the joints in the maser cavity and produce a drift of less than 2.5×10^{-15}/day [Vessot *et al.*, 1984].

Later tests of the NASA NR maser at the Johns Hopkins University, Applied Physics Laboratory, showed an instability of 4×10^{-15} at 10^5 s when the drift was removed. The drift rate was constant over one year to an uncertainty of $\pm 5 \times 10^{-16}$/day [Rueger, 1981].

Work on hydrogen masers in the USSR has been aimed at increasing the long-term frequency stability to 1×10^{-14} and improving their reliability. By inverting the population densities of Zeeman sub-states of the atoms entering the bulb [Zhestkova and Elkin, 1979], the shift due to the inhomogeneity of the permanent magnetic field in the area of the storage bulb was reduced by a factor of several tens to a value 1 to 3×10^{-14} [Elkin *et al.*, 1980]. A determination of the shift in the frequency of the tuned hydrogen maser by spin-exchange processes [Elkin and Zhestkova, 1979] showed that a further improvement in the long-term frequency stability of the hydrogen maser calls for strict control on the stability of the relaxation time of the atoms radiating in the bulb. A more serius obstacle to the further increase in frequency stability for long averaging times is the hydrogen maser frequency change due to the variation in wall shift. A frequency change of the continuously tuned hydrogen maser of 1×10^{-14} per month is fairly characteristic [Gaygerov *et al.*, 1982] and may be due to various reasons relating to changes of the bulb coating, including crystallization or contamination. Research into improved wall shift reproducibility is proceeding in two directions; the use of a flexible storage bulb with zero shift temperature selection, and the search for new bulb coating materials [Demidov *et al.*, 1978]. At present, hydrogen frequency standards are the main means of maintaining the State standard time scale and a number of secondary time and frequency standards in the USSR.

Work on hydrogen masers has been continued since 1966 at the Radio Research Laboratories of Japan (RRL) [Saburi *et al.*, 1974; Ohta *et al.*, 1974]. The performance of hydrogen masers was improved by the single-state selection method (Majorana method). A reversible magnetic field and double focusing method were used in this state selection. About 90% of the undesirable atoms in the Zeeman subs-state were eliminated, and the magnetic inhomegeneity shift was reduced to about one-tenth of the shift observed in the conventional state selection [Urabe *et al.*, 1984]. Work on auto-tuned masers with the new state selector is now continuing so that they can be used as clocks. The RRL has also developed two hydrogen masers capable of operating in the field [Morikawa *et al.*, 1984] for use as the time and frequency standard of the K-3 VLBI system, which was developed for the joint VLBI experiment between the RRL and NASA [VLBI Research Development Group, RRL, 1984]. The measured frequency stability is 2.4×10^{-15} for a sample time of 830 s and 1.4×10^{-14} for 10^5 s. The sensitivy to the room temperature is 2.3×10^{-14}/K and the sensitivy to the external magnetic field is 2.5×10^{-9}/T, which is good enough for the usually encountered geomagnetic fields. At VLBI stations, however, the tracking of the antenna may produce large external magnetic field disturbances, which shows the necessity for careful control of the static magnetic field.

4. Superconducting-cavity 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 demonstrated stability performance that exceeds that of any other known oscillator [Jiménez and Septier, 1973; Turneaure and Stein, 1975]. Instabilities of 6×10^{-16} at averaging times of hundreds of seconds were observed under particularly favourable conditions [Stein, 1975]. The super-conducting cavity oscillator appears adaptable to commercial design given reliable low-temperature cryostats, and would be the best oscillator for short or medium-term stabilities (averaging times of up to thousands of seconds). It could be of interest for special uses such as very long baseline interferometry and for the production of high spectral purity microwave and higher frequencies. While the earlier designs showed excessive sensitivity to environmental conditions which would militate against wide usage in spite of their ruggedness and small size, newer designs promise to greatly reduce the environmental effects [Dicks and Strayer, 1984].

The Radio Research Laboratories of Japan (RRL) have studied the 9.2 GHz superconducting cavity stabilized oscillator (SCO) since 1976. A stability of $1.1 \times 10^{-14} \tau^{-1/2}$ was calculated from the measured S/N of a SCO and from the cavity, Q of 2.9×10^8. However, the frequency fluctuation of the SCO due to mechanical deformation of the cavity, caused by the tilt and vibration of the dewar container, appears to be serious. The measured acceleration sensitivity of the superconducting cavity was 6.5×10^{-8}/g for vibration frequencies less than 80 Hz [Komiyama, 1985].

5. Ion storage devices

An $199_{Hg}+$ trapped ion device demonstrated a frequency instability of $\sigma_y(\tau) = 3.6 \times 10^{-11} \tau^{-1/2}$ for 10 s $< \tau <$ 3500 s [Jardino *et al.*, 1980]. Several such devices have been built which show an instability of $\sigma_{y\tau} = 1.2 \times 10^{-12} \tau^{-1/2}$ [Cutler *et al.*, 1981]. A $9_{Be}+$ trapped ion standard using laser cooling and optical pumping, double resonance exhibited stability equal to that of a commercial caesium standard [Bollinger *et al.*, 1984]. Studies have shown that the main limitation of this technique is the uncertainty of the second order Doppler due to rotation of the ion cloud, which is not affected by the cooling.

A new concept for a frequency standard based on "sympathetic cooling" is being studied theoretically and experimentally. In sympathetic cooling, one ion species is cooled by Coulomb coupling with another ion species which is laser cooled. This was proposed and demonstrated (on the Mg^+ isotopes) a few years ago at NBS and is now being considered for use in the mercury standard. The advantage is that the "clock" ions can be continuously cooled, as a.c. Stark shifts from the cooling radiation can be made negligibly small.

6. Performance of various devices

The particular type of frequency standard selected 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 sufficiently well-documented long-term data do not exist for most of the devices.

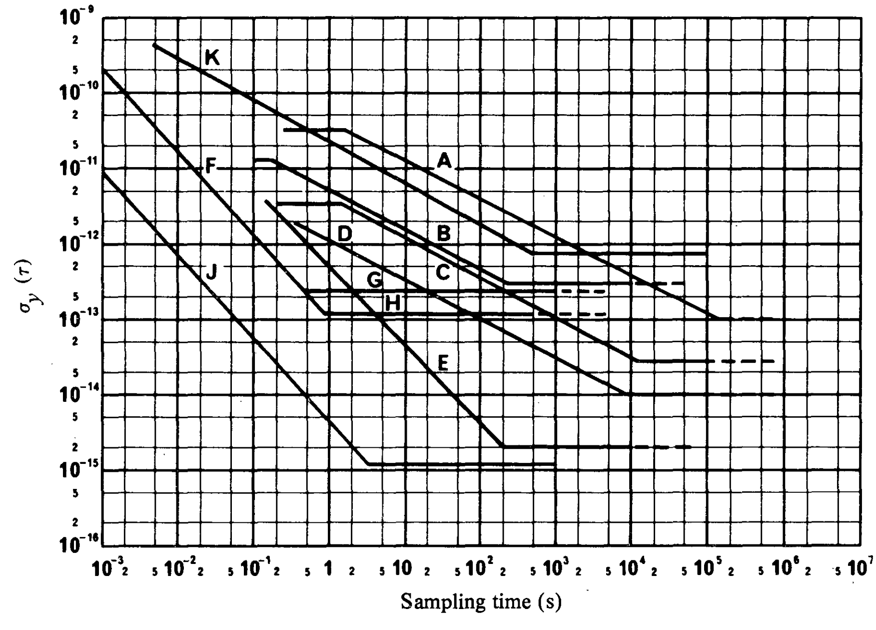

FIGURE 1 – *Typical measured instabilities of several tested types of standards*
The data are based on publications and specifications

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 1 shows that quartz crystal oscillators and superconducting cavity oscillators (SCC) or rubidium masers provide the best stability for short ($\tau < 1$ s) sampling times. The hydrogen maser and the superconducting cavity oscillator show a medium-term (1 s $< \tau <$ 10 000 s) stability superior to any other standard available today. Representations of instability 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 $S_y(f)$ are all normalized to υ_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 s to 300 ms. Caesium beam standards show presently the best long-term ($\tau >$ 10 000 s) stability, although the passive hydrogen standard may produce performance in the near future. 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].

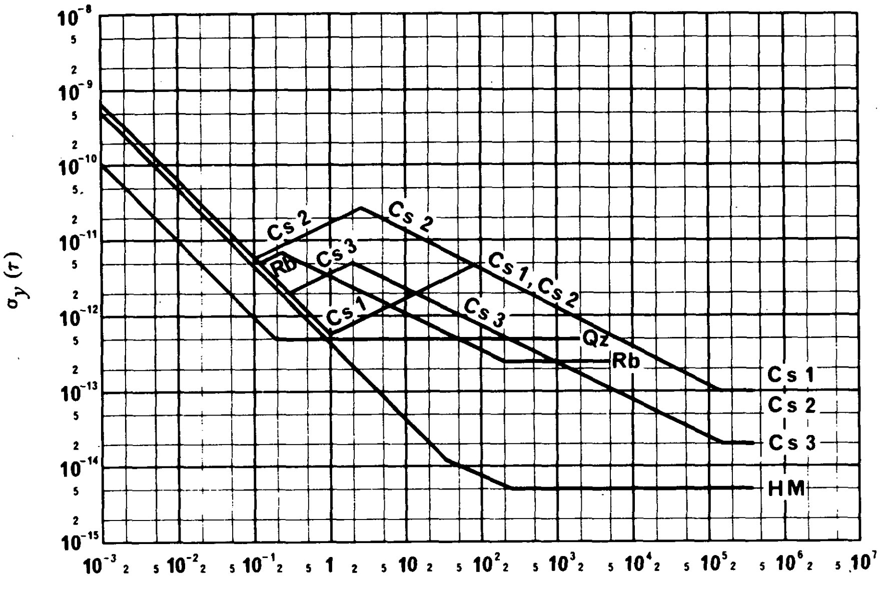

FIGURE 2 – *Frequency instability measures of typical atomic frequency standards and a selected quartz crystal controlled oscillator in the time domain*

OSC	Servo loop time const (s)	f_h (kHz)
Cs1: (long time constant) caesium beam	60	10
Cs2: (short time constant) caesium beam	2	10
Cs3: (high performance constant) caesium beam	2	10
Rb: rubidium maser	0.3	10
Qz: quartz oscillator	–	10
HM: hydrogen maser	–	0.01

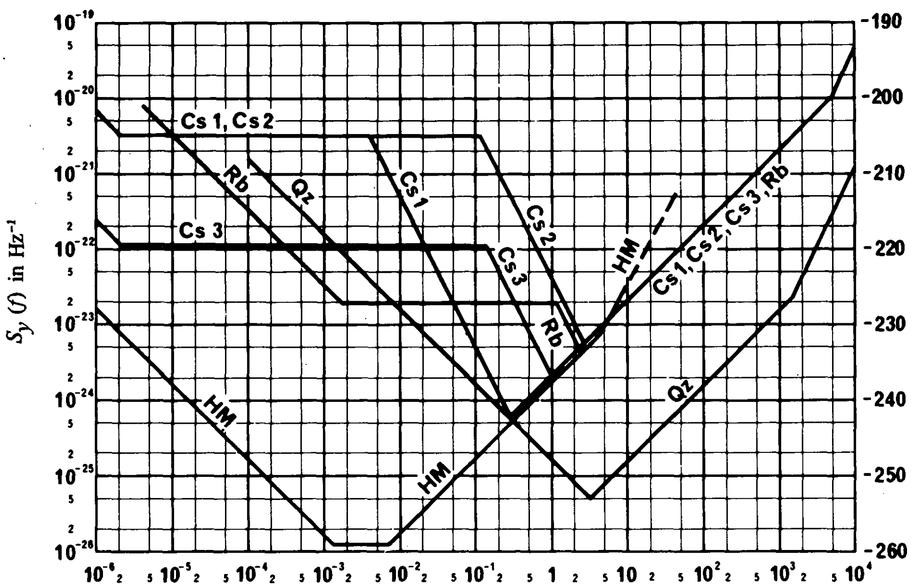

FIGURE 3 – *Frequency instability measures of typical atomic frequency standards and a selected quartz crystal controlled oscillator in the frequency domain*

OSC	f_h (Hz)
Cs1: (long time constant) caesium beam	10^4
Cs2: (short time constant) caesium beam	10^4
Cs3: (high performance constant) caesium beam	10^4
Rb: rubidium maser	10^4
Qz: quartz oscillator	10^4
HM: hydrogen maser	10

A frequency instability 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].

At the IEN (Istituto Elettrotecnico Nazionale) research has been performed for several years on submillimetre beams using magnesium atoms [Strumia, 1972]. This work may result in a potential primary standard with an accuracy in the region of 10^{-13} [De Marchi *et al.*, 1983]. In early 1983, resonances were observed [Godone *et al.*, 1983; Bava *et al.*, 1983] at the frequencies of 601 277 160 kHz and 601 278 866 kHz for ^{24}Mg and ^{26}Mg, respectively. The uncertainty in the frequency determination reached so far is of the order of ± 4 kHz (7×10^{-9}); work is in progress in order to assess the feasibility of a laboratory frequency standard based on this device.

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 achievable in the 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 with a view to the application of the devices 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, and performance 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 other pertinent 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 three alternatives: either to adjust his system parameters to accommodate one of the available standards, choose a combination of these standards to fulfil his need or to initiate a research programme to develop the required standard. It is important to realize that a combination of available standards may satisfy his requirements; 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 use of this system's concept as a solution to a design problem, is a very powerful tool, as it can be realized technically without sacrificing the performance of the individual components of the system. The only actual restrictions may be physical size and cost. It may be that, since most frequency standards are already combinations of several technologies, i.e. the caesium standard incorporates a quartz crystal oscillator, as does the hydrogen maser, a minor modification of one of the devices by the substitution of a higher quality quartz crystal oscillator, for example, and a small change in the system time constants may satisfy the design requirements.

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]) (dm^3)	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 439-4

RELATIVISTIC EFFECTS IN A TERRESTRIAL COORDINATE TIME SYSTEM

(Study Programme 3C/7)

(1970–1974–1978–1982–1986)

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:

$$\Delta t = \int_P^Q \mathrm{d}s \left[1 - \frac{\Delta U(\vec{r})}{c^2} + \frac{v^2}{2c^2} \right] + \frac{2\omega}{c^2} A_E \tag{1}$$

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:

$$\Delta t = \frac{1}{c}\int_P^Q \mathrm{d}\sigma \left[1 - \frac{\Delta U(\vec{r})}{c^2}\right] + \frac{2\omega}{c^2} A_E \qquad (4)$$

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:

$$\Delta t = \frac{1}{c} \int_P^Q d\sigma \left[1 - \frac{U(\vec{r}) - U_g}{c^2} \right] \tag{5}$$

where $U(\vec{r})$ and U_g are defined as in equation (3), and $d\sigma$ is the increment of standard length, or proper length, along the transmission path. The quantities of $d\sigma$ 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 (Earth radius = 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:

$$-4.06 \times 10^{-13} + 9.82 \times 10^{-13} - 1.072 \times 10^{-12} = -4.96 \times 10^{-13}$$

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:

$$B - A = -\frac{\omega}{c^2} \int_P r^2 \cos^2 \varphi \, d\lambda \tag{8}$$

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 579-3

TIME SCALE ALGORITHMS AND ASSOCIATED AVERAGING PROBLEMS

(Study Programme 1D/7)

(1974-1978-1982-1986)

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].

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 (Cs 2 and Cs 3).

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 the People's Republic of China [Chuang and Jair, 1980 and 1981; Shaanxi Observatory, 1979].

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.

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 (Cs 2 and Cs 3). 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).

In France, a method of comparison by television, which has been applied since 1968, uses data from a dozen caesium clocks placed in different laboratories to calculate the French atomic time-scale TA(F). A statistical weighting method, using as a criterion the long-term stability of each of the standards, is employed to form the average scale; each weight may vary from 0-1. The average weight improved from 0.4-0.5 in 1972-73 to 0.8-0.98 in 1981-82. The stability of the TA(F) time scale in relation to the TAI has been of the order of $\pm 3 \times 10^{-13}$, since 1972. On 1 January, 1977, the frequency of the TA(F) was reduced by 15×10^{-13}, so as to make it agree as closely as possible with the SI second. In 1983, it varied between -3 and -5×10^{-13}. Since it is not derived from a primary laboratory standard, the TA(F) has an accuracy given by the mean frequency of the commercial clocks used.

During June 1982, the National Bureau of Standards and the BIH co-sponsored the 2nd International Symposium on Atomic Time Scale Algorithms at NBS/Boulder. Some of the topics discussed included:

- timekeeping processes;
- an automated high-accuracy phase measurement system [Stein *et al.*, 1982];
- the history and structure of ALGOS;
- a maximum likelihood method for estimating clock parameters and the development of a Kalman filter algorithm based on these parameters for minimum time dispersion in an ensemble [Jones and Tryon, 1983];
- the use of robust statistics in forming time scales;
- international clock comparisons at the 10 ns accuracy level using common view of GPS satellites [Davies *et al.*, 1981];
- a real-time ensemble clock system at NBS; and
- reports on timekeeping at various international laboratories.

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.

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. For eight years the annual evaluation has shown that the clock has maintained its estimated accuracy of 5×10^{-14}. In 1979 three smaller primary standards, CsVIA, B and C were put into continuous operation as clocks. On evaluation, the CsVI clocks have usually been within 5×10^{-14} of CsV, with the outside limit of 1×10^{-13}. However, their magnetic fields and cavity phase differences tend to be less stable than in CsV, and evaluations at about 6 months intervals have been necessary to maintain their accuracy limit of 1.5×10^{-13} [Mungall and Costain, 1983]. With the more frequent evaluations, the ensemble cannot be considered to behave in a statistical manner, and no algorithms are used to combine their outputs. Routine reports are made to the BIH on the individual clocks. 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]. This steering algorithm has the advantage of incorporating the short-term (days-to-weeks) stability of the NBS clock ensemble but also of having the long-term stability determined by the accuracy of the primary standard. Thus, the rate of TA(NBS) is always steered toward the SI second.

Until July 1978, the atomic time scale TA(PTB) of the Physikalisch-Technische Bundesanstalt at Braunschweig was derived from the weighted average of an ensemble of commercial clocks [Hübner, 1979]. With the aid of the primary standard CsI, a frequency calibration of the TA(PTB) was performed four times a year on an average. Since the continuous operation of CsI, which started at that time, TA(PTB) has been directly derived from the primary standard. The most important operational parameters of CsI are measured at regular intervals. A beam reversal is executed every five to six weeks [Becker, 1979]. Since 1978, the relative frequency difference of the atomic time scale TA(NRC) of the National Research Council in Canada and the atomic time scale TA(PTB), both directly derived from primary standards, has remained smaller than 7×10^{-14} on an 80-day average.

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).

Early in 1981, the BIH decided to modify the rules for weighting clocks participating in TAI; a stricter selection of clocks was introduced. Details of this new weighting procedure are given in the BIH Annual Report for 1981.

For the TAI type of algorithm, the BIH has studied the problem of clock inputs/outputs and has shown that they produce a slight but not negligible noise of the order of 1×10^{-14} for a sampling period of 50 days [Granveaud, 1982].

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REPORT 580-2

CHARACTERIZATION OF FREQUENCY AND PHASE NOISE

(Study Programme 3B/7)

(1974–1978–1986)

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 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 by Winkler [1976].

Lindsey and Chie [1976] have 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, 1978].

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:

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

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

where $x(t)$ 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:

$S_y(f)$ of $y(t)$, $S_\varphi(f)$ of $\varphi(t)$, $S_{\dot{\varphi}}(f)$ of $\dot{\varphi}(t)$, $S_x(f)$ of $x(t)$, 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

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

$< >$ denotes an infinite time average. The x_k and x_{k+1} are time residual measurements made at t_k and $t_{k+1} = t_k + \tau$, $k = 0, 1, 2, \ldots$, and $1/\tau$ is the fixed sampling rate which gives zero dead time between frequency measurements. By "residual" it is understood that the known systematic effects have been removed.

If the initial sampling rate is specified as $1/\tau_0$, then it has been shown [Howe *et al.*, 1981] that in general one may obtain a more efficient estimate of $\sigma_y(\tau)$ using what is called "overlapping estimates". This estimate is obtained by computing equation (7).

$$\sigma_y^2(\tau) = \frac{1}{2(N-2m)\tau^2} \sum_{i=1}^{N-2m} (x_{i+2m} - 2x_{i+m} + x_i)^2 \tag{7}$$

where N is the number of original time departure measurements spaced by τ_0, ($N = M + 1$, where M is the number of original frequency measurements of sample time, τ_0) and $\tau = m\tau_0$. The corresponding confidence intervals [Howe *et al.*, 1981], discussed in § 6, are smaller than those obtained by using equation (12), and the estimate is still unbiased.

If dead time exists between the frequency departure measurements and this is ignored in computing equation (6), it has been shown that the resulting stability values (which are no longer the Allan variances), will be biased (except for the white frequency noise) as the frequency measurements are regrouped to estimate the stability for $m\tau_0$ ($m > 1$). This bias has been studied and some tables for its correction published [Barnes, 1969; Lesage, 1983].

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 practical to decide whether the oscillator is perturbed by white phase noise or by flicker phase noise. Alternative techniques are suggested below. This is a limitation of 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 typically more adequate for Fourier frequencies greater than about 1 Hz. 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.

A "modified Allan variance", *MOD* $\sigma_y^2(\tau)$, has been developed [Allan and Barnes, 1981] which has the property of yielding different dependences on τ for white phase noise and flicker phase noise. The dependences for *MOD* $\sigma_y(\tau)$ are $\tau^{-3/2}$ and τ^{-1} respectively. The relationships between $\sigma_y(\tau)$ and *MOD* $\sigma_y(\tau)$ are also explained in [Allan and Barnes, 1981; IEEE 1983; Lesage and Ayi, 1984]. *MOD* $\sigma_y(\tau)$ is estimated using the following equation:

$$MOD\,\sigma_y^2(\tau) = \frac{1}{2\tau^2 m^2 (N - 3m + 1)} \sum_{j=1}^{N-3m+1} \left[\sum_{i=j}^{m+j-1} (x_{i+2m} - 2x_{i+m} + x_i) \right]^2 \tag{8}$$

where N is the original number of time measurements spaced by τ_0, and $\tau = m\tau_0$ the sample time of choice. Properties and confidence of the estimate are discussed in Lesage and Ayi [1984]. Jones and Tryon [1983] and Barnes *et al.* [1982] have developed maximum likelihood methods of estimating $\sigma_y(\tau)$ for the specific models of white frequency noise and random walk frequency noise, which has been shown to be a good model for observation times longer than a few seconds for caesium beam standards.

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]:

$$\sigma_y{}^2(\tau) = 2 \int_0^{f_h} S_y(f) \frac{\sin^4 \pi\tau f}{(\pi\tau f)^2} \, df \tag{9}$$

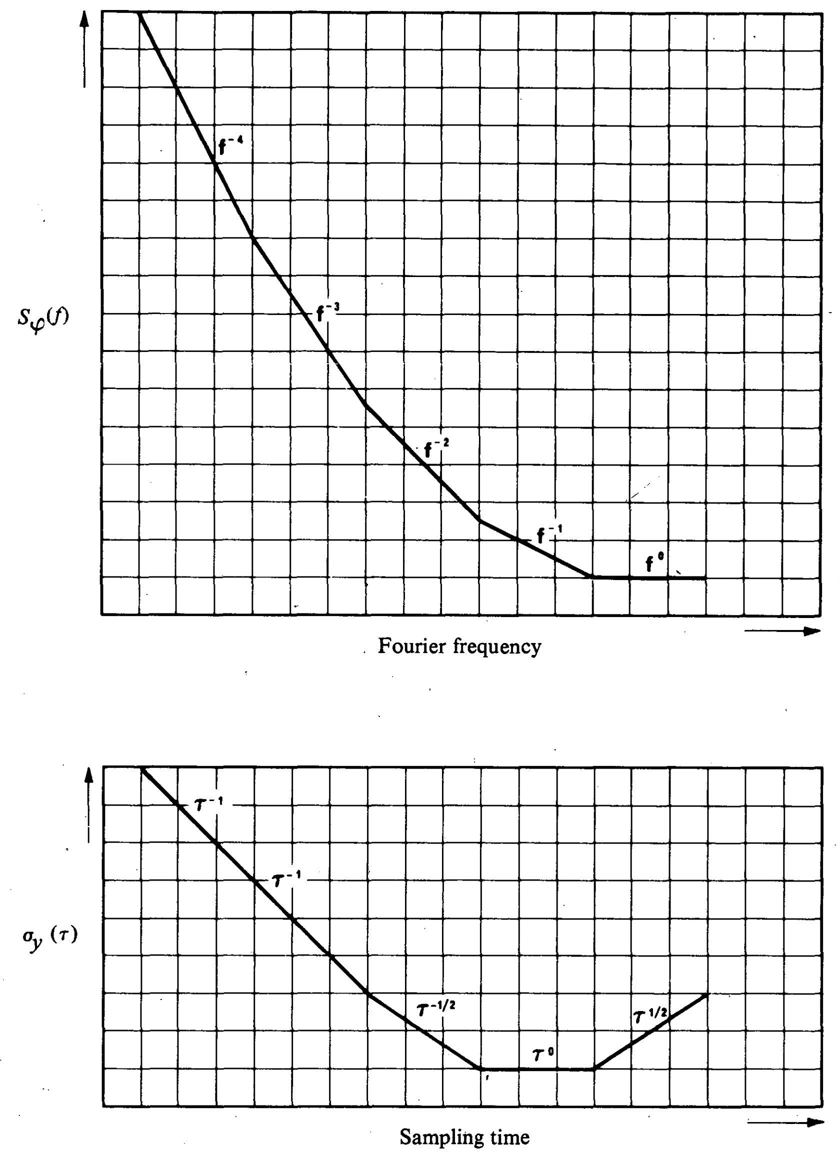

FIGURE 1 – *Slope characteristics of the five independent noise processes* (log scale)

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 (9).

$$\sigma_y^2(\tau) = h_{-2}\,\frac{(2\pi)^2}{6}\,\tau + h_{-1}\,2\log_e 2 + h_0\,\frac{1}{2\tau} + h_1\,\frac{1.038 + 3\log_e(2\pi f_h\,\tau)}{(2\pi)^2\,\tau^2} + h_2\,\frac{3f_h}{(2\pi)^2\,\tau^2} \qquad (10)$$

Note. – The factor 1.038 in the fourth term of equation (10) is different from the value given in most previous publications.

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; also a very high quality oscillator is used as the reference. 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 have been introduced with picosecond time precision [Allan and Daams, 1975], and of measuring the Fourier frequencies of phase noise with 30 dB more sensitivity than the previous state of the art [Walls *et al.*, 1976].

Several measurement systems using frequency counters have been 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:

$$\hat{\sigma}_y(n\tau_0) = \hat{\sigma}_y(\tau) \simeq \left| \frac{1}{2(M-1)} \sum_{j=1}^{M-1} (\bar{y}_{j+1} - \bar{y}_j)^2 \right|^{1/2} \tag{11}$$

or equivalent

$$\hat{\sigma}_y(\tau) \cong \left| \frac{1}{2\tau^2(M-1)} \sum_{j=1}^{M-1} (x_{j+2} - 2x_{j+1} + x_j)^2 \right|^{1/2} \tag{12}$$

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:

$$\text{Confidence Interval } I_\alpha \simeq \sigma_y(\tau) \cdot \kappa_\alpha \cdot M^{-1/2} \text{ for } M > 10 \tag{13}$$

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:

$$I_\alpha \simeq \sigma_y(\tau) \cdot \kappa_\alpha \cdot M^{-1/2} = \sigma_y(\tau) \cdot (0.77) \cdot (100)^{-1/2} = \sigma_y(\tau) \cdot (0.077), \tag{14}$$

which gives:

$$\sigma_y(\tau = 1 \text{ second}) = (1 \pm 0.08) \times 10^{-12} \tag{15}$$

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 (9) shows that the spectral density can be unambiguously transformed into the time-domain measure. The converse is not true in all cases but is true for the power law spectra often used to model precision oscillators.

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-domaine		Time-domaine	
	$S_y(f)$	$S_\varphi(f)$ or $S_x(f)$	$\sigma^2(\tau)$	$\sigma(\tau)$
	α	$\beta \equiv \alpha - 2$	μ	$\mu/2$
Random walk 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

$S_y(f) = h_\alpha f^\alpha$

$S_\varphi(f) = \nu_0^2 h_\alpha f^{\alpha-2} = \nu_0^2 h_\alpha f^\beta \quad (\beta \equiv \alpha - 2)$

$S_x(f) = \frac{1}{4\pi^2} h_\alpha f^{\alpha-2} = \frac{1}{4\pi^2} h_\alpha f^\beta$

$\sigma^2(\tau) \sim |\tau|^\mu$

$\sigma(\tau) \sim |\tau|^{\mu/2}$

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	$A\left[f^2 S_y(f)\right]\tau^1$	$\frac{1}{A}\left[\tau^{-1}\sigma_y^2(\tau)\right]f^{-2}$	$\frac{\nu_0^2}{A}\left[\tau^{-1}\sigma_y^2(\tau)\right]f^{-4}$
Flicker frequency	$B\left[f S_y(f)\right]\tau^0$	$\frac{1}{B}\left[\tau^0\sigma_y^2(\tau)\right]f^{-1}$	$\frac{\nu_0^2}{B}\left[\tau^0\sigma_y^2(\tau)\right]f^{-3}$
White frequency	$C\left[f^0 S_y(f)\right]\tau^{-1}$	$\frac{1}{C}\left[\tau^1\sigma_y^2(\tau)\right]f^0$	$\frac{\nu_0^2}{C}\left[\tau^1\sigma_y^2(\tau)\right]f^{-2}$
Flicker phase	$D\left[f^{-1} S_y(f)\right]\tau^{-2}$	$\frac{1}{D}\left[\tau^2\sigma_y^2(\tau)\right]f^1$	$\frac{\nu_0^2}{D}\left[\tau^2\sigma_y^2(\tau)\right]f^{-1}$
White phase	$E\left[f^{-2} S_y(f)\right]\tau^{-2}$	$\frac{1}{E}\left[\tau^2\sigma_y^2(\tau)\right]f^2$	$\frac{\nu_0^2}{E}\left[\tau^2\sigma_y^2(\tau)\right]f^0$

$$A = \frac{4\pi^2}{6} \qquad D = \frac{1.038 + 3\log_e(2\pi f_h \tau)}{4\pi^2}$$

$$B = 2\log_e 2 \qquad E = \frac{3 f_h}{4\pi^2}$$

$$C = 1/2$$

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REPORT 738-2

STANDARD-FREQUENCY GENERATORS IN THE SUBMILLIMETRE, INFRA-RED AND VISIBLE LIGHT REGIONS OF THE SPECTRUM

(Question 53/1)

(1978-1982-1986)

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. 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.

Special interest in frequency measurements in the visible domain arises from the new definition of the metre, which is defined as the distance travelled by light in vacuum in $\frac{1}{299\,792\,458}$ s (Comptes rendus des séances de la 17[e] Conférence générale des poids et mesures, Paris [1983]). Absolute measurement of frequency thus allows the calculation of wavelength by use of the equation $\lambda = c/f$ without any additional uncertainty (speed of light $c = 299\,792\,458$ m/s).

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; 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). Figure 1 shows typical $\sigma_y(\tau)$ 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, $\lambda = 10$ µm) and He-Ne lasers (88 THz, $\lambda = 3.39$ µm; 474 THz, $\lambda = 0.633$ µm).

Generally speaking, the stabilities obtained are comparable with those of the conventional atomic standards (see Fig. 1 of this Report and Fig. 1 of Report 364) but no existing stabilized laser has an accuracy comparable with that of the primary caesium beam standard (10^{-13}).

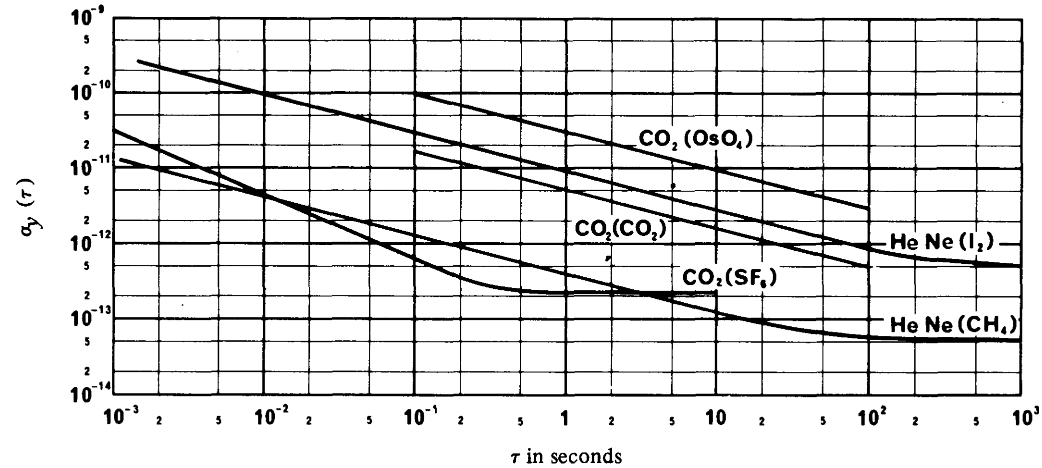

FIGURE 1 – *Typical frequency instability of the main stabilized gas lasers*

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 (CH_4) laser stabilized on E-component of ν_3 P(7) methane transition has a frequency reproducibility around 5×10^{-13} [Malyshev *et al.*, 1980].

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 Bureau international des poids et mesures (BIPM) in connection with the metrology of length.

The 260 THz line has been stabilized by doubling the radiation in the cavity, and detecting saturated absorption in iodine of the 520 THz yellow light [Hanes, 1979].

The limitation of the reproducibility of He-Ne lasers stabilized by saturated absorption, which is due to the diffraction losses being dependent on frequency, has been studied and solutions have been proposed to minimize this effect [Le Floch *et al.*, 1982; Cérez and Felder, 1983].

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 ($\sigma_y(1\ s) \approx 10^{-13}$ [Camy *et al.*, 1976; Spieweck *et al.*, 1980] and by using a molecular iodine beam: $\sigma_y(1\ s) \approx 10^{-11}$, 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 $\sigma_y(100\ s) = 1 \times 10^{-14}$ [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: $\sigma_y(0.05\ s) \approx 2 \times 10^{-12}$ for the 70 μm line, $\sigma_y(0.05\ s) \approx 4 \times 10^{-12}$ for the 118 μm line of the CH_3OH laser [Plainchamp, 1979] and $\sigma_y(1\ s) \approx 1.8 \times 10^{-9}$ 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 [Dahmani and Clairon, 1983a]. The limitations of frequency stability due to the instability of the pumping laser have been studied [Dahmani and Clairon, 1983b].

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 $\sigma_y(1\ s) \approx 10^{-12}$.

By phase synchronization on a harmonic of a primary frequency standard HCN (890 GHz) and D_2O (3.6 THz), lasers were synchronized with a standard at an accuracy around 10^{-13} [Domnin *et al.*, 1980].

Many new lines of laser emission by diatomic sodium and lithium molecules have been observed [Man-Pichot and Brillet, 1980]. They present an intrinsic frequency stability which is useful for obtaining secondary frequency and wavelength standards in the visible regions.

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 520 THz ($\lambda = 0.58$ 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. Values of laser frequencies recommended by the Comité international des poids et mesures (CIPM) in 1983 for the realization of the metre are given in Table II. Table III 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.*, 1980; Domnin *et al.*, 1980].

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	He-Ne (3.39)	88.376 245	$\pm 5 \times 10^{-7}$
1973	CO_2 (10.18) CO_2 (9.33) He-Ne (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	$\pm 1.3 \times 10^{-7}$
1979	CO_2 (OsO_4) (10.53)	28.464 676 938 5	$\pm 3 \times 10^{-11}$
1980	He-Ne (CH_4) (3.39)	88.376 181 618	$\pm 1.6 \times 10^{-10}$
1981	He-Ne (CH_4-F_2^2) (3.39)	88.376 181 603 4	$\pm 1.6 \times 10^{-11}$
1981	He-Ne (CH_4-E) (3.39)	88.373 149 033 0	$\pm 2 \times 10^{-11}$
1982	Dye (I_2) (0.576)	520.206 808 547	1.6×10^{-10}

TABLE II – *Values of laser frequencies recommended by the CIPM in 1983 for the realization of the metre*

Laser	Frequency (THz)	Relative uncertainty (3σ)
He-Ne laser, stabilized by saturated absorption in CH_4 (transition ν_3, P (7), component F_2^2)	88.376 181 608	$\pm 1.3 \times 10^{-10}$
Dye laser (or He-Ne laser with doubling of frequency), stabilized by saturated absorption in $^{127}I_2$ (transition 17-1, P (62), component o)	520.206 808 51	$\pm 6 \times 10^{-10}$
He-Ne laser, stabilized by saturated absorption in $^{127}I_2$ (transition 11-5, R (127), component i)	473.612 214 8	$\pm 10 \times 10^{-10}$
He-Ne laser, stabilized by saturated absorption in $^{127}I_2$ (transition 9-2, R (47), component o)	489.880 355 1	$\pm 11 \times 10^{-10}$
Ar^+ laser, stabilized by saturated absorption in $^{127}I_2$ (transition 43-0, P (13), component a_3)	582.490 603 6	$\pm 13 \times 10^{-10}$

TABLE III – *Main properties of point contact diodes usable as frequency multipliers*

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 520 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}.

A phase-locked chain comprising HCOOH and CH_3OH optical pumping lasers as transfer oscillators has permitted a new CO_2 (OsO_4) laser measurement around 29 THz to a precision of about 1.5×10^{-12}.

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, when 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.*, 1981].

At the United States National Bureau of Standards, the o hyperfine component of the $^{127}I_2$ 17-1 P(62) transition at 520 THz (576 nm) in iodine was measured with respect to the CH_4-stabilized 88 THz He-Ne laser. A 26 THz CO_2 laser, a central colour laser at 130 THz, and an He-Ne laser at 260 THz, were used as transfer oscillators. The measured I_2 frequency was 520.206 808 547 THz with a total uncertainty of 1.6×10^{-10}. The 1.15 nm ^{20}Ne Lamb-dip stabilized laser was measured to be 260.103 249 26 THz, with a total uncertainty of 3.1×10^{-10}.

By mutual and primary standard phase synchronization of multiplier chain lasers, a standard-frequency comb was produced up to the 30 THz region and high-accuracy frequency measurements were carried out on the F_2^2- and E-components of optical CO_2 (OsO_4) and He-Ne (CH_4) standards. For the CO_2 (OsO_4) laser, the measurement accuracy was around 3×10^{-11} [Domnin *et al.*, 1980], for the He-Ne (CH_4) laser around 1.6×10^{-11} (F_2^2- component) and around 2×10^{-11} (E-component) [Domnin *et al.*, 1981a and b].

A novel method of extending a frequency chain from the Cs standard to 30 THz using only CO_2 lasers was demonstrated and used to obtain absolute frequency measurements of five CO_2 lines [Whitford, 1980]. The chain has been phase-locked to the Cs frequency for periods of up to 20 min [Whitford, 1984a and b].

Laser frequencies of the hot bands $^{12}C^{16}O_2$ and $^{13}C^{16}O_2$ and of the sequence bands of $^{13}C^{16}O_2$ and $^{12}C^{18}O_2$ have been measured by heterodyning against the known regular CO_2 laser frequencies [Petersen *et al.*, 1981 and 1984; Siemsen, 1980 and 1981].

A cw NH_3 laser pumped by a CO_2 laser has been built and 30 Lamb-dip stabilized frequencies of $^{14}NH_3$ and $^{15}NH_3$ were measured by heterodyning against known CO_2 laser frequencies [Siemsen and Reid, 1985].

The first reported direct frequency measurement of a visible transition [Baird *et al.*, 1979] was of iodine hyperfine components in the yellow (520 THz), at twice the known frequency of a 260 THz He-Ne laser.

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). Examples are: in-depth studies 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, it should be remembered 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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REPORT 898-1 *

PERFORMANCE AND RELIABILITY OF REFERENCE CLOCKS

(Question 8/7 and Decision 29)

(1982-1986)

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.

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.

2. Terms and definitions concerning the characterization of clock performance

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 $\pm$ 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 non-stationary nature of the time interval errors (TIE) of actual clocks over long 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 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 t_0 is the starting time of the interval S, one has:

$$TIE = x(t_0 + S) - x(t_0) = \int_{t_0}^{t_0 + S} y(t)\,\mathrm{d}t \tag{1}$$

using the notation of Report 580. The slope indicated as a dashed line in Fig. 1/G.811 thus represents the average frequency departure:

$$\bar{y}_0(t_0, S) = \frac{1}{S} \int_{t_0}^{t_0 + S} y(t)\,\mathrm{d}t \tag{2}$$

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 Director, CCIR, is requested to bring this Report to the attention of the CCITT. This Report replaces the previous version of Report 898 and Report 737 which is hereby cancelled.

The following estimate of the standard deviation of the TIE, 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:

$$(TIE)_{est} = \frac{a}{2}\, t^2 + t \cdot (\sigma_{y_0}^2 + \sigma_y^2(\tau = t))^{1/2} \qquad (3)$$

where:

a : normalized linear frequency drift per unit of time (ageing);

σ_{y_0} : two sample standard deviation of the initial frequency setting; and

$\sigma_y(\tau)$: 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

3.1 *General*

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 MTBF estimate requires many clock-years of data to develop a useful statistic. These data can be obtained from the large number of clocks in operational use as reported in § 3.3. However, the MTBF statistic ignores the time-dependent characteristic of atomic clock reliability. Section 3.2 shows that those caesium clocks of a carefully managed clock ensemble that have been in operation for more than one year appear to be more reliable than new units. This may be due to ageing or end-of-life of some parts, such as the beam tube or optical package. Section 3.3 discusses why this characteristic was not found in the large set of clocks in general operation.

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 probability 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 $t + \Delta t$. If clocks are removed from further reliability evaluation following their first failure, the conditional failure rate function may be defined as:

$$Z(t)\,\Delta t = -\left[\frac{N(t + \Delta t) - N(t)}{N(t)}\right], \qquad (4)$$

where $N(t)$ represents the number of clocks expected to be operating at a time t and $N(0)$ represents the number of clocks initially in a given ensemble.

Under the same conditions, $Z(t)$ may be estimated to be:

$$Z(t) = -\left[\frac{\Delta N'(t)}{N'(t)\,\Delta t}\right] \qquad (5)$$

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 $\Delta N' = N'(t + \Delta t) - N'(t)$.

If clocks that fail are repaired and put back into operation, then $Z(t)$ can be estimated to be:

$$Z(t) = \frac{F}{U} \tag{6}$$

where:

F: number of failures during a given time interval; and

U: number of units in operation during the same time interval.

The slight conceptual difference between the two $Z(t)$ defined above are considered as unimportant.

$Z(t)$ 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. In this case, the MTBF can be estimated to be equal to the half-life t_{HL}.

$Z(t) = kt$, 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.

3.2 *Observations of a carefully managed caesium clock ensemble*

The conditional failure rate (in January, 1970) of a clock ensemble at the United States Naval Observatory was approximately described by $Z(t) = kt$ where $k = 0.1$. Most of these clocks were 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 Navel Observatory clock ensemble composed of two different commercial models, some of which were early production units.

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

3.3 *Operational clock reliability*

Data on the operational reliability are 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.

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 October, 1983. Up to this date, Reports have been received from the following countries: the People's Republic of China, Federal Republic of Germany, United States of America, France, Italy, Japan, the Netherlands, Sweden, Switzerland and the United Kingdom. The total number of units reported on was 4125 which included 1230 caesium clocks, 225 rubidium clocks and 2670 crystal oscillators.

Most of the data covered the 11-year period from 1970 to 1980.

In the processing of the data, 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.

There are several reasons why conditional failure rate functions as defined in § 3.1 cannot be estimated with less "uncertainty" than that of the MTBF estimate mentioned above. A large variation exists in the age and model design; moreover, in order to obtain a large statistical sample, data were taken from all available sources in the 11-year period, including clocks which failed, were repaired and subsequently may have failed again one or more times.

There is also a wide variance in the MTTR (mean time to repair a failed unit including shipping time) figures reported. Since the individual averages vary between 80 and 140 days and there is a strong influence due to 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 III, IV and V show the resulting MTBF estimates based on the available data.

TABLE III – *Caesium clocks*

Model (year)	ΣU	ΣF	MTBF (years)	MTTR (days)	No. of units in survey
Users' report					
HP5061A (1968)	3347	823	$4.07^{+0.69}_{-0.52}$	90	492
OSA 3200 (1975/76)	96	32	$3.0^{+0.6}_{-0.4}$	90	25
HP5061A-004 (1973)	118	44	$2.68^{+0.41}_{-0.31}$	90	24
HP5060A (1) (1965)	133	42	3.17	90	21
OSA 3000 (1976)	29	10	$2.9^{+0.9}_{-0.6}$	90	14
HP5062 (1) (1973)	1648	319 (2)	$5.2^{+1.0}_{-0.7}$		408
Manufacturers' report (see comment § 3.3)					
OSA 3000 (1976)	285	30	9.6	35	97
OSA 3200 (1975)	679	161	4.22	50	149

(1) Old model, no longer in production.

(2) Only caesium beam tube failures and other failures associated with beam tube failures are included for this particular type of clock.

TABLE IV – *Rubidium clocks*

Model (year)	ΣU	ΣF	MTBF (years)	MTTR (days)	No. of units in survey
HP5065A (1970)	159	21	7.6	120	31
FRT/FRK (1973)	584	52	11.2	90	159
XSRM (1972)	71	13	5.5	90	15
P01 (1976)	44	41	1.08	–	20

TABLE V – *Crystal clocks*

Model	1st year	ΣU	ΣF	MTBF (years)	No. of units in survey	Notes
Users' report						
B5400	1974	48	1	48	11	
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 III, 1σ confidence margins are given for the MTBF estimates. These margins have been computed in the following way:

The data on the largest population (HP5061A, 492 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:

$$Z_i = \frac{\Sigma F_i}{\Sigma U_i}$$

was computed for each year (1970 to 1980), as shown in Table VI 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 $Z_m = 0.22$ with a standard deviation of $\sigma_z = \pm 0.094$. The probable relative error of the median is thus about $\pm$ 6%. The inverse of the median value, $Z_m^{-1} = 4$ years is very close to the MTBF estimate of 4.07 years shown in Table III in which the confidence margins have been computed using the above 12.5% probable relative error estimate on the average failure rates of $1/4.07 = 0.246$.

The confidence margins of the other models have been computed in a similar way. Data on the HP5060A are of historical interest only. No such estimates have been done on the data summarized in Tables IV and V. For Table IV, the populations are too small and the units in Table V are quite diverse and some units have consistently high MTBF.

Table VII 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].

A comment is in order on the bias appearing between user and manufacturers reports, especially in Table III. One 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 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 VI

Year	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980
ΣU_i	51	70	104	162	204	255	291	328	349	370	386
ΣF_i	7	24	19	16	32	36	48	54	67	95	118
Z_i	0.137	0.343	0.183	0.099	0.157	0.141	0.165	0.165	0.192	0.257	0.306

TABLE VII – *Caesium beam clocks*

Model: HP5061A – OSA B3200 – HP5061A-004 – HP5062A – OSA 3000

Model		Atomic Resonator	Crystal Oscillator	Frequency conditioning circuits	Servo circuits	Output circuits	Internal power conditioning	Other parts	ΣU (ΣF) ([1])
Users' report									
HP5061A									
	F_i	175	72	97	50	12	68	28	3347
	%	35	14	19	10	2	14	6	(502)
OSA B3200									
	F_i	38	4	0	0	8	40	15	96
	%	36	4	0	0	8	38	14	(105)
HP5061A-004									
	F_i	16	9	4	4	1	2	4	118
	%	40	23	10	10	3	5	10	(40)
HP5062A									
	F_i	213	46	41	88	69	228	102	1648
	%	27	6	5	11	9	29	13	(787)
Manufacturers' report									
HP5061 ([2])									
5061-004	F_i	62	17	44	21	40	6	4	(194)
5062C	%	32	9	23	11	20	3	2	
OSA 3200	F_i	20	21	15	15	9	83	1	679
	%	12	13	9	9	5	51	1	(164)
OSA 3000	F_i	8	8	1	3	1	3	6	289
	%	27	27	3	10	3	10	20	(30)

([1]) Usually larger than the ΣF reported in Table III due to multiple simultaneous defects.

([2]) Number of units not available.

3.4 *Qualifications and acceptance tests*

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 (100 mbar = 10^4 Pa)) and geomagnetic field (per 100 mOe between -135 and 135 mOe (100 mOe = $8Am^{-1}$)) 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 the effects of the above environmental influences are not negligibly small and that the environmental conditions should be carefully controlled in order to keep the operation of atomic clocks as uniform as possible [Iijima *et al.*, 1978].

It should be noted, however, that the specific values could not be generalized in the form 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 limitations are established for a given design, *acceptance test levels* should be set, and it should be specified that each delivered unit has to be 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.

3.5 *Continuity of operation*

In most applications of time and frequency standards, particularly in the field of communications, stringent requirements are placed on continuity of operation which requires 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.

Other possibilities of securing continuity of operation exist such as using synchronized slave oscillators having a memory in the control system.

3.6 *Conclusions*

The survey on the reliability of precision clocks presented in § 3.3 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. It should also be realized that any statistic based on widely different sources and conditions of operation has limitations and is subject to possible biases.

Tables III and IV also show the importance of production experience for obtaining improved 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 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 a distance is the uncertainty of transmission path delay which usually determines the choice of the comparison method. Although synchronism in an extended network is feasible and desirable, the fact that transmission delays are not perfectly stable raises the question of the level of precision which should be provided. The effect of variations in transmission delay can be largely eliminated by two-way time comparisons. Such comparisons can be achieved relatively easily by using the normal synchronization pulses of duplex digital communications links, i.e., those providing simultaneous communication in both directions. This makes it practicable to provide very precise measurements of timing errors for use in the operation of digital communication networks.

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 each having their master clock individually referred to UTC. These two varieties have been examined 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).

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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.

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 3-1/7

STABILITY OF STANDARD-FREQUENCY AND TIME-SIGNAL EMISSIONS AS RECEIVED

(1956-1959-1963-1986)

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 in any medium, 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 degradation 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 and Report 271.

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 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).

STUDY PROGRAMME 5B-1/7

TIME KEEPING AND SYNCHRONIZATION AT LEVELS LESS THAN 1 NANOSECOND

(1983-1985)

The CCIR,

CONSIDERING

(a) that reference standard frequency and time signals are generated at remotely located sites and cannot at present be maintained in synchronism at nanosecond levels,

UNANIMOUSLY DECIDES that the following studies should be carried out:

1. improvement of the ability to make intercomparisons among frequency standards at levels of less than 1 ns;

2. determination of timing limitations based on instrumentation instabilities, propagation instabilities and other corrections including relativistic effects due to the influence of the nearer celestial bodies.

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 Report 898 ~~and Decision 29.~~

QUESTION 9/7

SIGNAL DELAYS IN ANTENNAS AND OTHER CIRCUITS FOR HIGH-PRECISION TIME TRANSFER

(1986)

The CCIR,

CONSIDERING

(a) that there is a need for accuracy in precision time transfer exceeding that currently available;

(b) that the antenna and other electrical circuits are critical elements in the radio signal path at the transmitting, relaying and receiving sites for the accuracies desired,

UNANIMOUSLY DECIDES that the following question should be studied:

what methods can be recommended to determine and characterize the delay introduced by the antennas and associated circuits for transferring precision time over a radio signal path?

STUDY PROGRAMME 9A/7

CHARACTERIZATION OF SIGNAL DELAYS IN ANTENNAS

(1986)

The CCIR,

CONSIDERING

(a) the need to account for antenna delay in radio paths for precision time signal transfer;

(b) the desirability to have standard antenna designs of known delay characteristics;

(c) the desirability to have international agreement on the measurement technology,

UNANIMOUSLY DECIDES that the following studies should be carried out:

1. an investigation of the antenna parameters to quantify the characteristics influencing delay in the passage of time signals, such as wavelength, aperture, bandwidth, impedance, polarization, directivity, dielectric effects, array factors, travelling wave effects, lens effects, anisotropic and inhomogeneous media effects;

2. an investigation of supporting electrical circuits as they affect signal delay;

3. an investigation of delay in standard type dipoles, horns or long wires suitable for covering the radio spectrum;

4. an investigation of these environmental effects that could affect delay such as temperature, pressure, humidity, magnetic field, acceleration, relative motion and relativistic effects;

5. an investigation of measurement technology to address accuracies in the microsecond, nanosecond and picosecond ranges.

QUESTION 10/7

PERFORMANCE OF FREQUENCY AND TIME STANDARDS

(1986)

The CCIR,

CONSIDERING

(a) that the World Administrative Radio Conference (Geneva, 1979) reaffirmed the needs for coordination of the establishment and operation of a standard frequency and time-signal service on a world-wide basis;

(b) that the accuracy with which standard frequencies and time signals may be transmitted depends essentially upon the performance of the frequency and time standards;

(c) that there is a need for increased accuracy of standard frequency and time signals in order to improve world-wide coordination of these emissions;

(d) that for many applications, the performance of frequencies and time standards is of primary importance,

UNANIMOUSLY DECIDES that the following question should be studied:

1. what are the limitations in the performance of frequency and time standards;

2. what are the applicable parameters for characterizing the performance of frequency and time standards;

3. what can be done to improve the performance of frequency and time standards?

STUDY PROGRAMME 10A/7

PERFORMANCE AND CHARACTERIZATION OF FREQUENCY AND TIME STANDARDS

(1986)

The CCIR,

CONSIDERING

(a) that there is a need for improved characterization of frequency and time standards;

(b) that there is a need for increased accuracy of frequency and time standards,

UNANIMOUSLY DECIDES that the following studies should be carried out:

1. an investigation of the characterization of frequency and time standards;

2. an investigation of the techniques for measurement and evaluation of the performance of frequency and time standards;

3. an investigation of the technology which might result in improved performance of frequency and time standards.

STUDY PROGRAMME 10B/7*

TIME SCALE ALGORITHMS AND STATISTICAL PROBLEMS

(1986)

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.

RESOLUTION 14-4

STANDARD-FREQUENCY AND TIME-SIGNAL EMISSIONS

(Question 1/7)

(1963–1966–1970–1974–1986)

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, to the Director, CCIR, and, for official publication, to the Director, BIH;

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) and the International Committee of Weights and Measures (CIPM).

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* Formerly Study Programme 1D-1/7.

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) and the International Union of Pure and Applied Physics (IUPAP).

OPINION 71-1 *

DOCUMENTATION OF TIME TRANSMISSIONS

(Question 1/7)

(1982–1986)

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,

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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.

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 and to the World Data Centres A, B and C.

ANNEX I

ADDRESSES OF THE WORLD DATA CENTRES

World Data Centre A: WDC-A, Rotation of the Earth
c/o US Naval Observatory
34th Massachusetts Avenue NW
WASHINGTON, DC 20390
United States of America

World Data Centre B: State Time and Frequency Commission
Gosstandart
Leninsky Prospect 9
MOSCOW 117049
USSR

World Data Centre C: Rutherford Appleton Laboratory
Chilton
DIDCOT
Oxon OX11 OQX
United Kingdom

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,

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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.

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.

DECISION 65

HANDBOOK ON THE USE OF SATELLITE TIME AND FREQUENCY DISSEMINATION

(1985)

CCIR Study Group 7,

CONSIDERING

(a) the extent and depth of the studies carried out by Interim Working Party (IWP) 7/4 over two study periods on the technical possibilities for time transfer and dissemination by means of satellites;

(b) that the utility and economy of satellite methods of time dissemination may find application in a number of developing countries desirous of establishing a national time and frequency reference;

(c) that satellite methods of dissemination may increasingly supplement and replace some of the existing ground-based services of standard-frequency and time-signal dissemination;

(d) that operational experience has been accumulated over many years with a time and frequency service allied to the GOES meteorological satellites;

(e) that the use of the geostationary-satellite orbit for regional telecommunication systems, e.g. ARABSAT, BRAZILSAT, INSAT, PALAPA, etc., offers technical possibilities for adding a time and frequency channel of modest bandwidth;

(f) that the advent of direct satellite TV broadcasting will similarly extend the possibilities for inserting a time reference in an already time-disciplined system;

(g) that Resolution 33 on technical cooperation encourages the prepartion of handbooks,

DECIDES

1. that an ad hoc Working Group should be formed with the task of preparing the text of a handbook on satellite-based services of time and frequency dissemination;

2. that this handbook should draw initially on the texts of Study Group 7 and should also include any relevant documentation from the text of IWP 7/4 and also of Study Groups 2, 4, 8, 10 and 11 and from the extensive literature associated with the systems of navigation and position determination by satellite;

3. that administrations should be encouraged to provide specific contributions to the text of the handbook in those areas in which they have developed special knowledge or expertise;

4. that a coordinator be appointed to supervise the overall compilation and integration of the contributions;

5. that the aim of the coordinator and the contributors should be to complete the text of the handbook before the XVIIth Plenary Assembly.

ANNEX I

At the end of the XVIth Plenary Assembly, 1986, the following Administrations and International Organizations have indicated their participation in the ad hoc Working Group:

Administrations:

Austria
Canada
United States of America
France
India
Japan
United Kingdom
Yugoslavia (Socialist Federal Republic of)
BIPM (BIH)

Coordinator of the ad hoc Working Group:

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Middlesex TW11 OLW
United Kingdom

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Telex: 262 344 NPL G

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