Bureau International des Poids et Mesures

Consultative Committee for Time and Frequency (CCTF)

Report of the 20th meeting
(17-18 September 2015)
to the International Committee for Weights and Measures

Comité international des poids et mesures

Note:

Following a decision made by the International Committee for Weights and Measures at its 92nd meeting in October 2003, Reports of meetings of Consultative Committees will henceforth be published only on the BIPM website in the form presented here.

Full bilingual printed versions in French and English will no longer appear.

M. Milton
Director BIPM

LIST OF MEMBERS OF THE CONSULTATIVE COMMITTEE FOR TIME AND FREQUENCY

as of 17 September 2015

President

L. Erard, Member of the International Committee for Weights and Measures [CIPM], Scientific advisor at the Laboratoire national de métrologie et d'essais, Paris [LNE].

Executive Secretary

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

Members

Centro Nacional de Metrología [CENAM], Mexico

Federal Office of Metrology [METAS], Wabern

Institute for Physical-Technical and Radiotechnical Measurements, Rostekhregulirovaniye of Russia [VNIIFTRI], Moscow

International Astronomical Union [IAU]

International GNSS Service [IGS]

International Telecommunication Union, Radiocommunication Bureau [ITU-R]

International Union of Geodesy and Geophysics [IUGG]

International Union of Radio Science [URSI]

Istituto Nazionale di Ricerca Metrologica [INRIM], Turin

Korea Research Institute of Standards and Science [KRISS], Daejeon

Laboratoire national de métrologie et d'essais, Observatoire de Paris, Systèmes de Référence Temps-Espace [LNE-SYRTE], Paris

National Institute of Information and Communications Technology [NICT], Tokyo

National Institute of Metrology [NIM], Beijing

National Institute of Standards and Technology [NIST], Boulder

National Measurement Institute of Australia [NMIA], Lindfield

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

National Metrology Institute of South Africa [NMISA], Pretoria

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 – Measurement Science and Standards Portfolio [NRC], Ottawa

Observatoire Royal de Belgique [ORB], Brussels

Physikalisch-Technische Bundesanstalt [PTB], Braunschweig

Real Instituto y Observatorio de la Armada [ROA], Cadiz

SP Sveriges Tekniska Forskningsinstitut [SP], Borås

Space Research Centre of Polish Academy of Sciences [SRC], Warsaw

Technical University of Graz [TUG], Graz

U.S. Naval Observatory [USNO], Washington

VSL [VSL], Delft

The Director of the International Bureau of Weights and Measures [BIPM], Sèvres.

Observers

Agency for Science, Technology and Research [A*STAR], Singapore

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

Observatório Nacional/Divisão Serviço da Hora [ON/DSHO], Rio de Janeiro

GLOSSARY

ACES	Atomic Clock Ensemble in Space
BIPM	Bureau International des Poids et Mesures
CCL	Consultative Committee for Length
CCTF	Consultative Committee for Time and Frequency
CCU	Consultative Committee for Units
CGPM	Conférence Générale des Poids et Mesures
CIPM	Comité International des Poids et Mesures
CMC	Calibration and Measurement Capability
DI	Designated Institute
EMRP	European Metrology Research Programme
EOP	Earth Orientation Parameters
ESA	European Space Agency
ESMA	European Securities and Markets Authority
FS	Frequency Standard
GNSS	Global Navigation Satellite System
IAG	International Association of Geodesy
IAU	International Astronomical Union
ICRF	International Celestial Reference Frame
ICRS	International Celestial Reference System
IERS	International Earth Rotation and Reference Systems Service
ITOC	International Time Scales with Optical Clocks
ITRF	International Terrestrial Reference Frame
ITRS	International Terrestrial Reference System
ITU	International Telecommunication Union
JCRB	Joint Committee of the Regional Metrology Organizations and the BIPM
KCDB	BIPM key comparison database
LoR	List of Radiations
MiFID II	Markets in Financial Instruments Directive II
NMI	National Metrology Institute
PFS	Primary Frequency Standard
PoW	Programme of Work
RMO	Regional Metrology Organization
SFS	Secondary Frequency Standard
SRS	Secondary Realization of the Second
TF	Time and Frequency
URSI	Union Radio Scientifique Internationale
WG-ALGO	CCTF Working Group on Time Scale Algorithms
WGFS	CCL-CCTF Frequency Standards Working Group
WGGNSS	CCTF Working Group on GNSS Time Transfer
WGPSFS	CCTF Working Group on Primary and Secondary Frequency Standards
WGTAI	CCTF Working Group on International Atomic Time
WGTWSTFT	CCTF Working Group on Two-Way Satellite Time and Frequency Transfer
WGSP	CCTF Working Group on Strategic Planning

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

The Consultative Committee for Time and Frequency (CCTF) held its 20th meeting at the International Bureau of Weights and Measures (BIPM) headquarters, at Sèvres on 17 and 18 September 2015.

The following were present:

J. Achkar (LNE-SYRTE), A. Bauch (PTB), R. Beard (ITU-R), J. Bernard (NRC), L.-G. Bernier (METAS), R. Biancale (IUGG), S. Bize (LNE-SYRTE), C. Boucher (IUGG), M. Coleman (IGS), J. Davis (NPL), P. Defraigne (ORB), E. Dierikx (VSL), Y. Domnin (VNIIFTRI), L. Erard (CIPM), H. Esteban (ROA), Z. Fang (NIM), F.J. Galindo Mendoza (ROA), M. Gertsvolf (NRC), P. Gill (NPL), Y. Hanado (NICT), W. Hanson (NIST), M.S. Heo (KRISS), F.-L. Hong (NMIJ/AIST), K. Hosaka (NMIJ/AIST), M. Hosokawa (NICT), T. Ido (NICT), K. Jaldehag (SP), S. Jefferts (NIST), N. Koshelyaevsky (VNIIFTRI), A. Landragin (LNE-SYRTE), F. Levi (INRIM), J. Levine (NIST), T. Li (NIM), L. Lobo (NPL), J. Lodewyck (LNE-SYRTE), J.M. Lopez Romero (CENAM), D.N. Matsakis (USNO), C. Matthee (NMISA), M. Milton (Director of the BIPM), J. Nawrocki (SRC), C. Oates (NIST), D. Piester (PTB), F. Riehle (PTB), S. Romisch (NIST), W. Walls (USNO), M. Wouters (NMIA), D.H. Yu (KRISS), A. Zhang (NIM).

Observers:

R. De Carvalho (ON/DSHO), A. Gedik (UME), R. Hamid (UME), H. Santos (ON/DSHO).

Guests: K.S. Al-Dawood (SASO), C. Bizouard (IERS), A. Czubla (GUM), C.-S. Liao (TL), H.T. Lin (TL)

Also present: E.F. Arias (Executive Secretary of the CCTF), A. Harmegnies, Z. Jiang, H. Konaté, G. Panfilo, G. Petit, S. Picard (Coordinator of the KCDB), L. Robertsson, L. Tisserand.

Mr Erard, CCTF President, opened the meeting at 9:00h.

Dr Milton, the Director of the BIPM, welcomed the participants. He mentioned that discussions had been held in the CGPM meeting (November 2014) on preparing a new strategy. A proposal has been made for a new strategic direction including a capacity building and knowledge transfer programme at the BIPM. This programme will require an increased level of involvement by the NMIs.

Dr Milton reported that Dr Barry Inglis had been re-elected as President of the CIPM. The CIPM is also working on a new strategy that will address the relationship between the CIPM and RMOs, and the interaction with the world of standardization.

Dr Milton recalled the successful World Metrology Day 2015, which focused on “Measurements and Light”. The theme for World Metrology Day 2016 will be “Measurements in a Dynamic World”.

The Chairman noted that the minutes of the 19th meeting of the CCTF had been commented and the final version published on the BIPM website.

The participants introduced themselves by name and affiliation.

Appointment of a rapporteur:

Mr Dierikx agreed to prepare the minutes of the meeting. There were no objections from the other participants.

Adoption of the agenda:

Dr Arias suggested that when the chairpersons of the working groups (WGs) present their reports, they should also present the draft recommendations proposed by their respective working group, and that the delegate from the VNIIFTRI should introduce its proposed recommendation when presenting the laboratory report. This will allow sufficient time to discuss and finalize the text of the recommendations before the end of the meeting.

The agenda was approved.

2 REVIEW OF ACTIONS SINCE THE LAST CCTF MEETING

In the previous meeting of the CCTF, there had been insufficient time to go through all the action points. The President of the CCTF asked the WG chairpersons to report on the actions taken by each WG.

3 PROGRESS IN FREQUENCY STANDARDS

3.1 Operating primary and secondary frequency standards and new standards under development (Delegates)

It was noted that detailed reports from laboratories had been submitted before the meeting and are available on the BIPM website. Participants were invited to give a short presentation on their work on frequency standards.

LNE-SYRTE (CCTF/15-22): Dr Bize reported that LNE-SYRTE is operating three primary cold caesium clocks that regularly contribute to TAI. Caesium fountain FO1 has been contributing to TAI since 1995, FOM is a transportable caesium fountain that has contributed since 2002 and FO2 is a double fountain operating with caesium, which has contributed to TAI since 2002, and with rubidium, reported in BIPM *Circular T* since 2012. The rubidium fountain has contributed to the steering of TAI since July 2013.

In October 2012, a new method was implemented for the realization of the French time scale UTC(OP). UTC(OP) is realized using a microphase stepper fed by the reference maser. The correction of the microphase stepper is determined from two terms, the main one corresponding to the current frequency of the maser as measured by the atomic fountains, the other term is a fine steering to maintain UTC(OP) close to UTC.

LNE-SYRTE has been leading the development of a cold atom primary standard for use in space, called PHARAO. The development of this programme is managed by the French space agency CNES. The PHARAO clock is a major component of the payload of the Atomic Clock Ensemble in Space (ACES) mission of the European Space Agency (ESA). The PHARAO flight model was delivered in July 2014.

LNE-SYRTE is developing two optical lattice clocks based on strontium and one optical lattice clock based on mercury. A short report was given on the progress on these optical clocks since the previous meeting of the CCTF.

VNIIFTRI (CCTF/15-03): Dr Koshelyaevsky reported that VNIIFTRI currently has two caesium fountains. SU-CsF02 has been operational since 2014. SU-CsF01 is being updated to achieve a better stability. VNIIFTRI is also working on the development of a rubidium fountain. A first prototype is nearly finished.

The development of an optical frequency standard based on cold atoms of ^{87}Sr has started. First experiments of the laser cooling have been successful.

Dr Koshelyaevsky presented the draft recommendation (CCTF/15-04) on “real time realizations of UTC(k) disseminated by global navigation satellite systems (GNSS)”.

It is recommended that Section 5 of BIPM *Circular T* “Relations of UTC and TAI with UTC(k) disseminated by GNSS and their System Times” continues to include information on the relationship of UTC with the predictions of UTC(k) disseminated by existing operational GNSS and will include such information on BEIDOU and GALILEO as soon as the systems become operational.

Dr Arias noted that this recommendation had been discussed in the WGTAI meeting. In general, there was an agreement on this recommendation, although it requires some small modifications. The modifications will be discussed under point 13 of the agenda.

CENAM (CCTF/15-15): Dr Lopez Romero mentioned that Ramsey fringes in the caesium fountain at CENAM had been reported to the previous meeting of the CCTF. However, since then, little progress has been made due to delays.

INRIM (CCTF/15-05): Dr Levi reported that since the previous meeting of the CCTF, the caesium fountain ‘IT CsF2’ has contributed several times to the computation of TAI. IT CsF2 has been compared against NIST CsF1 and CsF2 by means of TWSTFT.

IT CsF2 is now used for steering UTC(IT) and its reference frequency is also disseminated by optical fibre to the INAF radio-telescope near Bologna and to the Laboratoire Souterrain de Modane (LSM).

INRIM is developing an optical frequency standard based on ^{171}Yb atoms confined in an optical lattice. A first comparison of this optical clock against IT CsF2 has started.

INRIM has been heavily involved in the development of the European Global Navigation Satellite System, Galileo, in collaboration with other NMIs and industrial companies. Activities included: participation in the definition, realization, and validation of the Galileo timing system, and development and testing of timing services based on the Galileo signals (DEMETRA project).

NMIJ (CCTF/15-24): Dr Hosaka reported that the caesium fountain NMIJ-F2 is under construction. The operation of NMIJ-F1 stopped as a result of damage from the earthquake in 2011.

After the first ytterbium-based optical lattice clock, NMIJ has developed a second optical lattice clock. This system can be used as a strontium and ytterbium optical lattice clock.

NICT (CCTF/15-13): Dr Ido reported that NICT has two caesium fountain primary frequency standards. NICT-CsF1 has been in operation since 2006 and is currently being upgraded to achieve both high frequency stability and accuracy. NICT-CsF2 has a different laser cooling geometry than NICT-CsF1. After a vacuum problem in NICT-CsF2, the system was reconstructed. Re-evaluations of the frequency shift are ongoing.

At NICT, an ^{87}Sr optical lattice clock has been in operation since 2011. Recently, this clock has been compared with the ^{87}Sr lattice clock at PTB by means of a two-way satellite link. Good agreement between the clocks was found.

NICT has also been working on a $^{40}Ca^+$ single-ion optical clock. This project is suspended. Currently, a single-ion clock based on $^{115}In^+$ is being developed.

Furthermore, NICT is working on development of a THz frequency standard in the range 0.1 THz to 0.65 THz (this is not an atomic frequency standard).

NIM (CCTF/15-07): Dr Fang reported that the caesium fountain primary frequency standard NIM5 has been improved over the last three years, mainly with respect to microwave-related frequency shifts. From 2014, results from NIM5 have been reported to BIPM for the computation of TAI.

A new Cs fountain NIM6 is under development. It is expected to be completed in three to five years.

NIM has built an ^{87}Sr optical lattice clock. Evaluations of the frequency of this clock with respect to the caesium fountain NIM5 are in progress.

PTB (CCTF/15-10): Dr Bauch reported that PTB is currently operating four primary caesium standards. Two of these are the caesium thermal beam standards CS1 and CS2 which still perform better than the commercial caesium beam clock. The other two are the caesium fountains CSF1 and CSF2. Over the past three years, these caesium fountains have been operating nearly continuously, contributing to realization of UTC(PTB) and the computation of TAI.

PTB operates four optical frequency standards. One is an optical lattice clock based on ^{87}Sr atoms. Two standards are based on a single $^{171}Yb^+$ ion (one at 688 THz and the other at 642 THz). Research is being conducted towards a frequency standard based on a $^{27}Al^+$ with a Ca^+ logic ion.

NPL (CCTF/15-16): Dr Gill reported that NPL operates three microwave frequency standards based on cold atom fountain technology; two use caesium and one uses rubidium.

NPL-CsF2 has been operational since 2009 and contributes regularly to the BIPM steering process of TAI.

NPL-CsF3 became operational in 2014, and a full evaluation of its accuracy is currently underway.

Between 2009 and 2013, three measurement campaigns were performed with the rubidium fountain. The value of the ^{87}Rb clock transition obtained with NPL-CsF2 was in good agreement with earlier measurements by LNE-SYRTE. Regular operation of the NPL Rb fountain has currently been suspended.

$^{171}Yb^+$ has two optical clock transitions that are being studied at NPL (E3 at 467 nm and E2 at 436 nm). Changes to the hardware and software controlling the experiment have enabled both the E3 and E2 transitions to be probed at the same time, in an interleaved manner, in a single ion of $^{171}Yb^+$. This allowed the direct optical ratio to be measured.

NPL has developed two Sr^+ endcap trap systems. One of these traps has been used to measure the frequency of the $^{88}Sr^+$ 674 nm clock transition referenced to NPL-CsF2.

A Sr optical lattice clock is now in operation at NPL, known as NPL-Sr1.

Over the past two years, NPL's optical clocks have been compared against optical clocks in other laboratories using GPSPPP, broadband TWSTFT and optical fibre transfer techniques.

KRISS (CCTF/15-29): Dr Yu reported that at KRISS, a Cs/Rb double fountain, KRISS-F1, has been under development since 2010. For the moment it is only operational as a caesium fountain clock.

A ^{171}Yb optical lattice clock is under development and the evaluation of its uncertainty is ongoing.

NIST: Dr Oates reported that a new Rb fountain has become operational at the NIST.

Development of optical lattice clocks is ongoing and progress has been made on making the operation of frequency combs more reliable.

3.2 Report of the CCTF Working Group on Primary and Secondary Frequency Standards (S. Jefferts, NIST) (CCTF/15-12) and (CCTF/15-34)

Since the previous meeting of the CCTF, five new laser cooled caesium primary frequency standards (PFS) have been recommended for acceptance into TAI: from NPLI (India), NIM (China), VNIIFTRI (Russia), INRIM (Italy) and NIST (USA).

This currently gives 17 PFS reporting to TAI. Generally, there are more than five PFS available in any month. The fountains are in good agreement within the estimated uncertainties.

This working group had no recommendations.

Dr Matsakis asked how many more PFS are expected to start reporting to TAI in the next three years. About a dozen new PFS are anticipated.

Dr Bauch asked how the weighted mean of PFS is determined. The weights are based on the claimed uncertainties.

Mr Erard asked if the five PFS that are now typically contributing per month is enough. It was confirmed that five contributions are fine, but it was acknowledged that it would be better to have more PFS contributing.

3.3 Report of the CCL-CCTF Frequency Standards Working Group (WGFS) (F. Riehle, PTB and P. Gill, NPL) (CCTF/15-35)

Following the previous CCTF meeting of 2012, the WGFS met in 2013 in Prague, in 2014 in Neuchâtel and just before this meeting at the BIPM.

Absolute frequency measurements of secondary representations of the second (SRS) are limited by the Cs realizations. The availability of direct optical frequency ratio measurements with low uncertainties is increasing. For example successful comparisons of optical clocks have been demonstrated in the EMRP project 'International Timescales with Optical Clocks (ITOC)'.

Currently, five direct optical frequency ratio measurements have been realized: ^{171}Yb to ^{87}Sr, ^{199}Hg to ^{87}Sr, ^{40}Ca^{+} to ^{87}Sr, ^{171}Yb^{+} E2 to ^{171}Yb^{+} E3 and ^{199}Hg^{+} to ^{27}Al^{+}.

With the over-determined set of clock comparison data, frequency ratios can be determined in different ways. As such, a matrix of frequency ratios can be built to evaluate the level of consistency and to derive optical values for the frequency ratios. Software has been developed to analyze and evaluate the data. In this analysis, correlations have been neglected so far, but it is recognized that these need to be taken into account.

No new entries are proposed in the list of radiations (LoR), but frequency values and uncertainties of SRS have been updated for: ^{87}Sr, ^{199}Hg, ^{1}H, ^{171}Yb,^{171}Yb^{+} E2, ^{171}Yb^{+} E3, ^{88}Sr^{+}, ^{40}Ca^{+}and ^{87}Rb (see recommendation CCL-CCTF 1(2015)).
There have been three requests for additions to the LoR from the CCL:

- NPL requests the addition of hydrogen cyanide $H_{13}C_{14}N$ transitions (around 1530 nm to 1565 nm).
- NMIJ requests the addition of ^{87}Rb at 384THz (780 nm)
- NMIJ requests the addition of $^{127}I_2$ at 531 nm.

The WGFS has set up a study group comprising: P. Gill, F. Riehle, F.-L. Hong, and K. Hosaka to evaluate these requests.

As a next step, the WGFS has asked the CCTF to approve the update frequencies and uncertainties for the LoR and to provide these in a recommendation of the CCTF to the CIPM.

The WGFS will pass this recommendation to the CCL for approving the updated frequencies and uncertainties for the LoR, and will ask to support this recommendation to the CIPM. The CCL meeting will be held in the week following the CCTF meeting.

Dr Oates noted that NIST will develop its own software for analysis of frequency ratios. In this way, there will be an independent check.

3.4 Frequency standards in TAI and realization of TT(BIPM) (G.Petit, G. Panfilo, BIPM) (CCTF/15-36)

TAI is computed in “real time” and never corrected in retrospect, because this is not optimal. Therefore the BIPM computes a post-processed time scale TT(BIPM).

The computation of TT(BIPM) is based on estimates of f(EAL) using the available PFS. These estimates are smoothed and integrated each month. Since the previous meeting of the CCTF in 2012, there have been no significant changes to the computation of TT(BIPM). From 2010, the BIPM has started publishing predictions of TT(BIPM), first as monthly extensions, and since TT(BIPM13) as a function of TAI valid for the whole year. For example, for 2015:

$$\mathrm{TT(BIPM14)_{ext}} = \mathrm{TAI} + 32.184\ \mathrm{s} + 27697.0\ \mathrm{ns}$$

With the introduction primary frequency standards (Cs fountains) the uncertainty of the frequency of TT(BIPM) has steadily decreased, and is currently at the level of approximately 2×10^{-16}.

TT(BIPM) allows evaluation of the performance of primary and secondary frequency standards. A total of 1228 evaluations have been made over 22 years, showing that most standards do not have a systematic frequency offset.

TT(BIPM) also allows estimation of the accuracy of TAI. An overview was given of the difference between f(TAI) and f(TT(BIPM14)) from 2000 to 2015. Over the last two years, the difference was less than 1×10^{-15}.

Contributions of frequency standards are published in BIPM *Circular T*. Since July 2013, secondary representations of the second (SRS) also contribute to the steering of TAI. SRS are reported together with PFS. In 2014, there have been 68 contributions from ten PFS and ten contributions from one SRS. Four Cs fountains are operating almost continuously.

Knowing that for some SRS, the systematic effects can be estimated with an uncertainty much lower than for the best PFS, the BIPM is expecting to receive more contributions from SRS in the near future.

4 PRESENT STATUS OF TAI

4.1 Report of the CCTF Working Group on TAI (L. Erard) (CCTF/15-37)

Mr Erard has accepted the role of interim chairman of the WGTAI. The membership of WGTAI includes: laboratories participating to TAI, the Director of the BIPM, the Director of the BIPM Time Department and representatives of IAU, CIPM, URSI and ITU-R.

The WGTAI held a meeting on the 16 September 2015, the day before this CCTF meeting. The meeting was attended by more than 50 participants.

Topics discussed in the meeting were:

- A report of BIPM Time Department
- Calibration of time transfer for UTC (GNSS and TWSTFT calibrations)
- Activities at laboratories and new participants in preparation
- Revision of definition of UTC at ITU-R
- Recommendations proposed to the CCTF.

Furthermore, there has been a discussion on the format of the WGTAI. Some members think that, considering the number of participants, this group is no longer a real working group. It has therefore been suggested to change the format of this group to a forum. Opinions on this proposal differ and it has therefore been decided to discuss this further in the Working Group on Strategic Planning (WGSP).

4.2 Report of the BIPM Time Department (F. Arias, BIPM) (CCTF/15-38)

The permanent staff of the BIPM Time Department over the last three years consisted of nine persons. Włodek Lewandowski retired in 2014 and there have been four guest researchers, for visits of up to one year.

An overview was given of investments in equipment made by the BIPM Time Department over the last three years. The investments included a GNSS receiver, a Cs clock, time interval counters and computers.

Achievements over the past three years include:

- A new algorithm for the computation of TAI has been introduced. A new model of clock weighting was implemented in January 2014. In this model, it is not the stability, but the predictability of the clock that determines its weight in the EAL. Besides, the maximum weight of the clocks has been adjusted. Now, more H-masers and less Cs-clocks are at the maximum weight. This has improved the stability of EAL and TAI.

- Rapid UTC (UTCr) has been implemented since July 2013. Currently, 42 laboratories contribute to UTCr. This represents approximately 70 % of the clocks that contribute to UTC. UTCr is steered to UTC once per month after the publication of BIPM *Circular T*. In some cases, significant differences are observed between UTC and UTCr. Therefore, an improvement of the steering of UTCr is still required.
- The METODE technique (MEasurement of TOtal DElay) for calibration of time links with a set of portable GNSS receivers has been validated by comparing this technique with respect to time transfer through an optical fibre. The validation was performed in Poland between the UTC laboratories of GUM and AOS. The two laboratories are connected by a 420 km fibre link on which a self-calibrating two-way optical time and frequency transfer (TWOTFT) technique has been implemented. This fibre link was compared against the GPS-based link. The results from the GPS link had been analyzed by NRCan PPP and IPPP. IPPP is an improved version of precise point positioning capable of solving integer cycle slips of received GPS signals at day boundaries. There is a good agreement between the fibre and GPS-based techniques. The systematic uncertainties are estimated to be less than 2 ns.
- The BIPM has actively contributed to the realization of calibration guidelines for GNSS equipment calibrations, GNSS link calibrations and TWSTFT link calibrations. These guidelines have been approved by the respective working groups.
- The BIPM has established cooperation with the RMOs on the sharing of work with respect to the characterization of delays in GNSS time transfer equipment. Within each RMO, a limited number of laboratories have been selected for calibration by the BIPM. These are referred to as “Group 1” laboratories (G1). The RMOs will organize calibrations for the remaining laboratories, referred to as “Group 2” laboratories (G2). It is expected that with repeated calibrations the systematic uncertainties for GNSS-based links can be reduced to less than 2.5 ns (k = 1).
- The BIPM has actively contributed to the discussion of a possible redefinition of UTC by participating in meetings of the working group of the ITU-R with this responsibility. On 19-20 September 2013, a joint ITU/BIPM workshop was organized in Geneva on “the future of the international time scale”. These activities have resulted in information and insights to support the discussion of this topic at the next World Radiocommunication Conference in November 2015 (WRC-15).

The publication of the results of key comparison CCTF-K001.UTC in the BIPM key comparison database (KCDB) has been revised after the discussions in the 19th meeting of the CCTF. From 2015, monthly publication of the results has restarted. This monthly publication is an extract from BIPM *Circular T*, which contains only the results from National Metrology Institute (NMI) signatories of the CIPM Mutual Recognition Arrangement (CIPM MRA) and designated institutes (DIs).

Publications from the BIPM over the past three years include: BIPM *Annual Report on Time Activities* 2012, 2013, 2014; monthly BIPM *Circular T*; weekly UTCr; annually TT(BIPMXY); and about 50 scientific publications from the Time Department staff. These publications can be found on the BIPM website or on the FTP server.

Dr Achkar expressed appreciation on behalf of LNE-SYRTE for the revision of the publication of CCTF-K001.UTC in the KCDB in its current format.

Related to the redefinition of UTC, Dr Achkar asked if there is a formal definition of TAI. According to Dr Arias, there is no formal definition of TAI in the form of a CGPM resolution. It is recorded as an action point that the definition of TAI and relationship to UTC shall be clarified, as well as the role of the BIPM in their definition and realization.

5 LATEST AND FUTURE DEVELOPMENTS IN TIME SCALE ALGORITHMS AND TIME SCALES

5.1 Report of the CCTF WG on Time Scale Algorithms (WG-ALGO), (Y. Hanado, NICT) (CCTF/15-14)

The WG-ALGO was established in September 2012. Based on the terms of reference of this WG, a brief overview was presented of the aims of the working group and the rules for its membership. Currently, the WG has 18 members.

Over the past three years, the WG has supported the work on the new algorithm for the computation of TAI. The algorithm for weighting of the clocks was updated following approval by the WG-ALGO.

The WG-ALGO has organized the 6th Timescales algorithms symposium on 9-11 September 2015. There was one day of tutorials and two days of symposia. The presentations of both the tutorials and the symposium have been made available on the BIPM website. The symposium was attended by about 70 persons from 30 different countries. The organizers are grateful to NICT and ONRG (Office of Naval Research, Global) for their financial support.

The organizers are discussing the possibility of publishing a selection of papers from the symposium in a special issue of a scientific journal.

Dr Matsakis remarked that scientific papers are often valued by the number of citations in other papers and therefore he recommended that authors should include references in their papers to work from colleagues within our community.

Dr Arias noted that the presentations (and possibly the papers) from this symposium will have a significant impact on the work in the laboratories and also from a pedagogic point of view. The presentations gave a good overview of the actual status of timescale algorithms that are currently used in laboratories and can serve as a reference for laboratories that are working on development or improvement of their algorithms.

For future activities of the WG-ALGO, it is anticipated that the working group can contribute to the generalization of uncertainty computations to accommodate complementary time transfer techniques in the computation of TAI.

5.2 Improvements in the algorithms for TAI (G. Panfilo, BIPM) (CCTF/15-40)

The weighting algorithm

A revised algorithm for the computation of TAI was implemented in January 2014. This algorithm introduces a new weighting procedure for clocks. In this procedure, a “good” clock is a predictable clock. The weight of a clock is a function of its predictability. The procedure also considers the frequency drift of the clock. As such, all types of clocks are used in an optimal way. Furthermore, the maximum weight has been limited to 4/N. With this procedure, typically a hydrogen maser receives a higher weight and a caesium clock receives a lower weight than before.

As a result of this, the frequency of EAL shows almost no drift with respect to the primary and secondary frequency standards. The relative frequency instability of EAL has been estimated with respect to the USNO rubidium fountain and was found to be less than 1×10^{-15} (in terms of overlapping Allan deviation).

The uncertainty of [*UTC* - *UTC*(*k*)] (with G. Panfilo, G. Petit and A. Harmegnies, BIPM)

A revision of the uncertainty evaluation of the values of [*UTC* - *UTC*(*k*)] as reported in BIPM *Circular T* is being investigated. The current model for the computation of TAI uses PTB as a pivot for time links. Since, in this model, correlations between the links are not taken into account, the uncertainty of [*UTC* - *UTC*(*PTB*)] is underestimated.

A new formalism for the computation is proposed that will solve two problems: correlations between links will be taken into account, and available data will be used in a more optimal way.

It is proposed that for the calculation of uncertainties for TWSTFT links, PTB will still be used as a pivot, and for GNSS-based links, the GNSS timescale will serve as a pivot. Tests with existing data show that this approach results in more realistic uncertainty values for [*UTC* - *UTC*(*PTB*)].

A first application of the Kalman Filter routine to UTC (with G. Panfilo and F. Parisi, from the University of Torino)

Investigations have started on the use of Kalman Filtering in the realization of UTC. Initial studies have been performed with the Kalman filter to “clean” white phase noise from time transfer data. As such, a Kalman filter can be used as a powerful tool to combine TWSTFT and GPS data.

Furthermore, the application of a Kalman filter is being investigated for the calculation of EAL.

The first results of these studies are promising, but much work remains to be done.

5.3 Report on Rapid UTC (G. Petit, BIPM) (CCTF/15-41)

In January 2012, the BIPM started a pilot study on the realization of a more rapid solution of UTC on a weekly basis. The results of this study were successful, and a more rapid solution was found to be desirable, because the monthly solutions of UTC are not suitable for quasi real-time applications. This has resulted in a recommendation from the 19th meeting of the CCTF, for the BIPM to continue its work on the rapid UTC (UTCr) project.

As of July 2013, UTCr became an official BIPM product, following approval by the WGTAI. A description of UTCr has been published in *Metrologia*, 2014, **51**, 33.

UTCr is a weekly solution of daily clock data and time transfer data. The computation interval is 27 to 31 days. So the result is a sliding solution. The weekly publications of UTCr provide daily values of [*UTCr*-*UTC*(*k*)]. Publication occurs each Wednesday at 18:00 UTC at the latest.

Initially, the algorithm for the computation of UTCr was the same as that for UTC. However, in January 2014, a new clock weighting procedure was implemented in UTC, but this is not yet available for UTCr.

The processing of UTCr is an automated process that occurs in four steps:

1. Data checking
2. Computation of time links (TWSTFT, GPS P3 or GPS MC)
3. Stability algorithm (clock weighting)
4. Steering to UTC.

A graph of the differences between UTCr and UTC shows that the difference is within ±4 ns. To avoid significant differences, participating laboratories have been requested to check the consistency of their data reported to UTC and to UTCr.

The impact of the realization of UTCr is considered to be significant; for laboratories contributing to UTC, for users of UTC(k) and for the steering of GNSS times to UTC realizations.

Dr Matsakis asked if there are systematic differences between [*UTCr*-*UTC*(*k*)] and [*UTC* - *UTC*(*k*)] for some laboratories. This is possible, because in some links the technique of time transfer used for UTCr differs from that for UTC.

Mr Erard asked why the algorithms for UTC and UTCr are not the same. In January 2014, the procedure for weighting and prediction of the clocks was changed for UTC, but this change has not yet been implemented in UTCr.

5.4 Reports on progress on other time scales (Delegates)

Dr Bize reported that a new realization of the French time scale UTC(OP) had been implemented in October 2012. UTC(OP) is now based on a H-maser and a microphase stepper. The daily steering of the time scale is based on the atomic fountains at LNE-SYRTE (details were presented at the 6th Time Scale Algorithm Symposium).

Dr Matsakis remarked that several laboratories have made good improvements in the realization of their time scale with the implementation of fountain clocks, and wondered if this has also improved the realization of UTCr. Such a relation has not yet been investigated.

Mr Jaldehag reported that SP is evaluating a time scale algorithm based on a Kalman filter. The intention of this work is to include other clocks distributed throughout Sweden in the Swedish national time scale (details were presented at the 6th Time Scale Algorithm Symposium).

6 TIME AND FREQUENCY TRANSFER METHODS

6.1 Report of the CCTF Working Group on TWSTFT (D. Piester, PTB) (CCTF/15-42)

A short introduction was given of the TWSTFT technique and method, with an overview of the TWSTFT networks and the satellites that are currently used.

The members of the WGTWSTFT are typically experts from the participating laboratories. The secretary of the group is Dr Jiang from the BIPM. From 2009 to 2015, Dr Piester has been the chairman of this group. Dr Victor Zhang from NIST has been proposed as the new chairman to commence his appointment after this CCTF meeting. The members of the working group supported this proposal.

In the past three years, annual meetings have been held in Taiwan (2013), Russia (2014) and at the BIPM (2015). Several meetings of the participating stations have also been held at EFTF and PTTI conferences.

A number of important activities are reported:

- In May 2013, a comparison of six fountain clocks was organized between NIM, NPLI, PTB and VNIIFTRI by means of combined TWSTFT and GPS carrier-phase measurements.
- The technique of two-way carrier-phase has been investigated, mostly by NICT. Experiments have been performed on the link NICT-PTB and also on the link OP-PTB. The short- and long-term stability of this technique is very promising.
- In June 2015, a broadband TWSTFT experiment, using a chip rate of 20 Mcps, was performed among four laboratories (INRIM, NPL, OP, PTB) in the framework of the ITOC project. Within this experiment, Cs fountains and optical clocks have been compared.
- A software defined receiver (SDR) has been developed by TL in Taiwan and the first experiments have been performed.
- ITU-R recommendation ITU-R TF.1153 "The operational use of two-way satellite time and frequency transfer employing pseudo-random noise codes" has been updated to version 4. The revision is related to the Sagnac corrections. Since the shape of the earth is not exactly spherical, a small correction to the coordinates needs to be applied.
- In order to harmonize the organization and reporting of TW calibration results, the WG has developed a guideline document: "TWSTFT calibration guidelines for UTC time links".
- An overview was presented of TW-link calibrations from 2012 to 2015, with a mobile TW station or with the BIPM travelling GNSS receiver.
- Unfortunately, the direct TW links between Europe and Asia are currently not active after the operation of satellite AM-2 stopped. Investigations for alternative satellites are still ongoing.

The working group has prepared a recommendation for continued support of participating laboratories for TWSTFT activities (CCTF/15-03).

6.2 Report of the CCTF WG on GNSS Time Transfer (P. Defraigne, ORB) (CCTF/15-11) and (CCTF/15-43)

Most of the members of this working group are experts from laboratories contributing to UTC. In addition, a representative of the CCTF WGATFT, a representative of the International GNSS Service (IGS) and members of the BIPM Time Department are represented in the WGGNSS. The chairman of this group is Dr Defraigne (ORB) and the secretary is Dr Petit (BIPM).

A brief summary of the objectives of the WG is presented.

Between 2012 and 2015, the WG has been active on the following subjects:

- A proposal has been developed for further evolution of the CGGTTS format.
  Beside the existing systems GPS and GLONASS, several new GNSS (Galileo, BeiDou, QZSS) are currently under development. To allow the time and frequency community to profit from these new systems, an extension of the current CGGTTS format is proposed. The new name will be: Common Generic GNSS Time Transfer Standard. The new version will be 2E. The proposed changes have been published in *Metrologia*, 2015, **52**, G1.

- Development of guidelines for GNSS calibration
  The calibration of GNSS equipment and links is shared between the BIPM and the RMOs. The BIPM calibrates GNSS equipment in a limited number of laboratories selected by each RMO ("Group 1" laboratories, G1). The RMOs organize the calibrations in the other laboratories, included in the "Group 2" (G2), with the exception of AFRIMETS and GULFMET, where equipment will be calibrated by the BIPM until they develop adequate capacity. The BIPM is responsible for linking the G2 calibrations to the reference established by the G1.

  In addition, a file format has been proposed for keeping track of the calibration history of a GNSS receiver. The format can be included in the header of CGGTTS files.

- Improvement of time and frequency transfer performance by GNSS based methods.
  Several investigations have been made for realizing continuous PPP solutions. Different approaches have been followed: using long data batches, using moving windows or solving integer ambiguities. For this latter solution, it is important that code and phase measurements in the receiver are synchronized. For some types of receivers this is not the case. Therefore, collaboration with receiver manufacturers remains important.

  The WGGNSS has prepared three recommendations:

- Recommendation on the BIPM guideline for GNSS calibrations; asking RMOs to organize calibrations of G2 laboratories (CCTF/15-27).
  Dr Milton asked if there should be a recommendation on periodicity of the calibration. The calibration guideline recommends that the calibration should be repeated every two to three years. This is based on observations from different types of receivers. Dr Romisch added that it is not possible to repeat the calibrations more frequently for practical reasons.

- Recommendation on the Common generic GNSS time transfer standard; to implement CGGTTS v2E in the R2CGGTTS software, and to start using CGGTTS v2E (CCTF/15-26).
  There was some discussion on how to interact with the receiver manufacturers that produce the CGGTTS output files.

  Dr Levine asked how the laboratories should deal with the transition day from the old format to the new format. Considering that the format is not very different, the BIPM will prepare its data handling software to accept both the old and new format. The version of the format is given in the header of the file.

- Recommendation on the design of GNSS receivers; alignment of the latching point for code and phase measurements (CCTF/15-30).
  Dr Milton asked if a recommendation from the CCTF is the best way to communicate with manufacturers. Dr Matsakis responded that it is complementary to other ways of communication, and mentioned that one of the manufacturers has collaborated to diagnose this problem. Dr Arias added that the time and frequency community has privileged relations with (some) manufacturers, and that receivers for geodetic purposes will also benefit from solving this problem.

6.3 GNSS calibrations for UTC (G. Petit, BIPM, RMOs, delegates) (CCTF/15-44)

The BIPM has initiated the implementation of a new scheme for GNSS calibrations. Calibration of GNSS equipment in laboratories contributing to UTC involves a lot of work that cannot be carried out by the BIPM alone. To make sure that all laboratories can use calibrated equipment, and to ensure that calibrations are repeated regularly, the workload has been divided between the BIPM and the RMOs. Each RMO assigns a few Group 1 (G1) laboratories that will be regularly visited for calibration by the BIPM. Other laboratories within the RMO are Group 2 (G2) laboratories. GNSS equipment in G2 laboratories will be calibrated in calibration trips, and responsibility for this is that of the RMO, using travelling receivers from G1 laboratories.

The BIPM will maintain a database of all calibration results, in which each calibration will be identified by a unique calibration identifier (Cal_Id). From the equipment calibrations, the BIPM will determine the UTC link uncertainties. Calibration reports are available via the website: http://www.bipm.org/jsp/en/TimeCalibrations.jsp.

In order to use the calibration trips contributed by RMOs in a consistent and optimal manner, a document “BIPM Guidelines for GNSS calibrations” has been developed. The most recent version is v3.1 from September 2015. Many details covering operation, computation and reporting are provided in the annexes.

In addition to the document on equipment calibration, another document on link calibration “BIPM guideline for UTC time link calibration” is being prepared. The current version is v2.2 from March 2014. It describes the computation of links by GPS PPP to be used to calibrate the corresponding (non-calibrated) TWSTFT link, for example. A simplified link calibration procedure has been approved by the WG TWSTFT and is described in “TWSTFT calibration guidelines for UTC time links”.

The actual status of the G1 calibrations is that the BIPM has performed calibrations for EURAMET, APMP, SIM and COOMET. The BIPM travelling system (B3TS) has been used in these calibrations, with the exception of Russia, where a single receiver was sent. In these trips, equipment delay results as well as time link results were computed. Both solutions were found to be consistent within the uncertainties. Also, if possible, the new results were compared with results from previous calibrations, and again the new results were found to be consistent within the combined uncertainties.

As a next step, Section 6 of BIPM *Circular T* will be revised to give better information on the link calibrations. Definitions of the present uncertainties will be revised. The involved equipment will be identified. Calibration identifiers will be included. Where applicable, calibration alignment of equipment will be mentioned.

RMOs have been requested to start the G2 calibration trips as soon as possible and to report the results to the BIPM.

Dr Hosokawa asked whether the calibrations of all G2 laboratories can be handled by the G1 laboratories. It is the responsibility of each RMO to organize the calibration trips and to propose G1 laboratories to share the workload. If necessary, the RMO should contact the BIPM to assign an additional G1 laboratory.

Dr Arias developed the cases of UTC contributing laboratories that are not represented in RMOs (e.g. time laboratories that are not NMIs or DIs). The RMOs are requested to take responsibility for calibrations of G2 laboratories within their geographical region, which are not members of the RMO.

Dr Matsakis suggested including the result of the previous calibration and the difference between the new and old values in calibration reports. It is to be expected that this information will become more easily accessible in the BIPM calibration database.

Dr Bize mentioned that a joint calibration campaign of GNSS measurements and T2L2 measurements has been performed with several laboratories. The estimated uncertainty was approximately 1 ns (k = 1). The agreement between the two different methods was about 0.2 ns.

6.4 Report of the IGS WG on Clock Products (M. Coleman, IGS) (CCTF/15-45)

An overview was presented of the IGS products, including the clock products. Ultra-rapid (IGU) products are published every 6 hours with a latency of about 6 hours. Rapid (IGR) products are published daily with a latency of 1 to 2 days. Final (IGS) products are published weekly with a latency of about 2 weeks.

An explanation was given on the production line of the clock products, including a list of involved data centres and analysis centres.

The IGS timescale is formed for both rapid (IGRT) and final products (IGST) and is derived using a Kalman filter. This Kalman filter was introduced in version IGS2.0 in 2011.

The IGS timescale is based on a weighted mean of 50 to 60 member clocks. The instability is at the level of 1×10^{-16} for longer averaging intervals. The IGS timescale is steered to UTC via AMC2 or USNO.

Station clocks contributing to the IGS timescale are implemented in the filter by a four state clock model. For satellite clocks, two fixed period harmonics are added to the total phase state, resulting in up to eight states per clock.

Graphs of IGRT and IGST with respect to GPS time (GPST) and with respect to UTC show an agreement within ±50 ns, and most of the time to within ±20 ns.

Proposals for further improvements are:

- always to include a collection of UTC(k) laboratories in the computation of IGRT and IGST;
- improve the initialization of clock states and covariances in the Kalman filter process;
- increase the number of GNSS clocks in the computation, in particular from Galileo, GLONASS and BeiDou.

Dr Matsakis remarked that the Galileo System Time (GST) is steered to some good UTC(k) laboratories. Some of these also contribute to the IGS timescale. There was no answer from the participants regarding the question on whether IGST is better or worse than GST.

6.5 Report of the CCTF WG on Coordination of the Development of Advanced Time and Frequency Transfer Techniques (WGATFT) (F.-L. Hong, NMIJ) (CCTF/15-46)

A brief overview of the terms of reference of this WG was presented. The WG is composed of representatives from other CCTF WGs and experts from laboratory members of the CCTF. The chairman of the group is Dr F.-L. Hong from NMIJ and Yokohama National University and the secretary is Dr L. Robertsson from the BIPM.

In the past three years, the WG has held two meetings: one at the EFTF 2014 conference in Neuchâtel and another prior to this CCTF meeting at the BIPM.

At the meeting in Neuchâtel, a study group on fibre links for UTC was established. Furthermore, status reports were presented on the ACES project, NEAT-FT project, VLBI, TWSTFT and transportable optical clocks.

A questionnaire has been circulated among the members of the WG inquiring about the status and activities related to time and frequency transfer through optical fibres. Responses to this questionnaire were received from six laboratories. However, it is difficult to summarize the results. It can be concluded that more than ten optical fibre links are already operational and that additional projects are ongoing in several countries. Most of the active fibre links used for frequency transfer are achieving uncertainties of 10^{-17} to 10^{-20}. In the meantime, possible applications are becoming clearer.

During the WGATFT meeting in 2015, a remarkable achievement was reported on the realization of a fibre link between LNE-SYRTE (Paris) and PTB (Braunschweig) with frequency instability of 2×10^{-17} at 10^5 s averaging time. With this link, two Sr clocks at LNE-SYRTE and PTB have been compared. The agreement was at the level of 5×10^{-17}.

Other topics discussed in the 2015 meeting were:

- Planned actions from the study group on fibre links for UTC;
- Progress of the ACES project: a laser cooled Cs clock will be launched into space for realizing accurate time transfer experiments. Most of the flight models of the equipment have been finished. Launch is scheduled during the first semester of 2017.
- Status of transportable optical clocks: Currently, five transportable optical clocks are under development. These are mostly Sr lattice clocks and one Al^+ quantum logic clock.
- A two-way carrier-phase experiment has been performed between PTB and LNE-SYRTE in collaboration with NICT. A frequency comparison at the level of 10^{-16} seems feasible.
- Applications of accurate clocks in geodesy have been discussed (chronometric geodesy). By using frequency difference measurements between two clocks, it is possible to directly measure gravity potential differences.

The WGATFT has prepared a recommendation on “development of national and international time and frequency links, to improve methods for intercontinental clock comparisons and for dissemination to stakeholders” (CCTF/15-31).

6.5.1 Report on the status of fibre links (CCTF ATFT study Group of fibre links, BIPM and delegates)

Dr Arias reported that within the WGATFT a study group on fibre links has been established to follow the developments on the realization of optical fibre links for time and frequency transfer. From a BIPM perspective, important objectives are: that laboratories operating optical time links make their data available for analysis; and to come to a standard report format for this data exchange. In the development of the report format, it should be noted that this data is not only useful for the computation of UTC, but also for other applications.

The terms of reference of the Study Group on fibre links have been drafted under the coordination of its Chairman, Dr Calonico from INRIM.

Dr Jiang reported on the activities of BIPM related to optical fibre links (CCTF/15-47). The BIPM is willing to exploit results from optical fibre TF links in the realization of the UTC time scale, and activities on this topic have started for this purpose.

In recent years, more than 80 scientific papers have been published on time and frequency transfer using optical fibres, in which at least 18 UTC contributing laboratories were actively involved.

For the time link between BEV (Austria) and UFE (Czech Republic) and for the link between AOS (Poland) and GUM (Poland) data are regularly submitted to the BIPM for monthly comparison with the respective GPS links.

The BIPM has also been involved in the use of optical fibre links for validating other accurate time and frequency transfer techniques. The measurements with the BIPM travelling system (B3TS) were assessed with the optical fibre, self-calibrated link between AOS and GUM in Poland. Also GPS-based time links using “Integer ambiguity PPP” and “Revise Rinex-Shift” methods of analysis were validated against this fibre link.

For future applications of optical fibre links in UTC, a standard data format needs to be developed. A format similar to the TWSTFT format, with some modification has been proposed and could be considered among other options by the Study Group on optical fibre links.

Furthermore, the configuration of the network for UTC computation should be reconsidered. The current configuration with a single pivot laboratory does not take advantage of the improved stability of time links based on optical fibres.

Mr Erard asked if a recommendation should be prepared for a common format. Dr Arias responded that the Study Group will investigate the issue and will formulate a proposal.

6.6 GNSS processing techniques (G. Petit, BIPM, delegates) (CCTF/15-48)

Over the past years, investigations have been made to improve the performance of GNSS time and frequency transfer to the level of less than 1×10^{-15} in frequency instability over 1 day averaging and several hundred ps in time.

With improvements on GPS PPP, frequency transfer with instability in the 10^{-16} region has been demonstrated by:

- Petit *et al*., using GPS PPP with integer ambiguity resolution;
- Droste *et al*., using GPS carrier-phase compared with an optical fibre link;
- Yiao *et al*., using GPS PPP with the revised Rinex shift technique (RRS).

Time offsets are observed between the codes (e.g. GPS C1, P1 and P2) transmitted by navigation satellites. The IGS has a “Bias and Calibration Working Group” (BCWG) working on the determination of these biases. This working group also studies inter-frequency biases of GLONASS signals.

The ORB in collaboration with Septentrio, and USNO have concluded that biases between code and phase measurements are (at least to some extent) caused by limitations of the receiver hardware. Based on this discovery, a recommendation has been drafted to receiver manufacturers (CCTF/15-30). This recommendation was discussed in section 6.3.

Dr Levine added that a student at NIST (Yiao) has developed new software for GPS PPP analysis. This new software appears to be better than the commonly used NRCan software. Time links based on GPS PPP using this new NIST software are performing better than TWSTFT.

7 CIPM MRA AND RMOS

7.1 Report of the CCTF WG on the CIPM MRA (M. Lopez Romero, CENAM) (CCTF_15-49)

The members of this working group are the chair persons of the RMO technical committees for time and frequency, experts from time laboratories and experts from the BIPM.

The chairman is Dr Lopez (CENAM) and the secretary is Dr Panfilo (BIPM).

An overview was presented of the terms of reference of this working group.

The working group maintains several guidelines:

1. Service category classification for TF CMC table entries
2. The estimation of uncertainties for TF CMC entries
3. The uncertainty interpolation for TF CMC entries
4. The uncertainty in frequency
5. The prediction uncertainty (revised)
6. Rules for participation on the computation of the UTC (new)
7. Participation in the key comparison CCTF.K001-UTC (new).

Currently, 49 countries are listed as suppliers of calibration services for Time and Frequency, with a total of 738 CMCs.

Following the decision taken at the CCTF 2012, the publication of results of key comparison CCTF.K001-UTC in the key comparison database was re-established in March 2015. From the participants of BIPM *Circular T*, only results from NMIs and DIs are presented.

The new guidelines 6 and 7, and the revision of guideline 5 were briefly explained. Dr Lopez, on behalf of the WGMRA asked the CCTF to approve these documents.

The WGMRA has three issues remaining open:

- implementing a guideline on technical criteria on the CMCs revision to make sure that CMC reviews are performed in a more or less similar way within all RMOs;

- regularly collecting information from RMOs on regional comparisons and pilot projects in the field of TF;
- establishing the rules for periodic evaluation of adequacy of the CMCs claimed by the NMIs and available in the KCDB.

Mr Erard remarked that in preparation for a revision there has been a survey of the current MRA. He asked what the impression is of the TF community. Dr Lopez commented that, in general, the TF community is happy with the current form of the MRA.

Dr Milton asked who would be the users of this MRA and the KCDB. Dr Arias mentioned that the MRA in the field of TF is not only useful for calibration purposes, but also for different fields such as space research and (radio) astronomy, radiocommunications and telecommunications, etc. Dr Milton recommended providing this information as input to the MRA survey.

Dr Achkar asked how to get access to the new and revised guidelines. These are available on the BIPM website, in the restricted area of the WGMRA.

The revision of Guideline 5 concerns the inclusion of tables of prediction uncertainties for “good” and “bad” Cs and H-maser clocks over 20 days.

Dr Arias commented that the uncertainty values in this document are useful for declaration and revision of CMCs because it sets reasonably acceptable limits.

The members of the CCTF agreed on this document and Guideline 5 was approved.

The new Guideline 6 concerns the rules for participation in the computation of UTC.

Dr Bauch asked if this guideline applied only to new laboratories or also to laboratories that already contribute to UTC. Laboratories that already contribute to UTC are assumed to be compliant with this guideline.

The members of the CCTF agreed on this document and Guideline 6 was approved.

The new Guideline 7 concerns the rules for participation in the key comparison CCTF.K001-UTC.

The members of the CCTF agreed on this document and Guideline 7 was approved

There were no recommendations from the WGMRA to be submitted to the CCTF.

7.2 Reports from RMOs Technical Chairs (or substitutes)

7.2.1 SIM region (M. Lopez, CENAM, on behalf of M. Lombardi, NIST) (CCTF_15-50)

In the SIM region, there are 30 time laboratories. From these laboratories, 13 contribute to the realization of UTC.

A continuous regional time comparison is organized under the name ‘SIM Time Network’. This time comparison is mainly based on GPS common-view measurements. The comparison data is processed automatically and the results are published and updated hourly on a website operated by NIST (http://www.tf.nist.gov/sim). Through this comparison, laboratories that do not contribute to UTC are able to obtain traceability to the SI second via the NMIs that are involved in the UTC network.

Within the SIM region, there is a strong training programme in the field of time and frequency. Countries with limited resources have been equipped with customized, minimal equipment to have national time and frequency references traceable to the SI second.

7.2.2 APMP region (M. Wouters, NMIA, and former chairman H.T. Lin, TL) (CCTF_15-25)

The APMP Technical Committee for Time and Frequency (TCTF) has working groups on the MRA, GNSS and TWSTFT. With the Technical Committee for Length (TCL) there is a joint TCL/TCTF working group on Optical Frequency Metrology (OFM).

The APMP WG MRA handles the intra- and inter-regional CMC reviews. This WG MRA also maintains guidelines for calculation of CMC uncertainties. These are intended as a guide for NMIs submitting CMCs for the first time. The guidelines are available on the TCTF website.

The APMP WG GNSS is currently organizing the first calibration campaign for Group 2 laboratories in the region. This campaign is coordinated by NIM.

Under the framework of collaboration between NMIA, NPLI, NIMT and SIRIM, an initiative has been started to develop a low-cost GNSS time-transfer system for time-dissemination services. The system’s hardware design and software will be openly available.

The APMP WG TWSTFT is responsible for the TW links in this region. The working group has investigated alternative satellites for AM-2 to restore the link between Asia and Europe.

Research on TWSTFT includes: link calibration; the use of dual pseudo-random noise codes; software-defined receivers; and the use of a carrier-phase.

The APMP WG OFM organized a workshop on calibration of I_2-stabilized HeNe lasers, in July 2014. Research on OFM includes: optical clocks; optical frequency combs; and dissemination of microwave and optical frequency standards over optical fibres.

7.2.3 EURAMET region (R. Hamid, UME) (CCTF_15-51)

The EURAMET TCTF held its annual meeting in March 2015 at BEV in Austria. The next meeting will be in March 2016 at VTT-MIKES in Finland.

Within EURAMET the technical committee has worked out strategy roadmaps. For time and frequency, the topics for research and development are:

- development of accurate ground atomic clocks with uncertainties in the range 10^{-14} to 10^{-18};
- space applications of atomic clocks and TF metrology with uncertainties down to 10^{-17};
- time and frequency dissemination and comparison, with uncertainties of 10^{-18} and 0.1 ns on ground and 10^{-16} and 0.1 ns in space;
- accurate time scale generation and traceability with an uncertainty of less than 2 ns;
- creating wide impact from the developments mentioned above.

These research topics are elaborated in projects funded under the European Metrology Research Programme (EMRP) and its successor European Metrology Programme for Innovation and Research (EMPIR).

Within these projects, the first successful international comparisons of optical clocks have been realized, by broadband TWSTFT and by optical fibre techniques.

For the GNSS receiver delay calibrations within the EURAMET region, LNE-SYRTE, PTB and ROA have been assigned as G1 laboratories.

8 LABORATORIES REPORTS (NPL, GUM, UME, MIRS, SASO)

8.1 Financial sector engagement (L. Lobo, NPL) (CCTF_15-52)

The financial sector is becoming more aware of the importance of timing in financial transactions. For financial organizations involved in algorithmic trading and high-frequency trading, it is important to minimize latencies in the transfer. In some cases, this is solved by colocation of trading computers, but this is not always possible. For trading between Europe and North-America, expensive transatlantic fibre links are applied, following the shortest route.

Timestamping and synchronization instrumentation is being improved to the nanosecond level for latency monitoring and network performance.

Due to increased transaction speed, regulators lose the transparency during the trading process. In order to trace back through the order of execution of transactions, the European Securities and Markets Authority (ESMA) is preparing requirements on the timing that will be described in the Markets in Financial Instruments Directive II (MiFID II). This directive will require that timestamps are traceable to UTC, with uncertainties ranging from 1 s to 1 ns depending on the trading process.

NPLTime is an implementation of a time link from the NPL to the London Stock Exchange by an existing protocol. First, the time is transferred by dark fibre from the NPL to Telehouse in the centre of London. At Telehouse there is a Cs clock for redundancy in case the signal from the NPL should become temporarily unavailable. From Telehouse, the signal is distributed to the end users which are typically banks. This solution is independent from GNSS.

On the 28 October 2015, in the London Banking Hall, there will be an “International workshop on timestamp traceability” aimed at the financial sector.

Dr Matsakis asked if the end user relies on continuous time transfer or if they have holdover clocks like a rubidium oscillator. Some end users have holdover clocks.

Dr Beard asked if NPLTime can deal with the insertion of leap seconds. Mr Lobo responded that the introduction of leap seconds can cause problems, because it is not always clear how commercial equipment at the user end responds.

8.2 GUM (A. Czubla, GUM) (CCTF_15-53)

Mr Erard remarked that GUM (Poland) has requested to become a member of the CCTF and had therefore been asked to give a presentation of its activities in the field of TF.

Główny Urząd Miar (GUM) is the national metrology institute of Poland. The institute is located in Warsaw and has 20 laboratories, including a TF laboratory. The main activities of the TF laboratory are:

- Realization of the Polish national timescale UTC(PL) and the Polish contribution to UTC. This work by the GUM is done in collaboration with five other institutes in Poland that also maintain atomic clocks. Currently, Poland contributes to UTC with about 15 clocks.
- In collaboration with the University of Kraków (AGH), GUM has been actively involved in the deployment of time transfer links by optical fibres. Within the Warsaw area, there are several operational links to e.g. telecom providers. There is also a 420 km link between GUM and AOS (Borowiec). The methods applied are either via a standard two-way method (for short link) or a one-way method with active stabilization of the propagation delay. The combined uncertainty of the link GUM-AOS is about 0.11 ns (k = 1).
- The optical fibre-based time link has been compared with GPS-based measurements, with excellent agreement. The uncertainty in this comparison is dominated by the GPS PPP analysis.
- For more than five years, GUM has coordinated the EURAMET project 1152 on monitoring the performance of GNSS time transfer systems. The objective of this project is to find out if jumps that are occasionally observed in GNSS measurement data could be explained by events in the laboratory or traced back to some other cause.
- GUM has carried out an analysis of precise time interval measurements performed with time interval counters. In collaboration with AGH, a time interval generator has been developed that will be used as a travelling standard in a regional comparison.
- During the last ten years, GUM has published or contributed to more than ten scientific papers in the field of TF.

Dr Milton asked if there are plans to establish time links by optical fibres outside Poland. Possibilities have been investigated for links towards Germany and to Vilnius, Lithuania, but sources of funding will need to be found.

Based on this presentation, Mr Erard asked if the members of the CCTF agree that GUM should become a member of the CCTF. All members agreed.

8.3 UME (R. Hamid, UME) (CCTF_15-54)

Mr Erard remarked that UME (Turkey), which is an observer at the CCTF, has also requested to become a member of the CCTF and had therefore been asked to give a presentation of its activities in the field of TF.

UME is responsible for the generation of the Turkish national time scale. It is generated with a frequency uncertainty of approximately 1×10^{-14} (k = 1). The link to UTC is realized by two GPS receivers. This link mainly determines the time uncertainty of 7 ns (k = 1). The frequency signal is distributed to several other laboratories at UME and the time signal is disseminated by NTP servers.

Calibrations for customers are performed using a highly automated system. Calibration capabilities include frequency, time interval and Doppler radar calibrations.

The laboratory has several stabilized laser sources in the optical spectral range from 532 nm to 3390 nm:

- Nd:Yag/I2, 532 nm,
- He-Ne/I2, 633 nm,
- ECDL/Rb, Cs, 778 nm, 780 nm, 852 nm
- He-Ne/CH4, 3390 nm

A Ti:Sa femtosecond comb and a Yb fibre comb are used for frequency scaling.

Besides applications in optical frequency calibrations, this equipment is also used in several European research projects (Nanotrace, Sub-nano, EMF&SAR, Mikro Clocks, Angle), for length measurement and displacement measurement.

Over the past six years, UME has published or contributed to about 20 scientific papers related to the field of TF.

Based on this presentation, Mr Erard asked if the CCTF agreed that UME should become a member of the CCTF. All members agreed.

Mr Erard will submit a proposal to the CIPM that both GUM and UME should become members of the CCTF.

8.4 MIRS (R. Lapuh, MIRS) (CCTF_15-20)

Mr Erard remarked that MIRS (Slovenia) has requested to become an observer to the CCTF. Dr Lapuh had been invited to present the activities of MIRS in the field of TF, but he was not able to attend the meeting. Instead, he submitted a report to the CCTF which is available on the BIPM website under the working documents.

Considering this report and the continuous activities of Dr Lapuh in the field of TF within EURAMET, Mr Erard asked if the members of the CCTF agreed that MIRS should become an observer of the CCTF. All members agreed.

8.5 SASO (K. Aldawood, SASO) (CCTF_15-17, CCTF_15-55)

Mr Erard introduced Mr Aldawood from SASO. SASO started contributing to UTC in 2013. As a guest of the CCTF, Mr Aldawood was invited to present the activities of SASO in the field of TF.

The Saudi Standards, Metrology and Quality Organization (SASO) established a National Measurement and Calibration Center (NMCC) in 1986. Among its different facilities, NMCC has a time and frequency laboratory that is responsible for the realization of the national time scale. This time scale, UTC(SASO), is based on five industrial high performance caesium clocks. The link to UTC can be realized by any of the two GNSS receivers. The frequency uncertainty is less than 2×10^{-14} and the time uncertainty is about 7 ns.

The time scale is disseminated over the internet and intranet by three NTP servers.

Facilities for TF calibration cover: atomic clocks, quartz frequency standards, signal generators, spectrum analyzers, counters, rise time of high frequency oscilloscopes, tachometers, chronometers and timers.

Typical CMCs for frequency calibrations are $1 \times 10^{-11} f$ Hz. Also for time interval, RF power, modulation and phase noise CMCs have been prepared.

SASO has participated in a EURAMET pilot study for a time interval comparison.

Mr Erard asked if SASO intends to submit CMCs to the BIPM KCDB. For now, these CMCs have been prepared for national accreditation.

Mr Dierikx remarked that in the CMCs the frequency range is stated from DC to 50 GHz. Considering that DC is not a valid value for frequency measurements he recommended stating a more realistic value.

9 REDEFINITION OF UTC

9.1 Report of events at the ITU-R, future actions (R. Beard, ITU-R) (CCTF_15-56)

Dr Beard presented a historical overview of the process so far.

In 2000 a questionnaire was sent concerning the requirements of the future of the UTC time scale. As a reminder, the current definitions of TAI, UTC and DUT1 as described in ITU-R TF.460-6 were shown.

A study group prepared a proposal for modification of the recommendation ITU-R TF.460-6. This was discussed at the Radiocommunication Assembly and the World Radiocommunication Conference 2012 (WRC-12), but no consensus was reached. The WRC-12 decided, in Resolution 653, that further studies should be performed on the consequences of a change in the reference time scale, and that the results should be reported at the WRC-15 under the proposed agenda item 1.14 “to consider the feasibility of achieving a continuous reference time-scale, whether by the modification of coordinated universal time (UTC) or some other method, and take appropriate action, in accordance with Resolution 653”.

Several studies were conducted. In 2013, a workshop was organized jointly by the ITU-R and the BIPM. With this input, ITU-R Working Party 7A was designated to prepare a text for the WRC-15. Based on the information received from administrations and organizations, the Working Party 7A prepared a proposal with the several possible methods to satisfy this item:

- Method A1/A2 – Discontinue Leap Seconds, not earlier than five years after the date of entry of Final Acts of WRC (with and without change of name)
- Method B - Retain UTC as currently defined and introduce a continuous reference atomic time-scale based on TAI with an offset with respect to UTC to be broadcast on an equal basis.
- Method C1/C2- No change in definition of UTC as specified in Recommendation ITU-R TF.460-6, which will remain the only time-scale which is broadcast in order to avoid any

confusion. Clarification/definition of the method to derive TAI and continuous system times from UTC should be established.

- Method D -No change to the Radio Regulations as the results of studies are inconclusive.

The WRC-15 will be held in November 2015 in Geneva (Switzerland).

Mr Erard recommended that all CCTF members should give their opinions to the national representatives in the WRC. Mr Erard hoped that the CCTF members agree with recommendations A1 or A2, or that they will propose a method that is metrologically acceptable.

Several members expressed concerns about method B, because broadcasting two reference time scales will lead to confusion.

Dr Gill reported that the position of the UK government remains the same, and that the preferred method for the UK is method C1.

9.2 Dissemination of UT1 (C. Bizouard, IERS) (CCTF_15-57)

The International Earth Rotation and Reference Systems Service (IERS) provides the International Celestial Reference System (ICRS), the International Terrestrial Reference System (ITRS), and their respective realizations by reference frames (ICRF and ITRF), the earth orientation parameters (EOP), the conventions related to reference systems and EOP, and geophysical data. These products are used by a broad community.

The earth rotation time (UT1) is determined from the earth's rotation angle (with respect to the non-rotating origin, by observing "fixed" objects that are far away from the earth. Measurements are performed by very long baseline interferometry (VLBI), using radio telescopes located around the world.

A plot of the difference between UT1 and TAI, starting from 1962, was shown. Variations in this difference reflect the earth's non-uniform rotation rate. Over the last 40 years, this has resulted in fluctuations of the average length of day between −1 ms and +4 ms.

The cumulative effect of these fluctuations causes UT1 to diverge from UTC. Therefore, following the recommendation of the ITU-R, leap seconds are inserted in the UTC time scale to ensure that |UT1-UTC| < 0.9 s.

Since 1972, 26 positive leap seconds have been inserted. (Negative leap seconds have never occurred so far). The IERS announces the insertion of a leap second about six months in advance.

For real-time users, the IERS provides predictions of earth rotation parameters. The prediction uncertainty is < 0.1 ms for 1 hour and < 0.1 s for 1 year.

The IERS products are disseminated in the form of bulletins that can be downloaded from the IERS websites:

http://www.usno.navy.mil/USNO/earth-orientation/eo-products
http://hpiers.obspm.fr/eop-pc (Earth Orientation Center)

New ways of data delivery are under development. For example dissemination of UT1 by means of a NTP server has been implemented.

Dr Beard remarked that the ITU expects that IERS will continue its work, independent of the decision of a possible redefinition of UTC without leap seconds.

Dr Levine added that in support of the IERS, the NIST has set up an NTP server transmitting a prediction of UT1 published in IERS Bulletin B in NTP format. Users of this service need to register to obtain access. Additional information is available on the NIST website:

http://www.nist.gov/pml/div688/grp40/ut1_ntp_description.cfm

10 SPACE-TIME REFERENCES AND GENERAL RELATIVITY:

10.1 Report on the IERS Conventions Product Centre (G. Petit, BIPM) (CCTF_15-58)

The IERS Conventions (2010) is a 180-page book, defining the standard reference systems realized by the IERS, and the models and procedures used for this purpose.

The latest full version was published electronically in December 2010 and on paper in the spring of 2011.

Since 2001, the IERS Conventions Centre has been provided jointly by the BIPM and the U.S. Naval Observatory (USNO).

From 2014, the organization has changed. The “advisory board” has been abolished and a new “editorial board” has been installed. The editorial board consists of eleven members, each of whom covers one topic/chapter of the Conventions.

The most recent updates include: the leap second inserted in June 2015, correction of software bugs, a new IERS Conventional Mean Pole and modifications in chapter 9.

10.2 Actions for the international recognition of the International Terrestrial Reference System and Frame (C. Boucher, IUGG) (CCTF_15-08, CCTF_15-59)

The International Terrestrial Reference System (ITRS) has been defined and realized from 1988 by the IERS. Since then, several solutions of the primary realization “International Terrestrial Reference Frame (ITRF)” exist: ITRF88 up to ITRF2014.

The ITRS has been adopted by the International Union of Geodesy and Geophysics (IUGG) in 2007. Following a recommendation of the CCTF in 2009 to the CIPM, the CGPM decided in 2011 to adopt the ITRS as the unique international reference system for terrestrial reference frames for all metrological applications (Resolution 9 of the 24th meeting of the CGPM).

It is recognized that other geodetic references are used by various communities and that the link between ITRS and these other systems must be clarified.

Furthermore, within a working group of the International Association of Geodesy (IAG) an initiative was launched to develop an ISO standard related to the ITRS. This work is taken up by the ISO TC211 (Geographic Information). The metrological community is invited to contribute to the establishment of this standard.

Dr Milton noted that the BIPM’s policy for participating in ISO committees is that the BIPM will mainly facilitate the contribution of NMIs or DIs in the committee. After the “doors have been opened” for the NMIs or DIs, the BIPM will no longer participate.

Dr Boucher remarked that considering the progress on optical clocks and TF transfer, the IUGG is prepared to reactivate the working group on relativistic geodesy and to propose the involvement of the CCTF in this group. The BIPM will be informed of the activities and progress of this working group.

11 GLOBAL NAVIGATION SATELLITE SYSTEMS

11.1 Reports on the present state of GNSS

11.1.1 GPS

There was no report on the status of GPS.

11.1.2 GLONASS (CCTF_15-03)

Dr Koshelaevsky reported that in the monitoring of GLONASS System Time (GLO ST), there has been a discrepancy between the results from VNIIFTRI and the results from European laboratories for many years. The difference was about 200 ns. To solve this issue, in 2014, VNIIFTRI and BIPM arranged a calibration of GNSS receivers specifically for GLONASS. In this delay calibration, the antenna, the antenna cable and the receiver's internal delay were determined separately. VNIIFTRI made the absolute calibration of a BIPM receiver.

The results of the calibration confirmed that there was an offset of about 200 ns of GLO ST with respect to UTC(SU). In August 2014, the GLONASS administration decided to steer GLO ST back to UTC(SU) over a period of about four months as a corrective action. Currently, the difference between GLO ST and UTC(SU) is typically within 20 ns.

It is expected that in new GLONASS satellites the Frequency Division Multiplexing Access (FDMA) signal structure will be replaced step-by-step by Code Division Multiple Access (CDMA) (similar to GPS).

11.1.3 Galileo

There was no report on the status of Galileo.

11.1.4 GAGAN/IRNSS

There was no report on the status of GAGAN/IRNSS.

11.1.5 BeiDou/COMPASS

There was no report on the status of BeiDou/COMPASS.

11.2 Report on activities at the International Committee for GNSS (ICG) (BIPM)

Dr Arias reported that the contribution of the BIPM to the ICG will continue.

As explained by Dr Koshelaevsky in section 11.1.2, the alignment of the GLONASS System Time to UTC is visible in Section 5 of BIPM *Circular T*. Following the absolute calibration of the GLONASS receiver of VNIIFTRI, VNIIFTRI has proposed to calibrate also the receivers of BIPM and AOS. The BIPM receiver has been calibrated and will soon be returned to the BIPM. The AOS receiver has not yet been calibrated.

Dr Arias mentioned that the ICG has strongly supported the development of rapid UTC, because it enables better steering of the GNSS time to UTC.

The next meeting of the ICG will be held in November 2015. Dr Petit will attend this meeting on behalf of BIPM.

Dr Arias noted that in the WGTAI there was a discussion on Section 5 of the BIPM *Circular T*. The data of the difference between the GNSS times and UTC is sometimes considered as a source of traceability. This interpretation is not correct. To avoid this confusion, it is proposed that *Circular T* should only report the difference between the predictions of UTC(k) broadcast by the GNSS and UTC/TAI. The difference between the GNSS time and UTC/TAI will only be published on the BIPM FTP server.

Dr Walls (USNO) noted that this is a good proposal, as it supports the use of the broadcast predictions of UTC(k) instead of GNSS times by end users.

The members of the CCTF agreed that Section 5 of BIPM *Circular T* should be modified. This action is to be carried out by the BIPM TF department.

12 STRATEGIC PLANNING

12.1 Outcome of the 25h CGPM (L. Erard, CIPM) (CCTF_15-60)

The 25th meeting of the CGPM was held from 18-20 November 2014 in Versailles, France. The meeting was attended by delegates from 46 of the 56 Member States, representatives from 20 of the 41 Associates of the General Conference and representatives of six intergovernmental organizations and international bodies.

The chairman of the meeting was the president of the Académie des Sciences.

Reports were presented by the president of the CIPM, the Director of the BIPM and the presidents of the CIPM Consultative Committees. There were also scientific presentations, including one on “The measurement of time” by Dr C. Salomon.

Collaborations between international organizations (ILAC, OIML, WMO, ISO) and the BIPM were reported.

Elections for the renewal of the members of the CIPM were held.

From the meeting, five resolutions were proposed:

Resolution 1: On the possible future revision of the International System of Units, the SI. This revision is foreseen for 2018 and the preparations are on schedule.

Resolution 2: On the election of the International Committee for Weights and Measures, CIPM. The process for the election of members of the CIPM has been revised.

Resolution 3: On the Pension and Provident Fund of the BIPM. Plans for the sustainability of the Pension and Provident Fund of the BIPM have to be implemented.

Resolution 4: Dotation of the BIPM for the years 2016 to 2019. The dotation will remain constant over the next four years. Member States and related organizations were asked to continue their voluntary support for the activities of the BIPM with emphasis on work related to capacity building.

Resolution 5: On the importance of the CIPM Mutual Recognition Arrangement (MRA). A review of the implementation and operation of the CIPM MRA will be performed in 2015. Contributions are requested from the Consultative Committees and the JCRB.

Dr Levine remarked that with respect to the redefinition of the SI, an interesting paper has been published in *Metrologia* on redefining the unit Hertz (Hz).

Dr Matsakis asks whether it would be possible to transfer the "definition of UTC" from the ITU to the CGPM. Mr Erard responded that the CGPM will appreciate proposals from the CCTF in this direction, but added that the discussion with the ITU on this topic is difficult.

12.1.1 Update of the BIPM Programme of Work for 2016-2019 (F. Arias, BIPM) (CCTF_15-61)

Over the past three years, a new Programme of Work (PoW) has been developed for the BIPM for the period 2016 to 2019. The PoW was established through interactions with NMI Directors and representatives from BIPM Member States. After modification to fit the PoW within the allowed budget, the PoW was approved by the CIPM in March 2015.

With respect to the time metrology, the proposed PoW is consistent with the Strategy Document that was adopted by the CCTF in 2012 and is a continuation of the PoW 2013-2015.

The unique role of the BIPM and its objective were briefly explained.

Key activities of the Time Department that follow directly from the strategy are:

1. The realization and continuous improvement of UTC;
2. Contributing to the comparison of optical standards in view of their possible use in TAI and in view of a possible redefinition of the SI second;
3. Contributing to the provision of a coherent set of space-time references and models for application in space and earth sciences.

A detailed overview was presented of all proposed activities and deliverables.

An activity related to frequency comb validation was not adopted, for budgetary reasons.

An overview was presented of the permanent staff of the Time Department. Currently, there are eight persons. It is foreseen that over the next four years the permanent staff will be reduced to six persons. Dr Arias will retire in 2017 and Dr Jiang and Dr Robertson will retire in 2018.

In the PoW, it is also foreseen that in the next four years, there will be four visiting scientists; typically one per year.

Dr Milton explained that there will be more flexibility for activities outside the PoW that are supported by NMIs and visiting scientists. The BIPM is open to proposals for collaborations.

Mr Erard took the opportunity to thank laboratories that have sent scientists to work at the BIPM Time Department over the past four years.

12.2 Report of the Strategic Planning Working Group (CCTF_15-62)

12.2.1 Update on the Strategic Planning Document (L. Erard, CIPM)

The members of this working group are: the chairpersons of the CCTF working groups, the president of the CCTF, the director of the BIPM Time Department and experts.

Discussions by the group are usually made by correspondence; a meeting was held on 15 September 2015 at the BIPM.

As requested by the CIPM and the Member States, the working group is developing a CCTF strategy document to have a longer view of the strategy in the future. The first version was issued on 11 February 2013 and is available on the BIPM website.

Suggestions for modifications and improvement are still welcome. Input can be submitted to the WG members before the end of January 2016. Each of the WG chairpersons is requested to send a paragraph to Dr Arias and Mr Erard.

The strategy document should be finalized at a meeting of the WG-SP at EFTF 2016.

12.2.2 Roadmap for the new definition of the SI second (WGSP)

The Working Group on Strategic Planning is developing a “Roadmap to the redefinition of the second”. This roadmap is based on EURAMET / NPL roadmaps and published papers. A first version for the next decade has been made and consists of two pages: one page on development of atomic frequency standards and one page on development of TF transfer techniques. Modifications and improvements are requested from the TF community through the WG chairpersons.

For the next version, a set of visible milestones should be defined and communication issues will be included. Dr Riehle would be happy to write the first draft with the milestones by the end of January 2016 for discussion at a WGSP meeting during the EFTF in April 2016.

12.3 Designation of chairs of Working Groups

In April 2015, Dr Fisk resigned as chairman of the WGTAI. Since then, Mr Erard has been acting as interim chairman.

There was a discussion on the format of the WGTAI. An idea has been proposed to transform this working group into a “Forum of Contributing Laboratories”, with updated terms of reference and rotating chairs. This idea had been discussed at the meeting but no agreement on this proposal was reached.

The WGTAI consists of about 70 members from contributing time laboratories and several representatives from relevant unions. The Working Group is an important meeting point. This structure combining all the laboratories promotes the sharing of experience and exchange of ideas with the BIPM. Within the working group, several study groups have been created. Some members feel that these actions may be more difficult in a forum. It was noted that in the terms of reference of the WGTAI there is some overlap with the WG-ALGO.

Mr Erard concluded that a proposal for the future of this group shall be developed over the next three years. This proposal should also include a revision of the terms of reference of the working group. The members of the CCTF agreed on this procedure.

For now, it is proposed that Dr Arias becomes the chairperson of the WGTAI. The WGSP will decide on this proposal.

Working Group chairs at the end of their mid-terms have been asked by the CCTF President to confirm whether they are willing to complete the second mid-term, until the next meeting of the CCTF. Dr Hanado (WG-ALGO), Dr Jefferts (WGPSFS), Dr Defraigne (WGGNSS), Dr Hong (WGAFTF) and Dr Lopez (WGMRA) agreed to fulfil a second term as chair of their respective working groups. Mr Erard will continue as chair of the WGSP.

For the CCL-CCTF WGFS, Dr Gill and Dr Riehle will continue to co-chair this working group. They have agreed to think about a strategy for a smooth transition to a renewal of chair of this group.

Concerning the WGTWSTFT, Dr Piester has been the chairman for two mid-terms, and has arrived at the end of his mandate. Dr Victor Zhang (NIST) has been proposed as new chairman. Dr Zhang was not at the meeting, but has agreed to accept this chair.

13 RECOMMENDATIONS

In this meeting of the CCTF, seven recommendations were proposed. All of them were briefly reviewed. Comments were mainly on the formulation of the recommendations. The titles of the recommendations are:

- Recommendation 1(2015): Updates to the list of standard frequencies;
- Recommendation 2(2015): Predictions of UTC(k) disseminated by GNSS;
- Recommendation 3(2015): On the GNSS time transfer equipment calibration;
- Recommendation 4(2015): On the common generic GNSS time transfer standard (CGGTTS);
- Recommendation 5(2015): On the design of GNSS receivers;
- Recommendation 6(2015): Development of national and international time and frequency links to improve methods for intercontinental clock comparisons and for dissemination to stakeholders;
- Recommendation 7(2015): On the operation and maintenance of TWSTFT networks for international atomic clock and time scale comparisons.

The members of the CCTF agreed on the proposed recommendations.

Mr Erard will inform the CIPM of these recommendations and Recommendation 1(2015) will be submitted to the CIPM for approval.

14 OTHER BUSINESS

14.1 Comments on the definition of the second (N. Koshelyaevsky, VNIIFTRI)

Resolution 1 of the 24th meeting of the CGPM (2011) proposed a new formulation of the definition of the second:

"The second, symbol s, is the unit of time; its magnitude is set by fixing the numerical value of the ground state hyperfine splitting frequency of the caesium 133 atom, at rest and at a temperature of 0 K, to be equal to exactly 9 192 631 770 when it is expressed in the SI unit s^{-1}, which is equal to Hz".

The opinion of VNIIFTRI is that the current definition is clearer and more representative than the proposed new version. The current definition explains how to realize the second and appeals to duration and time interval counting. It is clear to a wide public. The proposed new version does not explain how to realize the second and appeals to the derived unit Hz. Also, with respect to the proposed new definition of the SI unit of length, the metre, the VNIIFTRI is not happy, for similar reasons.

Dr Arias said that this is a rewording of the old definition, proposed by the CCU, to be in line with other definitions of SI units.

Dr Bauch mentioned that colleagues in the time group at the PTB are also not happy with the new wording of the definition of the second.

Dr Riehle added that the wording "at a temperature of 0 K" is not correct. The correct wording should be "unperturbed".

Mr Erard responded that these comments will be taken into account. He asked Dr Riehle to send a proposal with the correct wording to the WG SP. Any other comments with respect to the proposed rewording of the definition of the second should also be sent to the WG SP.

14.2 IAU report (M. Hosokawa, IAU / NICT)

Dr Hosokawa reported that a proposal was submitted to the General Assembly of the IAU in August 2015 to create a new working group to deal with the link between astronomy activities and time and frequency standards. Creating this working group is important, because there is no longer a stable structure of committees under the IAU.

14.3 Next meeting of the CCTF

It was proposed that the next meeting of the CCTF should be held in the second week of September 2018. As usual, the WG meetings will be held in the days prior to the CCTF meeting.

15 CONCLUSIONS

The president, Mr Erard concluded the meeting by saying that:

- all actions will be reported in the minutes;
- all presentations will be published on the BIPM website, unless the presenter explicitly disagrees;
- the group photo will be published on the BIPM website.

Mr Erard thanked all participants for their attendance and their contributions.

He thanked the staff of the BIPM for the organization of the CCTF and WG meetings.

Special thanks were expressed to Dr Arias as the local host for this meeting.

Finally, thanks were expressed to Mrs Céline Fellag Ariouet and her staff for taking care of logistics and communications with the participants.

The meeting was closed at 15:50.

RECOMMANDATION CCTF-CCL 1 (2015) :
Mises à jour de la liste des fréquences étalons

Le Comité consultatif du temps et des fréquences (CCTF) et le Comité consultatif des longueurs (CCL),

considérant

- qu'une liste commune des « valeurs recommandées de fréquences étalons destinées à la mise en pratique de la définition du mètre et aux représentations secondaires de la seconde » a été établie,
- que le Groupe de travail commun au CCL et au CCTF sur les étalons de fréquence a examiné plusieurs fréquences candidates afin de mettre à jour cette liste,

recommandent

que les fréquences des transitions suivantes soient mises à jour dans la liste des fréquences étalons recommandées :

- la transition optique non perturbée $6s^2\ ^1S_0 - 6s6p\ ^3P_0$ de l'atome neutre de ^{199}Hg, à la fréquence de f_{199Hg} = 1 128 575 290 808 154,8 Hz avec une incertitude-type relative estimée de 6×10^{-16} ;
- la transition optique non perturbée $6s\ ^2S_{1/2} - 4f^{13}\ 6s^2\ ^2F_{7/2}$ de l'ion de $^{171}Yb^+$, à la fréquence de f_{171Yb+} (octupôle) = 642 121 496 772 645,0 Hz avec une incertitude-type relative estimée de 6×10^{-16} (cette radiation a déjà été approuvée par le CIPM comme représentation secondaire de la seconde) ;
- la transition optique non perturbée $6s\ ^2S_{1/2}$ (F = 0, m_F = 0) – $5d\ ^2D_{3/2}$ (F = 2, m_F = 0) de l'ion de $^{171}Yb^+$, à la fréquence de f_{171Yb+} (quadripôle) = 688 358 979 309 308,3 Hz avec une incertitude-type relative estimée de 6×10^{-16} (cette radiation a déjà été approuvée par le CIPM comme représentation secondaire de la seconde) ;
- la transition optique non perturbée $5s\ ^2S_{1/2} - 4d\ ^2D_{5/2}$ de l'ion de $^{88}Sr^+$, à la fréquence de f_{88Sr+} = 444 779 044 095 486,6 Hz avec une incertitude-type relative estimée de $1,6 \times 10^{-15}$ (cette radiation a déjà été approuvée par le CIPM comme représentation secondaire de la seconde) ;
- la transition optique non perturbée $4s\ ^2S_{1/2} - 3d\ ^2D_{5/2}$ de l'ion de $^{40}Ca^+$, à la fréquence de f_{40Ca+} = 411 042 129 776 398,4 Hz avec une incertitude-type relative estimée de $1,2 \times 10^{-14}$;
- la transition optique non perturbée 1S – 2S de l'atome neutre de ^{1}H, à la fréquence de f_{1H} = 1 233 030 706 593 514 Hz avec une incertitude-type relative estimée de $9,0 \times 10^{-15}$;

  Remarque : cette fréquence correspond à la moitié de l'écart en énergie entre les états 1S et 2S ;
- la transition optique non perturbée $5s^2\ ^1S_0 - 5s5p\ ^3P_0$ de l'atome neutre de ^{87}Sr, à la fréquence de f_{87Sr} = 429 228 004 229 873,2 Hz avec une incertitude-type relative estimée de 5×10^{-16} (cette radiation a déjà été approuvée par le CIPM comme représentation secondaire de la seconde) ;

- la transition optique non perturbée $6s^2\ {}^1S_0 - 6s6p\ {}^3P_0$ de l'atome neutre de ^{171}Yb, à la fréquence de f_{171Yb} = 518 295 836 590 864,0 Hz avec une incertitude-type relative estimée de 2×10^{-15} (cette radiation a déjà été approuvée par le CIPM comme représentation secondaire de la seconde) ;
- la transition hyperfine non perturbée de l'état fondamental de l'atome de ^{87}Rb, à la fréquence de f_{87Rb} = 6 834 682 610,904 310 Hz avec une incertitude-type relative estimée de 7×10^{-16} (cette radiation a déjà été approuvée par le CIPM comme représentation secondaire de la seconde) ;

recommandent par ailleurs

que les fréquences des transitions suivantes soient incluses dans la liste des fréquences étalons recommandées :

- Molécule absorbante de $^{127}I_2$, composante a_1 du spectre d'absorption saturée, transition R(36) 32-0.

  Les valeurs f_{a1} = 564 074 632,42 MHz

  λ_{a1} = 531 476 582,65 fm

  avec une incertitude-type relative estimée de 1×10^{-10} s'appliquent à la radiation d'un laser à diode à rétroaction répartie doublé en fréquence, asservi à l'aide d'une cellule d'iode située à l'extérieur du laser.

- Atome absorbant de ^{87}Rb, transition $5S_{1/2}$ - $5P_{3/2}$, croisement de niveaux entre les composantes hyperfines d et f de l'absorption saturée à 780 nm (transition D2).

  Les valeurs $f_{\text{croisement d/f}}$ = 384 227 981,9 MHz

  $\lambda_{\text{croisement d/f}}$ = 780 246 291,6 fm

  avec une incertitude-type relative estimée de 5×10^{-10} s'appliquent à la radiation d'un laser accordable à diode et à cavité externe, asservi sur la résonance de croisement de niveaux d/f dans une cellule de rubidium située à l'extérieur du laser.

Remarque : La valeur de l'incertitude-type est supposée correspondre à un niveau de confiance de 68 %. Toutefois, étant donné le nombre très limité de résultats disponibles, il se peut que, rétrospectivement, cela ne s'avère pas exact.

et requièrent l'adoption de ces fréquences étalons recommandées par le CIPM.

RECOMMANDATION CCTF 2 (2015) :

Prédictions de l’UTC disséminées à l’aide de systèmes globaux de navigation par satellite (GNSS)

Le Comité consultatif du temps et des fréquences (CCTF),

considérant

- que le BIPM a pour mission d’assurer l’uniformité mondiale des mesures et leur traçabilité au Système international d’unités (SI),
- qu’à l’heure actuelle deux systèmes GNSS existent et que d’autres sont en cours de développement,
- qu’au moins deux autres systèmes GNSS, BeiDou et Galileo, offrent des services, ou sont sur le point d’en offrir,
- que la Section 5 de la *Circulaire T* du BIPM indique la relation UTC/TAI, ainsi que les prédictions d’UTC(k) disséminées à l’aide des systèmes GPS et GLONASS,

a pour objectif

- de faciliter l’accès des utilisateurs aux prédictions en temps réel de l’UTC disséminées à l’aide des systèmes GNSS actuels et à venir,

recommande

- que la Section 5 de la *Circulaire T* du BIPM soit renommée « Relations of UTC and TAI with predictions of UTC disseminated by GNSS » (Relations entre l’UTC et le TAI avec prédictions de l’UTC disséminées à l’aide de systèmes GNSS) et que des informations similaires sur les nouveaux systèmes GNSS soient intégrées à la *Circulaire T* à mesure que ces systèmes GNSS deviennent opérationnels.

RECOMMANDATION CCTF 3 (2015) :
Sur l’étalonnage des équipements de comparaison de temps par GNSS

Le Comité consultatif du temps et des fréquences (CCTF),

considérant

- que l’aptitude à comparer des étalons atomiques de fréquence afin de réaliser l’UTC dépend de l’exactitude et de la précision des méthodes de comparaison de temps fondées sur des observations obtenues à l’aide de systèmes globaux de navigation par satellite (GNSS),
- que la caractérisation des retards des équipements GNSS de comparaison de temps est essentielle pour garantir l’exactitude des liaisons horaires utilisées pour le calcul de l’UTC,
- que, pour une liaison horaire, toute variation due à des retards d’équipement qui n’est pas corrigée peut conduire à une instabilité conséquente de l’UTC,
- que des campagnes périodiques d’étalonnage sont nécessaires pour que l’incertitude des liaisons horaires utilisées pour le calcul de l’UTC soit égale ou inférieure à 3 ns,
- que le Comité consultatif pour la définition de la seconde (CCDS) puis le Comité consultatif du temps et des fréquences (CCTF) ont souligné, dans les recommandations qu’ils ont formulées, l’importance d’étalonner les équipements de comparaison de temps dans les laboratoires qui envoient des données au BIPM pour le calcul de l’UTC,
- que le Comité consultatif du temps et des fréquences (CCTF), dans sa Recommandation 2 (2009) et dans sa Recommandation 4 (2012), a recommandé aux organisations régionales de métrologie d’apporter leur soutien au BIPM en organisant des campagnes de mesure des retards des équipements GNSS au niveau régional, qui seront liées à celles menées par le BIPM,

notant

- que des directives d’étalonnage ont été préparées par le BIPM et le Groupe de travail du CCTF sur les comparaisons de temps par GNSS et qu’elles ont été publiées sur le site internet du BIPM,
- que, parmi les laboratoires contribuant au calcul de l’UTC, un ensemble de laboratoires constituant le « Groupe 1 » a été sélectionné par les organisations régionales de métrologie : le BIPM organisera les étalonnages des laboratoires du Groupe 1 qui procéderont à leur tour à l’étalonnage des équipements GNSS des autres laboratoires, constituant le « Groupe 2 »,
- qu’il est attendu que la mise en œuvre de ce nouveau schéma d’étalonnages permette d’améliorer de façon significative l’exactitude des liaisons horaires,
- que le BIPM a achevé la première campagne d’étalonnage des équipements GNSS des laboratoires du Groupe 1 et organisera sous peu la seconde,

recommande

- que les organisations régionales de métrologie ou les laboratoires membres d’une organisation régionale de métrologie organisent périodiquement des campagnes d’étalonnage pour les laboratoires du Groupe 2,

- que les campagnes d'étalonnage soient planifiées en étroite collaboration avec le BIPM afin que l'ensemble des laboratoires du Groupe 2 en bénéficient,
- que ces étalonnages soient réalisés conformément aux directives publiées par le BIPM.

RECOMMANDATION CCTF 4 (2015) :

Sur la procédure « Common Generic GNSS Time Transfer Standard » (CGGTTS)

Le Comité consultatif du temps et des fréquences (CCTF),

considérant

- que la procédure et le format CGGTTS sont utilisés par les laboratoires de temps pour transférer leurs données horaires afin de contribuer au calcul de l’UTC,
- que le logiciel R2CGGTTS est couramment utilisé par les laboratoires participant au calcul de l’UTC pour générer des données CGGTTS,
- que le déploiement des constellations de Galileo, QZSS et BeiDou progresse et devrait s’achever ces prochaines années,
- que plusieurs fabricants de récepteurs fournissent déjà des observations fondées sur des systèmes globaux de navigation par satellite (GNSS) de différentes constellations,

notant

- qu’une extension du format CGGTTS a été définie sous le nom V2E de façon à inclure les résultats de comparaisons de temps obtenus à partir des satellites GPS, GLONASS, BeiDou, Galileo et QZSS,
- qu’une description complète du format V2E est disponible dans *Metrologia* 2015 **52** G1,

recommande

- que le Groupe de travail du CCTF sur les comparaisons de temps par GNSS coopère avec les fabricants de récepteurs de temps afin de leur demander de mettre à niveau leur logiciel interne pour qu’ils puissent fournir la version V2E du format CGGTTS,
- que les laboratoires de temps fournissent au BIPM des fichiers CGGTTS au format V2E,
- que le logiciel R2CGGTTS soit mis à niveau pour générer la version V2E.

RECOMMANDATION CCTF 5 (2015) :

Sur la conception des récepteurs des systèmes globaux de navigation par satellite (GNSS)

Le Comité consultatif du temps et des fréquences (CCTF),

considérant

- que l'utilisation combinée de mesures de phase et de code des signaux du GNSS permettent d'effectuer des comparaisons de temps et de fréquences de très haute précision,
- que cette technique est couramment utilisée pour le calcul de l'UTC,
- qu'il est attendu que les mesures GNSS soient utilisées par un plus grand nombre d'applications requérant un haut niveau de précision, telles que la comparaison d'étalons optiques de fréquence et de fontaines atomiques,
- que l'exactitude des comparaisons de temps et de fréquences à partir de systèmes GNSS repose sur la connaissance précise du temps de verrouillage (temps réel de réception) de chaque mesure,

notant

- que, bien que considérés comme synchrones, les temps de verrouillage des données de phase et de code peuvent être systématiquement décalés de quelques microsecondes,
- que certains récepteurs produisent des mesures de code corrigées pour un biais constant afin de tenir compte des retards internes dus au matériel, ce qui induit un décalage manifeste du temps de verrouillage entre les mesures de phase de la porteuse et les mesures de code,
- que la différence entre les temps de verrouillage pour la phase et le code génère une variation de l'effet Doppler pour les mesures de phase de la porteuse par rapport aux mesures de code, ce qui crée un biais de fréquence pour les données de phase et donc pour la solution d'horloge obtenue par l'analyse GNSS,
- qu'en raison de ce biais de fréquence, la fréquence de l'horloge de laboratoire apparaît biaisée de 30 ps par jour pour chaque microseconde de décalage du temps de verrouillage,

recommande

- au Groupe de travail du CCTF sur les comparaisons de temps GNSS de coopérer avec les fabricants de récepteurs pour leur demander de mettre à jour la conception des récepteurs et leur logiciel interne afin que la valeur absolue concernant le décalage du temps de verrouillage entre les mesures de phase et de code, telle que fournie dans les fichiers d'observation, soit inférieure à 100 ns. Les fabricants devraient prendre en considération toutes les données pertinentes relatives aux retards internes des récepteurs et les intégrer aux spécifications des récepteurs.

RECOMMANDATION CCTF 6 (2015) :

Développement des liaisons nationales et internationales afin d'améliorer les méthodes intercontinentales de comparaison d'horloges et de dissémination des données de temps et de fréquence aux parties prenantes

Le Comité consultatif du temps et des fréquences (CCTF),

considérant

- que certains étalons optiques de fréquence ont déjà permis d'obtenir des incertitudes relatives de l'ordre de 10^{-18} et que l'incertitude et l'instabilité des étalons optiques de fréquence mis au point dans les laboratoires du monde entier vont continuer à être réduites,
- qu'il a été démontré qu'il était possible de comparer des horloges sur de longues distances avec des liaisons par fibre optique obtenant une stabilité et une incertitude compatibles avec les meilleurs étalons optiques de fréquence actuels et à venir,
- qu'il est nécessaire de comparer régulièrement ces étalons, ce qui est essentiel dans le cadre de la préparation d'une redéfinition de la seconde, ainsi que pour d'autres applications telles que l'établissement des échelles de temps,
- que la stabilité des techniques de comparaison de temps et de fréquence couramment utilisées dans le monde pour produire le Temps atomique international (TAI) n'est pas suffisante pour comparer les meilleurs étalons optiques de fréquence,
- que l'intérêt des communautés scientifiques des sciences de la Terre et de la géodésie ne cesse de croître vis-à-vis de la géodésie chronométrique, c'est-à-dire vis-à-vis de nouvelles applications pour les étalons optiques de fréquence afin de déterminer les différences de potentiel gravitationnel et d'améliorer, grâce à ces mesures, les modèles de gravité de la Terre ainsi que les systèmes de référence,
- que l'industrie, en particulier les secteurs des télécommunications et de l'aérospatiale, a de plus en plus besoin que soient améliorées les aptitudes dans le domaine du temps et des fréquences par l'utilisation de meilleures méthodes de comparaison,

recommande

- aux laboratoires nationaux de métrologie, fournisseurs de réseaux de fibre optique, agences spatiales, gouvernements, organisations régionales de métrologie, ainsi qu'à l'Union internationale des télécommunications (UIT) et aux autres organismes pertinents :
  - de soutenir vigoureusement la recherche et le développement sur les techniques de comparaison de temps et de fréquence afin qu'elles présentent une stabilité et une incertitude similaires à celles des étalons de fréquence les plus avancés. Ces techniques peuvent concerner les liaisons par fibre optique, les liaisons micro-ondes par satellite avancées, les liaisons optiques sol-espace et espace-espace, les étalons de fréquence transportables et les horloges spatiales de pointe,
  - de contribuer à la mise en place d'une infrastructure pérenne de liaisons continentales et intercontinentales sélectionnées qui formeront la colonne vertébrale métrologique dans le domaine du temps et des fréquences pour ces nouvelles technologies,

  - de prendre les dispositions nécessaires afin que ces nouvelles technologies puissent être appliquées, avec le degré d'exactitude approprié, à d'autres domaines de la science, de l'industrie et de la société,

- au BIPM de participer activement à ces développements, notamment en préparant, dans le cadre de l'établissement des échelles de temps, l'exploitation des données de comparaisons d'horloges obtenues à partir de nouvelles méthodes de comparaison de temps et de fréquence,
- aux laboratoires contribuant au calcul de l'UTC et effectuant des comparaisons de temps en continu par fibre optique de soumettre régulièrement leurs résultats au Département du temps du BIPM.

RECOMMANDATION CCTF 7 (2015) :

Sur la mise en œuvre et la maintenance des réseaux de comparaison de temps et de fréquences par aller et retour par satellite (TWSTFT) pour les comparaisons internationales des horloges atomiques et des échelles de temps

Le Comité consultatif du temps et des fréquences,

considérant

- que des comparaisons de temps et de fréquences par aller et retour par satellite (TWSTFT) sont effectuées depuis 16 ans pour réaliser l’UTC,
- qu’une vingtaine de laboratoires situés en Asie, en Europe et en Amérique du Nord participent régulièrement au calcul de l’UTC en fournissant des données de comparaisons de temps et de fréquences par aller et retour par satellite, de façon continue et quotidienne pour la plupart des laboratoires,
- que les liaisons TWSTFT entre l’Asie et l’Europe ont été interrompues en décembre 2014,
- que des étalonnages réguliers permettent d’obtenir une incertitude des comparaisons de temps de l’ordre de 1 ns, ce qui représente la meilleure incertitude atteinte pour les comparaisons de temps internationales opérationnelles,
- que les techniques de mesure redondantes et indépendantes accroissent la robustesse de l’UTC,
- que les récents développements des comparaisons de temps et de fréquences par aller et retour par satellite, tels que l’utilisation de la phase de la porteuse ou de récepteurs à technique radio logicielle SDR, pourraient améliorer de façon spectaculaire les comparaisons d’horloges optiques effectuées sur de longues distances à l’aide de satellites,
- que les liaisons par fibre optique ne sont opérationnelles que sur de courtes distances,

notant

- que la réalisation des comparaisons de temps par aller et retour par satellite repose sur les services satellitaires, ce qui représente des coûts conséquents pour les laboratoires participants,

recommande

- que les laboratoires participant au calcul de l’UTC continuent à soutenir les activités de comparaison de temps et de fréquences par aller et retour par satellite, telles que la mise en œuvre continue du réseau international de comparaisons de temps, la restauration des liaisons entre l’Asie et l’Europe, et l’étalonnage périodique des liaisons,
- que de nouveaux travaux de développement soient entrepris dans le domaine des comparaisons de temps et de fréquences par aller et retour par satellite afin d’améliorer de façon significative les comparaisons à distance de temps et de fréquences, en particulier celles effectuées entre continents, et de réduire les coûts en utilisant de nouveaux types de signaux transmis.

RECOMMENDATION CCTF-CCL 1 (2015):
Updates to the list of standard frequencies

The Consultative Committee for Time and Frequency (CCTF), together with the Consultative Committee for Length (CCL),

considering that

- a common list of “Recommended values of standard frequencies for applications including the practical realization of the metre and secondary representations of the second” has been established,
- the CCL-CCTF Frequency Standards Working Group (WGFS) has reviewed several candidates for updating the list,

recommend

that the following transition frequencies shall be updated in the list of recommended values of standard frequencies:

- the unperturbed optical transition $6s^2\ {}^1S_0 - 6s6p\ {}^3P_0$ of the ^{199}Hg neutral atom with a frequency of f_{199Hg} = 1 128 575 290 808 154.8 Hz and an estimated relative standard uncertainty of 6×10^{-16};
- the unperturbed optical transition $6s\ {}^2S_{1/2} - 4f^{\,13}\ 6s^2\ {}^2F_{7/2}$ of the $^{171}Yb^+$ ion with a frequency of f_{171Yb+} (octupole) = 642 121 496 772 645.0 Hz and an estimated relative standard uncertainty of 6×10^{-16} (this radiation is already endorsed by the CIPM as a secondary representation of the second);
- the unperturbed optical transition $6s\ {}^2S_{1/2}$ (F = 0, m_F = 0) – $5d\ {}^2D_{3/2}$ (F = 2, m_F = 0) of the $^{171}Yb^+$ ion with a frequency of f_{171Yb+} (quadrupole) = 688 358 979 309 308.3 Hz and an estimated relative standard uncertainty of 6×10^{-16} (this radiation is already endorsed by the CIPM as a secondary representation of the second);
- the unperturbed optical transition $5s\ {}^2S_{1/2} - 4d\ {}^2D_{5/2}$ of the $^{88}Sr^+$ ion with a frequency of f_{88Sr+} = 444 779 044 095 486.6 Hz and an estimated relative standard uncertainty of 1.6×10^{-15} (this radiation is already endorsed by the CIPM as a secondary representation of the second);
- the unperturbed optical transition $4s\ {}^2S_{1/2} - 3d\ {}^2D_{5/2}$ of the $^{40}Ca^+$ ion with a frequency of f_{40Ca+} = 411 042 129 776 398.4 Hz and an estimated relative standard uncertainty of 1.2×10^{-14};
- the unperturbed optical transition 1S – 2S of the ^{1}H neutral atom with a frequency of f_{1H} = 1 233 030 706 593 514 Hz and an estimated relative standard uncertainty of 9.0×10^{-15}.

Note: This frequency corresponds to half of the energy difference between the 1S and 2S states;

- the unperturbed optical transition $5s^2\ {}^1S_0 - 5s5p\ {}^3P_0$ of the ^{87}Sr neutral atom with a frequency of f_{87Sr} = 429 228 004 229 873.2 Hz and an estimated relative standard uncertainty of 5×10^{-16} (this radiation is already endorsed by the CIPM as a secondary representation of the second);
- the unperturbed optical transition $6s^2\ {}^1S_0 - 6s6p\ {}^3P_0$ of the ^{171}Yb neutral atom with a frequency of f_{171Yb} = 518 295 836 590 864.0 Hz and an estimated relative standard uncertainty of 2×10^{-15} (this radiation is already endorsed by the CIPM as a secondary representation of the second);

- the unperturbed ground-state hyperfine transition of ^{87}Rb with a frequency of f_{87Rb} = 6 834 682 610.904 310 Hz and an estimated relative standard uncertainty of 7×10^{-16} (this radiation is already endorsed by the CIPM as a secondary representation of the second).

and also **recommend**

that the following transition frequencies shall be included in the list of recommended values of standard frequencies:

- Absorbing molecule $^{127}I_2$, saturated absorption a_1 component, R(36) 32-0 transition.

The values f_{a1} = 564 074 632.42 MHz

$\lambda_{\alpha 1}$ = 531 476 582.65 fm

with an estimated relative standard uncertainty of 1×10^{-10} apply to the radiation of a frequency-doubled diode DFB laser, stabilized with an iodine cell external to the laser.

- Absorbing atom ^{87}Rb $5S_{1/2}$ - $5P_{3/2}$ crossover between the d and f hyperfine components of the saturated absorption at 780 nm (D2 transition)

The values $f_{\text{d/f crossover}}$ = 384 227 981.9 MHz

$\lambda_{\text{d/f crossover}}$ = 780 246 291.6 fm

with an estimated relative standard uncertainty of 5×10^{-10} apply to the radiation of a tunable External Cavity Diode Laser, stabilized to the d/f crossover in a rubidium cell external to the laser.

Note: The value of the standard uncertainty is assumed to correspond to a confidence level of 68 %. However, given the limited availability of data there is a possibility that in hindsight this might not prove to be exact.

and ask the CIPM for adoption.

RECOMMENDATION CCTF 2 (2015):

Predictions of UTC disseminated by Global Navigation Satellite Systems (GNSS)

The Consultative Committee for Time and Frequency (CCTF),

considering that

- the task of the BIPM is to ensure world-wide uniformity of measurements and their traceability to the International System of Units (SI),
- two GNSS already exist and others are under development,
- at least two additional GNSS – BeiDou and Galileo – currently offer or are close to offering services,
- section 5 of BIPM *Circular T* publishes the relationship between UTC/TAI and the predictions of UTC(k) disseminated by GPS and GLONASS;

aims to

- facilitate access for any user to real-time predictions of UTC disseminated by existing and future GNSS;

recommends that

- Section 5 of BIPM *Circular T* be retitled “Relations of UTC and TAI with predictions of UTC disseminated by GNSS”, and adds similar information on new GNSS as they become operational.

RECOMMENDATION CCTF 3 (2015):
On the GNSS time transfer equipment calibration

The Consultative Committee for Time and Frequency (CCTF),

considering that

- the ability to compare the atomic frequency standards for the realization of UTC is dependent on the accuracy and precision of time transfer methods based on Global Navigation Satellite Systems (GNSS) observations,
- the characterization of the delays of GNSS time-transfer equipment is essential to ensure the accuracy of the time links for UTC,
- uncompensated changes of the hardware delays in a time link may cause significant instability in UTC,
- periodic calibration campaigns are necessary to assure an uncertainty at or below 3 ns for the time links included in the computation of UTC,
- the Consultative Committee for the Definition of the Second (CCDS) and subsequently the Consultative Committee for Time and Frequency (CCTF) have stressed in past Recommendations the importance of calibrating the time transfer equipment in laboratories that contribute data for the calculation of UTC at the BIPM,
- the Consultative Committee for Time and Frequency (CCTF), in its Recommendation 2 (2009) and Recommendation 4 (2012), recommended that the Regional Metrology Organizations (RMOs) support the BIPM by organizing campaigns of delay measurements within the framework of regional comparisons to be linked to those conducted by the BIPM;

noting that

- calibration guidelines have been prepared by the BIPM and the CCTF WG on GNSS time transfer (WGGNSS) and published on the BIPM website,
- among laboratories contributing to UTC, a set of “Group1” laboratories was selected by the RMOs, for which the calibration is organized by the BIPM and from which the calibration of GNSS equipment of the other laboratories should be organized (named “Group 2”),
- significant improvement in time link accuracy is expected from the implementation of this new calibration scheme,
- the BIPM has completed the first calibration of the GPS equipment in Group 1 laboratories and will soon organize the second measurement campaign;

recommends that

- the RMOs or laboratories contributing to RMOs periodically organize calibration trips for Group 2 laboratories,
- the trips be planned in close collaboration with the BIPM, aiming at a complete coverage of Group 2 laboratories,
- these calibrations follow the guidelines published by the BIPM.

RECOMMENDATION CCTF 4 (2015):
On the Common Generic GNSS Time Transfer Standard (CGGTTS)

The Consultative Committee for Time and Frequency (CCTF),

considering that

- the CGGTTS format and standard is used by time laboratories to transfer the time of their clocks to the computation of UTC,
- the software ‘R2CGGTTS’ is commonly used by UTC laboratories to generate CGGTTS data,
- the deployment of the Galileo, QZSS and BeiDou constellations is in progress and should be completed in the coming years,
- several receiver manufacturers already provide Global Navigation Satellite Systems (GNSS) observations from the different constellations;

noting that

- an extension of the CGGTTS format has been defined under the name V2E so as to include the time transfer results from the GPS, GLONASS, BeiDou, Galileo and QZSS satellites,
- the complete description of the V2E standard has been made publicly available in *Metrologia* 2015 **52** G1;

recommends that

- the CCTF WG on GNSS Time Transfer (WGGNSS) interacts with manufacturers of timing receivers to request that they upgrade their firmware so as to provide version V2E of the CGGTTS,
- the time laboratories provide CGGTTS files to the BIPM in the V2E format,
- the software ‘R2CGGTTS’ be upgraded to generate the version V2E.

RECOMMENDATION CCTF 5 (2015):

On the design of Global Navigation Satellite System (GNSS) receivers

The Consultative Committee for Time and Frequency (CCTF),

considering that

- the use of a combination of code and carrier phase GNSS measurements enables time and frequency transfer with an extremely high precision,
- this technique is routinely used for UTC generation,
- GNSS measurements are expected to be used by a greater number of applications that require greater precision, such as the comparison of optical frequency standards and atomic fountains,
- the precision of the GNSS time and frequency transfer solution relies on the accurate knowledge of the latching time (effective reception time) of each measurement;

noting that

- while considered as synchronous, the latching times of phase and code data can be systematically offset by several microseconds,
- some receivers produce code measurements corrected for a constant bias to account for internal hardware delays, inducing an apparent latching time offset between the code and carrier phase measurements,
- the difference between the latching times of code and phase induces a Doppler increment in the carrier phase measurements relative to the codes, causing a frequency bias in the phase data and hence in the clock solution obtained from GNSS analysis,
- this frequency bias results in a laboratory clock's frequency appearing to be biased by 30 ps/day for every microsecond of latching offset;

recommends that

- the CCTF WG on GNSS time transfer (WGGNSS) interacts with manufacturers to request that they upgrade the design and firmware of receivers so that the absolute value of the latching time offset between the code and carrier phase measurements provided in the observation files is less than 100 ns. This should take into account all relevant receiver internal delays and this information should be included in the receiver specifications.

RECOMMENDATION CCTF 6 (2015):

Development of national and international time and frequency links to improve methods for intercontinental clock comparisons and for dissemination to stakeholders

The Consultative Committee for Time and Frequency (CCTF),

considering

- that some optical frequency standards have already demonstrated fractional uncertainties in the low 10^{-18} and that the reduction in the uncertainty and instability of optical frequency standards developed in institutes around the world will continue,
- that long-distance comparison with optical fibre links has been demonstrated with a stability and uncertainty that is compatible with the best present and future optical frequency standards,
- the need for regular comparisons between these standards as an essential part of the preparation for a redefinition of the second and for other applications such as contributions to time scales, that the stabilities of time and frequency transfer techniques currently and routinely used for comparisons around the world, i.e. for the production of International Atomic Time (TAI), are insufficient for comparisons between the best optical frequency standards,
- the growing interest of the Earth science and geodesy scientific communities for chronometric geodesy, i.e. new applications of optical frequency standards for determining gravitational potential differences and improving Earth gravity models and reference systems with these measurements,
- the growing needs of industry for improving time and frequency capabilities using better transfer methods, in particular in the telecommunication and aerospace sectors.

recommends that

- National metrology institutes (NMIs), optical fibre network providers, space agencies, national governments, regional metrology organizations (RMOs), International Telecommunication Union (ITU) and other relevant bodies:
  - vigorously support research and development of time and frequency transfer techniques matching the stability and uncertainty of the most advanced frequency standards. These techniques may include optical fibre links, advanced satellite microwave links, optical ground to space and space to space links and transportable frequency standards, and advanced space clocks,
  - help secure sustainable infrastructure of selected continental and intercontinental links forming a global time and frequency metrology backbone for these novel technologies,
  - make provisions for these novel technologies to be transferred with the relevant accuracy to other fields of science, industry and society,
- the BIPM participates actively in these developments, notably by making preparations for exploiting, in time scale realization, clock comparison data issued from new time and frequency transfer methods.
- those laboratories contributing to UTC and performing continuous time comparisons via fibre links regularly submit their results to the BIPM Time Department.

RECOMMENDATION CCTF 7 (2015):

On the operation and maintenance of Two-Way Satellite Time and Frequency Transfer (TWSTFT) networks for international atomic clock and time scale comparisons

The Consultative Committee for Time and Frequency (CCTF),

considering that

- TWSTFT has been used in the realization of UTC for 16 years,
- about 20 institutes in Asia, Europe, and North America have contributed regularly to UTC with their TWSTFT data, most of them providing their data continuously on a daily basis,
- the Asia-Europe TWSTFT links were interrupted in December 2014,
- regular calibrations offer a time transfer uncertainty at the level of 1 ns, which is the best uncertainty achieved for operational international time transfer,
- having redundant and independent measurement techniques increases the robustness of UTC,
- recent developments in TWSTFT, e.g. employing the carrier phase or software defined receivers (SDR), may dramatically improve satellite based optical clock comparisons over long baselines,
- fibre links are operational only over short distances;

and noting that

- TWSTFT operation relies on satellite services with substantial costs for the participating institutes;

recommends that

- institutes participating in UTC continue to support the TWSTFT activities, including continuous operation of the international TWSTFT network, restoration of the Asia-Europe TWSTFT links and periodic link calibrations,
- new developments in TWSTFT be undertaken to significantly improve remote time and frequency comparisons especially over intercontinental distances and also to reduce costs through the use of new kinds of transmitted signals.