

**Bureau International des Poids et Mesures**

# **Consultative Committee for Time and Frequency (CCTF)**

14th Meeting (April 1999)

#### Note on the use of the English text

To make its work more widely accessible the Comité International des Poids et Mesures publishes an English version of its reports.

Readers should note that the official record is always that of the French text. This must be used when an authoritative reference is required or when there is doubt about the interpretation of the text.

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**MEMBER STATES  
OF THE METRE CONVENTION**

Argentina	Japan
Australia	Korea (Dem. People's Rep. of)
Austria	Korea (Rep. of)
Belgium	Mexico
Brazil	Netherlands
Bulgaria	New Zealand
Cameroon	Norway
Canada	Pakistan
Chile	Poland
China	Portugal
Czech Republic	Romania
Denmark	Russian Federation
Dominican Republic	Singapore
Egypt	Slovakia
Finland	South Africa
France	Spain
Germany	Sweden
Hungary	Switzerland
India	Thailand
Indonesia	Turkey
Iran (Islamic Rep. of)	United Kingdom
Ireland	United States
Israel	Uruguay
Italy	Venezuela



## **THE BIPM AND THE METRE CONVENTION**

The Bureau International des Poids et Mesures (BIPM) was set up by the Metre Convention signed in Paris on 20 May 1875 by seventeen States during the final session of the diplomatic Conference of the Metre. This Convention was amended in 1921.

The BIPM has its headquarters near Paris, in the grounds (43 520 m<sup>2</sup>) of the Pavillon de Breteuil (Parc de Saint-Cloud) placed at its disposal by the French Government; its upkeep is financed jointly by the Member States of the Metre Convention.

The task of the BIPM is to ensure worldwide unification of physical measurements; its function is thus to:

- establish fundamental standards and scales for the measurement of the principal physical quantities and maintain the international prototypes;
- carry out comparisons of national and international standards;
- ensure the coordination of corresponding measurement techniques;
- carry out and coordinate measurements of the fundamental physical constants relevant to these activities.

The BIPM operates under the exclusive supervision of the Comité International des Poids et Mesures (CIPM) which itself comes under the authority of the Conférence Générale des Poids et Mesures (CGPM) and reports to it on the work accomplished by the BIPM.

Delegates from all Member States of the Metre Convention attend the General Conference which, at present, meets every four years. The function of these meetings is to:

- discuss and initiate the arrangements required to ensure the propagation and improvement of the International System of Units (SI), which is the modern form of the metric system;
- confirm the results of new fundamental metrological determinations and various scientific resolutions of international scope;
- take all major decisions concerning the finance, organization and development of the BIPM.

The CIPM has eighteen members each from a different State: at present, it meets every year. The officers of this committee present an annual report on the administrative and financial position of the BIPM to the Governments of

the Member States of the Metre Convention. The principal task of the CIPM is to ensure worldwide uniformity in units of measurement. It does this by direct action or by submitting proposals to the CGPM.

The activities of the BIPM, which in the beginning were limited to measurements of length and mass, and to metrological studies in relation to these quantities, have been extended to standards of measurement of electricity (1927), photometry and radiometry (1937), ionizing radiation (1960) and to time scales (1988). To this end the original laboratories, built in 1876-1878, were enlarged in 1929; new buildings were constructed in 1963-1964 for the ionizing radiation laboratories and in 1984 for the laser work. In 1988 a new building for a library and offices was opened.

Some forty-five physicists and technicians work in the BIPM laboratories. They mainly conduct metrological research, international comparisons of realizations of units and calibrations of standards. An annual report, published in the *Procès-Verbaux des Séances du Comité International des Poids et Mesures*, gives details of the work in progress.

Following the extension of the work entrusted to the BIPM in 1927, the CIPM has set up bodies, known as Consultative Committees, whose function is to provide it with information on matters that it refers to them for study and advice. These Consultative Committees, which may form temporary or permanent working groups to study special topics, are responsible for coordinating the international work carried out in their respective fields and for proposing recommendations to the CIPM concerning units.

The Consultative Committees have common regulations (*BIPM Proc.-Verb. Com. Int. Poids et Mesures*, 1963, **31**, 97). They meet at irregular intervals. The chairman of each Consultative Committee is designated by the CIPM and is normally a member of the CIPM. The members of the Consultative Committees are metrology laboratories and specialized institutes, agreed by the CIPM, which send delegates of their choice. In addition, there are individual members appointed by the CIPM, and a representative of the BIPM (Criteria for membership of Consultative Committees, *BIPM Proc.-Verb. Com. Int. Poids et Mesures*, 1996, **64**, 124). At present, there are ten such committees:

1. The Consultative Committee for Electricity and Magnetism (CCEM), new name given in 1997 to the Consultative Committee for Electricity (CCE) set up in 1927;



2. The Consultative Committee for Photometry and Radiometry (CCPR), new name given in 1971 to the Consultative Committee for Photometry (CCP) set up in 1933 (between 1930 and 1933 the CCE dealt with matters concerning photometry);
3. The Consultative Committee for Thermometry (CCT), set up in 1937;
4. The Consultative Committee for Length (CCL), new name given in 1997 to the Consultative Committee for the Definition of the Metre (CCDM), set up in 1952;
5. The Consultative Committee for Time and Frequency (CCTF), new name given in 1997 to the Consultative Committee for the Definition of the Second (CCDS) set up in 1956;
6. The Consultative Committee for Ionizing Radiation (CCRI), new name given in 1997 to the Consultative Committee for Standards of Ionizing Radiation (CCEMRI) set up in 1958 (in 1969 this committee established four sections: Section I (X- and  $\gamma$ -rays, electrons), Section II (Measurement of radionuclides), Section III (Neutron measurements), Section IV ( $\alpha$ -energy standards); in 1975 this last section was dissolved and Section II was made responsible for its field of activity);
7. The Consultative Committee for Units (CCU), set up in 1964 (this committee replaced the “Commission for the System of Units” set up by the CIPM in 1954);
8. The Consultative Committee for Mass and Related Quantities (CCM), set up in 1980;
9. The Consultative Committee for Amount of Substance (CCQM), set up in 1993;
10. The Consultative Committee for Acoustics, Ultrasound and Vibration (CCAUV), set up in 1999.

The proceedings of the General Conference, the CIPM and the Consultative Committees are published by the BIPM in the following series:

- *Comptes Rendus des Séances de la Conférence Générale des Poids et Mesures*;
- *Procès-Verbaux des Séances du Comité International des Poids et Mesures*;
- *Reports of Meetings of Consultative Committees*.

The BIPM also publishes monographs on special metrological subjects and, under the title *Le Système International d'Unités (SI)*, a brochure, periodically updated, in which are collected all the decisions and recommendations concerning units.

The collection of the *Travaux et Mémoires du Bureau International des Poids et Mesures* (22 volumes published between 1881 and 1966) and the *Recueil de Travaux du Bureau International des Poids et Mesures* (11 volumes published between 1966 and 1988) ceased by a decision of the CIPM.

The scientific work of the BIPM is published in the open scientific literature and an annual list of publications appears in the *Procès-Verbaux* of the CIPM.

Since 1965 *Metrologia*, an international journal published under the auspices of the CIPM, has printed articles dealing with scientific metrology, improvements in methods of measurement, work on standards and units, as well as reports concerning the activities, decisions and recommendations of the various bodies created under the Metre Convention.

## **LIST OF MEMBERS OF THE CONSULTATIVE COMMITTEE FOR TIME AND FREQUENCY**

as of 20 April 1999

### **President**

S. Leschiutta, member of the Comité International des Poids et Mesures,  
Istituto Elettrotecnico Galileo Ferraris, Turin.

### **Executive secretary**

G. Petit, Bureau International des Poids et Mesures [BIPM], Sèvres.

### **Members**

All-Russian Research Institute for Physical, Technical and Radio-Technical  
Measurements [VNIIFTRI], Moscow.

Bureau National de Métrologie: Laboratoire Primaire du Temps et des  
Fréquences [BNM-LPTF], Paris.

Communications Research Laboratory [CRL], Tokyo.

CSIRO, Division of Applied Physics [CSIRO], Lindfield.

International Astronomical Union [IAU].

International Telecommunication Union [ITU], Radiocommunication  
Bureau.

International Union of Geodesy and Geophysics [IUGG].

International Union of Radio Science [URSI].

Istituto Elettrotecnico Nazionale Galileo Ferraris [IEN], Turin.

Korea Research Institute of Standards and Science [KRISS], Taejeon.

Laboratoire de l'Horloge Atomique [LHA] du Centre National de la  
Recherche Scientifique [CNRS], Orsay.

National Institute of Metrology [NIM], Beijing.

National Institute of Standards and Technology [NIST], Boulder.

National Physical Laboratory [NPL], Teddington.

National Physical Laboratory of India [NPLI], New Delhi.

National Physical Laboratory of Israel [INPL], Jerusalem.

National Research Council of Canada [NRC], Ottawa.

National Research Laboratory of Metrology [NRLM], Tsukuba.

Nederlands Meetinstituut: Van Swinden Laboratorium [NMi-VSL], Delft.

Observatoire Royal de Belgique [ORB], Brussels.

Office Fédéral de Métrologie [OFMET], Wabern/Observatoire Cantonal [ON], Neuchâtel.

Physikalisch-Technische Bundesanstalt [PTB], Braunschweig.

Real Instituto y Observatorio de la Armada [ROA], San Fernando.

Technical University [TUG], Graz.

U.S. Naval Observatory [USNO], Washington DC.

B. Guinot.

The Director of the Bureau International des Poids et Mesures [BIPM],  
Sèvres.

**Consultative Committee  
for Time and Frequency**

**Report of the 14th meeting**

(20-22 April 1999)

**to the Comité International des Poids et Mesures**

## Agenda

- 1 Opening of the meeting; appointment of a rapporteur.
- 2 Progress in primary frequency standards:
  - 2.1 Operating primary frequency standards and new primary standards under development;
  - 2.2 Report of the CCTF working group on the expression of uncertainties in primary frequency standards.
- 3 Present status of TAI:
  - 3.1 Report on TAI of the BIPM Time Section;
  - 3.2 Report of the CCTF working group on TAI.
- 4 The future of leap seconds.
- 5 Time and frequency transfers using the two-way method: report of the CCTF working group on TWSTFT.
- 6 Time and frequency transfer methods and techniques using navigation satellites:
  - 6.1 GPS phase measurement: report on the IGS/BIPM Pilot Project,
  - 6.2 GPS and GLONASS time transfer standards: report of the sub-group on GPS/GLONASS.
- 7 General relativity and space-time references:
  - 7.1 Report of the BIPM/IAU Joint Committee on General Relativity for Space-Time Reference Systems and Metrology,
  - 7.2 Conventional terrestrial reference system.
- 8 Timing of millisecond pulsars.
- 9 Clocks in space: problems and opportunities.
- 10 Key comparisons and the Mutual Recognition Arrangement in the time and frequency domain.
- 11 *Mise en pratique* of the SI second.
- 12 The BIPM work programme.
- 13 Recommendations.
- 14 Other business.
- 15 Closure of the meeting.

## **1 OPENING OF THE MEETING; APPOINTMENT OF A RAPPORTEUR**

The Consultative Committee for Time and Frequency (CCTF) held its 14th meeting at the Bureau International des Poids et Mesures (BIPM), at Sèvres. Six sessions took place, from 20 to 22 April 1999.

The following were present: A. Bauch (PTB), C. Boucher (IUGG), J.-S. Boulanger (NRC), G. de Jong (NMi-VSL), N. Dimarcq (LHA), K. Dorenwendt (PTB), G. Dudle (OFMET), P. Fisk (CSIRO-NML), M. Granveaud (BNM-LPTF), B. Guinot, M. Imae (CRL), D. Kirchner (TUG), J. Kovalevsky (IAU), J. Lavery (NPL), H.S. Lee (KRISS), A. Lepek (INPL), S. Leschiutta (President of the CCTF, IEN), F.M. Ma (NIM), J. McA. Steele (URSI), D. McCarthy (USNO), T. Morikawa (CRL), S.I. Ohshima (NRLM), J. Palacio (ROA), P. Pâquet (ORB), L. Prost (OFMET), S.B. Pushkin (VNIIFTRI), T.J. Quinn (Director of the BIPM), A. Sen Gupta (NPLI), D.B. Sullivan (NIST), P. Tavella (IEN).

Observers: C. Audoin (LHA), A.B. Demichev, Yu. S. Domnin (VNIIFTRI), R. Douglas (NRC), J. Levine (NIST), D.N. Matsakis (USNO), T.E. Parker (NIST).

Invited: E.F. Arias, H.A. Chua (PSB), W.J. Klepczynski, C.S. Liao (TL), L. Marais (CSIR-NML), J. Ray (USNO).

Also present: P. Giacomo (Director emeritus of the BIPM); J. Azoubib, Z. Jiang, W. Lewandowski, G. Petit, P. Wolf (BIPM).

Sent regrets: A. Clairon (BNM-LPTF), K. Johnston (USNO).

The President opened the meeting, noting that the forty-eight people present comprised the largest Consultative Committee meeting which had yet been held, and that some organizations had considered the meeting sufficiently important to send two or three delegates. He also noted that Dr Fisk had agreed to serve as rapporteur.

Dr Quinn was invited to make some general remarks. He reported that since the 13th CCDS meeting Dr Claudine Thomas had moved from her position as Head of the BIPM Time Section to other duties within the BIPM. He thanked her for her eight years of effort in her previous position, and said that the present healthy status of TAI was one outcome for which she is largely responsible. Dr Thomas is now managing the key comparison database, which is a central component of the new system of Mutual Recognition Arrangement (MRA).

Dr Quinn introduced Dr Elisa Felicitas Arias as the person nominated to replace Dr Thomas as Head of the Time Section. Dr Arias is presently Director of the Naval Observatory in Buenos Aires, and Professor of astronomy at the University of La Plata (Argentina). She will take up her new position at the BIPM in November 1999. Dr Quinn thanked Dr Gérard Petit for serving as interim Head of the Time Section.

Dr Quinn said that one of the major tasks of the BIPM was the maintenance of International Atomic Time TAI, and suggested that an agenda item on the work programme of the BIPM Time Section be added. The President agreed.

## **2        PROGRESS IN PRIMARY FREQUENCY STANDARDS**

The President remarked on the growing interest in atomic frequency standards, as evidenced by more than seventy papers on this subject being presented at the recent joint meeting of the European Frequency and Time Forum and the IEEE Frequency Control Symposium (EFTF/FCS). He noted that the 1997 Nobel Prize for Physics was awarded for activities which led to important new developments in primary frequency standards.

The President also commended the PTB and BNM-LPTF for carrying out important measurements of the frequency shift in caesium due to black-body radiation, following recommendation S 2 of the 13th CCDS held in 1996.

### **2.1      Operating primary frequency standards and new primary standards under development**

Dr Quinn pointed out that the CCTF working documents, including the reports from individual laboratories, will be bound and may be referred to, so that short summaries of the relevant sections of the reports will suffice under this agenda item.

Dr Lee presented the report from the KRISS (CCTF99-02). Three new primary Cs standards are under development:

- 1) an optically pumped conventional atomic beam standard: this is presently almost complete, and undergoing evaluation of its accuracy;



- 2) a fountain standard: laser cooling of the Cs atoms to 2.2  $\mu\text{K}$  has been demonstrated, and progress is being made towards launching the atoms through the microwave cavity;
- 3) a continuous slow atomic beam standard: a laser-cooled slow beam with a mean velocity of less than 50 m/s has been demonstrated.

Dr Tavella presented the report from the IEN (CCTF99-03). A prototype Cs maser is under development, and its predicted short-term stability is characterized by an Allan deviation  $\sigma_y(\tau)$  of  $1 \times 10^{-13} \tau^{-1/2}$ . The IEN is also building a Cs fountain standard in collaboration with the NIST and Turin Polytechnic, the optical system and vacuum chambers of which have been completed.

Dr Bauch presented the report from the PTB (CCTF99-04). The thirty year-old primary standard CS1 which was refurbished and modernized during 1995 and 1996 was returned to service in 1997, and its type B uncertainty has been calculated as 7 parts in  $10^{15}$ . Dr Bauch also reported that the fractional frequency shift in the Cs clock transition due to the electric field component of the black-body radiation field at 300 K was measured as  $-17.9 \times 10^{-15}$  with a standard uncertainty of  $1.6 \times 10^{-15}$ , in close agreement with the theoretical prediction of  $-16.9 \times 10^{-15}$ . The PTB is also building a Cs fountain standard and a preliminary comparison over five days with an hydrogen maser has recently been completed with encouraging results.

Dr Dudgeon presented the joint report from the Swiss Federal Office of Metrology (Office Fédéral de Métrologie, OFMET) and the Observatoire de Neuchâtel (ON) (CCTF99-05). A Cs fountain is under development, with the novel feature that the atoms are launched in a continuous stream. The first Ramsey fringes in this configuration are expected in late 1999 or early 2000, but no uncertainty budget is yet available.

Dr Boulanger presented the report from the NRC (CCTF99-06). The frequency of the 674 nm transition in a single, trapped, laser-cooled  $^{88}\text{Sr}^+$  ion has been measured with respect to a primary Cs standard with an uncertainty of 5 parts in  $10^{13}$ . The major factor contributing to the uncertainty was the microwave-optical frequency measurement chain. Dr Boulanger also reported progress on the NRC Cs fountain, from which Ramsey fringes are expected soon.

Dr Sullivan presented the report from the NIST (CCTF99-07). NIST-7 is still operating, and a similar standard (CRL-01) has been built under contract for the CRL (Japan). In collaboration with the IEN, a preliminary evaluation of the accuracy of the NIST Cs fountain standard, NIST-F1, has been

completed, yielding an uncertainty of 3.8 parts in  $10^{15}$ . The accuracy is presently limited by statistical noise, rather than systematics.

Dr Sullivan reported that the NIST 40.5 GHz  $^{199}\text{Hg}^+$  laser-cooled trapped ion frequency standard is presently being rebuilt with a view to continuous operation for the purpose of monitoring time scales. The uncertainty of this standard is presently 3 parts in  $10^{15}$  and an uncertainty of 1 part in  $10^{15}$  is expected from the rebuilt version.

Spectroscopy with sub-Hertz linewidth has been demonstrated on the 282 nm ultraviolet transition in trapped, laser-cooled  $^{199}\text{Hg}^+$  ions, and a microwave-optical frequency synthesis chain is under construction to measure the frequency of this transition. Results are expected within two years. A measurement of the frequency of the 282 nm transition with respect to the PTB Ca standard is planned in 1999.

Dr Sullivan said that for the foreseeable future the NIST is keen on pursuing developments for all possible clock designs and plans to put the same effort into developing trapped-ion frequency standards as into Cs standards.

Dr Granveaud presented the report from the BNM-LPTF (CCTF99-11). He said that the French National Research Centre (Centre National de la Recherche Scientifique, CNRS) and the BNM have decided to integrate the LPTF and the LHA into a single laboratory during the next twelve months, but there are still two reports for this meeting. He presented the following:

- 1) The optically-pumped conventional Cs beam standard, LPTF-JPO, has been modified with a new microwave cavity and a new two-laser optical pumping scheme. The standard now has a calculated uncertainty of 6.3 parts in  $10^{15}$ . It is intended that LPTF-JPO will operate continuously beginning in the near future.
- 2) Experiments to measure frequency shifts due to black-body radiation and collisions between Cs atoms have been carried out on the Cs fountain LPTF-FO1. The result for the black-body shift is in close agreement with that obtained by the PTB.
- 3) A second fountain standard, LPTF-FO2, has been constructed, and is capable of operating with Cs or  $^{87}\text{Rb}$  atoms. It is currently operating with Rb atoms, and the ground state hyperfine transition frequency has been measured with an uncertainty of 2 parts in  $10^{15}$ . Improvements in accuracy appear feasible, partly because the collisional frequency shift of rubidium is very much smaller than that of caesium.
- 4) Development of a cold/slow atomic beam Cs standard for space applications continues (PHARAO project, in collaboration with the LHA

and the LKB), with a prototype being tested under microgravity conditions in an aircraft in 1997. The prototype has been modified to operate as a fountain and will be evaluated soon.

- 5) The R(12) radiation frequency of a CO<sub>2</sub> laser has been measured with an uncertainty of 7 parts in 10<sup>13</sup>.
- 6) Absolute frequency measurements on laser diodes locked to a two-photon transition in Rb were carried out, with an uncertainty of 5.2 parts in 10<sup>12</sup>. This work and the CO<sub>2</sub> laser work was carried out in cooperation with the Lebedev Institute, the PTB and the BIPM, and both measured frequencies have been adopted by the most recent CCDM (1997) as recommended values for the realization of the metre.

Dr Dimarcq presented the report from the LHA (CCTF99-12). He reported the development of a new miniature clock based on a slow beam of Cs atoms, in which the atoms are laser-cooled within the microwave cavity. He also noted that the development carried out for PHARAO will result in a transportable Cs fountain.

Dr Morikawa presented the report from the CRL (CCTF99-15). The optically pumped conventional Cs standard CRL-01, a copy of NIST-7, has been completed, and its difference in frequency with NIST-7 was measured at NIST to be 1 part in 10<sup>15</sup>. CRL-01 has now been shipped to Japan, and is under evaluation. The development of a Cs fountain continues, with cold Cs atoms having been launched to a height of 30 cm.

Dr Fisk presented the report from the CSIRO-NML (CCTF99-16). Work has continued on the development of a buffer gas-cooled <sup>171</sup>Yb<sup>+</sup> trapped-ion standard, with a short term stability  $\sigma_y(\tau)$  of  $5 \times 10^{-14} \tau^{-1/2}$  having been demonstrated. Improvements in accuracy through laser-cooling the ions are being pursued, and Ramsey fringes have been obtained on laser-cooled ion clouds using pulse separations of 10 s. The temperature of the ion cloud was shown to remain below 1 K throughout the 10 s interrogation period.

Dr Ohshima presented the report from the NRLM (CCTF99-23). The optically pumped Cs beam standard NRLM-4 has been substantially modified, resulting in a total uncertainty of 3 parts in 10<sup>14</sup>. Work continues towards the goal of reducing this uncertainty to less than 1 part in 10<sup>14</sup>. Work on the NRLM Cs fountain standard has continued slowly, owing to technical problems. Ramsey fringes from the previous experimental set-up were reported at the 1996 CCDS meeting and a new apparatus is under development. A microwave-optical frequency synthesis chain incorporating optical parametric oscillators is also being developed.

Dr Domnin reported that the VNIIFTRI began a Cs fountain project in 1998, and that the optical system is now complete. Ramsey fringes are expected in 2000.

In closing the discussion on point 2.1 of the agenda, the President commented on the surge in activity since the 1996 CCDS meeting, especially concerning fountains. He noted that the development of several different arrangements was of special interest.

The President said that Dr Quinn wished to address the committee, and invited him to do so.

Dr Quinn reported that he had received a letter from Dr Douglas, in which it was pointed out that a footnote added to the 7th edition of the SI brochure is incorrect in both the French and English texts. The intention of the footnote was to make it clear that the definition of the SI second is based on a Cs atom unperturbed by black-body radiation, that is, in an environment whose temperature is 0 K, and that the frequencies of primary frequency standards should therefore be corrected for this shift. However, the footnote in the English version of the brochure refers to “a caesium atom in its ground state at a temperature of 0 K”, whereas the French version reads “un atome de césium au repos à une température de 0 K”. The two versions are mutually inconsistent and unclear.

Dr Quinn accepted responsibility for the error, and said it would be corrected in the next edition of the Brochure. He also said that some thought should be given to the wording, and indeed the necessity, of the footnotes. (Further discussion of this point occurred after agenda item 3.1.)

The President thanked Dr Quinn, and complimented him on the way he had responded to this issue.

## **2.2 Report of the CCTF working group on the expression of uncertainties in primary frequency standards**

The President invited Dr Douglas to present this report (CCTF99-09).

Dr Douglas said that the working group was formed at the 1996 CCDS meeting, with the task of reporting to the 1999 meeting on how the accuracy of primary frequency standards should be communicated. This issue arose in response to questions raised at the 1996 CCDS meeting concerning how the *ISO Guide to the expression of uncertainty in measurement* should be applied to measurements involving frequency standards.

In explaining his approach to the problem, Dr Douglas said that end-users of uncertainties need information on the accuracy of their present and future measurements, whereas an uncertainty statement generally refers to the status of a measurement made in the past. Consequently, in addition to a consistent method of calculating and expressing uncertainties of primary frequency standards, a method for projecting these uncertainties into the future is needed, but it was decided that this latter task was too large to accomplish in three years. The working group therefore focussed on the problem of expressing the uncertainty in comparisons using primary frequency standards which are the top end of a traceable chain for frequency.

Dr Douglas listed a number of factors which simplified, or limited the scope of, the task of the working group:

- The accuracy of primary frequency standards is ample for most applications.
- Uncertainty statements with a fractional uncertainty in the uncertainty better than 0.2 are rarely needed.
- The ISO Guide shapes the expectations of many users of uncertainty statements.
- The results of CIPM key comparisons are to be published in *Metrologia*.
- The accuracy of most primary frequency standards is independent of averaging time.
- Most uses of primary frequency standards result in a time series of comparisons.

Dr Douglas explained that the working group viewed the expression of uncertainty in a metrological context as communicating the range of possible values of the quantity being measured, all things considered. The effective communication of an uncertainty statement to an end-user therefore relies on three factors:

- sharing a physical understanding of primary frequency standards;
- sharing a definition of the scale unit (i.e. the SI second) for primary frequency standards;
- sharing an understanding of the expressed range, that is, how the contributions to the total uncertainty were determined and combined.

On the basis of the above principles and constraints, the working group formulated a number of draft recommendations (annexes 5 and 6 of the working group's report).

The intention behind these recommendations is that the ISO Guide should be followed, but only where appropriate, and that sufficient detail of how the total uncertainty was arrived at should be published (preferably in *Metrologia*) so that it can be fully understood by all users, and also so that if necessary it can be revised *post factum* by an end-user on the basis of new information and understanding.

The President thanked Dr Douglas for the report, and remarked that in recent years time and frequency metrologists have generally had the luxury of a large gap (more than two orders of magnitude) between the requirements for accuracy by end-users, and the accuracy available from primary frequency standards. This situation has now changed, with some applications (e.g. optical frequency metrology) being much more demanding of accuracy, and consequently the importance of how uncertainty statements are expressed and used has increased greatly. The establishment of the Mutual Recognition Arrangement is also highlighting the importance of establishing and documenting the accuracy of comparisons between laboratories.

The President then asked the committee for its reaction to the report.

Dr Petit said that he and other members of the BIPM Time Section had had extended discussions with Dr Douglas on these issues. He stressed that it is important that the first evaluation, or any major re-evaluation, of a primary frequency standard should be subjected to peer review. He also commented that although the report focuses on publication of bilateral comparisons between primary frequency standards, or a primary frequency standard and TAI, it would be useful to have in addition a (possibly annual) synthesis publication produced by the BIPM containing information on all the comparisons between primary frequency standards and TAI for archiving purposes.

The President, noting the recommendation of the working group concerning steering of TAI, gave the opinion that the establishment of guidelines for steering TAI should be referred to the CCTF working group on TAI.

Dr Tavella agreed with Dr Douglas that type A or type B uncertainty classification is related to the method of evaluation of that particular contribution. A particular uncertainty contribution may first have a type B evaluation but, when repeated measures are at one's disposal, a type A evaluation becomes possible (e.g. black-body correction) or vice-versa. She added that a future edition of the ISO Guide should include an appendix on time-series analysis.

Dr Guinot commented that there is much to be learned from a global treatment of all comparisons between primary frequency standards, in that systematic differences between standards may become clearer, and it would show up authors and organizations that tend to underestimate uncertainties.

Dr Quinn said that metrologists are now thinking more broadly about uncertainties, and that the authors of the ISO Guide would certainly agree that it is not the last word on the subject. He noted that a working group has been convened to revise the ISO Guide under the leadership of Dr Barry Taylor of the NIST, and one important task for this group will be to clarify the analysis of time-series measurements. Dr Quinn then drew the committee's attention to a paper (submitted to *Metrologia*) written by Dr Witt of the BIPM, which examines the consequences of treating all measurements as a time series and concludes that all measurements should be treated in this way.

At the end of the discussion, Recommendations S 2 (1999) and S 3 (1999) were adopted.

### **3 PRESENT STATUS OF TAI**

#### **3.1 Report on TAI of the BIPM Time Section**

The President expressed his appreciation of Dr Quinn's earlier remark (under agenda item 1) on the importance of TAI in the BIPM work programme, and invited Dr Petit to present this report (CCTF99-13).

Dr Petit began by saying that the primary duty of the Time Section is the computation of TAI and UTC. He recalled that, since 1 January 1996, access to TAI has been provided every 5 days, instead of every 10 days.

Dr Petit noted that of the clocks contributing to TAI, 75 % are Hewlett-Packard 5071As or auto-tuned hydrogen masers, and that these clocks contribute 89 % of the total weight in the ALGOS algorithm used to generate TAI. At the end of 1997, more than half of these clocks were contributing maximum individual weight, resulting in poor performance discrimination between clocks.

To alleviate this problem, the weighting method used in ALGOS was changed as of 1 January 1998, to one in which the maximum weight of a single clock is given a relative value of the total weight, initially fixed at 0.7 %. This

relative weighting scheme has slightly reduced the number of clocks at maximum weight and has improved the relative frequency stability of EAL from  $1.4 \times 10^{-15}$  at an averaging time of 40 days during 1996-1997 to  $6 \times 10^{-16}$  over an averaging time of 20 to 40 days during 1998-1999. The minimum stability required of an individual clock in order to reach maximum weight is now variable, and is typically  $1 \times 10^{-14}$  over an averaging time of one month.

Also since 1 January 1998, TAI has been calculated using one-month blocks of data, instead of two as used previously.

The steering of TAI has continued since 1996, and the departure of its scale unit from the SI second has been reduced from  $2.4 \times 10^{-14}$  with a standard uncertainty of  $0.7 \times 10^{-14}$  in 1996 (due to the correction recommended by the 1996 CCDS of primary frequency standards for the black-body shift) to  $-0.4 \times 10^{-14}$  with a standard uncertainty of  $0.4 \times 10^{-14}$  in early 1999. The regular steering corrections implemented in 1995 to compensate for the black-body shift were stopped in March 1998. Nine primary frequency standards were used in these evaluations, some regularly and some not.

After thanking Dr Petit for the report and for the work of the BIPM Time section, the President called for discussion.

Dr Lepek remarked that the uncertainty of a comparison between TAI and a primary frequency standard depended among other things on the duration of the comparison, and asked how this uncertainty was accounted for in the steering of TAI. Dr Petit replied that two uncertainty components were combined:  $\sigma_B$ , which is the uncertainty of the primary frequency standard originating from systematic effects and is provided by the laboratory which maintains it, and  $\sigma_A$ , which is the statistical uncertainty on the frequency comparison and therefore includes the transfer to TAI over the comparison interval and depends on the duration of the comparison.

Dr Matsakis pointed out that steering a time scale is a more complicated process than one might imagine, and that the optimum steering algorithms depend strongly on the desired features of the time scale: for example, frequency stability, phase stability or accuracy. He suggested that this would be one topic for consideration by a working group on time-scale algorithms, the formation of which was scheduled to be discussed under the next agenda item.

The President closed the discussion on the Time Section report, and returned to the issue, originally raised at the end of agenda item 2.1, of the rewording of the erroneous footnotes in the SI Brochure.



An extended discussion followed, the conclusion of which was that at the time the footnote was inserted, the intention was to draw attention to the fact that the frequencies of primary frequency standards should be corrected for the shift resulting from ambient black-body radiation. Dr Quinn remarked that at the most recent meeting of the CCU it was proposed that all of the definitions of the base SI units should be reworded to a common format. The CIPM decided that this could only be done with the agreement of the relevant Consultative Committees, noting that the CCPR did not agree. The CCL suggested that more specific guidelines on practical realizations would be useful and Dr Quinn therefore proposed that a *mise en pratique* for the SI second be included as an appendix to the SI Brochure.

Prof. Kovalevsky agreed, and suggested that the CCTF prepare such a document for inclusion in the next edition of the SI Brochure. This conclusion is embodied in Recommendation S 1 (1999).

### 3.2 Report of the CCTF working group on TAI

The President invited Prof. Pâquet to present this report (CCTF99-28).

Prof. Pâquet said that a meeting of representatives of laboratories contributing to TAI had been held on the previous day, and that the principal topics of discussion were time-scale algorithms, time and frequency transfer hardware, and the IGS/BIPM Pilot Project.

#### 1) Time-scale algorithms

Prof. Pâquet noted that several laboratories (including the BNM-LPTF, NIST, NRC, USNO, VNIIFTRI) had developed their own algorithms for computing time scales. In view of this available expertise, the working group on TAI had decided that a working group should be formed to study, develop and compare time-scale algorithms.

#### 2) Time- and frequency-transfer hardware

Improvements in time-transfer techniques have led to time comparisons being routinely possible with a precision of 0.1 ns or better, but there exist constant offsets to be determined by calibration. However, even with calibration of the time delays through the receivers, operational time comparison typically has an accuracy level of between 1 ns and 3 ns, and the accuracy is much poorer when no calibration has been performed. The BIPM has been addressing this problem with their continuing circulation of calibrated receivers between laboratories. These measurements have shown unexplained changes in the

delays through many time-transfer receivers, highlighting the need for regular calibration and further study. Dr Palacio agreed to coordinate additional calibrations through EUROMET activities.

It has also become clear that the temperature sensitivity of receiver delays is significant, prompting a recommendation on laboratory temperature stabilization to be prepared for consideration by the CCTF.

In fact the discussion ended by the following declaration being approved by the committee:

The Consultative Committee for Time and Frequency

**noting that**

- from experiments conducted in the recent years, relative comparisons of clocks exhibit a precision better than one nanosecond;
- it has been demonstrated that such a level is obtained only if environmental conditions are kept as constant as possible;
- any future improvement in clock comparisons requires such conditions;

**recommends** that all necessary steps be taken to keep environmental effects as small as possible

- by use of equipment revealing a low sensitivity to environmental effects;
- by keeping the environmental conditions as stable as possible.

Prof. Pâquet said that the old, but very efficient NBS-type time-transfer receivers were becoming difficult to maintain, and proposed that the BIPM should consider developing a means of incorporating data from more modern multi-channel GPS receivers into the computation of TAI. He noted that this raises many issues, including algorithms, mathematical methods and calibration, and said that the BIPM would need some support with this task. After discussion on this subject, the committee adopted Recommendation S 4 (1999).

*3) IGS/BIPM Pilot Project*

This project was started at the end of 1997 at the initiative of the IGS, to study accurate time and frequency comparisons using GPS phase and code measurements. Several speakers presented data showing that clock comparisons with precision well below 1 ns were being achieved, but a lack of receiver delay calibration and the unstable temperature environment of many receivers were limiting the accuracy.

Another related topic of discussion was the effect of the ionosphere. One of the products of the IGS is a map of the ionosphere updated every two hours, which Dr Wolf of the BIPM had suggested might be the best source of ionospheric delay correction data for GPS time transfer. This may be of particular importance since solar activity is presently increasing.

The President thanked Prof. Pâquet for the report, and called for comments from the committee.

Prof. Kovalevsky asked if the decision to form a working group on time-scale algorithms had been prompted by specific criticisms of the algorithm used to calculate TAI. Prof. Pâquet replied that this was not the motivation for this decision. Dr Matsakis pointed out that the output of the new working group would nevertheless be helpful to the BIPM in making use of new time-transfer technology.

Dr Quinn said that because of the importance of TAI to the BIPM, it would participate in these activities, and would have no objection to the terms of reference of that working group on TAI being extended to include algorithms.

An extended discussion followed on the need for, and terms of reference of, a working group on algorithms. The general consensus was that the study of time-scale algorithms was a high priority, and should be added to the tasks of the working group on TAI. Therefore a working sub-group was formed with Dr Tavella nominated as chairman, and the following terms of reference were adopted:

Taking into account

- 1) the present developments of algorithms experienced by time laboratories to test the performances of their clocks and/or to generate time scales;
- 2) the new conception in atomic frequency standard and comparison techniques which need suitable data processing;
- 3) the emerging needs for comparable characterization of clock performances and reliable time scales also for new applications (telecommunications, satellite navigation systems...);

the working group on TAI is invited to set up a group having the following tasks

- 1) to present a list of algorithms for use in clock comparisons and generation of local time scales;
- 2) to estimate the performances of these algorithms;
- 3) to address potential new approaches for the above-mentioned objectives;
- 4) to stimulate publications on the methods and experience gained.

Dr Lepek expressed concern that some individuals and organizations involved in time-scale research are not members of the working group on TAI, and that this might not be efficient. The President replied that membership of this group was not frozen, and that others could join.

## 4 THE FUTURE OF LEAP SECONDS

The President invited Dr McCarthy to present this report (CCTF99-18).

Dr McCarthy began by reviewing the history of the SI second, noting that its duration has its origin in the ephemeris second, which is based on 19th century astronomical observations. Slowing of the Earth's rotation rate since then results in the present need for the introduction of approximately one leap second into UTC every 1.5 or 2 years.

This convention results in several causes for concern:

- possible increasing frequency of leap seconds in the future;
- communications problems;
- annoyance of people in charge of systems disseminating time and consequent proliferation of independent time scales, not including leap seconds, for specific purposes (e.g. GPS time).

Dr McCarthy listed some options for responding to these issues:

- maintain the status quo;
- discontinue leap seconds in UTC:
  - Pro: would be supported by those in charge of disseminating time.
  - Con: unlimited growth of  $[UTC - UT1]$ .
- redefine the second:
  - Pro: fundamental solution;
  - Con: would require redefinition of other physical units; the solution is only temporary and its efficiency is not certain.
- increase tolerance for  $[UTC - UT1]$ :
  - Pro: easy to accomplish;
  - Con: date of adjustment unpredictable, difficult to establish acceptable limit.

- periodic adjustments of UTC at larger intervals:

Pro: date of adjustment predictable;

Con: number of leap seconds unpredictable, larger discontinuities.

Because none of these options is obviously satisfactory for the majority of users of UTC, Dr McCarthy suggested that a working group on this issue be formed, and that it should include representation from the IAU, IERS, ITU-R and navigation bodies.

The President thanked Dr McCarthy for the report, and called for discussion, which is summarized by the following points:

- The CCTF, or a working group thereof, probably does not have the authority to recommend the cancellation of leap seconds (raised by Dr Guinot). However, there is a general consensus that leap seconds should be discontinued and that the CCTF should draw the attention of the IAU, ITU, URSI and other bodies to this issue via a letter written by Dr Quinn (raised by the President).
- The use of TAI should be encouraged in applications where leap seconds cause problems (raised by Dr Bauch), such as Global Navigation Satellite Systems (GNSS), although for this to be generally feasible it would be necessary to make TAI more accessible (raised by Dr McCarthy). The letter mentioned in the previous point should recommend the use of TAI where a time scale without discontinuities is needed.

Dr Quinn agreed to write the above-mentioned letter, in collaboration with Dr McCarthy.

## **5 TIME AND FREQUENCY TRANSFERS USING THE TWO-WAY METHOD: REPORT OF THE CCTF WORKING GROUP ON TWO-WAY SATELLITE TIME AND FREQUENCY TRANSFER (TWSTFT)**

The President invited Dr Klepczynski to present this report (CCTF99-26).

Dr Klepczynski reported that the working group had held three full meetings since the 1996 CCDS meeting, at the IEN (October 1996), NIST (December 1997) and the ROA (October 1998). At the NIST meeting four study groups were convened:

- verification and validation;
- calibration and satellite simulators;
- comparisons between TWSTFT and GPS carrier phase;
- calibration using a transportable TWSTFT station.

Over the last three years, there have been seven significant achievements:

- 1) Commencement of the use of INTELSAT 706 on a commercial basis for European and trans-Atlantic links: stations involved are the DTAG, NIST, NPL, OCA, PTB, TUG, USNO and VSL, with the IEN and ROA coming on-line soon. Transfers take place in one-hour windows on Mondays, Wednesdays and Fridays. Two years of data are now available.
- 2) Completion of a study on interpolation of unevenly spaced data: Dr Tavella presented a report on this topic, saying that the IEN has evaluated three different techniques for calculating the Allan deviation from unevenly spaced data points. Moreover, the problem of interpolating unevenly spaced data to evenly spaced dates was addressed and the best estimates and their uncertainty were evaluated.
- 3) Calibration of some TWSTFT stations by BIPM GPS common-view measurements: Dr Lewandowski presented a report on this topic, saying that the BIPM had been circulating a calibrated GPS common-view time transfer receiver among several TWSTFT stations. Delay changes of up to 50 ns were observed but were attributed to known changes in the hardware. He pointed out that GLONASS P-code with frequency-dependent biases removed would be capable of time transfers with sub-nanosecond RMS noise (CCTF99-24). This will be investigated for possible application to TWSTFT station calibration.
- 4) Comparison of TWSTFT data and GPS common-view data: Mr Azoubib presented data from a short baseline comparison over two years of TWSTFT and GPS common-view between the PTB and the TUG. The mean difference between the GPS and TWSTFT methods was 0 ns, with a standard deviation of 1.5 ns, which demonstrated close agreement between the two methods. Over a longer baseline, between the PTB and the NIST, the mean difference was 9 ns and the standard deviation was 3 ns, over two years. The larger difference is thought to be related to the fact that only modelled ionospheric delays were used to correct the GPS data.
- 5) Calibration using the TUG transportable TWSTFT station at the DTAG and the PTB: Dr Kirchner reported that over four calibration trips

between the TUG and the PTB, calibration differences of less than 1 ns were observed.

- 6) TWSTFT stability studies: Dr Kirchner reported that zero-baseline common-reference clock comparisons between two Earth stations showed a time deviation of 100 ps over a one-day averaging time. In addition, he said that measurements of the closed-loop delay between the transmitter and receiver of Earth stations at the TUG and VSL showed a time deviation of 200 ps over averaging times of one hour, and a peak-to-peak variation of approximately 1 ns over two years. The latter is thought to be due to temperature variations.
- 7) Commencement of TWSTFT activities in Asia: Dr Imae reported that a TWSTFT link between the CRL and the NML had been operating since April 1998, with two 30-minute transfers per week on INTELSAT 702 (Ku-Band). Since October 1998, a link between the CRL and the CSAO using JCSAT 128E has been operating, with two transfers per week. A link between the CRL and the NRLM has been operating using the same satellite since March 1999. Future links to the KRISS, NIST, TL and European laboratories are planned. A C-Band link between the NML and the NIST is expected to become operational in 1999.

Finally Dr Klepczynski drew the meeting's attention to the recommendation, which, among other things, proposes that plans be developed to use TWSTFT data in the computation of TAI.

The President thanked Dr Klepczynski and the working group members for the report, and proposed that the recommendation be adopted. He then called for discussion, which is summarized in the following points:

- There are still unexplained differences of more than 1 ns between TWSTFT data and GPS common-view data (raised by Dr Levine), which are thought to be mainly due to the GPS side of the comparisons (opinion of Dr Kirchner). The need for further and more frequent calibration trips is clear.
- There are a number of practical considerations related to the incorporation of TWSTFT data into the calculation of TAI. For example, when both TWSTFT data and GPS data are available, how should the decision be made on which to use (raised by Dr Wolf)? The President asked the BIPM Time Section to consider these issues and develop proposals, and expressed confidence in their handling of the question.
- There was general agreement on the draft recommendation proposed by the working group and it was adopted as Recommendation S 7 (1999).

The President then asked Dr Klepczynski to make a statement on the requirements with respect to timing systems of the Wide Area Augmentation System (WAAS) and similar GNSS augmentation systems.

Dr Klepczynski said that the WAAS comprised twenty-seven or twenty-eight reference stations, located in the United States, Alaska and Hawaii. Each station is equipped with three Cs clocks, and the timing of the stations is coordinated via TWSTFT using two geostationary satellites, giving near-hemispherical coverage. A network time scale, known as WAAS time, is formed, and steered to within 50 ns of GPS time. In addition to their primary role of transmitting GPS augmentation data, the geostationary satellites have the capability of transmitting the differences between WAAS time and eight different UTC(k) time scales, if appropriate national laboratories will monitor WAAS time and transmit the differences to the appropriate satellites.

The President thanked Dr Klepczynski and suggested that it would now be appropriate to consider a recommendation on future global navigation satellite systems proposed by the BIPM (CCTF99-14). In this context he invited reports on activities related to new GNSS systems.

Dr Imae said that the CRL is conducting research related to the next generation of GNSS. In particular, a space-borne H-maser is under development, and a geostationary satellite (ETS-8) equipped with two Cs clocks intended for time transfer applications is scheduled for launch in 2002.

Dr Tavella reported that the IEN had commenced a study, in collaboration with the DLR (Germany) and the ESA, on the development of a suitable time scale for future GNSSs. Issues such as the relative importance of short-term and long-term stability, and of accuracy and stability, are of particular interest. She said that although the ESA has no particular requirement for a GNSS time scale to be synchronized with UTC, methods by which this could be achieved are nevertheless being studied. She suggested that this could be a topic for the working group on TAI to study, as part of their proposed work on time-scale algorithms.

Dr Quinn commented that in his opinion it is a profound error to set up systems which require stability without striving for the goal of accuracy as well. He pointed out that long-term observations of small changes require accurate links to the SI, and in the present context, to TAI. It is important to bear in mind that any system which is available in the long term will have uses found for it which were not thought of at the time of its development. He proposed that there should be a recommendation on this issue. Dr Petit



stressed that one aim of the proposed recommendation is to inform developers of satellite systems on the needs of the time community.

At the end of the discussion, Recommendation S 6 (1999) was adopted by the committee.

The President then invited Dr Quinn to present a draft of the letter referred to at the end of the discussion on agenda item 5. Dr Quinn did so, and Prof. Pâquet commented that to achieve the target accuracy of WAAS systems accurate satellite positioning would be needed, and suggested that Dr Quinn's letter also make a recommendation that a particular position reference frame be used.

In view of the increasing scope of this letter, the President suggested that Dr Quinn's letter should be recast into two letters, one addressing the leap second issue, and the second aimed at developers of GNSS, WAAS and similar systems, and making recommendations on time scales and position reference frames. Dr Quinn agreed to consider this. [In the end a single letter was sent.]

The President then invited Dr Sen Gupta to address the meeting on the NPLI satellite time dissemination system (CCTF99-29).

Dr Sen Gupta said that this system was based on a satellite owned by the Indian Government with a footprint mainly over India. One-way time signals synchronized with UTC (NPLI) are broadcast from the satellite on an S-Band transponder. Uplink from the NPLI is via a C-Band link. Satellite position coordinates accurate to 5 km are also broadcast in real time. The system accuracy for a typical end-user is limited to approximately  $\pm 20 \mu\text{s}$ , and is primarily limited by the uncertainty in the position of the satellite. The potential accuracy has recently been improved to  $\pm 1 \mu\text{s}$  through monitoring of timing residuals at the NPLI and broadcasting them. The number of users of the system has recently increased to more than one hundred.

Dr Sullivan commented that Egypt is considering developing a similar system, and that Dr Sen Gupta might consider working with them. Dr Sen Gupta replied that he has been approached by several countries interested in the Indian system, including the Republic of Korea, Mexico and Turkey.

The President thanked Dr Sen Gupta, and turned to agenda item 6.

## **6 TIME AND FREQUENCY TRANSFER METHODS AND TECHNIQUES USING NAVIGATION SATELLITES**

### **6.1 GPS phase measurement: report on the IGS/BIPM Pilot Project**

The President invited Dr Ray to present this report (CCTF99-20), who in turn asked representatives of laboratories to report on their work in GPS carrier phase.

Dr Duddle reported for the OFMET and said that a comparison between TWSTFT and GPS carrier phase over a 6000 km baseline using the PTB-USNO link had been carried out; 200 days of data had been recorded (CCTF99-05). Frequency transfer at the  $10^{-13}$  stability level was achieved over an averaging time of 300 s and a drift of 33 ps per day between the two time-transfer methods was observed. The cause of this drift is under investigation.

Dr Douglas, for the NRC, referred the meeting to the appropriate section of the NRC report (CCTF99-06).

Dr Levine reported that the NIST had conducted both short- and long-baseline tests of GPS carrier-phase time transfer, in particular, comparing the latter technique with TWSTFT using as references the GPS alternate master clock in Colorado Springs and the USNO clock in Washington DC. He said that the experiments had shown that over averaging times less than 1000 s, the GPS carrier phase technique was superior to TWSTFT.

Dr Petit reported that the BIPM had found that two modified Ashtech Z12 dual-frequency GPS receivers referenced to a common clock had shown frequency differences of less than 1 part in  $10^{16}$  over one day of averaging when used in properly controlled environmental conditions. He said that comparison of primary frequency standards was one important motivation for this work at the BIPM.

Dr Ray then presented the IGS/BIPM Pilot Project report (CCTF99-20).

He began by noting that the project commenced at the end of 1997 with the following objectives:

- to deploy dual-frequency geodetic GPS receivers at timing laboratories;
- to develop refined GPS data analysis techniques;
- to study the problem of calibrating geodetic GPS receivers;
- to conduct time transfer using geodetic GPS receivers.

A time-transfer accuracy of better than 200 ps is potentially available using these techniques.

There are now more than twenty-five research groups involved in the Pilot Project, more than half of which are from timing laboratories. In the IGS at large, more than two hundred observation sites are distributed globally, seventy of which use external frequency references, and eleven are located at timing laboratories. The Allen-Osborne Turbo-Rogue receiver dominates the observation sites, but a new generation of receivers (Y codeless tracking) is emerging.

The data are analysed at eight centres, which generate and publish a range of products, including satellite orbits at the cm accuracy level, satellite clock data, polar motion data, ionospheric data, receiver clock data and receiver coordinates.

The time scale underlying the IGS system is GPS time. The IGS would prefer to link its products to UTC, but there is presently no easy way to do this. The assistance of BIPM is being sought on this problem.

Dr Ray said that Selective Availability (SA) was presently a limitation, and noted that the President of the United States has ordered that SA be turned off by 2006, and that the GPS Program Office is now required to report annually on the reason why SA has not yet been turned off.

In summary, Dr Ray said that the project had got off to a good start, and that the immediate issues to be addressed, summarized in the proposed recommendation are:

- receiver delay calibration;
- improved environmental control for receivers;
- more receivers located at timing laboratories;
- change of reference time scale to UTC.

The President thanked Dr Ray, Dr Petit and the other members of the working group, and observed that it was unusual for a cooperative activity on this scale to accomplish so much in less than two years. Dr Quinn said that this rapid progress was facilitated by clear objectives being set at the beginning of the project.

The President asked Dr Petit what would be required to align the IGS time scale with UTC. Dr Petit replied that this would require more timing laboratories to become IGS observation stations, and that work on calibrating the delays of geodetic receivers would also be needed.

Dr Sen Gupta proposed to the IGS that more observation stations are needed in equatorial latitudes since variations in the ionosphere occur over relatively small spatial scales in that region. Dr Ray replied that he believed dual-frequency GPS receivers might be a more cost-effective solution, since they provide measurements of ionospheric delays along the line-of-sight to specific satellites.

Dr Boucher said that it is important to remember that organizations must apply to be IGS observing stations; merely purchasing and installing the equipment is not sufficient.

At the end of the discussion, Recommendation S 5 (1999) was adopted by the committee.

## **6.2 GPS and GLONASS time transfer standards: report of the subgroup on GPS/GLONASS**

The President invited Dr Levine to present this report.

### *1) Data formats*

Dr Levine began by noting that the availability of multi-channel GPS receivers, dual-frequency GPS receivers and GLONASS receivers suitable for time and frequency transfer had prompted the working group to develop an extension of the original CCTF GPS common-view data reporting format to accommodate data from such receivers, and he emphasized the importance of using a common format.

Dr Levine continued with a summary of recent developments in GPS/GLONASS time and frequency technology.

### *2) Allen Osborne TTR4-P GPS receivers*

Most laboratories have stopped experimenting with these receivers owing to multiple intrinsic software and hardware problems.

### *3) Motorola Oncore GPS receivers*

Dr Levine reported that a number of laboratories have been experimenting with this type of multi-channel receiver in time and frequency applications.

The knowledge available to date indicates that:

- the Oncore receivers, being single-frequency, will be affected by increasing solar-driven ionospheric effects;
- the performance in time-transfer applications is as good or better than existing single-channel receivers;

- the receivers do not appear to have Y2K or GPS week rollover problems;
- the receivers exhibit significant sensitivity to temperature, cable impedance and other factors;
- because the receiver cost is a small fraction (about 6 %) of a time transfer system based on it, it can readily be replaced as better receivers become available;
- unfortunately the VP-Oncore model, on which most work has been done in this context, will not be manufactured after November 1999; other similar receivers will continue to be manufactured by Motorola, but their time and frequency transfer performance has not been extensively studied.

#### *4) 3S Navigation GPS/GLONASS receivers*

These combined, multi-channel single-frequency GPS/dual-frequency GLONASS receivers have become commercially available during the previous eighteen months. These receivers have been purchased by about twelve laboratories, some of which have had difficulties with them. The receivers produce multi-channel GPS and GLONASS data in the BIPM format, as well as other data in the IGS RINEX format.

#### *5) The GLONASS*

Dr Levine said that the GLONASS has potential advantages for time transfer purposes over the GPS system in that no performance degradation analogous to GPS's Selective Availability is implemented. However, there are also several potential disadvantages:

- because each GLONASS satellite transmits on a different frequency, calibration of receiver delays is complicated;
- the GLONASS and GPS systems use different spatial coordinate reference frames;
- of the approximately fourteen space vehicles currently operating, nine are within two years of their life expectancy;
- it is currently unclear if further space vehicle launches will take place, although this situation may clarify within the next year.

#### *6) Tracking schedules*

Dr Levine noted that more optimal use of multi-channel GPS/GLONASS receivers could be made by:

- not using tracking schedules, since they are not necessary for such receivers;
- shortening the conventional 13-minute track length, which was originally adopted to ensure that a single channel receiver could receive a complete ephemeris message during each track;
- simplifying the method by which GPS data are averaged, since the current combination of quadratic and linear fitting is not optimal for the known spectral characteristics of Selective Availability.

#### *7) Summary*

Dr Levine reiterated that most present receivers are of the single-channel NBS-type, which are becoming increasingly difficult to maintain owing to their age, and appear to exhibit long-term variations in internal delays which are not fully understood. He noted that none of the currently available GPS or GLONASS receivers are obviously ideal in all respects, and some of them have potentially serious problems. Nevertheless, he said that there are significant performance benefits to be gained by making use of the newer receivers, especially if the data-processing protocols are modified to suit them.

The President thanked Dr Levine for the report, and called for discussion.

Dr Sullivan said that it is important to remain aware of the potential impact of changes to GPS processing methods on the workload of the BIPM Time Section, and that it is important to maintain the capability of effectively using data from cheaper and existing receiver types to maximize the input to TAI.

Dr Petit pointed out that, as long as some laboratories continue to provide data from single channel receivers, the BIPM cannot make use in an optimal way of common-view data from multi-channel receivers.

Finally, Dr Lewandowski said that the GLONASS should be used while it is available, since it is the only way the time and frequency community can gain experience of using a GNSS which is free of Selective Availability.

## 7 GENERAL RELATIVITY AND SPACE-TIME REFERENCES

### 7.1 Report of the BIPM/IAU Joint Committee on General Relativity for Space-Time Reference Systems and Metrology

The President invited Dr Petit to present this report (CCTF99-19).

Dr Petit began by explaining that the BIPM/IAU Joint Committee on General Relativity for Space-Time Reference Systems and Metrology was created in 1997 in response to a proposal by the BIPM to the IAU that a working body be established to study problems related to the application of general relativity to space-time reference systems and metrology. To date, the Joint Committee has been considering issues related to the extension of the metric tensor for use in the barycentric reference system, the transformation of coordinate time scales between geocentric and barycentric systems, and the accuracy limits imposed by the definitions of such time scales.

Dr Petit reported that in 1991 the IAU defined a new barycentric coordinate time scale (TCB) to replace the relatively poorly defined barycentric dynamic time scale (TDB). The present definition of TCB is adequate for its calculation in terms of the geocentric coordinate time scale TCG to an accuracy level of a few parts in  $10^{16}$  in rate, and therefore the metric needs to be extended to accommodate higher accuracy. Furthermore, the present definition of terrestrial time (TT) limits the accuracy of its calculation to approximately 1 part in  $10^{17}$  in rate due to uncertainties in realizing the geoid.

The Joint Committee has identified and proposed at least partial solutions for some problems which must be solved in order to improve on this situation:

- clearer definitions of the scaling constants which express the mean rates between TCB, TCG and TT;
- extension of the 1991 IAU metric for the barycentric system to include terms of order higher than  $c^{-2}$ ;
- determination of a formula to calculate TCB in terms of TCG;
- determination of a convention to realize TT and TCG from clocks on, and in the vicinity of, the Earth;
- change the definition of TT by using a specific value of  $L_G$ , given by  $L_G = W_0/c^2$ , as a defining constant, where the value of the gravity potential at the geoid  $W_0$  might be the same as that chosen for a new geodetic reference system.

The President thanked Dr Petit and the committee for the report, and asked him to remain abreast of the activities of the IAU, IUGG and other related bodies on these issues, and to keep the CCTF informed.

## 7.2 Conventional terrestrial reference system

The President invited Dr Petit to address the CCTF on this subject (CCTF99-22).

Dr Petit said that the BIPM had been contacted by the French Bureau des Longitudes on the matter of global geodesy and terrestrial spatial reference systems. The Bureau des Longitudes pointed out that although the International Terrestrial Reference Frame (ITRF), which consists of several hundred points known with centimetric accuracy distributed globally is widely recognized among scientific users, there is no global agreement on the general use of a single spatial reference system, and discrepancies of up to several hundred metres exist between national systems.

The Bureau des Longitudes suggested that the BIPM convene a working group with representatives of all interested parties, such as scientific unions, navigation bodies and users, to recommend a spatial reference system for general use. The Bureau des Longitudes emphasized that the deliberations of this working group should be complementary to the scientific work of the IERS.

At the conclusion of Dr Petit's presentation, the President invited discussion.

Dr Boucher stressed the importance of a unified reference system being chosen so as to take account of the needs of all users, rather than just the geodetic community, for example. He also pointed out the strong parallels between the unit of time and time scales on the one hand, and unit of length and spatial reference systems on the other hand, which is a reason why the Bureau des Longitudes addressed their letter to the BIPM.

Dr McCarthy suggested that this issue should be referred to the International Association of Geodesy, and said he believed that it has little to do with time and frequency, and commented that it may be difficult to convince many countries to change their definitions of position.

Dr Sullivan concurred to some extent, saying that this activity should be encouraged but should not involve a large diversion of the BIPM's resources, as it could take the BIPM well outside its work in measurement standards.

Dr Guinot said that the Bureau des Longitudes sent the letter to the BIPM because the BIPM is very experienced at cooperating with, and facilitating



cooperation between international organizations. He pointed out that the BIPM was not originally active in the field of time scales, and that it was not necessarily inappropriate to add new activities. On the other hand these new activities do not involve scientific and technical activities related to the ITRF, which are under the responsibility of the IERS.

Further discussion followed, summarized by the President, who said that there was no general consensus within the CCTF on this topic, but that the CCTF recognized the importance of this issue being addressed by an appropriate organization. Dr Quinn added that the CCTF has no decision to make because this issue has a larger scope than time and frequency.

## 8 TIMING OF MILLISECOND PULSARS

The President asked Dr Petit to address the committee on this topic.

Dr Petit presented a brief report on progress in this area since the 13th CCDS meeting:

- The Arecibo observatory has been out of service for refurbishment for several years, and observations are presently beginning again.
- The Nançay observatory is also being refurbished to improve its sensitivity. Its programme of timing observations has continued despite this work.
- Other radio telescopes also have millisecond pulsar observation programmes, but with lower sensitivities than the above observatories.
- A number of search programmes for millisecond pulsars are in progress, the most important of which are:
  - the programme using the new Parkes multi-beam instrument, which has found more than 350 new pulsars so far, but only one millisecond pulsar;
  - the Nancay-Berkeley pulsar programme, which to date has found two new “classical” pulsars.

Dr Petit concluded by emphasizing the need for more long-term, low-noise observations of millisecond pulsars which have good rotational stability.

The President thanked Dr Petit, and asked the BIPM Time Section to remain abreast of developments in this field and keep the CCTF informed.

## 9 CLOCKS IN SPACE: PROBLEMS AND OPPORTUNITIES

The President invited Dr Dimarcq to begin the discussion of this agenda item with a report on the activities of the LHA in this area (CCTF99-12).

Dr Dimarcq said that most of the space-clock work at the LHA was oriented towards the Atomic Clock Ensemble in Space (ACES) project, which plans to fly several atomic clocks and associated precise time transfer systems aboard the International Space Station in 2003 or 2004. Clocks for the project based on laser-cooled Cs atoms are being developed in a collaborative effort (the PHARAO project) between the BNM-LPTF, CNRS, ENS-LKB and the LHA. A space-compatible hydrogen maser is also under development at the ON.

Several ground stations with accurate clocks and compatible time transfer equipment will also be involved in the ACES project. Time transfer between the ground and space segments will be via both microwave and optical links. The primary ground station for the laser link will be the OCA. A design team for the microwave link has yet to be selected.

The objectives of the ACES project are:

- demonstration of the performance of the atomic clocks (expected frequency stability  $10^{-16}$  to  $10^{-17}$  over one day averaging) and the timing links (expected stability 30 ps per day);
- fundamental physics experiments, including gravitational red shift and other relativistic experiments, and a search for drifts in the fine structure constant;
- synchronization of ground-based clocks at the  $10^{-16}$  accuracy level for time and frequency metrology experiments;
- construction of ultra-stable time scales.

Dr Dimarcq said that one of the major difficulties to be overcome if all the above objectives are to be met is the calculation of the position and velocity of the ACES timing reference point on the space station, which must be known to within 1 m and less than 1 mm/s, respectively.

Dr Sullivan then outlined the American activities in this area, saying that there are currently four programmes developing space-compatible atomic clocks for possible flight on the International Space Station:

- Primary Atomic Reference Clock in Space (PARCS), which is a joint laser-cooled Cs clock development collaboration between the NIST, the University of Colorado and the JPL;
- Rubidium Atomic Clock in Space (RACE), a collaboration between the Yale University and the JPL;
- Glovebox Atomic Clock in Space (GLACE), which is a programme undertaken by Yale University to develop a compact, self-contained Cs clock, for launch on the Space Shuttle;
- a NIST/Smithsonian Institution collaboration to develop a space-compatible hydrogen maser.

Dr Sullivan said that the cost of the International Space Station is resulting in pressure to conduct the time transfer aspects of the above programmes less expensively, and consequently the PARCS programme will use the GPS system for time transfer, rather than dedicated ground station equipment. He also pointed out that these projects represent the beginning of a longer programme of American research into the applications of clocks in space.

## **10 KEY COMPARISONS AND THE MUTUAL RECOGNITION ARRANGEMENT IN THE TIME AND FREQUENCY DOMAIN**

The President invited Dr Quinn to address the Committee on this topic.

Dr Quinn began by explaining the motivation for developing a system of Mutual Recognition Arrangement (MRA):

- international trade requires mutual recognition of standards conformance infrastructure;
- the important components of this infrastructure are the calibration, testing and verification laboratories, and the way they are accredited;
- National Measurement Institutes (NMIs) are required to oversee technical conformance of this infrastructure;

- mutual recognition of NMIs is therefore needed;
- the *ad hoc* recognition between NMIs which has been used in the past is no longer adequate, detailed documentation is now required.

The objectives of the MRA system are therefore to establish the degree of equivalence of national standards at NMIs, and to establish mutual recognition of these standards and the calibration certificates which are produced using them. The process by which this is achieved is a series of key comparisons, the results of which are held in the BIPM key comparison database. However, before being included in the database, the results of key comparisons must be approved by the appropriate CIPM Consultative Committee.

Dr Quinn continued, saying that the time and frequency activities overseen by the CCTF are a special case, since the existing TAI/UTC system already meets most of the guidelines for key comparisons. He said that the BIPM has no intention of making significant changes to this system to accommodate the MRA.

Dr Quinn suggested that all the only step possibly required would be to identify as the only key comparisons of the CCTF those comparisons between TAI and primary frequency standards or those between primary frequency standards themselves, but that the matter was open to discussion.

The President thanked Dr Quinn and invited discussion.

Dr Douglas expressed concern at the view that the current comparison procedures for UTC(k) are sufficient, in the light of known difficulties with time transfer receiver calibration. He proposed that the key comparisons of the CCTF should instead be:

- primary frequency standards, primary frequency standards-TAI;
- equivalence of UTC(k)s;
- equivalence of the rates of UTC(k)s.

Dr Quinn replied that all of that information is to be found in BIPM *Circular T*, although no uncertainties are reported in that bulletin, an issue which will be addressed, but which will take some time.

Dr Granveaud suggested that the key comparisons of the CCTF could be restricted to frequency, and exclude time, as it may presently be impractical for the reasons outlined by Dr Douglas.

Both Dr Palacio and Prof. Kovalevsky raised the point that there is no generally agreed protocol for expressing uncertainties in a calibration certificate in the time and frequency area. Prof. Kovalevsky suggested that a

working group be convened to address this problem and, recognizing the urgency of the situation created by the MRA, to report in one year.

Dr Douglas suggested that it would be helpful to time and frequency laboratories in NMIs seeking quality system accreditation under ISO Guide 25 if the BIPM also had such a quality system in place. Dr Quinn replied that he was very aware of the need for transparency and openness in the BIPM's procedures. However, although documentation of the BIPM's procedures is currently in progress, he did not wish to commit the BIPM to full ISO Guide 25 accreditation at this time.

Dr Douglas suggested that the CIPM might self-declare ISO Guide 25 compliance, and Dr Quinn replied that this could be considered.

Dr Sullivan said that he would need to have further discussions with the American regional metrology organizations before stating a position on this issue. Dr Boulanger agreed, saying that these issues should be agreed upon regionally in the first instance.

The President called for volunteers to serve on a working group, charged with determining the consequences for the CCTF of the MRA key comparison system, and recommending appropriate action. Dr de Jong consented to lead this group, and Drs Douglas, Ohshima, Palacio and Sullivan agreed to take part. Dr Quinn affirmed the BIPM's support for this working group. A report was requested to be presented in time for the next meeting of the CCTF. [Subsequent to the meeting, Dr Lepek requested that he be added to the membership of the group.]

The President then invited Dr Guinot to make some remarks on accuracy in the context of time and frequency.

Dr Guinot said that the problems of measuring frequency were not essentially different from other areas of metrology, as long as the time-series nature of such measurements is recognized and treated appropriately. However, time, being an integration of frequency, is more difficult, since a fixed frequency uncertainty translates into an increasing time uncertainty. This makes it difficult to express uncertainties in  $[UTC - UTC(k)]$ , as would be required in *Circular T*, since calibrations concern  $[UTC(i) - UTC(j)]$  and are very widely spaced. This raises the difficult issue of how to interpolate uncertainties between these calibrations.

Dr Guinot suggested that, as an interim measure, the BIPM publish the results of all calibrations of  $[UTC(i) - UTC(j)]$ .

The President thanked Dr Guinot, and said that this issue highlighted the importance of more frequent calibrations of  $[UTC(i) - UTC(j)]$ .

## 11 **MISE EN PRATIQUE OF THE SI SECOND**

The President invited Dr Quinn to address the CCTF on this topic.

Dr Quinn proposed the formation of a working party to develop a *mise en pratique* for the SI second, saying that it is now an appropriate time to do this because there might be a new edition of the SI Brochure before the next meeting of the CCTF. He asked the BNM-LPTF, the NIST and the PTB to collaborate with the BIPM on this working party.

After a brief discussion, the President summarized, saying that there was general approval for this proposal, also noting that there was no intention of changing the definition of the SI second and that care would be taken not to write the *mise en pratique* in such a way as to limit progress in primary frequency standards. In due course a draft will be circulated among the members of the CCTF.

## 12 **THE BIPM WORK PROGRAMME**

The President asked Dr Quinn to address the committee on this issue.

Dr Quinn began by saying that in 1985 the BIH Time Section was moved to the BIPM, and responsibility for TAI was later transferred to the BIPM by the CGPM. It was noted at the time that direct involvement in some experimental activities was required if the BIPM was to maintain relevant knowledge and experience in time metrology, and the BIPM time laboratory was set up in response to this. However, the possibility of maintaining a primary frequency standard at the BIPM was excluded, for many reasons.

Dr Quinn said that it is obviously important to ensure, by regular review, that the high-quality staff of the BIPM Time Section are used to best advantage, given the resources available to the BIPM. He said that the three primary tasks of the Time section are currently:

- maintaining and disseminating TAI and UTC;
- time transfer receiver calibration;
- research.

The research activities in which members of the Time Section currently have some involvement include:

- the accuracy of TAI;
- time links;
- GPS/GLONASS receivers;
- GPS phase/code measurements;
- TWSTFT: involvement via the secretary of the CCTF working group on this topic;
- pulsars;
- space-time reference frames and general relativity.

Dr Quinn noted that the above represents a broad range of topics, and that the capacity for undertaking this research exists because of the high level of ability of the staff, and the requirement for some redundancy to ensure that the regular tasks (e.g. TAI/UTC) continue without interruption despite staff absences due to illness, leave or other reasons.

The President thanked Dr Quinn for allowing the time and frequency community the opportunity to have some input into steering the activities of the Time Section, and congratulated the Time Section on the work they are performing. He noted that the BIPM would be prepared to accept any form of input on this issue.

Dr Matsakis offered the opinion that the topics listed above represented more work than could reasonably be carried out within the resources of the Time Section, and requested that the work on time transfer and time links be made as general as possible, so as to be applicable to TWSTFT, GPS carrier phase, etc.

## 13 RECOMMENDATIONS

The President noted that the recommendations had all been discussed under previous agenda items, and suggested that all that remained was for the BIPM staff to make the agreed amendments and translate them into French. This was generally agreed.

**14 OTHER BUSINESS**

Dr Sullivan, speaking as vice-chairman of the recent EFTF/FCS conference, requested that the BIPM consider rotating meetings of the various CCTF working groups among a wider range of international conferences. He said that he believed many conferences would be honoured to host such meetings.

The President agreed, and said that the proposal would be considered.

The President then asked the Committee to note that the next EFTF conference would be held in Turin in March 2000, and that in the same year an International School of Physics “Recent advances in metrology and fundamental constants” would be held in Varenna (Italy). A seminar on time scale formation, run jointly by the IEN and the Turin Polytechnic would also take place in 2001.

Dr Dorenwendt observed that increased cooperation between the CCTF and the CCL may be needed, owing to the increasingly close links between length and frequency measurements being provided by microwave-optical frequency multiplication chains. He suggested that combining the work of the CCL and the CCTF should be considered.

Dr Quinn agreed in principle, but said that such a combined committee might be impractically large.

Dr Sullivan suggested that a distinction between work aimed at optical frequency standards and optical length standards might be helpful in clarifying the future roles of, and interactions between, the CCL and the CCTF. He added that he thought these committees should remain separate.

Finally, Dr Quinn said that at the most recent meeting of the CCPR it was decided that a list of relevant recent publications by the Consultative Committee members would be compiled and published under the BIPM web page, with annual updates. He suggested that the CCTF should also do this.

The President, noting no objections, requested that the committee members provide this information in due course.



**15 CLOSURE OF THE MEETING**

The President asked the committee to stand in commemoration of the recent passing of three people who had made major contributions in the field of time and frequency, Dr Paul Vigoureux, Dr William Markowitz and Dr Gerhard Becker.

The President then thanked Dr Petit for organizing the work of the CCTF, and offered the best wishes of the CCTF to Dr Arias. He thanked Dr Quinn, the BIPM, the chairmen of the working groups, and the members and observers of the CCTF.

Finally, the President said that the next meeting of the CCTF would be held in Paris in 2001.

P. Fisk, Rapporteur

August 1999



**Recommendations of the  
Consultative Committee for Time and Frequency**

**submitted to the  
Comité International des Poids et Mesures**

**1 RECOMMENDATION S 1 (1999):**  
***Mise en pratique* of the definition of the second**

The Consultative Committee for Time and Frequency,

**considering**

- that at its 86th (1997) meeting, the CIPM introduced, in the 7th edition of the SI brochure, a footnote to the definition of the second,
- that the highest degree of clarity is desirable for those designing and operating primary realizations of the second,
- the CCDS Recommendation S 2 (1985) entitled “Corrections needed for the realization of the second”,

**recommends that**

- the footnote be expanded to read: “This definition implies that the caesium atom is at rest and unperturbed. In consequence, in its practical realization, measurements must be corrected for velocity of the atoms with respect to the clock reference frame, for magnetic and electric fields including ambient black-body radiation, for spin-exchange effects and for other possible perturbations”,
- in the next edition of the SI brochure, the footnote be expanded to take the form of a *mise en pratique* of the definition and that this *mise en pratique* be placed in Appendix 2 of the brochure alongside the *mises en pratique* of the definitions of the other base units of the SI.

**2 RECOMMENDATION S 2 (1999):**  
**On stating uncertainty in comparisons involving**  
**primary frequency standards**

The Consultative Committee for Time and Frequency,

**considering that**

- for a specific date and time interval, a comparison of a frequency standard with some other standard can accommodate most of the recommendations of the ISO *Guide to the expression of uncertainty in measurement*,
- the “Type A” and “Type B” methods, applied to primary frequency standards, have been found to be ambiguous,
- the ISO Guide recommends that the reader be provided with enough information to combine the uncertainty with other uncertainties,
- the comparison’s autocorrelation function has not been found to be a convenient way for communicating how the standard uncertainties in the sub-intervals of a larger interval are to be combined by the user,
- the ISO Guide recommends using the degrees of freedom  $\nu \approx \frac{1}{2} (\Delta u/u)^{-2}$  to communicate the uncertainty in the uncertainty and there are some differences of interpretation in assigning  $\nu$  to some components,

**recommends that**

- explicit descriptions be given by responsible metrologists for describing the method for evaluating an uncertainty component for a comparison involving a primary frequency standard, and that the ISO Guide designations “Type A” and “Type B” not be used where they appear ambiguous or unhelpful,
- in publishing a series of comparisons between a primary frequency standard and another standard, a formula be explicitly included for the method of combining uncertainties for the uncertainty in a composite interval,
- those revising the ISO Guide be asked to consider suggesting a word to serve for the deprecated term “systematic” in combining uncertainties in a time series,

- if the uncertainty in the uncertainty is to be expressed, the effective degrees of freedom,  $\nu \approx \frac{1}{2} (\Delta u/u)^{-2}$  is to be used, considering all sources of variation recognized by the author.

### **3 RECOMMENDATION S 3 (1999): On the comparison of primary frequency standards**

The Consultative Committee for Time and Frequency,

**considering that**

- the results of comparisons of primary frequency standards are essential for establishing the accuracy of TAI and ensuring traceability to the SI second,
- the steering of TAI could be best documented if it were to be based exclusively on discussion of the published results of comparisons of TAI with primary frequency standards,
- future work related to establishing the accuracy of long-term time intervals will require access to the results of such comparisons and hence archival publication now is necessary,
- the interpretation of results from a primary frequency standard is facilitated by these results taking the form of a comparison, over a specific interval, with respect to another frequency standard,
- the performance and understanding of a primary frequency standard, of the methods of comparison and their associated uncertainties, are not stationary,
- the *ISO Guide to the expression of uncertainty in measurement* recommends the formation of a combined standard uncertainty for any measurement and provision of enough information to combine uncertainties,

**recommends that**

- results from a primary frequency standard be given explicitly as a comparison for a specified date and time interval, with its combined

standard uncertainty, following the ISO Guide, in the light of Recommendation S 2 (1999),

- in a comparison involving more than one responsible metrologist, a jointly authorized uncertainty statement be associated with the particular comparison,
- this uncertainty statement either refer to the publication of all corrections, their methods of evaluation and descriptions of all instrumentation, or itself constitute such a publication,
- laboratories whose primary frequency standards are compared with TAI regularly publish the results of bilateral comparisons, in first preference in *Metrologia*, with joint authorship by those responsible for the comparison,
- the steering of TAI be guided primarily by these comparisons that have been, or are certain to be published.

#### **4 RECOMMENDATION S 4 (1999): On the use of multi-channel and multi-code GPS and GLONASS time receivers**

The Consultative Committee for Time and Frequency,

##### **considering that**

- a number of commercial multichannel and multi-code GPS and GLONASS time receivers have been developed,
- the performance of these receivers compares favourably with those currently used by timing laboratories for time and frequency coordination,
- the larger availability of data and their utilization can lead to improved common-view time transfer,
- the existing receivers are becoming more difficult to maintain,

**recommends**

- the inclusion of multi-channel and multi-code GPS and/or GLONASS time data for international time coordination,
- that this use of such receivers be studied by the Sub-group on GPS and GLONASS Time Transfer Standards (CGGTTS),
- that by June of 2000, the CGGTTS issue a report suggesting standards for hardware and software and calibration methods for these receivers,
- that the BIPM identify appropriate procedures to implement this technique for international time coordination.

## **5 RECOMMENDATION S 5 (1999): Time and frequency comparisons using GPS phase and code measurements**

The Consultative Committee for Time and Frequency,

**considering that**

- the International GPS Service (IGS) has established an infrastructure of a global observing network, a data distribution system, a robust analysis methodology and high-quality GPS products,
- a joint IGS/BIPM Pilot project has been established to study time and frequency comparisons using GPS phase and code measurements,
- calibration methods are still lacking to exploit fully the capabilities of these techniques for time comparisons,

**fully supports** the joint IGS/BIPM Pilot project,

**and recommends that**

- timing laboratories consider participation in the IGS by installing appropriate GPS receivers and following the IGS procedures and standards to the greatest extent possible,



- appropriate methods be developed to calibrate the instrumental delays relating the receiver internal reference to the external clock,
- the IGS reference for clock products be aligned as closely as possible with UTC and TAI,
- the timing laboratories and the BIPM take the necessary steps to allow the IGS to realize this goal.

## **6 RECOMMENDATION S 6 (1999): Future global navigation satellite systems\***

The Consultative Committee for Time and Frequency,

### **considering that**

- the former Consultative Committee for the Definition of the Second already recommended “that the reference times (modulo 1 s) of satellite navigation systems with global coverage be synchronized as closely as possible with UTC” and “that the reference frames for these systems be transformed to be in conformity with the ITRF” (Recommendation S 4 (1996)),
- both the GPS and GLONASS systems follow these guidelines,
- these systems are now widely used for time and frequency comparisons,

### **recommends that**

- all global navigation satellite systems be designed so that it is possible to use their signals for time and frequency comparisons,
- these systems broadcast, in addition to their own System Time (ST):
  1. the time difference between ST and a real-time realization of UTC and TAI,
  2. a prediction of the time differences between ST and UTC and TAI,

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\* This Recommendation was approved by the CIPM at its 88th meeting as Recommendation 1 (CI-1999).

- manufacturers develop receivers and processing systems designed for time and frequency comparison purposes.

## **7 RECOMMENDATION S 7 (1999): On Two-Way Satellite Time and Frequency Transfer**

The Consultative Committee for Time and Frequency

### **considering that**

- there is a need for comparison of new primary frequency standards using the best means available,
- during the past three years the Two-Way Satellite Time and Frequency Transfer (TWSTFT) method has become fully operational,
- a standard format for data exchange has been adopted,
- significant progress has been achieved with commercially available modems and calibration methods,
- TWSTFT performance is comparable with the GPS C/A-Code single-channel Common-View method for the current measurement schedule, and gives even more stable results over shorter baselines,
- the possible use of advanced techniques promises a further significant improvement in results,
- a number of timing centres around the world are now equipped with TWSTFT and others soon will be,
- TWSTFT offers the means to have a technique independent of GPS Common-View, which is now the sole means of time transfer contributing to the formation of TAI,

### **recommends that**

- timing centres continue to work with TWSTFT,
- the necessary studies be undertaken to allow the incorporation of TWSTFT data into the construction of TAI and that this be implemented as soon as practical.

**APPENDIX 1.****Working documents submitted to the CCTF at its 14th meeting**

(see the list of documents on page 65)



## LIST OF ACRONYMS USED IN THE PRESENT VOLUME

### 1 Acronyms for laboratories, committees and conferences

BIH*	Bureau International de l'Heure
BIPM	Bureau International des Poids et Mesures
BNM-LPTF	Bureau National de Métrologie, Laboratoire Primaire du Temps et des Fréquences, Paris (France)
CCDS*	Consultative Committee for the Definition of the Second
CCL	Consultative Committee for Length
CCPR	Consultative Committee for Photometry and Radiometry
CCTF	(formerly the CCDS) Consultative Committee for Time and Frequency
CGGTTS	CCDS Group on GPS and GLONASS Time Transfer Standards
CGSIC	Civil GPS Service Interface Committee
CIPM	Comité International des Poids et Mesures
CNRS	Centre National de la Recherche Scientifique, Orsay (France)
CRL	Communications Research Laboratory, Tokyo (Japan)
CSAO	Shaanxi Astronomical Observatory, Lintong (China)
CSIR-NML	Council for Scientific and Industrial Research, National Metrology Laboratory, Pretoria (South Africa)
CSIRO	Commonwealth Scientific and Industrial Research Organization, Division of Applied Physics, Lindfield (Australia)
DLR	Deutsche Forschungsanstalt für Luft- und Raumfahrt, Oberpfaffenhofen (Germany)
DTAG	Deutsche Telecom AG, Darmstadt (Germany)
EFTF	European Frequency and Time Forum
ESA	European Space Agency
EUROMET	European Collaboration in Measurement Standards
FCS	Frequency Control Symposium
IAU	International Astronomical Union

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\* Laboratories marked with an asterisk either no longer exist or operate under a different acronym.

IEEE	Institute of Electrical and Electronics Engineers, Piscataway NJ (United States)
IEN	Istituto Elettrotecnico Nazionale Galileo Ferraris, Turin (Italy)
IERS	International Earth Rotation Service
IGS	International GPS Service
IGS-RINEX	Receiver Independent Exchange Format of IGS
INPL	National Physical Laboratory of Israel, Jerusalem (Israel)
INTELSAT	International Telecommunications Satellite Organization
ISO	International Organization for Standardization
ITU	International Telecommunication Union
IUGG	International Union of Geodesy and Geophysics
JPL	Jet Propulsion Laboratory, Pasadena, Ca (United States)
KRISS	Korea Research Institute of Standards and Science, Taejon (Rep. of Korea)
LHA	Laboratoire de l'Horloge Atomique, Orsay (France)
LKB	Laboratoire Kastler-Brossel de l'École Normale Supérieure, Paris (France)
LPTF	Laboratoire Primaire du Temps et des Fréquences, Paris (France), see BNM
NBS*	National Bureau of Standards (United States), see NIST
NIM	National Institute of Metrology, Beijing (China)
NIST	(formerly the NBS) National Institute of Standards and Technology, Boulder (United States)
NMi-VSL	Nederlands Meetinstituut, Van Swinden Laboratory, Delft (The Netherlands)
NML*	National Measurement Laboratory, Lindfield (Australia), see CSIRO
NPL	National Physical Laboratory, Teddington (United Kingdom)
NPLI	National Physical Laboratory of India, New Delhi (India)
NRC	National Research Council of Canada, Ottawa (Canada)
NRLM	National Research Laboratory of Metrology, Tsukuba (Japan)
OCA	Observatoire de la Côte d'Azur, Grasse (France)
OFMET	Office Fédéral de Métrologie/Eidgenössisches Amt für Messwesen, Wabern (Switzerland)
ON	Observatoire Cantonal de Neuchâtel, Neuchâtel (Switzerland)

ORB	Observatoire Royal de Belgique, Brussels (Belgium)
PSB	Singapore Productivity and Standards Board (Singapore)
PTB	Physikalisch-Technische Bundesanstalt, Braunschweig (Germany)
ROA	Real Instituto y Observatorio de la Armada, San Fernando (Spain)
TL	Telecommunication Laboratories, Ching-Li (Taiwan)
TUG	Technical University, Graz (Austria)
URSI	International Union of Radio Science
USNO	U.S. Naval Observatory, Washington DC (United States)
VNIIFTRI	All-Russian Research Institute for Physical, Technical and Radio-Technical Measurements, Moscow (Russian Fed.)
VSL*	Van Swinden Laboratorium, Delft (The Netherlands), see NMI

## 2 Acronyms for scientific terms

ACES	Atomic Clock Ensemble in Space
ALGOS	Time-scale algorithm for TAI, BIPM
EAL	Free atomic time scale
GLACE	Glovebox Atomic Clock in Space
GLONASS	Global Navigation Satellite System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
ITRF	Terrestrial Reference Frame maintained by the International Earth Rotation Service
PARCS	Primary Atomic Reference Clock
PHARAO	Projet d'horloge atomique à refroidissement d'atomes en orbite
RACE	Rubidium Atomic Clock in Space
SA	Selective Availability
SI	International System of Units
ST	Specific Time
TAI	International Atomic Time
TCB	Barycentric Coordinated Time
TCG	Geocentric Coordinated Time
TDB	Barycentric Dynamic Time
TT	Terrestrial Time
UTC	Coordinated Universal Time
WAAS	Wide Area Augmentation System