BUREAU INTERNATIONAL DES POIDS ET MESURES

COMITÉ CONSULTATIF POUR LA DÉFINITION DE LA SECONDE

Rapport de la 13e session
Report of the 13th Meeting

1996

Organisation intergouvernementale de la Convention du Mètre

COMITÉ CONSULTATIF POUR LA DÉFINITION DE LA SECONDE

SESSION DE 1996

MEETING IN 1996

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LISTE DES SIGLES UTILISÉS DANS LE PRÉSENT VOLUME
LIST OF ACRONYMS USED IN THE PRESENT VOLUME

1. Sigles des laboratoires, commissions et conférences
Acronyms for laboratories, committees and conferences

*BIH	Bureau international de l'heure
BIPM	Bureau international des poids et mesures
BNM-LPTF	Bureau national de métrologie, Laboratoire primaire du temps et des fréquences, Paris (France)
CCDS	Comité consultatif pour la définition de la seconde
CGGTTS	CCDS Group on GPS Time Transfer Standards
CGSIC	Civil GPS Service Interface Committee
CIPM	Comité international des poids et mesures
CNRS	Centre national de la recherche scientifique, Orsay (France)
CRL	Communications Research Laboratory, Tokyo (Japon)
CSIRO	(ex NML) Commonwealth Scientific and Industrial Research Organization, Division of Applied Physics, Lindfield (Australie)
IAU	*voir* UAI
IEN	Istituto Elettrotecnico Nazionale Galileo Ferraris, Turin (Italie)
IERS	Service international de la rotation terrestre/International Earth Rotation Service
INPL	National Physical Laboratory of Israel, Jérusalem (Israël)
INTELSAT	International Telecommunications Satellite Organization
ISO	Organisation internationale de normalisation/International Organization for Standardization
ITU	*voir* UIT
IUGG	*voir* UGGI
KRISS	(ex KSRI) Korea Research Institute of Standards and Science, Taejon (Rép. de Corée)
*KSRI	Korea Standards Research Institute, Taejon (Rép. de Corée), *voir* KRISS
LHA	Laboratoire de l'horloge atomique, Orsay (France)
LPTF	Laboratoire primaire du temps et des fréquences, Paris (France), *voir* BNM

* Les laboratoires ou organisations marqués d'un astérisque soit n'existent plus soit figurent sous un autre sigle.

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

*NBS	National Bureau of Standards, Gaithersburg (É.-U. d'Amérique), *voir* NIST
NIM	Institut national de métrologie/National Institute of Metrology, Beijing (Rép. pop. de Chine)
NIST	(ex NBS) National Institute of Standards and Technology, Gaithersburg (É.-U. d'Amérique)
NMi	(ex VSL) Nederlands Meetinstituut, Delft (Pays-Bas)
*NML	National Measurement Laboratory, Lindfield (Australie), *voir* CSIRO
NPL	National Physical Laboratory, Teddington (Royaume-Uni)
NPLI	National Physical Laboratory of India, New Delhi (Inde)
NRC	Conseil national de recherches du Canada/National Research Council of Canada, Ottawa (Canada)
NRLM	National Research Laboratory of Metrology, Tsukuba (Japon)
OFMET	Office fédéral de métrologie/Eidgenössisches Amt für Messwesen, Wabern (Suisse)
ON	Observatoire cantonal de Neuchâtel, Neuchâtel (Suisse)
ORB	Observatoire royal de Belgique, Bruxelles (Belgique)
PTB	Physikalisch-Technische Bundesanstalt, Braunschweig (Allemagne)
ROA	Real Instituto y Observatorio de la Armada, San Fernando (Espagne)
TUG	Technical University of Graz, Graz (Autriche)
UAI/IAU	Union astronomique internationale/International Astronomical Union
UGGI/IUGG	Union géodésique et géophysique internationale/International Union of Geodesy and Geophysics
UIT/ITU	Union internationale des télécommunications/International Telecommunication Union
URSI	Union radio-scientifique internationale/International Union of Radio Science
USNO	U.S. Naval Observatory, Washington DC (É.-U. d'Amérique)
VNIIFTRI	Institut des mesures physicotechniques et radiotechniques/All-Russian Research Institute for Physical, Technical and Radio-Technical Measurements, Moscou (Féd. de Russie)
*VSL	Van Swinden Laboratorium, Delft (Pays-Bas), *voir* NMi

2. Sigles des termes scientifiques
Acronyms for scientific terms

EAL	Échelle atomique libre/Free atomic time scale
GLONASS	Global Navigation Satellite System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System

ITRF	Système de référence terrestre spécifié par le Service international de la rotation terrestre/Terrestrial Reference Frame maintained by the International Earth Rotation Service
MJD	Calendrier Julien modifié/Modified Julian Dates
PHARAO	Projet d’horloge atomique à refroissement d’atomes en orbite
SA	Accès sélectif/Selective Availability
SI	Système international d’unités/International System of Units
SONET	Synchronous Optical Network
TAI	Temps atomique international/International Atomic Time
TT	Temps terrestre/Terrestrial Time
UTC	Temps universel coordonné/Coordinate Universal Time

COMITÉ CONSULTATIF
POUR LA DÉFINITION DE LA SECONDE

MEETING IN 1996

Note on the use of the English text

To make its reports and those of its various Comités Consultatifs more widely accessible the Comité International des Poids et Mesures has decided to publish an English version of these 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.

Note sur l'utilisation du texte anglais

Afin de faciliter l'accès à ses rapports et à ceux des divers Comités consultatifs, le Comité international des poids et mesures a décidé de publier une version en anglais de ces rapports. Le lecteur doit cependant noter que le rapport officiel est toujours celui qui est rédigé en français. C'est le texte français qui fait autorité si une référence est nécessaire ou s'il y a doute sur l'interprétation.

THE BIPM

AND THE CONVENTION DU MÈTRE

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

The BIPM has its headquarters near Paris, in the grounds (43 520 m^2) 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 Convention du Mètre*.

The task of the BIPM is to ensure world-wide unification of physical measurements; its function is to:

- establish the fundamental standards and scales for measurement of the principal physical quantities and maintaining the international prototypes;
- carry out comparisons of national and international standards;
- ensure the co-ordination of corresponding measuring techniques;
- carry out and co-ordinate measurements of the fundamental physical constants relevant to these activities.

The BIPM operates under the exclusive supervision of the Comité International des Poids et Mesures (CIPM) which itself comes under the authority of the Conférence Générale des Poids et Mesures (CGPM).

Delegates from all the Member States of the Convention du Mètre attend the Conférence Générale which, at present, meets every four years. At each meeting the Conférence Générale receives the Report of the Comité International on the work accomplished, its function being to:

- discuss and instigate 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;
- adopt the important decisions concerning the organization and development of the BIPM.

The Comité International 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 Convention du Mètre. The principal task of the CIPM is to ensure world-wide 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 (1937) and ionizing radiation (1960), to time scales (1988) and to amount of substance (1993). 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 a new building for a library and offices was opened.

Some forty physicists or technicians work in the BIPM laboratories. They mainly conduct metrological research, international comparisons of realizations of units and

* As of 31 December 1996, forty-eight States were members of this Convention: Argentina (Rep. of), Australia, Austria, Belgium, Brazil, Bulgaria, Cameroon, Canada, Chile, China (People's Rep. of), Czech Republic, Denmark, Dominican Republic, Egypt, Finland, France, Germany, Hungary, India, Indonesia, Iran, Ireland, Israel, Italy, Japan, Korea (Dem. People's Rep. of), Korea (Rep. of), Mexico, Netherlands, New Zealand, Norway, Pakistan, Poland, Portugal, Romania, Russian Federation, Singapore, Slovak Republic, South Africa, Spain, Sweden, Switzerland, Thailand, Turkey, United Kingdom, U.S.A., Uruguay, Venezuela.

verifications of standards. An annual report, published in the Procès-Verbaux des séances du Comité International des Poids et Mesures gives the 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 Comités Consultatifs, whose function is to provide it with information on matters that it refers to them for study and advice. These Comités Consultatifs, which may form temporary or permanent working groups to study special topics, are responsible for co-ordinating the international work carried out in their respective fields and for proposing recommendations to the CIPM concerning units.

The Comités Consultatifs have common regulations (*BIPM Proc.-Verb. Com. Int. Poids et Mesures*, 1963, **31**, 97). They meet at irregular intervals. The chairman of each Comité Consultatif is designated by the CIPM and is normally a member of the CIPM. The members of the Comités Consultatifs are metrology laboratories and specialized institutes, agreed by the CIPM, which send delegates of their choice. In addition, individual members are appointed by the CIPM, and there is also a representative of the BIPM. At present, there are nine such committees:

1. The Comité Consultatif d'Électricité (CCE), set up in 1927;
2. The Comité Consultatif de Photométrie et Radiométrie (CCPR), new name given in 1971 to the Comité Consultatif de Photométrie (CCP) set up in 1933 (between 1930 and 1933 the preceding committee (CCE) dealt with matters concerning photometry);
3. The Comité Consultatif de Thermométrie (CCT), set up in 1937;
4. The Comité Consultatif pour la Définition du Mètre (CCDM), set up in 1952;
5. The Comité Consultatif pour la Définition de la Seconde (CCDS), set up in 1956;
6. The Comité Consultatif pour les Étalons de Mesure des Rayonnements Ionisants (CCEMRI), set up in 1958 (in 1969 this committee established four sections: Section I (Measurement of 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 Comité Consultatif des Unités (CCU), set up in 1964 (this committee replaced the "Commission for the System of Units" set up by the CIPM in 1954);
8. The Comité Consultatif pour la Masse et les grandeurs apparentées (CCM), set up in 1980;
9. The Comité Consultatif pour la Quantité de Matière (CCQM), set up in 1993.

The proceedings of the Conférence Générale, the Comité International and the Comités Consultatifs are published by the BIPM in the following series:

— *Comptes rendus des séances de la Conférence Générale des Poids et Mesures;*
— *Procès-Verbaux des séances du Comité International des Poids et Mesures;*
— *Sessions des Comités Consultatifs.*

The Bureau International also publishes monographs on special metrological subjects and, under the title "*Le Système International d'Unités (SI)*", a booklet, periodically up-dated, 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.

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 Convention du Mètre.

Comité International des Poids et Mesures

Secretary	*President*
J. Kovalevsky	D. Kind

MEMBERS
OF THE
COMITÉ CONSULTATIF
POUR LA DÉFINITION DE LA SECONDE

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J. Kovalevsky, Secretary of the Comité International des Poids et Mesures.

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

Communications Research Laboratory [CRL], Tokyo.

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

International Astronomical Union [IAU].

International Telecommunication Union [ITU], Radiocommunication Bureau.

International Union of Geodesy and Geophysics [IUGG].

International Union of Radio Science [URSI].

Istituto Elettrotecnico Nazionale Galileo Ferraris [IEN], Turin.

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

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NATIONAL INSTITUTE OF METROLOGY [NIM], Beijing.

NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY [NIST], Boulder.

NATIONAL PHYSICAL LABORATORY [NPL], Teddington.

NATIONAL PHYSICAL LABORATORY OF INDIA [NPLI], New Delhi.

NATIONAL PHYSICAL LABORATORY OF ISRAEL [INPL], Jerusalem.

NATIONAL RESEARCH COUNCIL OF CANADA [NRC], Ottawa.

NATIONAL RESEARCH LABORATORY OF METROLOGY [NRLM], Tsukuba.

NEDERLANDS MEETINSTITUUT: Van Swinden Laboratorium [NMi-VSL], Delft.

OBSERVATOIRE ROYAL DE BELGIQUE [ORB], Brussels.

OFFICE FÉDÉRAL DE MÉTROLOGIE [OFMET], Wabern/OBSERVATOIRE CANTONAL DE NEUCHÂTEL [ON], Neuchâtel.

PHYSIKALISCH-TECHNISCHE BUNDESANSTALT [PTB], Braunschweig.

REAL INSTITUTO Y OBSERVATORIO DE LA ARMADA [ROA], San Fernando.

TECHNICAL UNIVERSITY OF GRAZ [TUG], Graz.

U.S. NAVAL OBSERVATORY [USNO], Washington DC.

B. GUINOT.

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

AGENDA
for the 13th Meeting

1. Opening of the meeting; appointment of a rapporteur.
2. Progress in atomic frequency standards and clocks.
3. Report of the CCDS working group on TAI.
4. Report of the BIPM Time section.
5. Synchronization of clocks using satellites.
6. Timing of millisecond pulsars.
7. Report of the Sub-group of the CCDS working group on TAI on GPS time transfer standards.
8. Report of the CCDS working group on two-way satellite time transfer.
9. Report of the CCDS working group on the application of general relativity to metrology.
10. CIPM working group on the equivalence of national standards.
11. Reports on other meetings:
    - International Astronomical Union: 22nd General Assembly;
    - International Union of Geodesy and Geophysics: 21st General Assembly;
    - International Union of Radio Science: 24th General Assembly;
    - Study Group 7 of the Radiocommunication Bureau of the International Telecommunication Union.
12. Other business.
13. Recommendations.
14. Closure of the meeting.

REPORT

OF THE COMITÉ CONSULTATIF

POUR LA DÉFINITION DE LA SECONDE

(13th Meeting — 1996)

TO THE

COMITÉ INTERNATIONAL DES POIDS ET MESURES

by Dr P. Fisk, Rapporteur

The Comité Consultatif pour la Définition de la Seconde (CCDS) held its 13th meeting at the Bureau International des Poids et Mesures (BIPM) at Sèvres on Tuesday 12 and Wednesday 13 March 1996.

The following were present:

Prof. J. Kovalevsky, Secretary of the CIPM, President of the CCDS.

Delegates from the member laboratories and organizations:

All-Russian Research Institute for Physical, Technical and Radio-Technical Measurements [VNIIFTRI], Moscow (V. Koutcherov, S. Pushkin, N. Koshelyaevsky).

Bureau National de Métrologie: Laboratoire Primaire du Temps et des Fréquences [BNM-LPTF], Paris (M. Granveaud, A. Clairon).

Communications Research Laboratory [CRL], Tokyo (M. Imae).

CSIRO, Division of Applied Physics [CSIRO], Lindfield (P. Fisk).

International Astronomical Union [IAU] (G. M. R. Winkler).

International Telecommunication Union [ITU] (G. de Jong).

International Union of Geodesy and Geophysics [IUGG] (P. Pâquet).

International Union of Radio Science [URSI] (J. Mc A. Steele).

Istituto Elettrotecnico Nazionale Galileo Ferraris [IEN], Turin (A. Godone).

Korea Research Institute of Standards and Science [KRISS], Taejon (Nak Sam Chung).

Laboratoire de l'Horloge Atomique [LHA] du Centre National de la Recherche Scientifique, Orsay (C. Audoin, N. Dimarcq).

National Institute of Metrology [NIM], Beijing (MA Fengming).

National Institute of Standards and Technology [NIST], Boulder (D. B. SULLIVAN).

National Physical Laboratory [NPL], Teddington (R. W. YELL).

National Physical Laboratory of Israel [INPL], Jerusalem (A. LEPEK).

National Research Council of Canada [NRC], Ottawa (R. J. DOUGLAS).

National Research Laboratory of Metrology [NRLM], Tsukuba (Y. NAKADAN).

Nederlands Meetinstituut: Van Swinden Laboratorium [NMi-VSL], Delft (G. DE JONG).

Observatoire Royal de Belgique [ORB], Brussels (P. PÂQUET).

Office Fédéral de Métrologie [OFMET], Wabern/Observatoire Cantonal de Neuchâtel [ON], Neuchâtel (L. PROST).

Physikalisch-Technische Bundesanstalt [PTB], Braunschweig (K. DORENWENDT, A. BAUCH).

Real Instituto y Observatorio de la Armada [ROA], San Fernando (J. PALACIO).

Technical University of Graz [TUG], Graz (D. KIRCHNER).

U.S. Naval Observatory [USNO], Washington DC (W. J. KLEPCZYNSKI).

Member by appointment:

B. GUINOT, Chartrettes (France).

The Director of the Bureau International des Poids et Mesures [BIPM] (T. J. QUINN).

Invited guests:

D. W. ALLAN, Allan's TIME, Fountain Green, Utah (USA).

G. M. R. WINKLER, Washington DC (USA).

A. DE MARCHI, Politecnico di Torino, Turin (Italy).

Also attending the meeting: C. THOMAS, J. AZOUBIB, W. LEWANDOWSKI, G. PETIT, B. ROUGEAUX and P. WOLF (BIPM).

Absent:

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

1. Opening of the meeting; appointment of a rapporteur

The President welcomed the participants to the Committee, and informed them that Dr Fisk had agreed to serve as rapporteur. Dr Quinn welcomed the Committee on behalf of the BIPM. The President then asked for any other business that might be included under item 12 on the agenda. Dr Allan asked if he might be permitted to report on the activities of the Sub-committee on time of the Civil GPS Service Interface Committee (CGSIC). The President agreed and said that this would be taken under item 5 of the agenda: Synchronization of clocks using satellites. The draft agenda was then adopted and the President introduced the first item.

2. Progress in atomic frequency standards and clocks

The President asked each laboratory representative to report on progress in the development of new primary frequency standards.

2.1 Reports from laboratories

Prof. Dorenwendt presented the report from the PTB (Germany). The primary standard PTB CS1 was stopped after eighteen years of operation in order to apply to this standard the experience gained in the construction of PTB CS2, PTB CS3 and PTB CS4. Some of the improvements to be incorporated in PTB CS1 are in the areas of beam positioning, cavity phase difference, microwave leakage and a new De Marchi ring cavity design. The standard is expected to re-enter service in 1997.

The standard PTB CS2 has been in continuous operation since 1986, and has been the source of UTC(PTB) since 1991. Frequency changes of approximately 1 part in 10^{14} have been observed from time to time: these have been attributed to human activities in the course of the day, which disturb the ambient magnetic field and cause microwave leakage.

The standard PTB CS3 has been in operation since late 1992, and began contributing data to the BIPM in 1995. The standard uses a low-velocity thermal atomic beam. The accuracy of the standard is characterized by an uncertainty (1 σ) of 1,4 parts in 10^{14}; the corresponding uncertainty budget is to be published in *Metrologia**. The principal factors contributing to this uncertainty arise in the evaluation of the cavity phase difference, the quadratic Zeeman shift and a greater than expected degree of microwave leakage.

The PTB has postponed work on frequency standards based on a microwave transition in a buffer-gas cooled cloud of trapped ions, as it would be impossible to reach an uncertainty below 1 part in 10^{14}. However,

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* *See* BAUCH A., HEINDORFF T., SCHRÖDER R., FISCHER B., The PTB primary clock CS3: type B evaluation of its standard uncertainty, *Metrologia*, 1996, **33**, 249-259.

work continues on a candidate standard based on an optical transition in laser-cooled ytterbium ions; the clock transition line has recently been observed.

The frequency chain at the PTB, formely extending to the infrared, now includes the visible spectral range, and a phase coherent measurement of the frequency of the line λ = 657,5 nm of laser-cooled calcium atoms has been realized with an uncertainty of 1 part in 10^{12}. The PTB is also constructing a caesium fountain standard: this work is presently in its early stages.

Dr Lepek commented that laboratories use physical principles to calculate the uncertainties of primary frequency standards, but these uncertainties do not necessarily reflect the confidence that may be placed in the value of the frequency, since they do not include all kinds of instability. Dr Bauch replied that uncertainty calculations can only be based on physical laws and pointed out that the human related effects referred to by Prof. Dorenwendt cause changes in magnetic fields and microwave leakage, and were therefore included in the uncertainty calculations. Dr Douglas supported this opinion. (The question of uncertainties in primary frequency standards was treated later in this session).

Dr Prost presented the report from the Observatoire Cantonal de Neuchâtel (Switzerland). He remarked that he had come in place of a co-worker, Dr Thomann. He said that work on development of cold caesium atoms was progressing well, and referred the committee to the written version of the report for details of this and other activities.

Dr Godone reported on activities at the IEN (Italy). The first phase of experiments on their magnesium atomic beam has been completed, and the uncertainty in the frequency of the clock transition is 1 part in 10^{12}. The short-term noise of the standard is white frequency noise characterized by an Allan deviation $\sigma_y(\tau)$ of 1×10^{-11} for an averaging time τ of 1 s. The principal limitation in the accuracy of the frequency is the residual first order Doppler effect. The experiment has reached a point where further improvement will be difficult and its future is now being considered.

The development of diode laser pumped rubidium standards is also progressing. The objective of this work is to improve short-term stability, at present $\sigma_y(\tau = 1\ \text{s}) = 7 \times 10^{-12}$, and to study the possibility of pulsing the pumping light to reduce the effect of the light shift on the clock transition.

Prof. De Marchi reported on activities at the Politecnico di Torino (Italy). The optically pumped high C field caesium beam standard is now functioning, but figures specifying the stability and accuracy are not yet available. The standard features a new type of cavity, and Ramsey fringes of width 300 Hz have been obtained. The signal to noise ratio of the system is currently limited by laser noise. The system operates on the transition between the levels ($F = 4$, $M_F = -1$) and ($F = 3$, $M_F = -1$), at a magnetic induction of 82 mT. This situation is very close to the ideal two-level system, with the consequence that all effects related to neighbouring transitions are extremely small. The Zeeman correction at these high fields involves quadratic and higher terms, and is presently under study.

The President noted that this work is very important, in that it represents a new direction for caesium standards. He then asked Dr Yell to report on activities at the NPL (United Kingdom).

Dr Yell reported that the caesium fountain work, funded by the NPL but carried out at Oxford, has now been transferred to the NPL. A fountain is now in the early stages of construction and the first results are expected in two years.

Dr Sullivan reported on activities at the NIST (USA). The new optically pumped caesium beam standard NIST-7 has already reached its design goal accuracy, with an uncertainty of 1 part in 10^{14}. This uncertainty has recently been reduced to 5 parts in 10^{15}, but this new value has not yet been reported officially to the BIPM. It is thought that a further two-fold improvement is possible. High accuracy has been achieved, in part, by an automated system which monitors and controls systematic effects on the frequency of the standard. Confidence in the values obtained is enhanced by the fact that each systematic effect was measured in at least two different ways. The NIST plans to maintain this new standard for an extended period.

Dr Sullivan acknowledged the excellent performance of the caesium fountain developed at the BNM-LPTF (LPTF-FO1), and said that the NIST has begun to study a caesium fountain project as a joint effort between the Boulder and Gaithersburg laboratories. No detailed schedule has yet been set for this project.

Dr Sullivan then moved on to the subject of the NIST ion trapping work, which he regards as fundamental research leading towards frequency standards of a new generation. This NIST research team believes that systematic frequency shifts affecting cold single ions or strings of cold ions can be understood very well, giving the potential for very high accuracy. The ambitious work on 40 GHz transitions in a string of cold mercury ions was delayed as some redesign of the apparatus was required, but results are expected soon. Theoretical work on a technique based on the creation of correlated states with the objective of improving the signal to noise ratio of such standards was completed in 1993, and experimental work has begun. These techniques are also relevant to proposed “quantum computers”. Other theoretical work has led to an improved formula for the Allan variance, in which the confidence in $\sigma_y(\tau)$ for the longest value of τ obtainable from a given data set is significantly improved.

Prof. De Marchi commented that he was very impressed with the work which had been put into the evaluation of NIST-7, and noted that the absolute uncertainty achieved was only one part per million of the width of the central Ramsey fringe. He went on to say that the NIST-7 team has analysed the information available from all seven lines of the microwave spectrum, and that they have measured all systematic effects and their uncertainties. Prof. De Marchi concluded by remarking that the comprehensive nature of this work should be appreciated.

Dr Sullivan thanked Prof. De Marchi for his comments. The President then added his congratulations, and asked Dr Granveaud to report on progress at the BNM-LPTF (France).

Dr Granveaud said that the BNM-LPTF optically pumped caesium standard (LPTF-JPO) achieved an accuracy characterized by an uncertainty of 1 part in 10^{13} in 1993. Recent progress includes improved measurements of frequency shifts due to cavity phase differences and microwave leakage. A new cavity has been constructed and will be installed this year: following this, the team hopes to achieve an uncertainty of a few parts in 10^{14}.

The BNM-LPTF caesium fountain (LPTF-FO1) has demonstrated short-term stability characterized by $\sigma_y(\tau = 1\ \mathrm{s}) = 2 \times 10^{-13}$ which is presently limited by local oscillator noise. The instability of the hydrogen maser used as a reference, however, prevents observation of the intrinsic stability of the fountain for averaging times longer than 10^4 s. The fountain currently has a relative uncertainty of 3 parts in 10^{15} and its evaluation is being refined.

Work is also in progress at the BNM-LPTF on the Projet d'Horloge Atomique à Refroidissement d'Atomes en Orbite (the PHARAO project). It is expected that a prototype of a cold caesium atom frequency standard suitable for space applications will be tested in an aircraft under zero *g* conditions in early 1997. The device will also be used as a terrestrial clock: though not expected to be as accurate as the LPTF-FO1 fountain, it will be more compact and portable. This work is being done under a European Union contract, with the collaboration of the École Normale Supérieure and the LHA.

The BNM-LPTF has also demonstrated a carbon-dioxide laser with a stability of 6 parts in 10^{15} for averaging times of 1000 s, which is used in the BNM-LPTF frequency-multiplication chain. The chain has recently been used to measure the frequency of a diode laser locked to a two-photon transition in rubidium, with an accuracy characterized by an uncertainty of 3 parts in 10^{12}.

The President asked if further improvement in the accuracy of the LPTF-FO1 was expected. Dr Granveaud referred this question to Mr Clairon, who answered that most of the uncertainty evaluations were limited by the stability of the hydrogen maser. It follows that all the figures given in the uncertainty budget are conservative. Improvements in the estimation of the uncertainty may therefore be possible when a second fountain is completed.

Prof. Guinot indicated that the uncertainty quoted for the gravitational shift may be significantly reduced; Mr Clairon agreed on this point.

Dr Bauch commented that, based on the laws of physics, some of the frequency offsets affecting LPTF-FO1, as well as their uncertainties, should be significantly smaller than the corresponding values for NIST-7. Mr Clairon confirmed that the quoted LPTF-FO1 uncertainties are all based on measurements rather than calculations.

Dr Allan asked about the long-term reliability of the transportable cold caesium atom standard, and Mr Clairon replied that it was expected to be reliable but, of course, it has not yet been tested.

The President commented that, although the hydrogen maser has the best short-term stability of any atomic standard, it is now a limitation in primary frequency standard evaluation for averaging times of a few days. He asked the committee how much improvement in the middle and long term stability of hydrogen masers can be expected. Dr Audoin replied that, while caesium standards are produced on a large scale, hydrogen masers are produced in small numbers by small companies. Consequently the performance of the electronics is not always as good as it could be, and that there is considerable room for improvement in the auto-tuning systems. The performance of hydrogen masers can therefore be expected to improve, although the drift of the wall shift will limit long-term stability.

Dr Winkler said that the hydrogen masers available commercially from the Sigma-Tau Company are optimized for long-term performance. In addition, a ten-fold improvement in short-term stability may be available by increasing the hydrogen beam flux to the detriment of the maser lifetime.

Dr Audoin reported on the activities of the LHA (France). He began by saying that the goals of the LHA are to understand the physical phenomena involved in atomic frequency standards, and to build compact standards.

The LHA has constructed an optically pumped caesium beam tube which has demonstrated the best stability of any standard for such a small volume; its stability is $\sigma_y(\tau) = 4 \times 10^{-12}$ for an averaging time τ of 1 s. Some problems with microwave leakage have been encountered, but these are now solved. Some asymmetry in the microwave spectrum has also been observed, and residual detuning of the pumping laser was found to be responsible. Work aimed at providing better understanding of noise in optical detection systems is also in progress.

Fundamental work on the frequency stability of passive atomic frequency standards has continued, and the research team now understands the limitations introduced by intermodulation effects. Methods for reducing intermodulation effects by filtering and processing of signals have been developed; these are applicable to both slow and fast modulation rates. In addition, a system which automatically finds the optimal parameters has been demonstrated. A complete theory of the frequency control loop of pulsed standards, such as fountains and ion traps, has also been developed and is consistent with the effects already predicted by Dick *et al.*

The LHA group has also demonstrated the cooling of caesium atoms by isotropic light within an integrating sphere. The capture velocity is larger than that obtained by the conventional six-beam method, even if the power of the laser field is limited. The temperature achieved is thought to be relatively low, but it has not yet been measured precisely.

In collaboration with the Neuchâtel group, the LHA is developing a continuous, or quasi-continuous, beam of cold caesium atoms in an effort to overcome the limitations of standards based on pulsed clouds of atoms.

The LHA has also contributed to the PHARAO project, especially in the design and realization of the clock prototypes but also in the design of highly reliable diode laser sources already tested in zero *g* aircraft flights.

Following a question from Dr Sullivan, Dr Audoin indicated that a continuous cold beam of caesium atoms could also be used in a compact standard.

Dr Fisk then reported on the activities at the CSIRO National Measurement Laboratory (Australia). Two 12,6 GHz standards based on buffer-gas cooled ytterbium ions confined in a linear Paul trap have been constructed. A short-term stability characterized by $\sigma_y(\tau = 1\ \text{s}) = 6 \times 10^{-14}$ has been demonstrated, and the uncertainty of the standards is presently thought to be 2 parts in 10^{13}.

Prof. Dorenwendt asked about the factors which limit the accuracy of the standards. Dr Fisk replied that the principal limitation is the validity of the model used to describe the spatial extent of the ion cloud in the trap, which is used for calculation of the second-order Doppler shift.

The President invited Mr Imae to report on the activities of the CRL (Japan). Mr Imae said that progress on their optically pumped primary caesium standard had been slow, and that they had decided to rebuild the standard in collaboration with the NIST. Results are expected in two years. The CRL is also undertaking the development of a compact hydrogen maser for space applications. This work is presently in the design phase. A caesium fountain standard is also under development, and laser cooling of caesium atoms to less than 1 mK has been demonstrated.

Dr Allan remarked that he had heard that Japan plans to launch a satellite-based navigation system similar to the Global Positioning System (GPS). Mr Imae replied that the Japanese Ministries of Science and Transportation intend to establish such a system, but the goals and scheduling of the project are still under discussion. Dr Allan asked if time and frequency applications would be considered in the planning, and Mr Imae replied that they would.

Dr Douglas reported on the activities of the NRC (Canada). He said that the environmental chamber around their primary caesium beam standard NRC Cs V is being carefully refitted in order to control temperature gradients, which are a major source of instability. Improved radio-frequency shielding is also being installed, in order to protect the standard from the effects of cellular phones which are sometimes used nearby. A project is under way to develop a caesium beam standard using atoms in the velocity range 5 m/s to 10 m/s; cooling of caesium atoms in three-dimensional optical molasses to less than 3 μK has already been demonstrated. Work has continued on the development of infrared-optical frequency standards based on single trapped ions. A single barium ion has been cooled to

15 mK, and the frequency of the 12 μm clock transition has been measured using the NRC frequency chain with an uncertainty of 1,8 parts in 10^{11}. The frequency of the 674 nm transition in a single cold strontium ion has been measured with respect to a helium-neon laser stabilized on iodine with an uncertainty of 6,3 parts in 10^{11}.

A theoretical study of multi-step multi-photon ionization as a less perturbing method of measuring atomic polarization is in progress in collaboration with Prof. Gagné of the École Polytechnique of Montreal. This technique is also expected to overcome problems in optical detection caused by noise from background scatter of radiation.

Dr Yakadan, representing the NRLM (Japan), reported good progress on their caesium fountain standard: Ramsey fringes with a spectral width of 1 Hz have been obtained. Studies of their optically pumped caesium standard have continued, and a stability of 3 parts in 10^{14} has been achieved for averaging times of 20 000 s.

The report from the VNIIFTRI (Russian Fed.) was presented in Russian by Dr Pushkin, and translated by Dr Koshelyaevsky. Dr Pushkin reported that two primary caesium standards and several hydrogen masers have been operated at the VNIIFTRI. Secondary laboratories are also equipped with hydrogen masers, and time and frequency transfer between these laboratories has been carried out using the Global Navigation Satellite System (GLONASS) since 1989. More recently, the primary caesium beam standard MCsR 102 has been redesigned: this has demonstrated an uncertainty of 5 parts in 10^{14}, with an improved stability of 2 parts in 10^{14} to 3 parts in 10^{14} over averaging times of about three months. The primary caesium standard MCsR 103 is also being rebuilt with a shortened cavity. An uncertainty of 2 parts in 10^{14} is expected by the end of 1996.

The VNIIFTRI is continuing to develop other caesium beam standards, using the new De Marchi cavity design.

Dr Koshelyaevsky continued with the VNIIFTRI report, saying that the Russian national frequency standard, based on two caesium primary standards, has achieved State certification with an uncertainty of 5 parts in 10^{14}. The hydrogen maser ensemble has been certified as having a stability of 1 part in 10^{14} for averaging times of 100 s to 100 d. The actual stability of the ensemble over this interval is 3 parts in 10^{15}. Several of the masers in the ensemble have no detectable frequency drift (less than 3×10^{-17}/d), which highlights the problem of finding suitable references at this level of stability.

The VNIIFTRI has continued with the development of compact, sapphire-loaded hydrogen masers. Stabilities of a few parts in 10^{15} over averaging times between 1 hour and 1 day have been achieved, although no longer term data is yet available. The goal of this research is to develop an inexpensive portable clock suitable for space applications. Such a device is nearly ready for space testing, but there are no plans to launch it as yet. A spherical-cavity hydrogen maser is also being developed. This has a stability comparable with that of the sapphire-loaded masers.

On 23 March 1995 the scale unit of the Russian atomic time scale was matched to the SI second as produced by the Russian primary caesium standards, and the scale unit now coincides with that of TAI to within the uncertainty of these standards.

Dr Allan said he thought that hydrogen masers would be used in the next generation of GLONASS satellites, and enquired about their expected performance. Dr Koshelyaevsky replied that the masers will not be VNIIFTRI masers, and that he had no other information.

Answering a question from Dr Bauch, Dr Koshelyaevsky confirmed that the VNIIFTRI primary caesium standards operate continuously and contribute data to the BIPM.

Dr Chung then presented the report from the KRISS (Rep. of Korea). Dr Chung said that the optical pumping efficiency of their caesium beam primary standard had been improved by changing the polarization of the pumping light. Trapping and cooling of caesium and rubidium atoms has been demonstrated, as part of a project to develop a fountain standard.

2.2 Uncertainties in primary frequency standards

The President then thanked the delegates for their reports, and opened a general discussion on primary frequency standards. In response, Dr Quinn raised the question of how uncertainties in primary frequency standards are expressed. He observed that the ISO *Guide to the expression of uncertainty in measurement* recommends that uncertainties be expressed as a combination of statistical (type A) and other (type B) uncertainties. In view of this, he assumes that the uncertainties quoted for primary frequency standards are entirely type B, since no associated averaging times are quoted.

An extended discussion on this topic followed, which was summarized by Dr Allan who said that in time and frequency applications we usually analyse data in the form of a time series. This leads to the question of what is intended when an uncertainty is calculated, that is, is it the expected variation of the quantity over a period of time, or is it merely the uncertainty of a single measurement? He said that the ISO guide does not cover these issues, and that to try to follow it rigorously in time and frequency applications would lead to confusion.

Dr Quinn replied that the purpose of the ISO guide is to give uniformity in the calculation of uncertainties, so is it not applicable in these cases? Dr Winkler said that the evaluation of a frequency standard involves two steps: the determination of systematic effects and then the measurement of its frequency with respect to TAI. This second step involves the consideration of measurement times and instability. Prof. De Marchi agreed with Dr Winkler, saying that stability and accuracy are very different entities, and that he does not agree with the use of the term “standard uncertainty” when it is applied to accuracy. Prof. De Marchi said that there are many sources of uncertainty in an accuracy calculation, some of which cannot easily be quantified, for example, questions of validity of theories.

Dr Winkler gave the opinion that the ISO guide is applicable so long as the distinction is made between stability and accuracy.

Dr Sullivan added that some of the effects encountered in the uncertainty budget of a primary standard may not be independent. In such a case the quadratic sum of the uncertainty components is not sufficient.

Dr Bauch added that it is sometimes difficult to distinguish between type A and type B uncertainties; for example, the uncertainty in the first order Doppler effect in the fountain frequency is evaluated by measurement and thus cannot be treated as a type B uncertainty.

After some further debate, the President closed the discussion on uncertainties, noting that there was clearly some disagreement on how uncertainties should be presented. He suggested that the matter is of sufficient importance that the CCDS should form a working group to report on how the accuracy of primary frequency standards should be evaluated in accordance with the ISO guide. He asked Dr Douglas to act as Chairman of this CCDS working group on the expression of uncertainties in primary frequency standards. Dr Douglas agreed to do this. Besides Dr Douglas, the membership of the working group is Dr Allan, Dr Bauch, Dr Lepek, Prof. De Marchi and Dr Thomas: it is also open to other experts from timing laboratories.

2.3 Black-body radiation shift in primary frequency standards

The President invited Dr Audoin to address the meeting on the subject of the black-body radiation shift in the frequency of the ground-state hyperfine transition of the caesium atom.

Dr Audoin began his presentation by noting that the definition of the SI second ideally requires the observation of an unperturbed caesium atom, and that corrections for unavoidable perturbations must be made. He summarized the well known methods of correcting for the effects of static magnetic fields (DC quadratic Zeeman shift), static electric fields (DC Stark shift), and for Bloch-Siegert shifts (presently negligible) due to microwave radiation and the spurious spectral components thereof. He said that the physics of the effects of alternating magnetic (AC Zeeman shift) and electric (AC Stark shift) fields have been well understood for many years: the black-body shift in alkali metal hyperfine spectra is a combination of AC Stark and AC Zeeman shifts caused by the radiation emitted from all surfaces at finite temperatures. There are, therefore, two principal contributions to the black-body shift in the frequency of caesium atoms near room temperature:

— The coupling of the black-body radiation to the magnetic dipole of the 9 GHz clock transition, via the AC Zeeman effect. This results in a fractional frequency shift:

$$\frac{\Delta v_0}{v_0} = 1{,}3 \times 10^{-17} \left(\frac{T}{T_0}\right)^2,$$

where T_0 = 300 K and T is expressed in kelvin.

— The coupling of the black-body radiation to the electric dipole of the 850 nm optical resonance transition, via the AC Stark effect, resulting in a much larger fractional frequency shift:

$$\frac{\Delta v_0}{v_0} = 1{,}69\,(4) \times 10^{-14} \left(\frac{T}{T_0}\right)^4,$$

where T_0 = 300 K and T is expressed in kelvin.

The calculation is complicated by the semi-continuous spectral nature of this radiation, but is simplified by noting that at room temperature (T_0 = 300 K) most of the energy of the black-body spectrum is at frequencies greater than the frequency of the clock transition, and less than the frequency of the optical resonance transition.

Dr Audoin concluded by saying that the black-body radiation shift in the frequency of the caesium clock transition is significant, and that the uncertainty in our knowledge of this shift is between 2 parts in 10^{16} and 3 parts in 10^{16}, provided that the radiation is emitted by a perfect black body.

Dr Bauch congratulated Dr Audoin on his report and asked that it be tabled: Dr Audoin agreed.

3. Report of the CCDS working group on TAI

The President invited Dr Pâquet, Chairman of CCDS working group on TAI since 1996, to report on the activities of the working group. Dr Pâquet asked Dr Winkler, Chairman of the working group from 1985 to 1995, to give this report. Dr Winkler said that the main topic of discussion at the last meeting of the working group, held at the BIPM on 13 and 14 March 1995, was the effect of black-body radiation on the frequency of primary frequency standards, and asked Dr Petit, rapporteur of the 1995 meeting, to summarize the main points of the meeting. Dr Petit reported as follows:

— A draft recommendation that laboratories calculate the black-body radiation correction to apply to the frequency of their primary standards and communicate the results to the BIPM was produced for the consideration of the CCDS, and was distributed to laboratories contributing to TAI.

— The role of UTC and the needs of users in real-time was considered, however the working group did not reach agreement and concluded that studies should continue.

— The working group emphasized that laboratories should continue to study clock correlations and noted that no reports on this subject had been received by the BIPM.

— The working group concluded that data from hydrogen masers is used correctly in the calculation of TAI, but there may be room for improvement.

— The working group noted that the quality of commercial time transfer equipment specially designed for GPS common views seems to be deteriorating and that the situation calls for action. Furthermore, improvements in the accuracy and stability of the clocks suggest that other methods of GPS time transfer should be studied.

— The working group recommended that the maximum weight of clocks contributing to TAI should be increased by a factor of 2,5, and that the basic sample duration between two TAI updates should be shortened to 5 days. Laboratories have therefore been requested to provide clock data for the Modified Julian Dates ending in 4 and 9.

— The working group recommended that TAI should be steered in small increments to compensate for the deviations following the uniform application of the black-body radiation correction to all measurements from primary frequency standards. The group also recommended that, when possible, this steering should be announced in advance.

At the conclusion of Dr Petit’s report, Dr Winkler emphasized the importance of studying correlations between clocks, since the weighting system used in the calculation of TAI is not appropriate if such correlations exist. He said that such a study was carried out at the USNO and that among the 50 HP 5071A clocks operated there, uncorrelated frequency changes of 1 part in 10^{14} to 3 parts in 10^{14} have been observed over time intervals between 100 d and 300 d. Dr Winkler also commented that, from the point of view of the International Atronomical union (IAU), the most important feature of TAI is its long-term stability, and that this should be given top priority. With the recent rapid improvement in the short-term stability of TAI, we do not yet have enough data to evaluate its revised long-term stability.

The President pointed out that written draft recommendations concerning correlations between clocks and black-body radiation are available; he suggested that these be discussed at the end of the CCDS meeting together with other draft recommendations.

The President then asked Dr Pâquet to report on the meeting of representatives of the laboratories contributing to TAI, which was held the day before the CCDS meeting. Dr Pâquet said that there were fifty attendees, and that most of the items discussed had already been covered by Dr Winkler and Dr Petit. Dr Pâquet said that there was general agreement during the meeting about the new weighting system. However, it seems that TAI exhibits a residual seasonal variation and it was suggested that a study be made of the effect of excluding from the calculation of TAI all clocks which are not HP 5071A caesium clocks or hydrogen masers.

Dr Pâquet said that the meeting of laboratory representatives noted that most of the perturbations affecting GPS time transfer are already well known in the geodetic community: for example, the ionospheric correction and the effect of atmospheric pressure on the Earth's crust. He suggested that more contact with geodetic users of GPS would be valuable.

Dr Pâquet noted that although recommendations for features to be incorporated in GPS time transfer receiver software were made in 1992, only receivers of NBS type actually incorporate these features. During the meeting, the possibility of determining the market for a new receiver meeting all the needs of time metrology was discussed, as was the possibility of approaching a manufacturer. Dr Pâquet noted that the performance of receivers will become particularly important during the approaching maximum in solar activity.

The laboratory representatives also noted that the transformation between the GPS and GLONASS reference frames needs to be addressed. Finally, they expressed their appreciation to the BIPM for implementing all the recommendations of the previous meeting. This was formally addressed in the following declaration:

The Comité Consultatif pour la Définition de la Seconde,

considering that the BIPM Time Section has implemented all recommendations of the TAI advisory meeting 1995 in an exemplary manner and that it has conducted studies on the feasibility of making further improvements in its services to the international timing community, which have been most helpful in the deliberations of said advisory group,

expresses its thanks and congratulations to the BIPM for its outstanding service.

The President thanked Dr Pâquet for his report, and asked Dr Thomas to present the report of the BIPM Time section.

4. Report of the BIPM Time section

Dr Thomas reported that TAI has been computed every 5 days since 1 January 1996, which makes it easier for laboratories which wish to steer their local realizations of UTC to predict its behaviour. Data blocks of two months are used, and the decision to shorten this interval has not yet been taken. The maximum weight of clocks contributing to TAI has been increased by a factor of 2,5. BIPM *Circular T* now includes information on the steering of TAI; it includes evaluations of the duration of the TAI scale unit against the SI second produced by primary standards.

Dr Thomas noted that there has been a rapid improvement in the stability of data submitted to the BIPM since 1993. This is attributed to the increasing prevalence of the HP 5071A caesium clock, which appears to have a flicker noise floor of 6 parts in 10^{15} over averaging times between 20 days and 40 days. Presently, 42 % of the clocks included in the TAI computation are of this type, and this fraction is increasing. There are now forty-six timing centres maintaining a local realization of UTC, and four more will begin shortly. Nearly all of these centres make their GPS observations following the international GPS common-view schedule issued by the BIPM. Dr Thomas also noted that several hydrogen masers reported to the BIPM exhibit outstanding long-term stability.

In 1995, the stability of EAL, the free time scale obtained as a weighted average of clock data, was characterized by an Allan deviation of 2,6 parts in 10^{15} for an averaging time of 40 days. For the same year, the scale unit of TAI differed from the SI second by $1{,}8 \times 10^{-14}$ s, a discrepancy known with an uncertainty of 5×10^{-15} s. The deviation between the duration of the TAI scale unit and the SI second results from the uniform application of the correction compensating for the black-body radiation shift of the frequency of all primary standards. The reduction of the relative uncertainty to 5 parts in 10^{15} was made possible by the excellent accuracy of the frequency measurements provided by the LPTF-FO1.

Some studies have been carried out on the effects of changing the clock weighting procedure in the computation of EAL. The stability of EAL was evaluated via an N-cornered hat technique using four independent atomic time scales computed in different laboratories (BNM-LPTF, NIST, USNO, VNIIFTRI) and results from the continuously operating primary frequency standard PTB CS2. It was found that the best stability is obtained if, instead of using an absolute maximum weight as is presently the case, each clock is permitted a relative maximum weight of 1,37 %. This has the effect that very stable clocks reduce the weight of poorer clocks. Despite its apparent advantages, it was decided not to adopt this new algorithm until its sensitivity to seasonal and other long-term variations has been studied.

Dr Thomas said that current processing of hydrogen maser data is not optimal as it is difficult to predict frequency drifts, but a better method has yet to be developed.

Dr Thomas continued by saying that the steering of TAI is being made in steps of 1 part in 10^{15} every two months, so it will take several years for its scale unit to coincide with the SI second. The continuously operating PTB primary standards are used in the computation of EAL and also for the estimation of the TAI scale units at 60 day intervals. Primary standards which do not operate continuously cannot contribute to EAL, but provide independent evaluation of the TAI scale unit. These standards presently include the LPTF-F01, NIST-7 and SU MCsR 102.

Dr Lepek asked Dr Thomas if she could quote some numbers for the observed changes in hydrogen maser drift estimates. Dr Thomas replied that drift values had been observed to change by a factor of 2. Dr Lepek asked if these changes could in fact be due to instability of TAI, and Dr Thomas replied that she does not think so. Dr Bauch commented that the Russian hydrogen masers at the PTB initially had drifts of 10^{-16}/d, which reduced to zero after two years, and later changed sign.

Dr Allan suggested that given the 3 parts in 10^{15} uncertainty of the LPTF-F01, and the stability of EAL, a better approach to estimating the TAI scale unit would be to take a 30 day average of data from the LPTF-F01, which would reduce measurement noise and provide a better comparison. Prof. Guinot replied that a transfer standard of corresponding stability, over a 30 day average, would be required at the BNM-LPTF; such a standard is not presently available. Minimizing the noise introduced by this transfer standard calls for the averaging time of the TAI scale unit estimation to be as close as possible to the time duration over which the LPTF-FO1 frequency is measured.

Dr Winkler asked how hydrogen maser frequency drift is calculated at the BIPM. Dr Thomas replied that generally a parabola is fitted to timing data taken every 10 days. Dr Winkler approved this method which he considers to be the most efficient.

Dr Bauch asked if the estimates of the stability of EAL depend on the particular choice of the five time scales used for comparison. Dr Thomas replied that this point was studied and that there was no significant dependence.

Dr Allan pointed out that the finding that the stability of the EAL could be improved by giving very stable clocks more weight at the expense of poorer clocks is important, and that this work is commendable. He also noted that the stability of the time scale using a relative maximum weight and a computation time of 30 d, characterized by $\sigma_y(\tau = 20\ \mathrm{d}) = 6 \times 10^{-16}$, is close to the theoretical value he calculates assuming an optimal algorithm for combining the data from the HP 5071A array.

Dr Lepek pointed out that the N-cornered hat technique is applicable only in the case where the involved time scales exhibit white phase noise. Dr Thomas agreed that there could be a problem in that regard, but there is presently little choice in the available methods for evaluation of the stability of time scales.

Dr Bauch asked if the steering applied to TAI will affect the astronomical community, and if it would be better to have a single frequency step to bring the TAI scale unit into coincidence with the SI second. Dr Winkler replied that the steering is presently indistinguishable from other drifts, and consequently does not present a problem, whereas a single large step would be inconvenient.

Prof. Guinot commented that TAI suffers from a number of long-term defects, for example, the unforeseen correction for the black-body radiation shift. This may be a problem for radioastronomers studying millisecond pulsars. The BIPM addresses this problem by generating the time scale TT(BIPM) which is recomputed annually to give an accurate time scale in the long term. Thus, TT(BIPM) should serve the needs of the scientific community requiring long-term stability. The TAI should thus be corrected for the black-body radiation shift and the consequent degradation of stability must be tolerated.

Dr Bauch suggested that Dr Douglas's recently proposed working group should also study the validity, when estimating the duration of the TAI scale unit, of the hypothesis that consecutive 60 day measurements obtained from PTB CS2 are not independent of one another simply because this particular primary standard operates continuously. Dr Thomas agreed that this should be studied, particularly since the BIPM is not fully aware of how the uncertainty evaluations are performed. Dr Sullivan agreed that this is a worthwhile point, since it is important to optimize the use of the data.

The President closed the discussion on the stability of the BIPM time scales, and moved on to the topic of synchronization of clocks. He invited Dr Thomas to address the meeting.

5. Synchronization of clocks using satellites

Dr Thomas said that the BIPM issues common-view GPS schedules twice per year, and that the raw data obtained is treated as uniformly as possible. Variations in the internal delays of GPS time receivers continue to be a subject of study. The BIPM Time section has been working with a dual-frequency multi-channel receiver from Allen-Osborne Associates (TTR4-P model) which, although it does not work well, appears to be capable of frequency transfer with an uncertainty of 1 part in 10^{15} over averaging times of 1 day when carrier-phase measurements are used. Important issues continue to be the measurement of ionospheric delays, and the estimation of tropospheric delays using temperature and pressure data.

The BIPM issued its first GLONASS common view schedule in January 1996, and an experiment between the 3S Navigation company, California (USA), the USNO and the BIPM on GLONASS time transfer by the common-view technique, has given encouraging results. White phase noise, characterized by a standard deviation of 9 ns, is observed over single

13 minute tracks, but problems remain concerning the absolute calibration of the GLONASS time receivers.

The President thanked Dr Thomas for her report, and invited Dr Allan to present a report on the activities of the Civil GPS Service Interface Committee (CGSIC), a body which acts as an interface between the civilian users of GPS and the GPS operational management. Dr Allan noted that civil use of GPS now far exceeds military use, so this committee is of increasing importance. A task force, chaired by Dr Allan, has been set up within the CGSIC to improve the interface with the civilian timing community, and Dr Allan called for input to this task force to be submitted via himself or Dr Lewandowski.

The CGSIC has identified the need for improved measurement of ionospheric delays, because of the approaching maximum in solar activity. In addition, current time transfer methods now clearly limit the degree to which the accuracy and stability of new frequency standards can be transferred to international time scales. Dr Allan said several new techniques are being studied, including the use of GPS carrier-phase, and also a technique for determining the orbits of GPS satellites very precisely, which will theoretically permit time transfers with an accuracy of 10 ps. He also added that Selective Availability (SA) is very disturbing for most civil users.

Dr Winkler commented that two US reports, from the National Academy of Sciences and the National Academy of Public Affairs, have recommended that Selective Availability be turned off. It is possible therefore that SA will be reduced or even turned off during periods free of international stress. Dr Sullivan expressed concern that this would not necessarily benefit the time and frequency community, since it may remove the incentive to develop the new and better methods of time transfer which will be needed if SA is reinstated. Dr Winkler replied that some users may see this as a problem, but gave the opinion that such arguments will carry little weight in making decisions on SA.

Dr Pâquet observed that although much progress in frequency standards has been made over the last ten years, the GPS receivers used for time transfer are still largely of the first generation. He emphasized the need to convince a manufacturer or laboratory of the need to develop a receiver which fits the needs of time laboratories. He also emphasized the value of a uniform system, so that knowledge about calibration and maintenance can be shared, and asked for the support of the CCDS in these issues. The President agreed and asked Dr Pâquet to draft a recommendation for consideration by the present meeting of the CCDS. This draft recommendation became a formal request from the CCDS to the group dealing with GPS standardization. (The detailed wording is given in Section 7.)

The President then closed the discussion on clock synchronization, and asked Dr Petit to present a report on the timing of millisecond pulsars.

6. Timing of millisecond pulsars

Dr Petit remarked that Recommendation S 2 (1993) entitled “Timing of millisecond pulsars”, adopted by the CCDS at its 12th meeting, has been of help to radioastronomers. He noted that pulsars are the most stable astronomical clocks and that a pulsar time, obtained as an average of data from several pulsars observed over a long period (at least ten years), would exhibit a stability of 2 parts in 10^{15} over averaging times of several years and so could help to monitor the long-term instabilities of TAI. He said that three pulsars have been observed for more than eight years, but only two of these are good candidates for clocks and only one of these two exhibits near-white noise characteristics. The apparent limitations to their stability are noise intrinsic to the pulsar and gravitational interaction in the vicinity of the pulsar or close to the path of the radio signal.

Dr Petit mentioned that timing observations are presently carried out in ten centres spread world-wide and that about twenty survey programmes are devoted to the search for new millisecond pulsars. He concluded that it will take several years before time metrology takes full advantage of millisecond pulsar timing.

Prof. Guinot asked if the long-term instability of TAI contributes to the apparent long-term instability of pulsar time. Dr Petit replied that this is an important point, and it is not yet clear which is the best time scale to use as a reference for pulsars.

Dr Winkler observed that the most stable pulsars are those which are least understood, since they provide little data on changes in their internal structure. He expressed concern about the use of poorly understood entities as clocks. He also expressed concern about using a non-local timing system for anything other than comparison.

The President closed the discussion on pulsars, and called for the report from the Sub-group of the CCDS working group on TAI on GPS time transfer standards. Dr Allan, Chairman of the sub-group, presented this report.

7. Report of the Sub-group of the CCDS working group on TAI on GPS time transfer standards

Dr Allan said that technical directives for the standardization of GPS time receiver software have been defined by the Sub-group of the CCDS working group on TAI on GPS time transfer standards and published in *Metrologia* (1994, **31**, 69-79). These directives are already implemented in software provided by the companies Allen-Osborne Associates and 3S Navigation: both companies are willing to cooperate on other issues. The new data format, with 0,1 ns resolution, is expected to satisfy time transfer requirements for the next several years. Dr Allan said that in view of the recent availability of GLONASS time receivers and the promising results being obtained, the work of the sub-group is not yet complete and that it should be extended to cover GLONASS time transfer standards. (Later in the meeting it was decided to rename the sub-group as “Sub-group on GPS and GLONASS time transfer standards”.) A formal request from the CCDS to this sub-group was written with the objective of strengthening contacts between the manufacturers of GPS and GLONASS time receivers and the time community.

The Comité Consultatif pour la Définition de la Seconde,

noting the marked improvements in the quality of both primary frequency standards and commercial atomic clocks,

recognizing that the performance of commercially available GPS and GLONASS receivers currently used does not meet time transfer requirements,

asks the CCDS Sub-group on GPS and GLONASS time transfer standards

— to contact manufacturers of receivers and request them to adapt the hardware and software of their systems to match the requirements of time and frequency laboratories so that their receivers can record the signals of GPS and GLONASS satellites in dual-frequency mode, in multi-channel mode and in a data format defined by the sub-group, can provide internal calibration and be as insensitive as possible to environmental conditions,

— to keep time and frequency laboratories informed of its actions.

Dr Allan noted that GLONASS time and UTC(SU) are respectively displaced by 25 μs and 7 μs from UTC, and that this is undesirable. Dr Koshelyaevsky suggested that a request from the CCDS for the synchronization of these time scales might be helpful. Dr Klepczynski added that, in the framework of the coming Global Navigation Satellite System (GNSS), the navigation community will consider it important to have GLONASS time closer to UTC. The President suggested that Dr Allan and Dr Koshelyaevsky draft a discussion document. He added that this document should also mention the difficulties caused by the different coordinate systems used by GPS and GLONASS.

In the discussion which followed, it was unanimously recognized that GLONASS time should be as close as possible to UTC (± 100 ns seemed a realistic goal to Dr Winkler) and that the coordinate frame used by GLONASS should be as close as possible to the Terrestrial Reference Frame (ITRF) drawn up by the International Earth Rotation Service (IERS).

The President closed the discussion on GPS and GLONASS time transfer standards, and called for the report of the CCDS working group on two-way satellite time transfer. Dr Klepczynski, Chairman of the working group, presented this report.

8. Report of the CCDS working group on two-way satellite time transfer

Dr Klepczynski said that the goal of the CCDS working group on two-way satellite time transfer was to establish how the two-way satellite time transfer technique can best contribute to TAI. In this regard, he highlighted several problems, in particular the fact that two-way facilities are often installed far from the building where the local time scales are generated with the result that an accurate link does not always exist between the two.

The present two-way satellite time transfer network consists of six stations in Europe, with two more about to come on-line, and a few stations in the USA. The principal problem is lack of uniformity between systems; for example, differences in equipment, cable lengths and procedures for calibration. Another problem is the cost and availability of time on suitable satellites, since the recent experimental period of free time on satellites from the International Telecommunications Satellite Organization (INTELSAT) has come to an end.

Dr de Jong said that the NMi-VSL has developed an automated system for calibrating delays in two-way satellite time transfer Earth stations, and that such a system will be required at each Earth station if optimum performance is to be achieved. Dr Kirchner said that the TUG also has a satellite simulator for calibration purposes, and that they have been using it for fifteen months. He said that the TUG group had established an uncertainty budget of 50 ps for individual data points, although they observe a seasonal variation with a peak-to-peak amplitude of 1,5 ns caused by equipment sensitivity to temperature and humidity.

Dr Sullivan congratulated Dr de Jong and Dr Kirchner on their work in improving the accuracy of the Earth stations, but added that, so far, the NIST has been disappointed with the performance of the two-way satellite time transfer technique, and would like to see a clear demonstration of its superiority over the use of GPS for time and frequency transfer over very long distances. He said that such a demonstration will be needed to justify the capital and labour cost of the two-way satellite time transfer technique research work.

Dr Kirchner pointed out that it is difficult to demonstrate the superior performance of the two-way method over the GPS common-view method unless very good clocks are connected to the Earth stations, and not all Earth stations are so equipped.

Dr Bauch referred to time comparisons carried out between the USNO and the PTB, and the NIST and the PTB, using both methods. In his opinion, the results give evidence that both methods are suitable for comparison of the frequencies of primary frequency standards at their present level of uncertainty. This opinion was not shared by all participants.

The President suggested that to evaluate the performance of the two-way satellite time transfer method, someone should take all the available data, assess the behaviour of clocks with respect to one another and submit the data to the BIPM. Dr Klepczynski said that a format for two-way observations is being drawn up by the working group, together with a unified treatment for short-term measurements. In addition, he informed the meeting that the USNO will maintain a time link between the GPS master clock in Colorado and the USNO in Washington DC, using similar two-way Earth stations. This should provide a long-term set of reliable and well characterized data.

Dr Sullivan asked if the BIPM has an opinion on how to incorporate the results from two-way satellite time transfer into TAI. Dr Thomas replied that there are two fundamental problems; one is to calibrate the time links involved and the other is that two-way measurements are not carried out on standard dates (MJDs ending in 4 and 9, 0 h 00 UTC). Dr Petit added that two-way satellite time transfer offers little advantage for TAI at present, since GPS time transfer averaged over a few days is as effective. Dr Lewandowski said that over very long baselines the two-way satellite time transfer method may be superior to the GPS common-view method, due to ionospheric and other perturbations which affect GPS time transfer, but only under the condition that appropriate calibrations of the equipment are carried out.

Dr Kirchner pointed out that one should distinguish between the method and its implementation. He said that the two-way method was an immediate success when it was first started twenty years ago, and thus should not be condemned simply on the basis of hardware problems which came afterwards. A significant improvement in the performance of the two-way satellite time transfer technique can be expected from promising new equipment coming into use, such as the SATRE modem and a novel automated calibration system now under development at the TUG. Concluding, Dr Kirchner said that the two-way method was undergoing a period of change: he pointed out that we now have two comparable systems of time and frequency transfer available, GPS common view and two-way satellite time transfer, and both should be maintained and developed.

Some discussion followed, the general tone of which was support for the further development of the two-way satellite time transfer technique. The President closed the discussion and asked Prof. Guinot, Chairman of the CCDS working group on the application of general relativity to metrology, to present his report.

9. Report of the CCDS working group on the application of general relativity to metrology

Prof. Guinot began by saying that the goals of the CCDS working group on the application of general relativity to metrology were to prepare a report on the interpretation and use of the SI units in the framework of general relativity, and to study the consequences of the increasing accuracy of realizations of the SI units. He pointed out that the report written by the working group concerns only the first of these items.

Prof. Guinot tabled a comprehensive and detailed report, and said that according to Einstein's equivalence principle local physics retains its familiar form everywhere and at any time when measurements are referred to local standards. This remains true even in the accelerated and rotating reference frame of the Earth's surface. A consequence is that the constants of physics must be seen as local quantities expressed with units provided by local standards. As all base units are presently defined on the basis of local experiments, using the constants of physics, there is no need to modify their definition to take account of general relativity, but it must be understood that they are "proper" units at the location of the standards which realize them.

The mathematical modelling of experiments in an extended space domain requires the use of space-time coordinates. In general relativity it is essential to distinguish coordinates from locally measurable quantities. For space coordinates, the report gives a simple example. For coordinates in time, the report provides a more detailed development. It gives the definition of the coordinate times in use, including TAI, recalls the convention for comparison at a distance of proper quantities and develops the most useful formulae resulting from this convention for time and frequency comparisons.

In conclusion, Prof. Guinot emphasized that it is dangerous to apply relativistic corrections to data, as opposed to analysing the data using a more global treatment of measurement in the framework of general relativity. In the former case, there is a serious danger of omitting corrections or applying the same correction twice.

The President congratulated the working group on its report, saying that it is an excellent introduction to more complicated papers. He agreed that we must change our culture, and think in terms of general relativity, rather than including separate relativistic corrections. He invited Dr Brumberg, especially invited to the CCDS meeting for this item, to add his comments.

Dr Brumberg said that general relativity is entering a new era. It was previously applied as small corrections to Newtonian physics, but ten or fifteen years ago, with the advent of very precise local and cosmological measurements, it was realized that this is unsatisfactory.

Dr Pâquet asked if relativistic corrections are routinely applied to data received by the BIPM. Dr Petit replied that a correction is applied to primary standard data to ensure that they reflect the SI second on the rotating geoid. Mr Wolf added that a correction for the Sagnac effect is applied to GPS time transfer data.

Prof. Guinot pointed out that there are practical difficulties in applying gravitational corrections as it is difficult to estimate the local gravitational potential. Dr Petit emphasized that the Earth is not sufficiently well understood to compare frequency standards at the 10^{-18} level.

Prof. De Marchi asked if, in view of the changing gravitational potential of the Earth, there is a resulting problem with the definition of TAI. Prof. Guinot replied that there is as yet no answer to this question, but he expects it will become important at the level of some parts in 10^{17}: this will be a future task for the working group.

Dr Quinn added his congratulations to Prof. Guinot, and recommended the report to the meeting as a clear expression of basic principles. Dr Quinn also said that the report is to be published in *Metrologia*.

The President then thanked the Chairman of the working group and closed the discussion.

10. CIPM working group on the equivalence of national standards

Dr Quinn made some remarks on the deliberations of the CIPM working group on the equivalence of national standards. He said that Consultative Committees are now being asked to identify key comparisons to enable equivalence to be demonstrated between national measurement standards. Dr Quinn said that he thought there are no problems in the case of time and frequency, as the standards are routinely and continuously compared and the results are published in *Circular T*. Dr Douglas raised the question of the equivalence of related quantities, for example, phase noise. Dr Quinn suggested that this falls in the province of another consultative committee, but Dr Douglas did not agree. Dr Quinn replied that it was not possible to address all issues, and that the CCDS should concentrate on the key ones.

Dr Steele asked about international equivalence in frequency measurements. Dr Quinn replied that he thinks *Circular T* provides the data from which frequency equivalence between primary frequency standards could be demonstrated.

11. Reports on other meetings

11.1 International Astronomical Union: 22nd General Assembly

The President, in place of Dr Winkler who had to leave the meeting, presented the report on the 22nd General Assembly of the International Astronomical Union (IAU) that was held in the Hague (Netherlands) in 1994. He reported that the 1991 recommendations of the IAU have been confirmed and that the definition of the celestial reference frame was completed in October 1995, when the coordinate values for a number of quasars and galaxies were adopted. Dr Brumberg added that a working group has been established to investigate the astronomical constants in the framework of general relativity.

Dr Allan commented that there are two other working groups of the IAU, one on time transfer, chaired by himself, and one on millisecond pulsars, chaired by Dr Petit.

Prof. Dorenwendt asked if the IAU intended to abandon the use of Modified Julian Dates (MJD). The President explained that even if, for some applications, the IAU recommends that the use of the modified Julian calendar be avoided, to the profit of the Julian calendar, it will not recommend its total abandonment.

11.2 International Union of Geodesy and Geophysics: 21st General Assembly

The President requested from Dr Pâquet a report on the 21st General Assembly of the International Union of Geodesy and Geophysics (IUGG) that was held in Boulder (USA) in 1994. Dr Pâquet said that little was done about time during the meeting in Boulder, mainly because the same persons were present in the IUGG and IAU meetings, and time is much more extensively discussed within the IAU. He recalled that geophysicists and geodesists know a lot about some of the concerns of the time community, for instance the behaviour of the ionosphere. It is thus of utmost interest to have close contact with this community.

11.3 International Union of Radio Science: 24th General Assembly

Dr Steele reported on the activities of Commission A (Metrology) of the International Union of Radio Science (URSI) during its 24th General Assembly in Kyoto (Japan) in 1993. The principal resolution concerns the definition of the kilogram and recommends that it should be replaced by a ratio of fundamental constants. Dr Steele also reported that the 25th General Assembly will be held in Lille (France) from 28 August to 5 September 1996.

11.4 Study Group 7 of the Radiocommunication Bureau of the International Telecommunication Union

Dr de Jong gave a report on the work of Study Group 7 of the Radiocommunication Bureau of the International Telecommunication Union (ITU-R). He said that this Study Group is no longer concerned only with time and frequency: it is now called “Science Services”. At its most recent meeting, the Study Group modified the recommendation concerning time signals and time codes. The Study Group also produced recommendations concerning the operational use of the two-way satellite time transfer method, in particular it defined a data format for two-way measurements. A draft recommendation on the use of the two-way satellite time transfer technique on the Synchronous Optical Network (SONET) was produced; Dr Hanson of the NIST was nominated as rapporteur to the Telecommunications Section of the ITU, to provide an interface with the Radiocommunication Bureau.

Dr Steele reported that an ITU handbook on satellite time dissemination is being prepared and will be completed in October 1996. Dr Allan reported that a corresponding handbook on the selection and use of time and frequency systems is being submitted to the ITU-R secretariat for translation and distribution.

12. Other business

Dr Lepek suggested two-way optical fibre time and frequency transfer as an additional item for discussion. He proposed that a working group be established on this subject. Dr Quinn replied that the issues involved are not yet clear, and suggested that laboratories contact their local telecommunications companies to gauge the need for the CCDS to consider this technology. Dr Sullivan noted that the ITU is already working on this subject.

13. Recommendations

The President then moved on to discussion of the recommendations to be submitted by the CCDS to the CIPM. Four recommendations entitled “Primary frequency standards”, “Black-body frequency shift”, “Correlations among clocks contributing to TAI” and “Coordination of satellite systems providing timing” were adopted.

A draft recommendation on a new real-time UTC (CCDS/96-23) was prepared by Dr Allan, and the President asked him to address the meeting on this subject. Dr Allan said that his draft recommendation was the result of collaborative work between himself, Dr Lepek, Dr Cutler and Dr Giffard, the latter two collaborators being employees of Hewlett Packard. Dr Allan said that the usefulness of UTC is greatly diminished because it is not available in real time. However, its stability is such that it can be predicted to within ± 3 ns one month in advance if clocks are used in an optimum way. He therefore suggested that the CCDS recommend that each laboratory contributing to TAI maintain its own prediction of UTC with respect to a common reference, for example GPS time, and report the results to the BIPM. The BIPM could then produce a weighted average of these predictions, and publish the results on the Internet in near real-time.

Prof. Guinot noted that this would involve breaking the rigid link between TAI and UTC, which was adopted by the Bureau International de l'Heure (BIH) in 1965, and that he saw no reason to do this. Dr Lepek said that correlation between UTC and TAI is not the main point, and that UTC could be maintained in its original form, in parallel with the new scale which would be available in near real-time.

Dr Allan emphasized that he would not propose abandoning UTC without being sure that something better is available: he merely proposed that the possibility and performance of this near real-time UTC be investigated.

Dr de Jong expressed concern that the availability of this new UTC would circumvent national standards laboratories. Dr Sullivan commented that such a time scale would be more vulnerable, and that he would like more time to consider the proposal.

The President agreed, and suggested that the proposal be considered by the CCDS working group on TAI, but it should not yet be considered as a recommendation by the CCDS.

Dr Douglas asked Dr Thomas to comment on the work done at BIPM on UTCp, a similar provisional time scale. Dr Thomas replied that it had been completely abandoned, and Dr Quinn added that the reason for this was that at the time consensus was not reached in the CCDS and the working group on TAI.

The President closed the discussion on the recommendations. He then thanked Dr Winkler for leading the CCDS working group on TAI for the last ten years.

14. Closure of the meeting

Before closing the meeting and thanking the delegates the President noted that there has been much improvement in the time and frequency situation since the last meeting three years ago, and that there is every reason to suppose that this will continue.

March 1996

Recommendations of the Comité Consultatif pour la Définition de la Seconde submitted to the Comité International des Poids et Mesures

Primary frequency standards

Recommendation S 1 (1996)

The Comité Consultatif pour la Définition de la Seconde,

considering

— the importance of maintaining an adequate number of primary frequency standards to assure the accuracy and long-term stability of TAI,

— that new primary standards are being developed using new technology,

— that these new standards are significantly more accurate than the traditional primary standards upon which TAI and UTC have been based in the past,

— that in consequence, the accuracy of TAI and UTC will rapidly become dependent on these new standards,

— that considerable resources are required to maintain primary frequency standards as operational facilities to assure the accuracy of TAI,

recalling its Recommendation S 1 (1993) on the accuracy of primary frequency standards,

requests national metrology institutes and other laboratories developing new primary standards, to make every effort to provide the human and other resources necessary to maintain as operational facilities these new standards upon which the accuracy of TAI and UTC is based.

Black-body frequency shift

RECOMMENDATION S 2 (1996)

The Comité Consultatif pour la Définition de la Seconde,

considering

— that the relative uncertainty of some primary frequency standards is now below 5×10^{-15} and that even smaller uncertainties are expected in the near future,

— that the relative frequency shift due to black-body radiation may be as large as $-1{,}7 \times 10^{-14}$ at 300 K,

— that there is a growing need for more accurate comparisons of the frequencies of primary standards,

— that, even though no measurement has yet been made of the caesium black-body radiation frequency shift, there is consistency between the theoretical understanding and experimental verification of AC Stark shift measurements in other systems,

— that there is a need for uniformity in reporting the frequency and the corresponding uncertainty of primary standards, and

— that there is a need for improved accuracy in TAI,

recommends that a correction for black-body radiation be applied to all primary frequency standards.

Correlations among clocks contributing to TAI

Recommendation S 3 (1996)

The Comité Consultatif pour la Définition de la Seconde,

considering

— that there have been reports of correlations among clocks operating at a given site,

— that the basis upon which TAI is calculated assumes that such correlations do not exist,

— that correlated behaviour of clocks contributing to TAI can lead to a degradation of TAI,

— that there is insufficient evidence to warrant taking any specific action at this time,

requests

— that laboratories contributing to TAI perform clock-data studies as well as experiments aimed at developing a better understanding of correlations among clocks and quantifying these effects, and

— that the results of such work be shared with all laboratories contributing to TAI and be sent to the Bureau International des Poids et Mesures.

Coordination of satellite systems providing timing

Recommendation S 4 (1996)*

The Comité Consultatif pour la Définition de la Seconde,

considering

— the international value of having both Global Positioning System (GPS) and Global Navigation Satellite System (GLONASS) operational with a composite contribution of 48 satellites,

— the desirability of using either or both systems interchangeably,

— that currently significant time differences exist between the two systems,

— that significant differences exist in the coordinate reference frames used for each,

— that other important satellite timing systems are now being designed and developed,

recommends

— that the reference times (modulo 1 second) of satellite navigation systems with global coverage** be synchronized as closely as possible to UTC,

— that the reference frames for these systems be transformed to be in conformity with the terrestrial reference frame maintained by the International Earth Rotation Service (ITRF),

— that both GPS and GLONASS receivers be used at timing centres.

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* This Recommendation was adopted by the CIPM as Recommendation 1 (CI-1996) at its 85th meeting in September 1996.

** Such as Global Positioning System (GPS), Global Navigation Satellite System (GLONASS), International Maritime Satellite Organization (INMARSAT), Global Navigation Satellite System 1 (GNSS1), Global Navigation Satellite System 2 (GNSS2).

APPENDIX S 1

Working documents
submitted to the CCDS at its 13th meeting

(*see* the list of documents on page S 35)

ANNEXE S 1

Documents de travail présentés à la 13^{e} session du CCDS

Ces documents de travail peuvent être obtenus dans leur langue originale sur demande adressée au BIPM.

Document CCDS/	
96-1	BIPM. — Report on the discussions and decisions of the meeting of the CCDS Working Group on TAI (13 and 14 March 1995), by G. Petit, 10 p.
96-2	PTB (Allemagne). — Report on Activities to the 13th session of the Comité Consultatif pour la Définition de la Seconde, 4 p.
96-3	B. Guinot. — Report of the Working Group on the Application of General Relativity to Metrology to the Comité Consultatif pour la Définition de la Seconde, 58 p.
96-4	KRISS (Rép. de Corée). — Report to the 13th Session of CCDS, 9 p.
96-5	Report of the CCDS Group on GPS Time Transfer Standards (CGGTTS), by D.W. Allan and C. Thomas, 4 p.
96-6	Report of the CCDS Working Group on Two Way Satellite Time Transfer, by W.J. Klepczynski, 2 p.
96-7	OFMET (Suisse), Observatoire de Neuchâtel (Suisse). — Report to the 13th session of the Comité consultatif pour la définition de la seconde, by L. Prost and P. Thomann, 6 p.
96-8	BIPM. — Timing of millisecond pulsars, by G. Petit, 2 p.
96-9	BIPM. — Realization of Terrestrial Time and definition of TAI, by G. Petit and P. Wolf, 1 p.
96-10	NMi-VSL (Pays-Bas). — Contribution of the NMi Van Swinden Laboratorium 1993-1996, by G. de Jong, 2 p.
96-11	BIPM. — Report of the BIPM Time Section 1993-1995, by C. Thomas, 14 p.

Document CCDS/

96-12 IEN (Italie). — Report to the 13th Session of CCDS, 7 p.

96-13 TUG (Autriche). — Report to the 13th Meeting of the CCDS, by D. Kirchner, 6 p.

96-14 NPL (Royaume-Uni) . — Report of Activities to the 13th Session of the Comité Consultatif pour la Définition de la Seconde, 8 p.

96-15 NIST (É.-U. d'Amérique). — Report on Activities of the National Institute of Standards and Technology, 6 p.

96-16 BNM-LPTF (France), LHA (France). — Contribution to the 13th CCDS, by M. Granveaud and C. Audoin, 19 p.

96-17 ORB (Belgique). — Generation of the reference time scale UTC(ORB), by F. Collin and P. Defraigne, 3 p.

96-18 CSIRO-NML (Australie). — Report to the 13th session of CCDS, by P. Fisk, 5 p.

96-19 PTB (Allemagne). — The PTB primary clock CS3 : type B evaluation of its standard uncertainty, by A. Bauch, T. Heindorff, R. Schröder and B. Fischer, *Metrologia*, 1996, **33**, 249-259.

96-20 CRL (Japon). — Research Activities on Time and Frequency at Communications Research Laboratory, 3 p.

96-21 NRC (Canada). — Report from the National Research Council of Canada to the 13th Session of the CCDS, 6 p.

96-22 A. De Marchi. — Contribution to the 13th CCDS, 3 p.

96-23 D. W. Allan. — Proposal for a recommendation on new real-time UTC, 11 p.

96-24 NRLM (Japon). — Report to the 13th Session of CCDS, 2 p.

96-25 LHA (France). — About the blackbody radiation frequency shifts, by C. Audoin, 7 p.

TABLE DES MATIÈRES

TABLE OF CONTENTS

COMITÉ CONSULTATIF POUR LA DÉFINITION DE LA SECONDE

13^{e} session (1996)
13th Meeting (1996)

Pages

Liste des sigles utilisés dans le présent volume V

List of acronyms used in the present volume V

Le BIPM et la Convention du Mètre IX

Liste des membres du Comité consultatif pour la définition de la seconde XI

Ordre du jour XIV

Rapport au Comité international des poids et mesures, par P. Fisk .... S 1

1. Ouverture de la session ; nomination d'un rapporteur........ S 2

2. Progrès faits sur les étalons de fréquence et les horloges atomiques .... S 3

   2.1 Rapports des laboratoires .... S 3

   2.2 Incertitudes des étalons primaires de fréquence .... S 11

   2.3 Déplacement dû au rayonnement du corps noir dans les étalons primaires de fréquence........ S 12

3. Rapport du Groupe de travail du CCDS sur le TAI .... S 13

4. Rapport de la Section du temps du BIPM .... S 16

5. Synchronisation des horloges au moyen de satellites .... S 19

6. Étude des pulsars-milliseconde........ S 20

7. Rapport du Sous-groupe de travail du CCDS sur la normalisation des comparaisons d'horloges utilisant le GPS .... S 21

8. Rapport du Groupe de travail du CCDS sur les comparaisons d'horloges par aller et retour sur satellite ..... S 23

9. Rapport du Groupe de travail du CCDS sur l'application de la relativité générale à la métrologie ..... S 25

10. Groupe de travail du CIPM sur l'équivalence des étalons nationaux ..... S 27

11. Comptes rendus d'autres réunions ..... S 27

11.1 Union astronomique internationale : 22e Assemblée générale ..... S 27

11.2 Union géodésique et géophysique internationale : 21e Assemblée générale ... S 28

11.3 Union radio-scientifique internationale : 24e Assemblée générale ..... S 28

11.4 Groupe d'étude n° 7 du Bureau des radiocommunications de l'Union internationale des télécommunications..... S 28

12. Questions diverses ..... S 29

13. Recommandations ..... S 29

14. Clôture de la session ..... S 30

Recommandations présentées au Comité international des poids et mesures

S 1 (1996) : Étalons primaires de fréquence ..... S 31

S 2 (1996) : Déplacement de fréquence dû au rayonnement du corps noir ..... S 32

S 3 (1996) : Corrélations entre les horloges qui contribuent au TAI ..... S 33

S 4 (1996) : Coordination des systèmes satellitaires qui diffusent le temps ..... S 34

Annexe

S 1. Documents de travail présentés à la 13e session du CCDS ..... S 35

English text of the report

Note on the use of the English text. Note sur l'utilisation du texte anglais ..... S 39

The BIPM and the Convention du Mètre ..... S 41

Members of the Comité Consultatif pour la Définition de la Seconde ..... S 43

Agenda ..... S 46

Report to the Comité International des Poids et Mesures, by P. Fisk ..... S 47

1. Opening of the meeting; appointment of a rapporteur ..... S 48

2. Progress in atomic frequency standards and clocks ..... S 49

2.1 Reports from laboratories ..... S 49

2.2 Uncertainties in primary frequency standards ..... S 56

2.3 Black-body radiation shift in primary frequency standards ..... S 57

3. Report of the CCDS working group on TAI ..... S 58

4. Report of the BIPM Time section ..... S 61

5. Synchronization of clocks using satellites ..... S 63

6. Timing of millisecond pulsars ..... S 65

7. Report of the Sub-group of the CCDS working group on TAI on GPS time transfer standards ..... S 65

8. Report of the CCDS working group on two-way satellite time transfer ..... S 67

9. Report of the CCDS working group on the application of general relativity to metrology ..... S 68

10. CIPM working group on the equivalence of national standards ..... S 70

11. Reports on other meetings ..... S 70

11.1 International Astronomical Union: 22nd General Assembly ..... S 70

11.2 International Union of Geodesy and Geophysics: 21st General Assembly ..... S 71

11.3 International Union of Radio Science: 24th General Assembly ..... S 71

11.4 Study Group 7 of the Radiocommunication Bureau of the International Telecommunication Union ..... S 71

12. Other business ..... S 72

13. Recommendations ..... S 72

14. Closure of the meeting ..... S 73

Recommendations submitted to the Comité International des Poids et Mesures

S 1 (1996): Primary frequency standards ..... S 74

S 2 (1996): Black-body frequency shift ..... S 75

S 3 (1996): Correlations among clocks contributing to TAI ..... S 76

S 4 (1996): Coordination of satellite systems providing timing ..... S 77

Appendix

S 1. Working documents submitted to the CCDS at its 13th meeting (*see* page S 35) ..... S 78

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