

Bureau International des Poids et Mesures

Consultative Committee for Time and Frequency (CCTF)

15h Meeting (June 2001)

Note on the use of the English text

To make its work more widely accessible the International Committee for Weights and Measures 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.

TABLE OF CONTENTS

Photograph of participants attending the 15th meeting of the Consultative Committee for Time and Frequency **2**

Member States of the Metre Convention and Associates of the General Conference **83**

The BIPM and the Metre Convention **85**

List of members of the Consultative Committee for Time and Frequency **89**

Report to the International Committee for Weights and Measures,
by P. Fisk **91**

Agenda **92**

1 Opening of the meeting; agenda; appointment of a rapporteur **93**

2 Progress in primary frequency standards **94**

2.1 Operating primary frequency standards and new primary standards under development **94**

2.2 CCTF Working Group on the Expression of Uncertainties in Primary Frequency Standards **99**

3 Present Status of TAI **101**

3.1 Report on TAI of the BIPM Time section **101**

3.2 Report of the CCTF Working Group on TAI **102**

3.3 Report of the CCTF Working Group on TAI Sub-Group on Algorithms **104**

4 Future developments for UTC and TAI **105**

5 Redefinition of UTC: leap seconds **107**

6 Conventional nomenclature for UTC **110**

7 Time- and frequency-transfer methods **111**

7.1 Report of the CCTF Working Group on TWSTFT **111**

7.2 GPS phase measurements: Report on the IGS/BIPM Pilot Project **112**

7.3 Report of the CCTF Sub-Working Group on GPS/GLONASS Time-Transfer Standards **114**

8 General relativity and space-time references **115**

8.1 Report of the BIPM/IAU Joint Committee on General Relativity for Space-Time Reference Systems and Metrology **115**

- 8.2 Report on the IERS Conventions Product Centre **117**
- 9 Clocks in space **118**
- 10 Future satellite navigation systems **120**
- 11 Key comparisons and the Mutual Recognition Arrangement in the time and frequency domain **122**
- 12 The BIPM work programme **126**
- 13 Recommendations **128**
- 14 Other business **130**

Recommendations submitted to the International Committee for Weights and Measures

- CCTF 1 (2001). Secondary representations of the second **132**
- CCTF 2 (2001). Time and frequency comparisons using Global Positioning System (GPS) phase and code measurements **133**
- CCTF 3 (2001). The meaning of the designation “ k ” in UTC(k) and TAI(k) **134**
- CCTF 4 (2001). Calibration of time links for International Atomic Time **135**
- CCTF 5 (2001). Technical guidelines for manufacturers of Global Navigation Satellite Systems receivers used for timing **136**

Appendix 1. Working documents submitted to the CCTF at its 15th meeting **137**

List of acronyms used in the present volume **139**

**MEMBER STATES OF THE METRE CONVENTION AND
ASSOCIATES OF THE GENERAL CONFERENCE**

as of 20 June 2001

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
Greece	Switzerland
Hungary	Thailand
India	Turkey
Indonesia	United Kingdom
Iran (Islamic Rep. of)	United States
Ireland	Uruguay
Israel	Venezuela
Italy	

Associates of the General Conference

Cuba	Latvia
Ecuador	Lithuania
Hong Kong, China	Malta

THE BIPM AND THE METRE CONVENTION

The International Bureau of Weights and Measures (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 m²) 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 International Committee for Weights and Measures (CIPM) which itself comes under the authority of the General Conference of Weights and Measures (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), time scales (1988) and to chemistry (2000). 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, in 1984 for the laser work, and in 1988 for a library and offices. In 2001 a new building for the workshop, offices and meeting rooms 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, the *Director's Report on the Activity and Management of the International Bureau of Weights and Measures*, 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 γ -rays, electrons), Section II (Measurement of radionuclides), Section III (Neutron measurements), Section IV (α -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 1998.

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

- *Report of the meetings of the General Conference on Weights and Measures;*
- *Reports of the meetings of the International Committee for Weights and Measures;*
- *Reports of the meetings of Consultative Committees.*

The BIPM also publishes monographs on special metrological subjects and, under the title *The International System of Units (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 *Director's Report on the Activity and Management of the International Bureau of Weights and Measures*.

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 June 2001

President

S. Leschiutta, member of the International Committee for Weights and Measures, Istituto Elettrotecnico Nazionale Galileo Ferraris, Turin.

Executive secretary

E.F. Arias, International Bureau of Weights and Measures [BIPM], Sèvres.

Members

Bureau National de Métrologie, Laboratoire Primaire du Temps et des Fréquences [BNM-LPTF]/Laboratoire de l'Horloge Atomique [LHA] du Centre National de la Recherche Scientifique [CNRS], Paris.

Communications Research Laboratory [CRL], Tokyo.

Institute for Physical, Technical and RadioTechnical Measurements, Gosstandart of Russia [VNIIFTRI], Moscow.

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], Taejon.

National Institute of Metrology [NIM], Beijing.

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

National Measurement Laboratory, CSIRO [NML-CSIRO], Lindfield.

National Metrology Institute of Japan, National Institute of Advanced Industrial Science and Technology [NMIJ/AIST], Tsukuba.

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.

NMi Van Swinden Laboratorium [NMi VSL], Delft.

Observatoire Royal de Belgique [ORB], Brussels.

Office Fédéral de Métrologie et d'Accréditation [METAS], 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 International Bureau of Weights and Measures [BIPM],
Sèvres.

Observers

CSIR, National Metrology Laboratory [CSIR-NML], Pretoria.

Singapore Productivity and Standards Board [PSB], Singapore.

Ulusal Metroloji Enstitüsü/National Metrology Institute of Turkey [UME],
Gebze-Kocaeli.

**Consultative Committee
for Time and Frequency**

Report of the 15th Meeting
(20 - 21 June 2001)

Agenda

- 1 Opening of the meeting; agenda; appointment of a rapporteur.
- 2 Progress in primary frequency standards:
 - 2.1 Operating primary frequency standards and new primary standards under development;
 - 2.2 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;
 - 3.3 Report of the CCTF Working Group on TAI Sub-Group on Algorithms.
- 4 Future developments for UTC and TAI.
- 5 Redefinition of UTC: leap seconds.
- 6 Conventional nomenclature for UTC.
- 7 Time- and frequency-transfer methods:
 - 7.1 Report of the CCTF Working Group on TWSTFT;
 - 7.2 GPS phase measurements: Report on the IGS/BIPM Pilot Project;
 - 7.3 Report of the CCTF Sub-Working Group on GPS/GLONASS Time-Transfer Standards.
- 8 General relativity and space-time references:
 - 8.1 Report of the BIPM/IAU Joint Committee on General Relativity for Space-Time Reference Systems and Metrology;
 - 8.2 Report on the IERS Conventions Product Centre.
- 9 Clocks in space.
- 10 Future satellite navigation systems.
- 11 Key comparisons and the Mutual Recognition Arrangement in the time and frequency domain.
- 12 The BIPM work programme.
- 13 Recommendations.
- 14 Other business.

1 OPENING OF THE MEETING; AGENDA; APPOINTMENT OF A RAPPORTEUR

The Consultative Committee for Time and Frequency (CCTF) held its 15th meeting at the International Bureau of Weights and Measures (BIPM), at Sèvres. Four sessions took place, on 20 and 21 June 2001.

The following were present: P. Banerjee (NPLI), A. Bauch (PTB), R. Beard (ITU), L.-G. Bernier (METAS), C. Boucher (IUGG), J.-S. Boulanger (NRC), G. de Jong (NMI VSL), A.B. Demichev (VNIIFTRI), Y.S. Domnin (VNIIFTRI), G. Duddle (METAS), N. Dimarcq (BNM-LPTF/LHA), P. Fisk (CSIRO-NML), T. Fukushima (IAU), X. Gao (NIM), A. Godone (IEN), M. Granveaud (BNM-LPTF/LHA), D. Henderson (NPL), M. Hosokawa (CRL), T. Ikegami (NMIJ/AIST), M. Imae (CRL), D. Kirchner (TUG), J. Kovalevsky (President of the CIPM), J. Lavery (NPL), H.S. Lee (KRISS), S. Leschiutta (President of the CCTF, IEN), J. Levine (NIST), F. Ma (NIM), J. Mc A. Steele (URSI), D. McCarthy (USNO), D. Matsakis (USNO), S. Ohshima (NMIJ/AIST), J. Palacio (ROA), P. Pâquet (ORB), S.B. Pushkin (VNIIFTRI), T.J. Quinn (Director of the BIPM), F. Riehle (PTB), D.B. Sullivan (NIST), P. Tavella (IEN), P. Thomann (METAS/ON).

Observers: H.A. Chua (PSB), R. Gamidov (UME), L. Marais (CSIR-NML).

Invited: S.-Y. Lin (TL), J. Ray (USNO).

Also present: P. Giacomo (Director emeritus of the BIPM), E.F. Arias (Executive Secretary of the CCTF), J. Azoubib, W. Lewandowski, G. Petit, P. Wolf (BIPM).

Sent regrets: R. Douglas (NRC), B. Guinot, T.E. Parker (NIST).

The President opened the meeting and welcomed the delegates and observers. Addressing the first item of the agenda, he said that he had received a letter from Prof. Guinot, apologizing for being unable to attend the meeting and asking to withdraw his name from the CCTF. The President expressed his good wishes and gratitude to Prof. Guinot for his contributions over a long period of time, and recommended that the CCTF ask Dr Quinn to prepare a letter of thanks on its behalf. The meeting agreed and Dr Quinn said he would write the letter.

The President then asked the meeting to stand for one minute in commemoration of Dr Louis Essen, who commissioned the first caesium

frequency standard at the NPL, London, in 1955. He suggested that because in 2005 it will be fifty years since that date, the CCTF might prepare a tribute to him at that time. Dr Quinn responded that although he will have retired as Director of BIPM by 2005, he will pass the suggestion on to his successor.

Finally, the President informed the meeting that Dr Fisk had agreed to serve as Rapporteur.

2 PROGRESS IN PRIMARY FREQUENCY STANDARDS

Introducing this agenda item, the President noted the large number of caesium fountains being constructed around the world, and that the PTB is currently operating its fountain as a clock. He then invited the representatives of each laboratory to present brief oral reports summarizing their written submissions, which will be available with the report of the CCTF meeting.

2.1 Operating primary frequency standards and new primary standards under development

Summaries of the following reports from the laboratories were then presented by the speakers indicated.

CCTF/01-01a (NIST, Dr Sullivan):

- The caesium fountain frequency standard NIST-F1 has been operating and four formal evaluations of its frequency against that of TAI have been submitted to the BIPM. The NIST is working towards operating the standard on a regular basis in order to contribute to TAI.
- NIST-F1 and the PTB caesium fountain CSF1 have been compared via TWSTFT and GPS carrier-phase time transfer, and their frequencies agree within their calculated uncertainties.
- The NIST has continued its collaborative involvement in the development of a Primary Atomic Reference Clock in Space (PARCS), and the project is on schedule for the planned flight of the device on the International Space Station (ISS) in 2005.

- An ultra-narrow linewidth ultraviolet laser has been locked to a transition in a single trapped $^{199}\text{Hg}^+$ ion. The observed Q of the resonance signal is 1.6×10^{14} , which is the highest observed in any optical transition. The uncertainty of the standard is expected to approach 1 part in 10^{18} . The frequency of the locked laser will be coherently linked to the RF and microwave region using femtosecond comb technology.
- The magnitude of fluctuations in the fluorescence from four trapped ions prepared in an entangled quantum state has been experimentally demonstrated to be lower than the standard quantum limit for four independent ions. This phenomenon may be of practical interest for future frequency standards.

CCTF/01-02a (CRL, Dr Hosokawa):

- The optically-pumped caesium beam frequency standard CRL-01 has been operating since early 2000, and uncertainty evaluations are presently in progress.
- A prototype CRL-developed space-flyable hydrogen maser is currently undergoing environmental tests.

CCTF/01-03 (METAS, Dr Thomann):

- A caesium fountain frequency standard which generates a continuous stream of cold caesium atoms, instead of isolated clouds, is under development. The continuous stream of atoms is expected to result in a reduction of the collisional frequency shift by a factor of 50, and a reduction of instability due to the Dicke effect by a factor of more than 100, compared with conventional caesium fountain designs. The target stability performance is $\sigma_y(\tau) = 7 \times 10^{-14} \tau^{-1/2}$.

CCTF/01-04 (NPLI, Dr Banerjee):

- The NPLI is planning to build a caesium fountain frequency standard, and funding is presently being negotiated.

CCTF/01-05 (KRISS, Dr Lee):

- A caesium fountain frequency standard has been under development since 1998, and a microwave resonance linewidth of less than 2 Hz has been achieved. This linewidth is expected to be reduced to less than 1 Hz during 2001.
- A caesium frequency standard based on a slow (30 m/s) continuous beam of atoms is under development, and Ramsey fringes of 60 Hz in width have been observed. A new transverse cooling technique using two-

dimensional optical molasses has been incorporated, which results in a tenfold increase in signal.

- The conventional beam caesium standard KRISS-1 has had its microwave cavity replaced in order to reduce troublesome microwave leakage. The evaluation of the uncertainty of the system will be completed soon.

CCTF/01-06 (ORB, Prof. Pâquet):

- Significant progress has been made in the area of the GPS Common View and GPS Carrier Phase time-transfer techniques.

CCTF/01-08 (VNIIFTRI, Dr Domnin):

- The uncertainty of the conventional caesium beam primary frequency standard MCs-102 has been evaluated as 2 parts in 10^{14} and its frequency difference with respect to TAI was measured as -5 parts in 10^{15} .
- A caesium fountain standard is under development, with trapping, cooling and manipulation of the atoms expected to be demonstrated during 2001.
- A high-power hydrogen maser has been developed to serve as a highly stable local oscillator for the caesium fountain.

CCTF/01-09 (NMIJ/AIST [formerly NRLM], Dr Ohshima):

- The NRLM has recently been restructured and combined with other organizations to form the much larger entity NMIJ.
- The conventional caesium beam primary frequency standard NRLM-04 has been moved to a new building and is being reassembled. It is expected to be operating again within a few months.
- The caesium fountain which has been under development for some time is becoming operational, with a frequency stability $\sigma_y(\tau=1\text{ s}) = 1 \times 10^{-12}$. This stability is worse than expected, and the cause is being investigated.
- The NRLM/NMIJ optical frequency division system based on continuous-wave optical parametric oscillators has been replaced by a femtosecond comb system. The system is presently being used to measure the frequencies of iodine-stabilized He-Ne and YAG lasers operating at 633 nm and 532 nm, respectively.

CCTF/01-11 (NML, Dr Fisk):

- Work on the $^{171}\text{Yb}^+$ trapped ion standard has recently been focused on measuring in three dimensions the heating rate of the cold ion cloud in

the absence of the cooling lasers during the Ramsey microwave interrogation sequence. Results indicate that a combined total uncertainty below 4 parts in 10^{15} is feasible.

- The NML Time and Frequency Group was granted accreditation to ISO Guide 25 for its calibration and timekeeping activities in late 1999.
- Significant progress has been made on the development and deployment of both single- and dual-frequency GPS common view time-transfer systems.

CCTF/01-12 (PTB, Dr Bauch):

- The PTB caesium fountain primary frequency standard CSF1 was completed during 2000, and is operating almost continuously (~28 days per month). Details of the evaluation of its uncertainty will be published in *Metrologia* during 2001.
- Several absolute frequency measurements of the 657 nm line in trapped Ca atoms and the 435 nm line in single trapped $^{171}\text{Yb}^+$ ions have been made, using the PTB harmonic mixing frequency measurement chain, and more recently, a femtosecond comb optical frequency measurement system. A linewidth of less than 30 Hz has been demonstrated on the 435 nm line of the $^{171}\text{Yb}^+$ system, and repeated measurements of its frequency have agreed to within less than 1 part in 10^{14} .

Dr Bauch remarked that in spite of the large number of caesium fountains being developed around the world, he still sees good reasons to continue the operation of conventional caesium beam primary frequency standards such as PTB's CS1 and CS2.

CCTF/01-13 (TUG, Dr Kirchner):

- He reported that operation of the Time laboratory was terminated at the end of 2000. Dr Bauch said that this was a great loss to the time community, and expressed his thanks for the contributions of Dr Kirchner and the TUG, especially in the field of TWSTFT.
- The President endorsed Dr Bauch's comments, and thanked Dr Kirchner on behalf of CCTF for his contributions.

CCTF/01-15 (IEN, Dr Godone):

- A caesium fountain has been constructed with the cooperation of the NIST and the University of Turin. The uncertainty budget is nearly complete, with work progressing on the collisional frequency shift. Progress is limited by the lack of a hydrogen maser as a frequency reference during the uncertainty investigations.

CCTF/01-18 (NMi VSL, Dr de Jong):

- The NMi VSL group has focused mainly on time-transfer problems, including the identification and correction of design deficiencies in certain GPS common view time-transfer receivers, and the study of issues related to signal reflections in antenna cables.

CCTF/01-25 (BNM-LPTF/LHA, Drs Granveaud and Dimarcq):

- The LHA moved from Orsay to the OP during 2000, which has resulted in close cooperation with the BNM-LPTF.
- The BNM-LPTF is currently operating three primary frequency standards: one (LPTF-JP0) is an optically pumped conventional caesium beam standard, and the other two (LPTF-F01 and PHARAO) are caesium fountain standards. No formal comparisons with TAI have been submitted to the BIPM due to problems with hydrogen masers.
- The relative uncertainty estimate for the caesium fountain standard LPTF-F01 has been improved to 1.1×10^{-15} , owing partly to a more accurate characterization of the black-body shift. Testing of a dielectric resonator oscillator built by the University of Western Australia as a local oscillator for this fountain is in progress.
- The PHARAO fountain, which was built four years ago, has been modified to be portable, and its uncertainty in its present form is estimated as better than 2 parts in 10^{15} . It was used at the Max Planck Institute for Quantum Optics in 2000 as a reference for measurements of optical transition frequencies.
- A caesium/rubidium “double” fountain is under construction, and presently has an estimated uncertainty of 2 parts in 10^{15} when operating with rubidium alone. The microwave cavity for caesium is now installed, and the system is expected to be operating in the double configuration by the end of 2001.
- A cold Sr atom optical frequency standard and a femtosecond comb optical frequency measurement system are under construction.
- A TWSTFT facility is being established.
- The ESA and French Space Agency (CNES) have approved the PHARAO and ACES projects for flight on the ISS in 2005.
- Optically pumped thermal caesium beam and cold caesium clocks are being developed. An important effort is being made in this field in Europe within the development of the Galileo GNSS system.

- New inertial and gravimetric sensors based on atom interferometry are under development, with expected performance superior to that of optical devices.

CCTF/01-31 (USNO, Dr Matsakis):

- Various systems are being upgraded to support the forthcoming changes to GPS architecture.
- The USNO Master Clock is being steered to within 5 ns of UTC.
- Effort is being applied to the calibration of TWSTFT links.
- The use of the Wide Area Augmentation System (WAAS) and of the European Geostationary Navigation Overlay Service (EGNOS) in time-transfer applications is being studied.
- Development work on GPS carrier-phase time transfer is being carried out in collaboration with hardware manufacturers, the JPL and the Canadian network of IGS monitoring stations.
- A caesium fountain primary frequency standard is under development.

CCTF/01-32a (NRC, Dr Boulanger):

- The NRC conventional caesium beam primary frequency standards are being upgraded to operate in a more automated manner.
- 100 MHz outputs are being installed on the NRC hydrogen masers to support caesium fountain development and optical frequency measurement.
- A caesium fountain primary frequency standard (NRC-F1) is under development, and the first Ramsey fringes were observed in December 1999. The 110 trapping geometry is used, and the fountain will operate with two cold caesium atom clouds in flight simultaneously.
- The frequency of the 574 nm line in a single trapped Sr^+ ion has been measured using the NRC harmonic mixing frequency chain, with an uncertainty of a few parts in 10^{13} .
- A femtosecond comb frequency measurement system is under development.
- Experiments using the WAAS for time transfer have been carried out.

2.2 CCTF Working Group on the Expression of Uncertainties in Primary Frequency Standards

Dr Petit presented a summary of report (CCTF/01-21) on the implementation of the recommendations of the working group.

He indicated that following Recommendations S 2 and S 3 of the 14th meeting of the CCTF in 1999, the BIPM Time section has reconsidered the way in which the data from primary frequency standards are used for evaluating the duration of the scale unit of TAI and how they are reported in *Circular T* and other BIPM publications. The changes first appeared in *Circular T* in May 2000. The main points are:

- All comparisons of primary frequency standards with TAI which are communicated to the BIPM for report are required to include specific details of the uncertainty budget of the standard, and of the timing link used for the comparison.
- CCTF Recommendation S 3 (1999) encouraged laboratories providing data from primary frequency standards to publish the results of bilateral comparison with TAI. At the initiative of the PTB, joint PTB/BIPM reports have been submitted for publication in *Metrologia*.

Dr Petit concluded by noting that the present treatment of comparison data between primary frequency standards is adequate for the current situation where the accuracy of the best standards, the stability of the best timing links and that of EAL are all similar, being around one to a few parts in 10^{15} . Further development of the algorithm for generating TAI and improvement of timing links will be needed in order to take advantage of further improvements in the accuracy of primary frequency standards.

The President thanked Dr Petit for the report, and asked if any further input from the CCTF on these issues is required at this point. Dr Petit replied that the situation is satisfactory for the present performance of primary frequency standards and timing links, but that before the next meeting of the CCTF the issue of taking the best advantage of further improvements in performance should be addressed.

Dr Quinn said that, independently of the CCTF, there is great momentum around the world in the development of primary frequency standards, and emphasized the importance of working to ensure that TAI makes optimum use of them.

3 PRESENT STATUS OF TAI

3.1 Report on TAI of the BIPM Time section

Dr Arias summarized report CCTF/01-29.

Since the 14th meeting of the CCTF in 1999, the BIPM Time section has published volumes 12 (1999) and 13 (2000) of its annual report, which include the data issued in the regular reports such as *Circular T* for those years. In future, the Time section wishes to disseminate this data primarily by electronic means such as e-mail and FTP, and after consulting with representatives of laboratories contributing to TAI, is proposing to issue paper reports only to those laboratories which specifically request them. The Annual Report will continue to be produced in paper form. There was general support for these proposals, and BIPM has distributed a questionnaire on this subject to laboratories contributing to TAI.

The process of computing TAI from data contributed by laboratories is gradually being automated, and one benefit will be that it will facilitate the calculation of near-real-time predictions of TAI and UTC (discussed under agenda item 4, “Future developments for UTC and TAI”).

An improvement in the stability of EAL has been observed, and is attributed to successive improvements (implemented in January 1998 and January 2001) in the algorithm for the weighting of contributing clocks, and also to a general improvement in the performance of equipment. The present stability of EAL is characterized by an Allan deviation $\sigma_y(\tau) = 0.6 \times 10^{-15}$ for averaging times τ between twenty and forty days. The most recent improvement in the clock weighting procedure is discussed in more detail under agenda item 4, “Future developments for UTC and TAI”.

As reported by Dr Petit under agenda item 2, “Progress in primary frequency standards”, the BIPM Time section has been working toward the implementation of Recommendations S 2 and S 3 of the 14th meeting of CCTF in 1999. One outcome of this work is that the results of bilateral comparisons between primary frequency standards and TAI have been published in *Circular T*, starting in issue 148, May 2000.

Since 1999, comparisons of the frequency of TAI with nine primary frequency standards (CRL-01, NIST-7, NIST-F1, NRLM-4, PTB CS1, CS2 and CS3, PTB CSF1 and LPTF-JP0) have been used in the evaluation of the scale unit of TAI. During this period the relative departure of the TAI scale

unit from the SI second has ranged between $+0.2 \times 10^{-14}$ and $+0.7 \times 10^{-14}$, with an uncertainty of 0.2×10^{-14} .

In response to a decision of the 14th meeting of CCTF in 1999, data from three TWSTFT links now contribute to TAI: NPL/PTB, USNO/NPL and VSL/PTB. The PTB/TUG link was also used until the closure of the TUG time laboratory in 2000. Conventional GPS common view data for the three currently operating links continue to be collected and evaluated as a back-up. Data from multichannel GPS links were introduced into the computation of TAI at the beginning of 2000, and the possible inclusion in TAI of data from GPS carrier-phase timing links is now being studied.

The use of multichannel GPS/GLONASS and GLONASS P-code data is also being studied, with data from suitably equipped laboratories being collected by the BIPM. A round-robin differential calibration exercise for GPS/GLONASS multichannel receivers was begun in 1998, and was coordinated by the BIPM. One of the GLONASS receivers operated at the BIPM has been contributing data to the International GLONASS Experiment (IGEX) and the International GLONASS Service Pilot Project (IGLOS-PP) since 1998.

In conclusion, Dr Arias reported that BIPM staff have also continued their collaborations with other organizations on space-time references (a report is presented under agenda item 8, “General relativity and space-time references”), millisecond pulsar timing, atom interferometry, and clocks in space.

The President congratulated Dr Arias and the BIPM Time section on their activities in such a wide range of fields.

3.2 Report of the CCTF Working Group on TAI

Prof. Pâquet and Mr Azoubib outlined the main points of report CCTF/01-14.

Prof. Pâquet began by explaining that he would make only general comments, because most of the output of the Working Group on TAI appears in other reports under this and other agenda items. Specifically, the work on algorithms will be presented under this agenda item by Dr Tavella (CCTF/01-28) and the work associated with the IGS/BIPM Pilot Project (CCTF/01-07a and 07b) will be presented under agenda item 7, “Time and frequency transfer methods”, by Dr Ray. The work on weighting of clocks in the algorithm for the computation of TAI (CCTF/01-14) will be presented by

Mr Azoubib under this agenda item and the work on timing links has already been presented by Dr Arias as part of the report on TAI of the BIPM Time section (CCTF/01-29).

A key issue which arose during the deliberations of the working group was that of calibration of timing links. This issue also emerged during discussions of the Mutual Recognition Arrangement (MRA). It is clear that the problem needs to be addressed very carefully by the time community, especially in view of the fact that the performance of primary frequency standards and other clocks is improving faster than the calibration accuracy and stability of timing links.

Collaborations between the geodetic and timing communities have been very fruitful, and there is clearly a need for closer links between timing laboratories and geodetic monitoring facilities. The potential benefits of co-location of these facilities is highlighted by the results of the IGS/BIPM Pilot Project.

Prof. Pâquet concluded by noting that this was his final year as Chairman of the working group. He thanked the members of the working group and proposed the nomination of Dr Tavella as his successor.

Mr Azoubib summarized the work (CCTF/01-14) on weighting of clocks in the algorithm for the computation of TAI:

He began by saying that the outcome of the work was implemented in January 2001, and since then a significant improvement in the stability of EAL and TAI has been observed.

Under the previous algorithm, data contributed by up to 83 % of Hewlett-Packard 5071A clocks were given maximum weighting (0.7 %) in the algorithm for the calculation of TAI. This was becoming increasingly inappropriate, as it was clear that some of these caesium clocks were significantly more stable than others, yet the algorithm did not take advantage of this by giving these more stable clocks greater weight. A similar problem existed with data contributed by hydrogen masers.

For some time the BIPM Time section has been researching alternative schemes for determining the maximum weighting, w_{\max} , to be assigned to a particular clock. It was found that the simple expression

$$w_{\max} = A/N,$$

where A is an empirical constant and N is the number of contributing clocks, yielded an improved maximum stability in EAL characterized by $\sigma_y(\tau = 40 \text{ d}) = 4 \times 10^{-16}$ when $A = 2.5$, compared with a maximum stability

of $\sigma_y(\tau = 40 \text{ d}) = 1 \times 10^{-15}$ under the previous weighting scheme. For $A = 2.5$, a clock would have to demonstrate a stability better than $\sigma_y(\tau) = 5.8 \times 10^{-15}$ for averaging times τ between twelve and thirty days in order to achieve maximum weighting.

Although the BIPM research indicated that the optimum stability of EAL would be obtained for $A = 2.5$, the value $A = 2.0$ was selected in order to make a more conservative change to the clock weighting scheme. For $A = 2.0$, a clock would have to demonstrate a stability better than $\sigma_y(\tau) = 7.8 \times 10^{-15}$ for averaging times τ between twelve and thirty days in order to achieve maximum weighting. Mr Azoubib concluded by saying that details of the proposed change to the weighting scheme was circulated to member laboratories in 2000, and were widely supported.

3.3 Report of the CCTF Working Group on TAI Sub-Group on Algorithms

Dr Tavella gave a summary of report CCTF/01-28.

She explained that the Sub-Group was established by the 14th meeting of CCTF in 1999, and assigned the following tasks:

- to promote deeper, wider and more diffused studies on algorithms for time and frequency;
- to stimulate publications, discussions and collaborations on this topic;
- to address potential new requirements of time and frequency data processing, and new applications.

The sub-group has only recently been established, and twenty-five people from fourteen institutions have expressed interest in contributing. One of the most pressing issues requiring the attention of this group is related to the optimum usage of data from new, highly accurate primary frequency standards which do not operate regularly. A similar problem exists with TWSTFT, where regular operation is often constrained by cost and other factors such as holidays and weekends.

The sub-group has prepared a website (<http://www.ien.it/tf/cctf/>), and is organizing the 4th International Symposium on Time Scale Algorithms, to be held at the BIPM on 18-19 March 2002.

Finally, Dr Tavella thanked Prof. Pâquet for proposing her nomination as his successor, and said that she would be available to serve in that position if chosen (discussed further under agenda item 14, "Other business").

The President thanked Prof. Pâquet, Mr Azoubib and Dr Tavella for their reports, and commented that it was clearly an appropriate time to consider new time-scale algorithms.

4 FUTURE DEVELOPMENTS FOR UTC AND TAI

Dr Petit presented a report from the BIPM Time section entitled “A rapid computation of a prediction of TAI and UTC” (CCTF/01-22).

He pointed out that the delay in access to TAI and UTC is presently between fifteen days (for data at the end of a calendar month) and forty-five days (for data at the beginning of a calendar month). However, many organizations (for example, metrology laboratories and satellite system operators) wish to steer their timing reference to UTC or TAI, and would like to have these time scales available more rapidly than this.

In order to accommodate these requirements, it would be necessary either to shorten the interval of computation of TAI, or to develop a rapidly available prediction of TAI. The option to shorten the computation interval was discarded, since the delay could realistically only be shortened to between ten and twenty-five days, which would not satisfy user requirements. In addition, it is possible that such a change would significantly alter the characteristics of TAI.

Consequently the BIPM Time section has been developing a method to calculate a prediction of TAI, known as TAIp. The objectives are:

- that TAIp should be computed by a simple, fast and safe procedure;
- that $[TAI - TAIp]$ should be minimized.

The approach taken is to use an algorithm similar to that used for TAI, with input from a subset of clocks which contribute to TAI. This subset is chosen from laboratories with a “good” record, since to facilitate rapid publication of TAIp, no attempt will be made to resolve non-trivial problems, or to obtain missing data.

Tests of the new algorithm on past data showed that it is possible to predict TAI to better than about 5 ns for periods of up to forty-five days. Furthermore, an unexpected benefit was that since TAI and TAIp are calculated by separate (but similar) algorithms and from different

combinations of clocks, a deviation of TAIp from TAI by amounts greater than about 5 ns was found to be a very useful indicator of errors in timing links or from other sources.

Dr Petit concluded by announcing that a pilot experiment for calculating TAIp in near-real time is planned for early 2002, with a computation interval of (probably) ten days. Laboratories participating in the pilot experiment will be asked to send their clock and timing link data promptly (preferably automatically) on each MJD ending in zero, following which TAIp will be calculated and disseminated on the next working day.

The President thanked Dr Petit for the report, asking if the BIPM needed a decision from the CCTF on this matter. Dr Petit replied that he would like an indication of which laboratories might be prepared to participate. The President requested the representatives of laboratories to indicate their willingness to participate, and also asked if they had a requirement for TAIp.

Dr Lavery replied that NPL would participate, and that their customers would benefit from TAIp. Dr Sullivan indicated that the NIST would also participate, although it calculated its own prediction of TAI. Dr Matsakis said that the USNO had also been working on a prediction of UTC, and that a deviation between their prediction and UTC of 7 ns or less had been achieved for a prediction forty-five days ahead.

Dr Banerjee asked if TAIp will be provided on demand, or if it will be published, and also asked if TAIp would affect TAI. Dr Petit replied that the present intention is that TAIp would initially be disseminated only through participating laboratories, and that TAIp would not affect TAI, apart from facilitating the detection and correction of errors which may otherwise go unnoticed.

Dr Tavella expressed concern that although the goal of TAI is to be the definitive, long-term time scale, the establishment of TAIp could be interpreted as a move toward a much shorter calculation/averaging interval for TAI. The President asked Dr Quinn to reply.

Dr Quinn said that one of the duties of the BIPM is to look to the future, and since the enabling technology and demand exists for TAIp, he thinks it should be studied, trialled, and discarded if it is not useful. He then took the opportunity to make some broader comments. He noted that there are currently three principal aspects to time and frequency: primary frequency standards, time comparisons and time scales. The stability/accuracy of each of these is currently similar, but the BIPM must prepare itself for the time when this is inevitably no longer the case.

Furthermore, the distinction between primary frequency standards and length standards is becoming less clear with the recent development of cold atom/ion optical frequency standards linked to the SI second by femtosecond comb technology. This powerful combination may soon outperform caesium standards in terms of accuracy and stability, and in particular, absolute accuracies better than 1 part in 10^{16} are being predicted. This raises the problem of comparing these standards, as our most accurate remote comparison technique, TWSTFT, presently appears unlikely to improve to this level of accuracy.

In conclusion, Dr Quinn said that an alternative solution to the problem of comparing the primary frequency standards currently being developed is through the circulation of portable frequency standards, and he asked the CCTF to consider whether BIPM should start taking steps to acquire this capability.

The President agreed that this was a very important point, and said that it would be discussed under agenda item 12, “The BIPM work programme”. He then invited further discussion on the issue of TAIp.

Prof. Pâquet said that despite the need for TAIp or an equivalent prediction, it is important not to increase the total workload of the BIPM. He therefore suggested that TAIp be regarded as a pre-processing step to TAI, and that it be published on the BIPM FTP site.

Dr de Jong expressed concern about the additional general publication of the differences [*UTCp* – *GPS*] or [*UTCp* – *GLONASS*], since it might be used to bypass national laboratories.

The President replied that these concerns would be considered.

5 REDEFINITION OF UTC: LEAP SECONDS

Mr Beard and Dr de Jong presented the reports from the ITU-R Special Rapporteur Group (SRG) 7a, “UTC time scale” (CCTF/01-17, CCTF/01-33).

The SRG was created to study the question raised in ITU-R 236/7, “The future of the UTC time scale”.

At its May 2001 meeting, with regard to the use of time scales in satellite navigation systems, telecommunications systems, computer networking, broadcast services and scientific uses, the SRG categorized the options for the future of UTC and leap seconds as follows:

Option 1: Maintain the status quo

- recommend use of UTC as currently defined;
- clarify time scales available and considerations for use;
- more advanced notice and information availability;
- creation of a navigation time scale.

Option 2: Modify leap second procedures or occurrence

- increase tolerance of $[UTC - UTI]$ and enable longer prediction interval and lower frequency of leap second occurrence;
- fixed-interval adjustment with multiple leap seconds possible;
- correction at predicted intervals based on a deceleration model of the Earth's rotation, re-evaluated at fixed intervals.

Option 3: Use of, or transition to, another time scale

- existing TAI made more accessible;
- new navigation time scale may be needed for celestial users;
- new time scale based on redefinition of the SI second.

In order to gather information before developing its recommendations which are to be released at its meeting in October 2002, the SRG plans to release a general letter to both sectors of the ITU announcing the SRG and its objectives, and also plans to publish articles and notices in journals and newsletters.

The President asked Mr Beard if any of the SRG outcomes presently available require the attention of the CCTF. Mr Beard replied that at this stage the likely outcomes are unclear, since the SRG has received little feedback from interested groups.

Dr Levine pointed out that many organizations are required to time-stamp events (often using time disseminated on computer networks), and that there is no satisfactory way of time-stamping an event which occurs during a leap second using UTC as the reference time scale. One solution might be to transmit $[UTC - TAI]$ on the computer network, and so effectively use TAI as the reference time scale, but this may raise legal issues, since TAI is not legally recognized in all countries. A solution which is both technically and legally acceptable must be found.

The President observed that the leap second issue is very important, and while noting that such an act was outside the terms of reference of the CCTF, conducted a poll of the CCTF on the three options for the future of UTC presented by Mr Beard. The results were:

Dr Sullivan: Option 1.

Dr Fisk: Option 1.

Dr Granveaud: Option 2, with TAI made more accessible.

Prof. Pâquet: Option 3.

Dr Matsakis: No further leap seconds.

Dr McCarthy: Option 3.

Dr Steele: Option 2, since UTC in its present form was defined more than thirty years ago, and is not necessarily appropriate now.

Dr Fukushima: (speaking for himself, not the IAU) Option 3.

Prof. Leschiutta: Option 3, but without redefining the SI second.

Dr Quinn: Expressed no preference, but agreed with the comment of Dr Steele.

Dr Arias: Option 1, with the introduction of a navigation time scale.

Dr Godone: Option 1, with the introduction of a navigation time scale.

Dr Palacio: Option 1, with TAI made more accessible.

Dr de Jong: Option 1, with TAI made more accessible.

Dr Imae: No further leap seconds.

Dr Hosokawa: Option 2.

Dr Ikegami: Option 3.

Dr Lavery: Expressed no preference, but emphasized the importance of maintaining the SI second as the scale unit.

Dr Henderson: No further leap seconds.

Dr Domin: Option 3, but without redefining the SI second.

6 CONVENTIONAL NOMENCLATURE FOR UTC

The President invited Dr McCarthy to speak on a recommendation (CCTF/01-10) proposed by the USNO, on the designation of institutes taking part in UTC.

Dr McCarthy began by reminding the meeting that CCIR Recommendation 536 (1978) defines the notation $TA(k)$ and $UTC(k)$ as being time scales realized by the institute k .

This raises several issues:

- What constitutes institute k ?
- Can any organization have a recognized realization of UTC or TAI?
- There is no distinction between the time scale and the means by which it is realized.

In order to clarify these issues, Dr McCarthy presented a draft recommendation (CCTF/01-10), which in essence proposes that the institutes denoted by “ k ” be limited to those which take part in the computation of TAI by contributing timing comparisons to the BIPM. The notation « UTC (k) via m » proposed in document CCTF/01-10 was not approved.

Prof. Pâquet, Dr Arias and Dr Lavery expressed support for this proposal, saying that it would be useful to designate clearly those institutes which are recognized sources of UTC.

Dr Quinn pointed out that the formalism to designate the degree of equivalence between institutes already exists, in the form of the MRA and that it is also possible for several institutes within a given country to be subject to the terms of the MRA. Consequently, a list of institutes maintaining timescales traceable in a recognized way to BIPM already exists, and Dr McCarthy’s proposal should therefore not be discussed independently of the MRA. Dr McCarthy replied that in his view the consequences of the MRA in this context are yet to be established, and that his proposal may be beneficial in the interim.

The President deferred further discussion of this proposal to agenda item 13, “Recommendations”.

7 TIME- AND FREQUENCY-TRANSFER METHODS

7.1 Report of the CCTF Working Group on TWSTFT

A summary of this report (CCTF/01-26) was presented by Dr de Jong and Dr Lewandowski.

Dr de Jong reported that the working group had met twice since the 14th meeting of the CCTF in 1999. He said that the most important point to emphasize is that since 1999, GPS has no longer been the sole means by which clock data is reported to the BIPM for use in the computation of TAI, and that this was accomplished in response to Recommendation S 7 of the 14th meeting of CCTF in 1999. Currently three TWSTFT links are used in the computation of TAI: PTB/NPL, PTB/VSL and USNO/NPL. As was reported previously, the station at TUG ceased operating in 2000.

The time transfers occur in three half-hour sessions per week. There is motivation to change to daily twenty-minute sessions, to provide evenly spaced data, but this would require Earth stations to be automated, and not all participating laboratories have yet done this.

The TWSTFT links have all been calibrated by one or more of three methods:

- a portable Earth station;
- the de Jong satellite simulator;
- comparison with GPS common view data.

There are also several active TWSTFT stations in the Pacific Rim area, namely the AUS, CRL, CSAO, NMIJ, TL and the KRISS. Some of these links are now ready to contribute data to the BIPM, with the proposed links being CRL/AUS, CRL/CSAO and CRL/NMIJ, with CRL/TL to be added soon. A TWSTFT link between the CRL and the European TWSTFT link is being considered, but the suitable satellites which have been investigated so far are not operated by INTELSAT, and would be much more expensive to use.

Dr de Jong listed the priorities for action by the working group in the immediate future:

- increase the number of sessions (as mentioned above) and automate Earth stations;
- establish a working group on the link between the Pacific Rim and European TWSTFT networks;

- calibrate participating stations through the use of portable X-Band Earth stations;
- develop an uncertainty budget for TWSTFT;
- introduce additional TWSTFT links into TAI.

Concluding his part of the report, Dr de Jong thanked Dr Kirchner on behalf of the working group for his contributions to its activities.

Dr Kirchner, in response to earlier comments made by Dr Quinn on the possible ultimate limitations of the TWSTFT technique, said that it should be recognized that much of the technology used by TWSTFT is twenty years old, and was not originally designed for time transfer. For example, the use of higher bandwidths and bit rates, higher transmission frequencies (eg: K_U band) and operation of the equipment in a controlled environment could result in substantial performance improvements, below the level of 1 part in 10^{16} .

Dr Lewandowski reported on some further details of the TWSTFT links involved in the computation of TAI.

He mentioned that the BIPM Time section has been publishing TWSTFT reports since 1999, in the form of TWSTFT/GPS comparisons for each participating timing link. More than two and a half years of data are available for some links, for example, the PTB-NIST link, and the performance advantage of TWSTFT over GPS common view time transfer is most obvious for averaging times shorter than about twenty days. The TWSTFT technique is expected to improve the accuracy of timing links, and has already been used for comparisons between caesium fountain standards and TAI.

Dr Lewandowski concluded by pointing out that further diversification of timing links was desirable in order to continue to improve the stability and reliability of TAI, and that to this end, the USNO/NPL link is served by TWSTFT, GPS common view, GPS-GLONASS multi-channel and GLONASS P-code receivers. Study and comparison of data from these links will help BIPM to introduce these time-transfer methods into the computation of TAI if and when it is appropriate.

7.2 GPS phase measurements: Report on the IGS/BIPM Pilot Project

The IGS and the BIPM have established a joint Pilot Project for Time and Frequency Comparisons using GPS. The goal of this Pilot Project is to

investigate the use of GPS phase and code measurements to improve worldwide availability of accurate time and frequency.

Dr Ray discussed report CCTF/01-07a, 07b.

He reported that there are approximately twelve IGS stations located at timing laboratories and which are included in the IGS/BIPM Pilot Project; five of these also participate in the European/North American TWSTFT network. There are other laboratories with suitable receivers but without IGS approval, and some of these also make their data available. Presently several types of receivers contribute data to the Pilot Project, but the Ashtech Z12-T is gaining wide acceptance for timing applications because of its demonstrated ability to be calibrated. Dr Petit of the BIPM Time section has demonstrated a method for absolute and differential calibration of this receiver model, and a calibration trip is currently under way. Evaluation of the newer Javad Legacy has recently begun in addition to the established AOA receivers. The additional requirements for temperature stabilization of receivers, cables and antennas has been recognized.

Progress in IGS data analysis includes the development of a new IGS time scale based on a dynamically weighted ensemble of IGS clocks. Currently this time scale is loosely steered to GPS time, and a closer link to UTC awaits the installation of more calibrated receivers at timing laboratories.

IGS Ultra Rapid products now provide near-real-time GPS satellite clock predictions with a precision of approximately 20 ns root-mean square, limited by instability of the IGS reference time scale.

Recommendations relevant to CCTF of the IGS Analysis Workshop, held at USNO in September 2000 were:

- to promote full integration of time laboratories into the IGS network;
- to document the accuracy and precision of clock-related products;
- to form a new IGS time scale;
- to promote a predicted form of UTC for real-time applications;
- to promote receiver calibration methods and documentation, as well as deployment at time laboratories;
- to promote closer cooperation with receiver manufacturers to improve performance;
- to re-establish the IGS/BIPM mailing list;
- to standardize the exchange of timing data.

Dr Ray concluded by saying that the benefits of IGS installations at time laboratories are well understood, and that wider implementation is needed. He recommended that the Pilot Project should aim to transform to operational status by 31 December 2002, and that the CCTF should consider the use of the resulting data in the computation of TAI at its next meeting.

Finally, Dr Ray introduced a draft recommendation (CCTF 2) covering the above issues for consideration under agenda item 13, "Recommendations".

7.3 Report of the CCTF Sub-Working Group on GPS/GLONASS Time-Transfer Standards

Although no formal report was submitted under this agenda item, the President said that he had received a letter (CCTF/01-27) from Dr Levine, and asked Dr Levine to address the meeting.

Dr Levine indicated that since Selective Availability was deactivated on the GPS system in May 2000, the precision of timing measurements with respect to GPS time using stand-alone receivers has greatly improved. He also noted that most national measurement institutes routinely record $[UTC(k) - GPS]$ as part of the process of maintaining their realizations of UTC. Consequently, GPS time is now a very effective real-time distribution mechanism for $UTC(k)$, provided that the measurements of $[UTC(k) - GPS]$ are available to users.

Dr Levine went on to say that many national measurement institutes make their measurements of $[UTC(k) - GPS]$ available electronically to the general public, and in his letter he suggests that the BIPM should also consider publishing this data, which they routinely receive and archive, in a suitable format which is yet to be determined. He emphasized that he is making this suggestion as Chairman of the CGGTTS, and not on behalf of the NIST, which has not yet taken an official position on this issue. Finally, Dr Levine drew the CCTF's attention to a draft recommendation and technical guidelines (CCTF 5) regarding GPS and GLONASS receivers, saying that they were the result of consultations with colleagues in many laboratories.

In reply to Dr Levine's suggestion regarding the publication of GPS data, Dr Arias said that the BIPM had also considered this possibility, and pointed out that *Circular T* contained sufficient information for users of GPS receivers to relate their measurements to $UTC(k)$. Dr Levine replied that the advantage of his proposal is that it would allow users to execute strict common view time transfer.

Dr Ray commented that although he agreed in principle with Dr Levine's suggestion, it was not obvious that the unsophisticated user would be able to interpret the CGGTTS format and apply the appropriate corrections.

Dr Wolf pointed out that the raw GPS common view data in CGGTTS format used for the computation of TAI is already available on the BIPM FTP site. Dr Levine replied that he was not aware of that, and said that he would withdraw his recommendation and consider the issue further.

The President asked Dr Arias to consider this issue as well, and to determine if there is anything that can be done to facilitate the spirit of Dr Levine's suggestion.

Dr Lavery suggested that it would be worth considering extending Dr Levine's concept to all forms of time-transfer data.

Drs Palacio and de Jong expressed their concern about the free access to laboratory data files, since some users could use them (correctly or not) to pretend a traceability they do not have.

8 GENERAL RELATIVITY AND SPACE-TIME REFERENCES

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

A summary of report CCTF/01-23 was given by Dr Petit.

He reminded the meeting that the BIPM/IAU Joint Committee on General Relativity for Space-Time Reference Systems and Metrology (JCR) was created in 1997 by the IAU, and worked in collaboration with the IAU Working Group on Relativity in Celestial Mechanics and Astrometry (RCMA). The task of the JCR is "to establish definitions and conventions to provide a coherent relativistic frame for all activities in space-time references and metrology at a sufficient level of uncertainty, to establish a uniform system of notations for quantities and units, and to develop the adopted definitions and conventions for practical application by the user".

Since the RCMA was developing a consistent framework (the IAU 2000 framework) for defining the barycentric and geocentric celestial reference systems at the first post-Newtonian level, the JCR therefore focussed its

attention on its application to time and frequency measurements in the solar system, in order to support the numerous upcoming space clock missions. It presented its work in the form of two resolutions adopted by the IAU General Assembly in 2000:

Resolution B1.5: “Extended Relativistic Framework for Time Transformations and Realization of Coordinate Times in the Solar System”. This resolution provides explicit formulae for time transformations, together with regions of validity and uncertainty (0.2 ps in time and 5 parts in 10^{18} in frequency).

Resolution B1.9: “Redefinition of Terrestrial Time (TT)”. This resolution provides a new definition for TT using a fixed value for its rate with respect to geocentric coordinate time TCG. Uncertainties in TT due to uncertainties in the realization of the geoid are thus eliminated.

Dr Petit concluded his presentation by saying that the adoption of these resolutions satisfied the original objectives of the JCR, which was disbanded in January 2001. At that time the BIPM proposed that the work be continued within the RCMA, that the word “Metrology” be added to its name to reflect this, and that its membership be extended accordingly. This proposal was adopted by the Executive Committee of the IAU in January 2001, bringing the IAU Working Group on Relativity for Celestial Mechanics, Astrometry and for Metrology (RCMAM) into existence.

Dr Fukushima expanded on Dr Petit’s outline of the redefinition of TT, saying that at the 10^{-16} level the Newtonian representation of the geoid becomes unreliable due to changes in its average potential, which in turn result from secular changes in the mass distribution within the Earth. The position of the equipotential surfaces of the geoid are also influenced by lunar and solar tidal effects. For the purposes of geodesy, it has proven adequate to eliminate the time-dependent part of the geoidal potential using a time-average, but this is unacceptable in time calculations, and further, the geoidal fluctuations are not yet sufficiently well characterized or understood to correct TT accurately beyond the 10^{-16} level under its previous definition. The IAU therefore decided to introduce a fixed equipotential surface to define the new TT time scale, which will allow it to be used at very high levels of accuracy without inconsistency with its definition.

The President asked Dr Petit to comment on the impact of these resolutions on TAI. Dr Petit replied that this issue must be carefully considered, since TAI is a realization of TT. The President then asked the BIPM Time section

to follow these developments closely, and to determine what action is required, if any.

Dr Levine asked about the impact of these resolutions on existing geoidal altitude corrections to the frequencies of primary frequency standards. Dr Fukushima replied that the equipotential surface on which the new definition of TT is based is, for practical application, equivalent to the geoid.

Dr Steele observed that the published relativistic correction for the NIST primary frequency standards has an uncertainty of the order of 10^{-16} , which is similar to the changes which may result from the new definition of TT. Dr Sullivan replied that at the time of its calculation (which was not done by the NIST) this uncertainty was insignificant.

Dr Petit asked that laboratories operating primary frequency standards not make any changes as a consequence of the new definition of TT. When the uncertainty of primary standards falls below the order of 10^{-16} , the BIPM will study and report on the issue.

8.2 Report on the IERS Conventions Product Centre

Dr Petit, as a co-director of the IERS Conventions Product Centre, presented a summary of report CCTF/01-24.

He commented that uniformity in the definitions of space-time reference systems is becoming increasingly important, especially in activities which use measurements which are not local, such as the astro-geodetic techniques used to obtain the raw data used by the IERS. The IERS therefore maintains a set of Conventions, which provides these definitions as well as procedures for transforming between reference systems.

At the request of the IERS, the BIPM and the USNO have been working with them to provide the Conventions Product Centre (CPC) since 1 January 2001. The task of the CPC is to maintain and update the IERS Conventions and associated software in electronic form, to study the consistency of the procedures used by the IERS analysis centres with the adopted conventions, and to analyse the impact on IERS products of any inconsistencies.

Concluding his report, Dr Petit said that Dr McCarthy was the other co-director, and that many scientists worldwide would contribute to this work. Dr McCarthy added that the CPC intended to publish the revised Conventions during 2001.

9 CLOCKS IN SPACE

The President invited Dr Thomann to address the CCTF on the ACES (Atomic Clock Ensemble in Space) project.

Dr Thomann said that the ACES project was first proposed to the European Space Agency in 1994, and planned to fly several atomic clocks on the International Space Station. The aims of the project are to:

- demonstrate that it is possible to have and use the best clock technology in space;
- perform tests of fundamental physics.

Since the original proposal, mass and power limitations on the ACES flight package have limited the number of clocks to be flown to two: A cold caesium atom clock (PHARAO) built by the BNM-LPTF, and a hydrogen maser built by the Neuchatel Observatory. It was also decided in April 2001 that due to the same limitations, the proposed optical space-ground link would be discarded, leaving a microwave link and a GPS receiver as the precise timing links to the flight package.

It is hoped that the cost of the Earth station for the microwave link will be less than \$100 000 US.

The objectives of the flight package are to:

- operate a clock with linewidth less than 50 mHz and a frequency stability $\sigma_y(\tau)$ better than $10^{-13} \tau^{-1/2}$;
- demonstrate clock accuracy in the 10^{-16} range;
- compare time scales on a worldwide basis with 30 ps time accuracy and 10^{-16} relative frequency accuracy, and for these comparisons to contribute to TAI;
- measure the relativistic red shift with a 25-fold sensitivity improvement over previous measurements;
- search for a drift in the value of the fine structure constant with a 100-fold sensitivity improvement over previous measurements;
- search for anisotropy in the speed of light with a 10-fold sensitivity improvement over previous measurements.

Dr Thomann concluded his presentation by saying that the ACES group are very interested in collaboration with other groups, for example the American

PARCS team (see below), and encouraged all those who are interested in participating to contact him.

The President thanked Dr Thomann, and invited Dr Sullivan to address the CCTF on the PARCS project and the other American space clock experiments.

Before beginning his presentation, Dr Sullivan responded to Dr Thomann's final comment, saying that the NASA and the ESA had already held meetings to discuss the coordination of the ACES and PARCS experiments. There is motivation to fly both experiments at the same time, and possible methods to connect the clocks on the International Space Station (ISS) are being investigated.

Dr Sullivan then continued with his report on the American space clock experiments. There are presently three American clock-related experiments scheduled for flight on the ISS:

- PARCS, a laser-cooled pulsed caesium beam clock, developed in collaboration between the NIST, JPL, Harvard-Smithsonian and the University of Turin;
- RACE (Rubidium Atomic Clock Experiment), a laser-cooled pulsed Rb beam clock, developed in collaboration between Yale University and the JPL;
- SUMO (Superconducting Microwave Oscillator), a super-high stability microwave oscillator developed by Stanford University; planned to fly concurrently with RACE, but presently in doubt because of the requirement for low temperature facilities.

The final project outlined by Dr Sullivan was the GRACE (Gravity Recovery and Climate Experiment), which is intended to provide a precise map of the Earth's gravitational field using high-accuracy microwave and GPS measurements of the distance between two satellites in a polar orbit. The GRACE satellites are scheduled for launch in 2001.

Dr Kovalevsky asked whether the microwave link used for the ESA experiments could also be used for the American experiments, if they were flown at the same time. Dr Sullivan replied that this was not possible. He said that the two experiment packages would be mounted at different locations on the ISS, and that a laser link between them had been considered but discarded as unfeasible. Dr Thomann added that a cable link between the packages was out of the question, even though the mounting locations have not yet been finalized. He said that the best method for comparing data from the two packages will probably be via the ground.

In closing the discussion on space clocks, the President remarked that a large fraction of current and proposed space experiments seems to be based on clocks or precision timing.

10 FUTURE SATELLITE NAVIGATION SYSTEMS

Dr Lavery presented a report (CCTF/01-34) on the activities of the GalileoSat Working Group on the Galileo Time Interface (WGGTI), of which he is Chairman and several other CCTF delegates are members.

Dr Lavery reported that the WGGTI was established by the ESA in consultation with the EC, and that all ESA member states were invited to participate. The tasks of the WGGTI were to:

- review the timing aspects of GalileoSat baseline;
- make recommendations to the GalileoSat team.

The initial meeting of the WGGTI was held in June 2000, and its final report was submitted to ESA in March 2001, and the conclusions have also been presented at several conferences.

The WGGTI focussed on three study areas:

- GPS comparisons (in terms of price and performance);
- the Galileo-UTC interface;
- time transfer and synchronization issues.

It was recognized that the GPS sets the benchmark for price/performance of a GNSS, and that combined GPS/Galileo timing receivers may be the best route to market for Galileo.

The WGGTI therefore recommended that from a timing point of view:

- Galileo should be independent of GPS;
- Galileo should be interoperable with GPS;
- Galileo's timing performance should be comparable with that of GPS;
- Galileo should anticipate future user requirements (GPS will improve).

The WGGTI recommended the following timing performance targets for Galileo (note that GST = Galileo System Time):

- $[GST - TAI]$ time offset: 33 ns (2σ) with a limit of 50 ns, 95 % of the time over a one-year interval;
- $[GST - TAI]$ relative frequency offset: 5.5×10^{-14} (2σ).

The current Galileo system design (which is not finalized) has a space segment consisting of thirty MEO satellites, each with two passive H masers and two rubidium standards on-board. The ground segment includes twelve orbitography and synchronization stations, two processing facilities and two precise timing stations each with two active hydrogen masers and twelve caesium clocks.

The WGGTI has recommended that:

- GST should be self-sufficient in the short term;
- GST should be steered to a prediction (the details of which have not yet been resolved) of TAI in the medium term, which will result in GST tracking TAI in the long term.

GST should therefore be continuous and based on TAI, and the UTC offset should be broadcast in the navigation message.

Dr Lavery noted that the industry groups supporting Galileo favour a single source for its UTC reference. In conclusion, he said that in its report the WGGTI has emphasized the benefits of redundancy, particularly in the areas of time-transfer links (including TWSTFT), orbit determination and time synchronization algorithms, and links to UTC, and that some of these principles are being included in the Galileo System Test Bed.

The President thanked Dr Lavery for the report and called for discussion.

Dr Matsakis asked how the accuracy requirements for the timing signals and underlying frequencies were determined. Dr Lavery replied that the performance of the GPS system was used as the benchmark in this area, and added that the industry groups supporting Galileo were unconvinced of these requirements.

The President asked whether additional Earth stations would be required for integrity assurance, and Dr Lavery replied that this is presently unclear, although the use of EGNOS stations has been considered.

Dr Matsakis observed that the current Galileo system design relied heavily on ground segment to space segment upload links, but only limited satellite-satellite cross links. He suggested that such cross links would improve system integrity. Dr Lavery replied that these details have not been finalized, but that the possibility has been recognized.

11 KEY COMPARISONS AND THE MUTUAL RECOGNITION ARRANGEMENT IN THE TIME AND FREQUENCY DOMAIN

The President invited Dr de Jong to present the report (CCTF/01-19) of the CCTF Working Group on the MRA, of which he is Chairman.

Dr de Jong said that the task assigned to the working group was to examine and report on the consequences of the MRA for the CCTF, and that the group comprised, in addition to himself, Dr Douglas (NRC), Dr Lepek (INPL), Dr Ohshima, Dr Palacio and Dr Sullivan.

The working group noted that the objective of the MRA is to establish the degree of equivalence between national metrology institutes (NMIs), which is determined by a series of key comparisons. The degrees of equivalence deduced from a key comparison are defined as the differences between the local values and the reference value, together with associated uncertainties.

The working group determined that EAL is the common reference for the clocks maintained by NMIs contributing to the computation of TAI, and the process of computing TAI and publishing $[UTC - UTC(k)]$ on *Circular T* could therefore be regarded as the key comparison for CCTF. However, the absence of uncertainty values for $[UTC - UTC(k)]$ on *Circular T* is a problem, and must be addressed.

The working group therefore recommended that:

- the computation of TAI and UTC be defined as the key comparison for the CCTF;
- the common key comparison reference value (KCRV) should be UTC.

With the above definitions, the degree of equivalence of the time scale $UTC(k)$ with respect to UTC will be known. Furthermore, since the scale unit of UTC is known with respect to the SI second, the traceability to the SI is assured.

The computation of uncertainties in $[UTC - UTC(k)]$ will require the following inputs:

- from contributing clocks to $UTC(k)$: stability, delay values and uncertainties in delay values in clock links to $UTC(k)$;
- from $UTC(k)$ to TAI/UTC: stability, delay values and uncertainties in delay values in GPS receivers and TWSTFT transceivers; uncertainties in

antenna coordinates; ionospheric delay uncertainties; TWSTFT transponder delay uncertainties, etc.

Dr de Jong listed three further recommendations:

- The BIPM should start the calculation of uncertainties in $[UTC - UTC(k)]$ using estimates of the above (and other) contributions, replacing the estimates with measurements as they become available. Regional supplementary comparisons should be organized for the purpose of absolute or relative calibration of time transfer equipment.
- Additional research should be carried out into methods for calibrating time-transfer equipment.
- The name of the key comparison should be CCTF-K 2001.UTC.

Concluding his report, Dr de Jong pointed out three remaining problems which must be addressed and four action items which require attention:

Problems:

- non-NMI laboratories contributing to TAI;
- countries with more than one NMI;
- countries which are not signatories to the Metre Convention.

Action items requiring further attention:

- establishment of the calibration and measurement capabilities (CMC) list in the field of time and frequency;
- coordination between regional metrology organizations on the determination and provision of data used for uncertainty calculations;
- the future of the MRA Working Group;
- practical organization of time-transfer equipment calibration trips.

The President thanked Dr de Jong and the working group for the report, and said that Dr Quinn wished to present material relevant to this agenda item, and also to agenda item 6, “Conventional nomenclature for UTC”.

Dr Quinn proposed the following definition:

“The institutes participating in the formation of TAI are:

- the NMIs and officially designated institutes of the Member States of the Metre Convention, and associates of the CGPM listed in the CIPM MRA;
- other institutes and observatories officially nominated to keep time scales for scientific, navigational or astronomical purposes.”

Dr Quinn further proposed that cases where non-national metrology institutes are responsible for time in certain countries could be satisfactorily addressed by an exchange of letters.

Dr Kovalevsky said that he had no objection to non-national metrology institutes participating in the formation of TAI, and asked about the possible situation where an institute is responsible for time in a non-Member State. Dr Quinn replied that there was only one such case, in Taiwan (China), which is about to be resolved through Taiwan becoming an Associate of the CGPM.

Dr Ohshima asked whether all the institutes in category (a) of Dr Quinn's proposal could be listed on Appendix C of the MRA even if there were plural NMIs or designated institutes in the country. Dr Quinn assured that they could be listed on Appendix C.

Dr Palacio suggested that institutions falling under category (b) of Dr Quinn's proposal should not be included in Appendix C of the MRA because they do not issue calibration reports. Dr Quinn replied that only designated institutes in the MRA will be included in Appendix C.

Dr Quinn said that he was fully in agreement with Dr de Jong and the MRA Working Group's conclusions that the procedures for computing TAI and UTC did not need to be changed to accommodate the requirements of the MRA. He agreed that there should be only one key comparison for the CCTF, and said that the proposed nomenclature was acceptable, although perhaps the year should be added to the name. Finally, he said that the BIPM was already working towards adding uncertainties to $[UTC - UTC(k)]$ in *Circular T*.

Dr de Jong agreed with the suggestion regarding the addition of the year to the name of the key comparison, since the *Annual Report of the BIPM Time section* would serve as the input to Appendix B of the MRA.

In agreement with Dr de Jong, Dr Quinn said that an alternative might be to call it a BIPM comparison instead of a CCTF key comparison, since the process will be ongoing. He added that he did not wish to encourage regional metrology organizations to conduct their own key comparisons in this area, since this is not necessary.

It was decided that the name of the CCTF key comparison should remain as proposed, CCTF-K2001.UTC.

Dr Sullivan pointed out that part of the key comparison is the measurement of delays and related tasks, which would appropriately be organized regionally by the RMOs. The President said that the general feeling of the

CCTF is that the UTC will be the key comparison reference value and will be organized by the BIPM and that the RMOs will coordinate activities such as delay measurements and other related investigations. Dr de Jong added that in the MRA these activities are called supplementary comparisons, and could be named as CCTF-S2001.GPSCAL, etc.

Dr Ohshima pointed out that any organization can send data to the BIPM and participate in RMO activities, and asked if that meant that any country could join the key comparison. Dr Quinn replied that in order to participate a country must be a member of the Metre Convention or an Associate of the General Conference, and that one of the roles of an RMO is to encourage their members to gain this status.

Dr Lavery asked whether UTC should appear instead of $[UTC - UTC(k)]$ in the MRA appendix C and consequently in the CMC list. Dr de Jong replied that time scale, time interval and frequency can all be derived from the key comparison, and he saw no reason why UTC could not appear on a CMC. Dr Lavery then requested that UTC be added to the list of CMCs.

Dr Quinn pointed out that the RMOs are responsible for the CMCs, and said that a mechanism for recommending the addition of UTC to the list would be established.

The President proposed that the MRA Working Group should continue, and that the RMOs should be encouraged to organize appropriate calibrations and related measurements. He asked Dr de Jong to present new terms of reference for the working group.

Dr de Jong proposed that until the next meeting of the CCTF the working group would have the following tasks:

- to execute all actions indicated in the MRA as being the responsibility of the CCTF, and which must be conducted before the next meeting; decisions made as part of this task will be in consultation with the President of the CCTF, and will be regarded as provisional;
- to coordinate any required action with RMOs;
- to act as the point of contact with the CCTF on matters related to the MRA;
- to report to the next meeting of the CCTF.

There being no disagreement, the President noted that the terms of reference were adopted.

Dr Fukushima asked about the case where a global private organization might wish to gain recognition of their time scale at a high level.

Dr Kovalevsky replied that this requirement should still be satisfied by establishing traceability to any laboratory which is a signatory to the MRA, and that only NMIs and designated laboratories would be recognized by the MRA.

Dr Quinn added that the MRA is organized under an intergovernmental agreement, and that governments may therefore designate laboratories which are responsible for time.

Dr Lavery cited the example of the University of Leeds, which contributes data to TAI and appears on *Circular T*, and is not designated by the British Government as responsible for time. Dr Quinn replied that the BIPM may, at its discretion, agree to include organizations in *Circular T* for scientific purposes, but will not do so for commercial purposes.

12 THE BIPM WORK PROGRAMME

In response to a previous question from Dr Banerjee (not recorded elsewhere in this report) concerning when the BIPM planned to include uncertainties in $[UTC - UTC(k)]$ in *Circular T*, Dr Quinn intimated that the BIPM would try to do this by 1 March 2002, but added that this would require close cooperation with the NMIs.

The President then asked Dr Quinn to address the meeting on the work programme of the BIPM Time section.

Dr Quinn affirmed that the principal task of the Time section continued to be the generation of the data on *Circular T* and other bulletins. They are presently working towards the automation of the TAI and UTC computation process, and when this is complete, they will have more time to devote to the computation of new products such as TAIp and UTCp.

Regarding the longer term, Dr Quinn said that he would like feedback on how the BIPM should respond to the issues raised by the rapidly improving accuracy of primary frequency standards and, in particular, the problems which will arise when their accuracy reaches a level where the performance of TWSTFT limits the benefit of their contributions to TAI.

While acknowledging the possibility of improving the performance of the TWSTFT technique, Dr Quinn said he still believed that the BIPM should

acquire the capability to transport a suitable clock between the institutes with the best primary frequency standards. He emphasized that he is not proposing that BIPM should develop such a clock; the required technology would be acquired or developed in collaboration with suitable institutions.

Dr Levine replied in support of Dr Quinn's proposal, saying that the BIPM had a long tradition of circulating reference standards for comparisons. He added that the best primary frequency standards are not all currently capable of continuous operation, so that they cannot be routinely compared even if TWSTFT or some similar technique was sufficiently accurate.

Dr Riehle also spoke in support of Dr Quinn, but raised the question as to whether the circulating standard should be a microwave or optical standard. Dr Quinn replied that he was open-minded on this point, and proposes to consult widely. He added that the BIPM already had the required femtosecond comb technology to compare optical and microwave standards.

Dr Matsakis remarked that Dr Quinn's proposal was a lofty goal, but that the BIPM should also concentrate on achieving a precision of 1 ns in the present time-transfer structure. Dr Quinn replied that there are no plans to do anything which might affect the current work and goals of the Time section, but he believed that it is now time to start thinking about the issues he raised.

Dr Granveaud pointed out that the accuracy of primary frequency standards will approach 1 part in 10^{16} in a few years, and that the experience of BNM-LPTF is that the realization of a portable clock with comparable accuracy will be very demanding. Nevertheless, the ACES and PARCS projects have goals which are similar to this, and that maintaining links with those projects, combined with the experience of more than twelve laboratories working on related problems, will be very valuable.

Dr Domnin expressed the opinion that there is a need to develop a flexible frequency comparison system which operates in both the optical and microwave regimes.

The President asked Dr Kirchner to comment on the possibility of improving the TWSTFT technique to meet the projected requirements. Dr Kirchner referred the meeting to his previous statements (made under agenda item 7.1, "Report of the CCTF Working Group on TWSTFT"), and added that he does not see a clear limit to the development potential of TWSTFT, since, for example, very little work has been done on the possibility of optical TWSTFT. On the other hand, he said that he believed that all promising clock comparison methods should be studied and developed.

Dr Lavery suggested that the BIPM Time section should maintain and possibly extend its interactions with the geodetic and astronomical communities, and that the development of new time scales was important.

Dr Quinn thanked the meeting for the support and suggestions, and re-emphasized that the current work programme of the Time section would not be affected by his proposal.

13 RECOMMENDATIONS

CCTF 1 (2001): Recommendation concerning secondary representations of the second

The President asked Dr Sullivan to speak on this recommendation.

Dr Sullivan said that this recommendation arose from informal discussions at the last CCTF, and was not originated by the NIST. The purpose of the recommendation is to develop a formal structure to study the data from highly accurate frequency standards, to make the data available to the BIPM and to enable them to contribute to TAI (noting that non-caesium based standards do not realize the SI second and cannot therefore contribute as primary standards). This will provide an established mechanism for evaluating the performance of new types of frequency standards, and if a need to redefine the SI second ever arose, this body of evidence would contribute to that decision.

Prof. Kovalevsky agreed with the spirit of the recommendation, and suggested that a working group be created on secondary representations of the second.

After extensive discussion regarding the form and content of the proposed *mise en pratique*, and also regarding whether it should be combined with the *mise en pratique* for the metre, Dr Quinn pointed out that the *mise en pratique* for the metre presents several realizations of the metre which are deemed equivalent to the definition, which is generally not realized directly. The situation of the SI second is different, since a direct realization of the definition is readily available and that a *mise en pratique* for the SI second should logically only refer to caesium. He suggested that in the context of alternative methods of realizing the SI second, the words “secondary

representation” be used instead of “alternative realization”, and that the proposed *mise en pratique* for the SI second could at this stage be replaced by a list of representations. Dr Sullivan agreed with this argument.

The Recommendation was adopted with modifications.

The President said that the working group proposed by Dr Kovalevsky would be established, and that it should consider these points. He proposed the following terms of reference for the CCTF Working Group on Secondary Representations of the Second:

- to see that Recommendation CCTF 1 (2001) is implemented;
- to establish appropriate links with the CCL;
- to present a list of proposed frequencies to the CCTF at its next meeting;
- to consult on this matter with member laboratories of the CCTF.

The President requested the BNM-LPTF, IEN, NIST, NPL, NRC, NMIJ, PTB and the VNIIFTRI to suggest delegates to work under the guidance of a CCTF representative to execute the terms of reference. Finally, he asked Dr Quinn to take action to establish the working group. Dr Quinn agreed to do this.

CCTF 2 (2001): Recommendation concerning time and frequency comparisons using GPS phase and code measurements

The Recommendation was adopted without changes.

CCTF 3 (2001): Institute designation “*k*” in UTC(*k*) and TAI(*k*)

After several members expressed concern that the post-designation “via *m*” discussed under agenda item 6 (Conventional nomenclature for UTC) of the agenda was either unnecessary or inappropriate, it was removed from the recommendation.

The Recommendation was then adopted as amended.

CCTF 4 (2001): Calibration of timing links used for TAI

The Recommendation was adopted without changes.

CCTF 5 (2001): Technical guidelines for GNSS timing receivers

The Recommendation was adopted with minor changes.

14 OTHER BUSINESS

Dr Sullivan suggested that the chairmen of BIPM working groups should be appointed for fixed terms, since any expectation that they will serve indefinitely would be an imposition on the incumbents. The President agreed, and said that he will ask CIPM to consider this issue.

Dr Kovalevsky mentioned that such a problem sometimes exists with presidents of CIPM Consultative Committees, but most usually serve only for between six or eight years. He added that it is sometimes difficult to find people with the unique knowledge and experience required.

Dr Quinn noted that BIPM working groups and their chairmen are normally reappointed at each Consultative Committee meeting, and that perhaps more care should be taken to ensure that reappointment of the chairperson is not the default.

Dr Sullivan nominated Dr Tavella as Chair of the Working Group on TAI and Dr Palacio supported the nomination.

The President, observing no disagreement, and noting that Dr Tavella had already indicated her willingness to accept, declared her formally appointed to that position.

Dr Tavella thanked the CCTF for its confidence. She noted that the output of the working group comes from all its members, and hopes that they will be able to put into practice the results of all the progress that has been made on time-scale issues.

The President then closed the meeting and thanked the delegates.

Dr P. Fisk, Rapporteur

July 2001

Revised October 2001

**Recommendations of the
Consultative Committee for Time and Frequency
submitted to the
International Committee for Weights and Measures**

RECOMMENDATION CCTF 1 (2001):
Secondary representations of the second

The Consultative Committee for Time and Frequency,

considering that

- the present definition of the second, based on the caesium 133 atom, remains unchanged,
- there are a number of new atoms and ions being studied as potential bases for atomic frequency standards,
- new optical-frequency measurement concepts may allow the use of optical transitions as practical frequency standards, since they provide for a direct microwave output from such standards,
- new frequency standards based on other microwave transitions are being studied,
- one of these new standards could eventually be considered as the basis for a new definition of the second;

intends to examine and approve accurate frequency measurements of atom and ion transition frequencies made relative to the caesium frequency standard as secondary representations of the second,

recommends that

- a list of such secondary representations of the second be established,
- the requirements for documentation of uncertainty that apply to secondary representations of the second be the same as those for primary caesium standards for use in International Atomic Time.

RECOMMENDATION CCTF 2 (2001):**Time and frequency comparisons using Global Positioning System (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 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 being developed to exploit fully the capabilities of these techniques for time comparisons;

fully supports the joint IGS/BIPM Pilot Project;

and recommends that

- timing laboratories participate in the IGS by installing appropriate GPS receivers and by following the IGS standards and procedures to the greatest extent possible,
- appropriate methods be exploited to calibrate the instrumental delays relating the receiver internal reference to the external clock,
- the IGS reference for clock products be aligned as much as possible with Coordinated Universal Time (UTC),
- the timing laboratories and the BIPM take the necessary steps to allow the IGS to achieve this goal.

RECOMMENDATION CCTF 3 (2001):**The meaning of the designation “ k ” in UTC(k) and TAI(k)**

The Consultative Committee for Time and Frequency,

considering that

- the International Bureau of Weights and Measures (BIPM) forms International Atomic Time (TAI) and, together with the International Earth Rotation Service (IERS), maintains Coordinated Universal Time (UTC) through the contributed timing data from institutes throughout the world,
- there is a need for a specific international notation for time scales to avoid all ambiguity as to their traceability to the international time references of the BIPM,
- Recommendation ITU-R TF.536-1 (1978, 1998) “Time Scale Notations” has established notation UTC(k) for time scales realized by institute “ k ”;

concurs with Recommendation ITU-R TF.536-1 (1978, 1998) “Time Scale Notations”; but

recommends that henceforth the designation of the institute “ k ” refers only to those institutes that participate in the formation of TAI and appear in Section 1, [$UTC - UTC(k)$], of the monthly BIPM *Circular T*;

requests the Director of the BIPM to write to the Director of the ITU-R to notify ITU-R of the recommendation above, and to seek ITU-R consideration for the adoption of nomenclature TAI(k) analogous to that of UTC(k).

Notes appended to Recommendation CCTF 3 (2001)

1. The institutes participating in the formation of TAI are:
 - (a) the national metrology institutes and designated laboratories participating in the CIPM Mutual Recognition Arrangement (MRA) and,
 - (b) other institutes and observatories of the Member States of the Metre Convention and Associates of the CGPM officially nominated to keep time scales for scientific, navigational or astronomical purposes.

2. It is suggested that $TAI(k)$ be defined by the relation $TAI(k) = UTC(k) + DTAI$, where $DTAI$ is the number of integral seconds specified by the IERS as being the difference between UTC and TAI.

RECOMMENDATION CCTF 4 (2001):
Calibration of time links for International Atomic Time

The Consultative Committee for Time and Frequency,

considering that

- previous recommendations of the Consultative Committee for the Definition of the Second (CCDS) and the Consultative Committee for Time and Frequency (CCTF) have stressed the importance of the calibration of time-transfer equipment to ensure the accuracy of time links,
- improvements in clock technology and in time transfer techniques have resulted in better stability for ensemble time scales, particularly for International Atomic Time (TAI),
- uncompensated changes of the hardware delays in a time link may cause a significant instability in an ensemble time scale like TAI;

recommends that

- absolute and differential calibration methods be continued to be developed and put into operation for all time transfer techniques used in TAI computation, with the aim of achieving 1 ns standard uncertainty,
- laboratories participating in TAI carry out regular calibration exercises and continuous monitoring of time-transfer equipment,
- techniques used for the time links of TAI be independently calibrated.

RECOMMENDATION CCTF 5 (2001):
Technical guidelines for manufacturers of Global Navigation Satellite Systems receivers used for timing

The Consultative Committee for Time and Frequency,

considering that

- the common-view method for observing satellites in the Global Positioning System (GPS) and the Global Navigation Satellite System (GLONASS) provides one of the most precise and accurate methods of time comparison between remote clocks on and close to the Earth, and is used for the formation of the international time references International Atomic Time (TAI) and Coordinated Universal Time (UTC),
- the uncertainty of this method due to space factors, such as satellite ephemerides and ionospheric delays, and other sources of uncertainty, with the exception of receiver hardware, is close to 1 ns,
- other methods using global navigation satellite systems data for time and frequency transfer are under development that may provide even smaller uncertainty,
- the main source of uncertainty of these methods is instability of time receiving hardware, being frequently of several nanoseconds for short periods (several days) and in extreme cases reaching up to tens of nanoseconds;

recommends that

- the manufacturers of receivers used for timing adopt the CCTF Group on Global navigation satellite systems Time Transfer Standards (CGGTTS) technical guidelines for receiver hardware for use in time and frequency transfer,
- timing laboratories pay particular attention to the conditions under which their time receiving equipment operates.

Note appended to Recommendation CCTF 5 (2001)

The CGGTTS technical guidelines are available in working documents of the 15th CCTF meeting.

APPENDIX 1.

Working documents submitted to the CCTF at its 15th meeting

(see the list of documents on page 69)

LIST OF ACRONYMS USED IN THE PRESENT VOLUME

1 Acronyms for laboratories, committees and conferences

AOA	Allen Osborne Associates Inc.
AUS	Consortium of laboratories in Australia
BIH*	Bureau International de l'Heure
BIPM	International Bureau of Weights and Measures/Bureau International des Poids et Mesures
BNM-LPTF	Bureau National de Métrologie, Laboratoire Primaire du Temps et des Fréquences, Paris (France)
CCDM*	Consultative Committee for the Definition of the Metre/Comité Consultatif pour la Définition du Mètre, see CCL
CCDS*	Consultative Committee for the Definition of the Second/Comité Consultatif pour la Définition de la Seconde, see CCTF
CCIR	International Radio Consultative Committee/Comité Consultatif International des Radiocommunications (permanent body of ITU)
CCL	(formerly the CCDM) Consultative Committee for Length/Comité Consultatif des Longueurs
CCTF	(formerly the CCDS) Consultative Committee for Time and Frequency/Comité Consultatif du Temps et des Fréquences
CGGTTS	CCTF Working Group on GPS and GLONASS Time Transfer Standards
CIPM	International Committee for Weights and Measures/Comité International des Poids et Mesures
CNES	Centre National d'Études Spatiales, Toulouse (France)
CNRS	Centre National de la Recherche Scientifique, Paris (France)
CPC	Conventions Product Centre of the IERS
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)

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

CSIRO*	see NML-CSIRO
ESA	European Space Agency
EUROMET	European Collaboration in Measurement Standards
IAU	International Astronomical Union
IEN	Istituto Elettrotecnico Nazionale Galileo Ferraris, Turin (Italy)
IERS	International Earth Rotation Service
IGS	International GPS Service
INPL	National Physical Laboratory of Israel, Jerusalem (Israel)
INTELSAT	International Telecommunications Satellite Organization
ISO	International Organization for Standardization
ISS	International Space Station
ITU	International Telecommunication Union
IUGG	International Union of Geodesy and Geophysics
JCR	BIPM/IAU Joint Committee on General Relativity for Space-time Reference Systems and Metrology
JPL	Jet Propulsion Laboratory, Pasadena, Ca (United States)
KRIS	Korea Research Institute of Standards and Science, Taejeon (Rep. of Korea)
LHA	Laboratoire de l'Horloge Atomique, Orsay (France)
LPTF*	Laboratoire Primaire du Temps et des Fréquences, Paris (France), see BNM
METAS	(formerly the OFMET) Office Fédéral de Métrologie et d'Accréditation, Wabern (Switzerland)
MRA	Mutual Recognition Arrangement
NASA	National Aeronautics and Space Administration, Washington DC (United States)
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)
NMIJ/AIST	National Metrology Institute of Japan, National Institute of Advanced Industrial Science and Technology, Tsukuba (Japan)
NML-CSIRO	National Measurement Laboratory, CSIRO, Lindfield (Australia)

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), see NMIJ/AIST
OFMET*	Office Fédéral de Métrologie/Eidgenössisches Amt für Messwesen, Wabern (Switzerland), see METAS
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)
RCMA	IAU Working Group on Relativity for Celestial Mechanics and Astrometry
RCMAM	IAU Working Group on Relativity for Celestial Mechanics, Astrometry and for Metrology
ROA	Real Instituto y Observatorio de la Armada, San Fernando (Spain)
SRG	Special Rapporteur Group (of the ITU)
TL	Telecommunication Laboratories, Ching-Li (Taiwan, China)
TUG	Technical University, Graz (Austria)
UME	Ulusal Metroloji Enstitüsü/National Metrology Institute, Marmara Research Centre, Gebze-Kocaeli (Turkey)
URSI	International Union of Radio Science/Union Radio-Scientifique Internationale
USNO	U.S. Naval Observatory, Washington DC (United States)
VNIIFTRI	Institute for Physical, Technical and Radiotechnical Measurements, Gosstandart of Russia, Moscow (Russian Fed.)
VSL*	Van Swinden Laboratorium, Delft (The Netherlands), see NMI
WGGTI	GalileoSat Working Group on the Galileo Time Interface

2 Acronyms for scientific terms

ACES	Atomic Clock Ensemble in Space
CMC	Calibration and Measurement Capabilities

EAL	Free atomic time scale/Échelle atomique libre
EGNOS	European Geostationary Navigation Overlay Service
GLONASS	Global Navigation Satellite System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GRACE	Gravity Recovery and Climate Experiment
GST	Galileo System Time
IGEX	International GLONASS Experiment
IGLOS-PP	International GLONASS Service Pilot Project
MEO	Medium Earth Orbit (satellite)
MJD	Modified Julian Day
PARCS	Primary Atomic Reference Clock in Space
PHARAO	Projet d'horloge atomique à refroidissement d'atomes en orbite
RACE	Rubidium Atomic Clock Experiment
SI	International System of Units/Système international d'unités
SUMO	Superconducting Microwave Oscillator
TA	Atomic Time/Temps atomique
TAI	International Atomic Time/Temps atomique international
TCG	Geocentric Coordinated Time/Temps-coordonnée géocentrique
TT	Terrestrial Time
TWSTFT	Two-way Satellite Time and Frequency Transfer
UT	Universal Time
UTC	Coordinated Universal Time
WAAS	Wide Area Augmentation System