Bureau International des Poids et Mesures

Consultative Committee for Time and Frequency (CCTF)

Report of the 21st meeting
(8-9 June 2017)
to the International Committee for Weights and Measures

Comité international des poids et mesures

LIST OF MEMBERS OF THE CONSULTATIVE COMMITTEE FOR TIME AND FREQUENCY
as of 8 June 2017

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

All-Russian Scientific Research Institute of Physical Technical Measurements, Rosstandart [VNIIFTRI], Moscow

Central Office of Measures [GUM], Warsaw

Centro Nacional de Metrología [CENAM], Mexico

Federal Office of Metrology [METAS], Wabern

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

RISE Research Institutes of Sweden AB [RISE], Borås

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

Technical University of Graz [TUG], Graz

U.S. Naval Observatory [USNO], Washington

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

VSL B.V. [VSL], Delft

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

Observers

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

Ministry of Higher Education, Science and Technology, Metrology Institute [MIRS], Celje

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

Liaisons

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]

GLOSSARY

ACES	Atomic Clock Ensemble in Space
BIH	Bureau International de l'Heure
BIPM	Bureau International des Poids et Mesures
CCL	Consultative Committee for Length
CCM	Consultative Committee for Mass and related quantities
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
EMPIR	European Metrology Programme for Innovation and Research
ESA	European Space Agency
ESMA	European Securities and Markets Authority
GNSS	Global Navigation Satellite System
IAG	International Association of Geodesy
IERS	International Earth Rotation and Reference Systems Service
ISO	International Organization for Standardization
ITRF	International Terrestrial Reference Frame
ITRS	International Terrestrial Reference System
ITU	International Telecommunication Union
ITU-R	International Telecommunication Union – Radiocommunication sector
JCRB	Joint Committee of the Regional Metrology Organizations and the BIPM
KCDB	BIPM Key Comparison Data Base
LoF	CIPM List of Recommended Frequencies
MiFID II	Markets in Financial Instruments Directive II
NMI / DI	National Metrology Institute / Designated Institute
PFS	Primary Frequency Standard
PoW	Programme of Work
RMO	Regional Metrology Organization
SDR	Software Defined Radio
SFS	Secondary Frequency Standard
SRS	Secondary Realization of the Second
TF	Time and Frequency
WRC	World Radiocommunication Conference of ITU
WG-ALGO	CCTF Working Group on Time Scale Algorithms
WGATFT	CCTF Working Group on Coordination of the Development of Advanced Time and Frequency Transfer Techniques
WGFS	CCL-CCTF Frequency Standards Working Group
WGGNSS	CCTF Working Group on GNSS Time Transfer
WGMRA	CCTF Working Group on Mutual Recognition Arrangement
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 21st meeting at the International Bureau of Weights and Measures (BIPM) headquarters, at Sèvres on 8 and 9 June 2017.

The following were present:

J. Achkar (LNE-SYRTE), K. Aldawood (SASO), H. Alvarez (ROA), A. Bauch (PTB), R. Beard (ITU-R), J. Bernard (NRC), L.-G. Bernier (METAS), S. Bize (LNE-SYRTE), C. Boucher (IUGG), D. Calonico (INRIM), M. Coleman (IGS), A. Czubla (GUM), J. Davis (NPL), R. De Carvalho (ON/DSHO), P. Defraigne (ORB), E. Dierikx (VSL), Y. Domnin (VNIIFTRI), L. Erard (CIPM/CCTF President), H. Esteban (ROA), Z. Fang (NIM), G. Garcia (INMETRO), A. Gedik (UME), M. Gertsvolf (NRC), P. Gill (NPL), N. Goldovsky (INPL), R. Hamid (UME), Y. Hanado (NICT), L. Hernández (INM Colombia), F.-L. Hong (NMIJ/AIST), M. Hosokawa (NICT), S.W. Hwang (KRISS), T. Ido (NICT), K. Jaldehag (RISE), S. Jefferts (NIST), P. Koppang (USNO), N. Koshelyaevsky (VNIIFTRI), R. Lapuh (MIRS), F. Levi (INRIM), J. Levine (NIST), J. Lodewyck (LNE-SYRTE), M. Lopez (CINVESTAV), H. Margolis (NPL), C. Matthee (NMISA), D. McCarthy (IAU), M. Milton (Director of the BIPM), A. Naumov (VNIIFTRI), J. Nawrocki (SRC), C. Oates (NIST), E. Peik (PTB), B. Pinter (MIRS), C. Pires (IPQ), F. Riehle (PTB), S. Romisch (NIST), D. Rovera (LNE-SYRTE), H. Santos (ON/DSHO), T. Suzuyama (NMIJ/AIST), P. Tavella (INRIM), A. Wallin (MIKES), W. Walls (USNO), M. Whibberley (NPL), M. Yasuda (NMIJ/AIST), D.H. Yu (KRISS), A. Zhang (NIM), V. Zhang (NIST).

Invited: H.T. Lin (TL), T. Quinn (BIPM Emeritus Director)

Also present: E.F. Arias (Executive Secretary of the CCTF), J. Gonçalves, Z. Jiang, S. Maniguet (KCDB), G. Panfilo, G. Petit, L. Robertsson, L. Tisserand, N. Zviagin (JCRB Executive Secretary).

Mr L. Erard, President of the CCTF, opened the meeting at 09:00 h and Dr M. Milton, Director of the BIPM, welcomed the participants.

The President noted that the minutes of the 20th 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: Dr J. Achkar agreed to prepare the minutes of the meeting. There were no objections from the other participants.

Adoption of the agenda: Dr F. 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. 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

The President proposed that all actions reported during the previous meeting of the CCTF should be considered.

- Action 1 – on a formal definition of TAI: the WGTAI has prepared a recommendation.
- Action 2 – on the revision of section 6 of the BIPM *Circular T* to give better information on the link calibrations: BIPM *Circular T* was revised.
- Action 3 – on the preparation of a recommendation on a standard data format for optical fibre links in UTC: only one link is provided to BIPM for analysis only, it is not included in UTC.
- Action 4 – on a guideline for the CMCs submission and/or revision: the WGMRA has prepared a Supplementary Guide for Appendix B and C of the CIPM MRA.
- Action 5 – on regularly collecting information from RMOs on regional comparisons and pilot projects in the field of time and frequency: RMOs now publish the information on their websites.
- Action 6 – on establishing the rules for periodic evaluation of adequacy of the CMCs claimed by the NMIs and available in the KCDB: the WGMRA has prepared a Supplementary Guide for Appendix B and C of the CIPM MRA.
- Action 7 – on request for membership/observership: the CCTF President recalled that since the last CCTF meeting, GUM and UME have become new members and MIRS is now an Observer. He added that the rules for membership/observership have changed and will be presented at this meeting.
- Action 8 – on the strategy document to be finalized in 2016 including an update of the Roadmap to the re-definition of the second with visible milestones: the updated version of the strategy document was issued on May 2016 and is available on the BIPM website.

The President commented that most of the actions have been completed. Those that have not will be included in new actions decided during the meeting. He added that the five new proposals for recommendations and the four input documents from the WGMRA, submitted to this meeting must be considered.

In memoriam Bernard Guinot

Dr Arias gave a short talk in memoriam of Bernard Guinot (1925-2017). Bernard Guinot was Director of the BIH, located at the Observatoire de Paris, between 1965 and 1985. He worked on the official transfer of BIH time scale activities to the BIPM in 1985 and organized and headed the Time Section. He made outstanding contributions to space and time metrology. Dr Arias concluded by saying that his competence, rigour and scientific authority have been unanimously recognized and therefore we have lost a prominent personality. A minute of silence was observed by the participants.

Dr Milton announced that the next director of the BIPM Time Department will be Dr P. Tavella, following the retirement of Dr Arias in November 2017. He presented an update on the redefinition of the SI, the Joint CCM and CCU Roadmap for the new SI to 2018, Recommendation G1 (2017) of the CCM to the CIPM for a new definition of the kilogram in 2018 and the CIPM decisions on the redefinitions at its next meeting (October 2017). He concluded by giving some information from the Task Group that was set up for the promotion of the SI and to help NMIs to use this important event to promote the work of the metrology community.

3. REPORT OF THE BIPM TIME DEPARTMENT (F. Arias, BIPM) (CCTF/17-35)

The permanent staff of the BIPM Time Department over the last two years consisted of eight persons. Hawaï Konaté retired in October 2016 and Johanna Gonçalves started in March 2017. There have been three visitors/secondees, for short visits.

An overview of the Programme of Work 2016-2019 was given, including projects (computation and dissemination of time scales, calibration of time transfer equipment, very accurate standards and appropriate transfer techniques, international liaison and coordination) and deliverables (UTC, Rapid UTC, TT(BIPM), improving the uncertainty of [UTC-UTC(k)], including SRS (optical) in TAI, and supporting activities within the framework of the CIPM MRA).

Achievements over the past two years include:

- Algorithm for TAI: a new algorithm for the computation of TAI was implemented in 2014, resulting in an improvement in the stability of EAL and TAI. Studies for implementing a new algorithm for the computation of the uncertainties of [UTC-UTC(k)] have been introduced. The major benefits will be to make use of the best available time transfer measurements (redundant links); avoiding a time link structure based on a unique pivot laboratory; and dealing with correlations. The process will be introduced in a series of steps.

- Rapid UTC (UTCr) has been implemented since July 2013. Currently, 52 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*. The main problems encountered are the big steps UTC-UTCr and UTCr-UTC(k). Studies found possible reasons due to differences between the algorithms of UTC and UTCr (in terms of weighting) or due to the start of the computation interval or some input data differences. Possible solutions are under way.

- Time transfer equipment calibrations: improving the accuracy of UTC-UTC(k) by implementing continuous calibration campaigns for reducing time link systematic uncertainty from 5 ns to less than 2.5 ns has been introduced. The process that has been set up is carried out in three steps: the BIPM calibrates time transfer equipment in selected laboratories “Group 1” per region (G1); RMOs calibrate equipment in other laboratories “Group 2” (G2); and the BIPM validates RMO calibrations and computes the final results. The first campaign to all G1 laboratories has been concluded and the results implemented. The second campaign in EURAMET and SIM G1 is ongoing.

- Time transfer uncertainty: the uncertainty budget now takes into account the following contributions: link stability accounts for measurement noise and random effects over a period of 1 to 30 days, calibration, calibration aging and alignment. The evolution of the systematic uncertainty increases with time as a random walk process is presented.

- Reducing diurnal measurement noise in TWSTFT: the degradation of TWSTFT link stability due to approximately 2 ns peak-to-peak diurnal noise led the TWSTFT working group to seek an effective solution by operating a software-defined radio (SDR) receiver. A pilot study with the BIPM and the WGTWSTFT shows significant noise reduction on short baselines.
- Uncertainty evaluation of optical frequencies to be recommended for secondary definition of the second: Optical transitions recommended by the CIPM as SRS are potential candidates to redefine the SI second. They are selected by the CCTF from measurements of frequencies and frequency rations reported by NMIs. The number of reported transitions and rations is increasing, as well as the number of NMIs developing the same atomic species, making the system more complex. It became necessary to develop independent mathematical methods to evaluate the recommended values of the transitions and ratios and to estimate their uncertainties. Based on the graph theory framework, another method for solving measurement and ratio loops with deviations to zero closure due to noise or systematic errors has been implemented and validated.
- International liaison and cooperation – ITU/Time scale definitions and dissemination: The BIPM participated actively in the ITU's WRC-15, particularly in the preparation of the resolution on UTC. Consequently, the BIPM Time Department organized and participated in the CCTF WGTAI task group on time scales definition and developed a strategy ready for the CGPM (2018) and the WRC-23 (2023).

In addition to the regular publication in the BIPM KCDB, of the monthly results of the single key comparison on UTC (CCTF-K001.UTC) since 2015, the publications from the BIPM Time Department over the past two years have included: the BIPM Annual Report on Time Activities 2015 and 2016; monthly BIPM *Circular T*; weekly Rapid UTC; annually TT(BIPMXY) for 2015 and 2016; and scientific publications from the Time Department staff. These publications can be found on the BIPM website or on the FTP server.

4. PROGRESS IN FREQUENCY STANDARDS

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

The President informed the CCTF that detailed reports from laboratories have been submitted to the meeting and are available on the BIPM website. He invited participants to give a short presentation on their laboratories' new developments and work on frequency standards.

<u>NPL (CCTF/17-18):</u> Dr Gill reported that the NPL has developed a number of cold atom fountain clocks for its own use as primary frequency standards and for installation in other NMI laboratories.

Two fountain standards are now operational at the NPL: NPL-CsF2 has been operational since 2009 and contributes regularly to the BIPM steering process for TAI. After several years of operation this fountain required an upgrade: an optical setup of the new design and a new electronic control system are being implemented. NPL-CsF3 was provisionally evaluated in 2015 with full evaluation pending an optics upgrade similar to NPL-CsF2 and the full implementation of a new local oscillator. During the upgrade work, fountain data were used internally for monitoring and steering the time interval of the local timescale UTC(NPL).

There are two optical clock transitions of $^{171}Yb^{+}$ being studied at the NPL (E3 at 467 nm and E2 at 436 nm). The optical frequency ratio E3:E2 was measured directly, along with the absolute frequencies of the E2 and E3 transitions relative to NPL-CsF2. New polarizability measurements have been carried out, recording the atomic frequency shift induced by the electric field from a 7-μm laser for both the E2 and E3 transitions. Preliminary results give an improved value for the E2 polarizability, and also show good agreement with PTB's recent measurement for the E3 polarizability. Direct comparisons with optical frequency standards at other European NMIs have been made via satellite links.

The NPL has developed two Sr^{+} endcap trap systems, which have been compared and shown to have a null offset at the 4 parts in 10^{17} level. The NPL plans to build new traps and to upgrade a number of its laser systems.

A Sr optical lattice clock (NPL-Sr1) is in operation at the NPL. Recently, NPL-Sr1 was compared to two Sr clocks in SYRTE over an 800 km dark fibre link operated between the NPL and LPL and the LPL to SYRTE. The comparison reached a fractional frequency instability of a few parts in 10^{17} after 104 s of averaging, limited by the performance of the clocks. Absolute frequency measurements of both ^{87}Sr and ^{88}Sr, together with local optical frequency ratios against Yb^{+} and Sr^{+} clocks, are currently being pursued.

<u>PTB (CCTF/17-07):</u> Dr Piek reported that the primary caesium fountain clocks PTB-CSF1 and PTB-CSF2 have been operated under normal operating conditions most of the time. In this operation mode, the fountains have been used for a multitude of measurements of the TAI scale unit, for daily steering of the timescale UTC(PTB), for international fountain clock comparisons and for optical frequency measurements. During 2015 and 2016, a total of 14 TAI scale unit measurements by CSF1, and 13 by CSF2, have been submitted to the BIPM.

The PTB operates optical frequency standards at 429 THz based on ^{87}Sr atoms in an optical lattice and standards at 688 THz and 642 THz based on a single $^{171}Yb^{+}$ ion. In addition, a transportable SR lattice clock has been set up for use in comparisons of remote optical clocks and for novel applications, such as relativistic geodesy. Two femtosecond frequency comb generators and a network of phase-coherent optical fibre links are used to link the standards to stable reference lasers and to connect them for optical frequency ratio measurements and to the primary Cs fountain clocks. Research is being conducted towards a frequency standard at 1 121 THz based on a $^{27}Al^{+}$ with a Ca^{+} logic ion, and on new reference systems: the Th-229 nuclear resonance, multiple In^{+} ions and highly-charged ions.

Investigations have been performed into the quality of a time scale that is referenced to an optical clock, which does not operate in a nearly continuous fashion. A formalism has been developed that allows for a simple estimation of the uncertainty introduced by a fly wheel oscillator, such as a maser, which bridges the downtimes of the optical clock. For the noise characteristics of a maser operating at the PTB and an availability of the optical clock of about 50 %, the uncertainty of the timescale can be improved to about 200 ps over a 25 day period.

NICT (CCTF/17-22): Dr Ido reported that NICT has been developing the Cs atomic fountain primary frequency standards NICT-CsF1 and NICT-CsF2 for contributions to the determination of TAI and the calibration of Japan Standard Time. CsF1 had been in operation with a typical uncertainty of 1.4×10^{-15} since 2006. However, its operation has been suspended for a number of years and the system is currently being upgraded to allow operation at the 10^{-16} level. CsF2 has a different laser cooling geometry than CsF1, enabling many atoms to be captured without a magnetic field gradient in large diameter laser beams, resulting in a reduction in the atomic density and thus a smaller collisional shift. The vacuum problem that occurred a few years ago has now been resolved and the systematics will be re-evaluated.

A ^{87}Sr optical lattice clock has been in operation at NICT since 2011. In 2015, the absolute frequency measurement with reduced uncertainty was performed with respect to International Atomic Time (TAI). The absolute frequency agrees with latest measurements at the PTB and SYRTE.

A single-ion optical clock based on $^{115}In^+$ is under development at NICT. The advantages of the clock transition at 237 nm are the ultimate relative frequency inaccuracy in the order of 10^{-18} and the prospective stability enhancement by use of multiple ions. A new approach of using two $^{40}Ca^+$ ions in a linear trap for sympathetic cooling of the In^+ as well as for micromotion and the magnetic-field probe has been successfully employed for the observation of the clock transition.

Furthermore, NICT has started to establish a new frequency standard in the THz (0.1 THz – 10 THz) region (this is not an atomic frequency standard). A wide frequency range and highly accurate THz frequency counter, based on a photocarrier THz comb in a photoconductive antenna using a femtosecond-pulse mode-locked laser, has been developed for measuring absolute THz frequencies.

NIM: Dr Fang reported briefly on the progress in frequency standards at NIM. *There was no report submitted by NIM.*

NMIJ (CCTF/17-28): Dr Yasuda reported that the operation of the first caesium fountain NMIJ-F1 stopped following the earthquake in 2011. The restart is still pending due to lack of funds and human resources. The second caesium fountain, NMIJ-F2, is still under construction.

NMIJ is developing a dual optical lattice clock system consisting of strontium and ytterbium. Both atomic species have been successfully laser-cooled and loaded to optical lattices at the same location in the vacuum chamber. NMIJ has also started developing a third optical lattice clock, which is intended for continuous long-term operation.

NRC (CCTF/17-19): Dr Gertsvolf reported that the new NRC caesium fountain frequency standard, FCs2, is currently under evaluation. FCs2 contains a new physics package as well as upgraded optical systems, microwave and RF electronics, and control systems. The physics package was constructed at the NPL and is similar to NPL-CsF2.

The $^{88}Sr^+$ ion optical frequency standard system has been evaluated. Its fractional frequency uncertainty is 1.2×10^{-17}, currently limited by the evaluation of the blackbody radiation field at the ion.

INRIM (CCTF/17-21): Dr Levi reported that since 2013 INRIM has been operating its cryogenic Cs fountain ITCsF2 to calibrate the UTC(IT) master clock and TAI. Since the last CCTF meeting, ITCsF2 provided eight TAI calibrations for a total measurement time of 200 days.

INRIM is developing an optical frequency standard based on ^{171}Yb atoms confined in an optical lattice. The absolute frequency of the Yb clock transition has been measured with respect to the INRIM cryogenic fountain ITCsF2. In 2016, the INRIM Yb clock was compared to the PTB transportable Sr optical frequency standard.

LNE-SYRTE (CCTF/17-30): Dr Bize reported that LNE-SYRTE operates two cold atom fountains, which regularly contribute to TAI: FO1 is a caesium fountain (PFS since 1995) and FO2 is a double fountain operating simultaneously with caesium as PFS (since 2002) and with rubidium as SFS also included in the steering of TAI (since 2013). From January 2015 to April 2017, the LNE-SYRTE PSFS, FO1, FO2-Cs and FO2-Rb provided 2, 27 and 29 calibration reports to the BIPM, respectively, to contribute to the steering of TAI.

A first international comparison of distant fountain PSFSs via an optical link was performed. LNE-SYRTE’s three fountain PSFSs were compared to the two PFSs of PTB (Braunschweig), CSF1 and CSF2, using the same link as that implemented for the comparison of the optical clocks from the two institutes. The results of the comparisons fully support the stated LNE-SYRTE and PTB PFSs’ uncertainties.

LNE-SYRTE is also leading the scientific development of a cold atom primary standard for 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).

LNE-SYRTE is developing two optical lattice clocks based on strontium and one optical lattice clock based on mercury. The best reported total fractional frequency uncertainty for Sr lattice clocks is 4.1×10^{-17}. The Hg optical lattice clock reached a total fractional frequency uncertainty of 1.7×10^{-16}. A short report was given on the work progress and results on these optical clocks since the previous meeting of the CCTF.

KRISS (CCTF/17-08): Dr Yu reported that KRISS is developing a Rb/Cs double fountain, KRISS-F1, which is at present operational as a caesium fountain clock. The accuracy evaluation of the atomic fountain is in progress.

KRISS is also developing a ^{171}Yb optical lattice clock for which significant improvements to reduce the systematic uncertainty of the clock have been carried out since the previous CCTF meeting. Good agreement on the absolute frequency measurement within the total uncertainty was obtained by direct comparison with the NICT ^{87}Sr lattice clock via a carrier phase two-way satellite frequency transfer technique.

VNIIFTRI (CCTF/17-09): Dr Koshelyaevsky reported that the VNIIFTRI currently has two caesium fountains. SU-CsF02 contributed to TAI more or less regularly for about 1.5 years over the period 2015-2016. SU-CsF01 has been considerably updated over the last two years (Su-CsF01M). Its accuracy estimation is six times better than the original SU-CsF01. VNIIFTRI is also developing two Rb fountain frequency standards; VNIIFTRI1 and VNIIFTRI2. The related research work is still in progress.

In the third quarter of 2016 the first stage of ^{87}Sr neutral atoms in an optical lattice frequency standard research programme has been completed. As a result, two standard prototypes have been developed.

NIST (CCTF/17-29): Dr Oates reported that the NIST-F1 primary frequency standard has recently been relocated and reconstructed, which resulted in the need to re-perform many of the tests to validate its performance in its new location. The NIST-F2 next generation caesium primary frequency standard has been approved by the WGPSFS and has submitted five formal frequency evaluations for inclusion into TAI (since the previous CCTF meeting).

NIST continues to work on the development of optical frequency standards based on: the transition of single trapped $^{27}Al^{+}$ ions at 267 nm, the 282 nm electric quadruple transition of single trapped $^{199}Hg^{+}$ ions, the thermal calcium beam in a Ramsey-Borde interferometer and the transition at 578 nm in ^{171}Yb atoms confined in optical lattices.

SRC: Dr Nawrocki reported briefly on the progress in frequency standards at the SRC. *There was no report submitted by SRC.*

METAS (CCTF/17-13): Dr Bernier reported that METAS is developing the continuous Cs fountain primary standard FoCS-2. A first one-month calibration of TAI was performed in March 2017. An article is in preparation for publication in *Metrologia* with a detailed report of the first evaluation of FoCS-2.

CENAM: Dr Lopez reported briefly on the progress in frequency standards at CENAM. *There was no report submitted by CENAM.*

USNO (CCTF/17-54, report submitted after the meeting): Dr Walls reported on the ensemble of atomic clocks consisting of hydrogen masers, Cs beams and six Rb fountains. The USNO is working on Hot Ca^{+} and Cold Ca^{+} optical clocks. GNSS simulators have been purchased for absolute calibration and validation of GNSS equipment to produce the GNSS to GPS Time Offset.

4.2 Report of the CCTF Working Group on Primary and Secondary Frequency Standards (S. Jefferts, NIST) (CCTF/17-14)

The past several years have seen the first submission of an optical standard to the group for inclusion into TAI calculations. This standard, based on Sr from the group at SYRTE, is an exciting and hopeful development for the future.

Rigorous discussions have been held over the last few years regarding re-evaluation by the working group in the event of a significant decrease in stated frequency uncertainty of a given standard. Finally, the consensus of the group seems to be that the standard should be re-evaluated by the group in the event of a significant reduction in uncertainty, but, so far, no consensus regarding the definition of a significant reduction has been forthcoming. This might be something to explore again in the future.

At the present time, the reported (fractional) systematic uncertainties in PFS range from 1.5×10^{-16} to 3.9×10^{-15}, and a statistical analysis seems to indicate that the PFSs are within reasonable statistical agreement. Currently, there are eleven PFS and one secondary standard that report regularly to TAI.

4.3 Frequency standards in TAI and realization of TT(BIPM) (G. Petit, BIPM) (CCTF/17-36)

TAI is computed in “real time” and is never corrected retrospectively, as 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 data. These estimates are smoothed and integrated each month. Since the previous meeting of the CCTF in 2015, there have been no significant changes to the computation of TT(BIPM). Since 2010, a prediction of TT(BIPM) has been published, first as monthly extensions, and since TT(BIPM13) as a function of TAI valid for the whole year.

For 2017: $TT(BIPM16)_{ext}$ = TAI + 32.184 s + 27679.0 ns – 0.05 × (MJD-57749) ns.

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

TT(BIPM) allows an estimate of the performance of primary and secondary frequency standards. A total of 1396 evaluations have been performed over 24 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(BIPM16)) from 2000 to 2017. A significant drift was observed in 2016, leading to a steering, which was reintroduced at the end of 2016.

Contributions of frequency standards are published in BIPM *Circular T*. Since July 2013, secondary representations of the second have also contributed to the steering of TAI. SRS are reported together with PFS. In 2016, there have been 44 contributions from seven PFS and 13 contributions from one SRS. Four Cs fountains are in almost continuous operation.

For the SRS, the BIPM Time Department expects to receive new SFS evaluations in order to provide visibility and to gain experience with their possible use in TAI steering.

Dr Petit concluded by stating that the full accuracy of PFS is not totally passed on to TAI and TT(BIPM) mainly because of the noise of frequency transfer. He added that the PFS reported uncertainties are globally consistent with the data, implying that TT(BIPM) is accurate at approximately 2×10^{-16} since 2012 and the TAI frequency is known with the same uncertainty.

5 TIME SCALES UTC AND TAI

5.1 Report of the CCTF Working Group on TAI (F. Arias, BIPM) (CCTF/17-37)

The WGTAI is temporarily chaired by Dr Arias, director of the BIPM Time Department. The terms of reference of the WGTAI were presented. The membership of WGTAI includes: representatives of IAU, CIPM, URSI and ITU-R, the Director of the BIPM, the individual responsible for TAI at the BIPM and representatives of the laboratories contributing to TAI.

The WGTAI held a meeting on 7 June 2017, the day before the CCTF meeting. The meeting was attended by about 80 participants. In the afternoon, a joint meeting of WGTAI and CCTF delegates took place.

Topics discussed in the meeting were:

- BIPM and laboratories' updates
- Presentation of recommendations to be submitted to the 21st CCTF
- Strategy towards the WRC-23
- Consideration of a recommendation with time scales definitions.

5.1.1 Task Group on Time Scales Definition

A task group was appointed in the WGTAI in 2016 for drafting the text of a recommendation to provide definitions of the current time scales. The recommendation was discussed and an agreement was reached.

5.1.2 Future actions in cooperation with the ITU and other international organizations

The main actions organized by the ITU-R, the CCTF and the BIPM were given in detail. Following the WRC-15 Resolution 655 on UTC, the BIPM presented a roadmap towards WRC-23 as follows:

- CIPM 2017: discussion and (possible adoption) of the recommendation on time scales definitions from the CCTF. The CIPM will decide on the submission to the CGPM of this recommendation as a Draft Resolution;
- CGPM 2018: approval (possible) of a Resolution on time scale definitions, and (possible) Resolution on the time scale to be adopted as reference for metrology after the revocation of the Recommendation ITU-R TF. 460-6;
- BIPM 2019-2022:
    - dissemination of information on the post-2023 reference time scale for metrology
    - coordination with the different communities of users (interaction with the different international unions)

- coordination with the ITU-R on the provision of the reference time scale for radio/telecommunications (via WP7A, SG7, CCTF, CIPM), in preparation for WRC-23.

5.2 Status of the algorithms for TAI (G. Panfilo, BIPM) (CCTF/17-24) and (CCTF/17-38)

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

The current values of u_A and u_B, reported in Section 1 of *Circular T*, are obtained by uncertainty propagation: they depend on the weights of the laboratories as the result of UTC algorithm and on the links' uncertainties. The time links connect each contributing laboratory to PTB, which plays the role of the pivot. No correlations are taken into account for the uncertainty propagation algorithm.

With the improvement of time link performance, the current algorithm for uncertainty propagation shows some limitations. Estimating the correlation in the uncertainty propagation is very difficult in the current formalism and a different approach is proposed.

The new algorithm for the calculation of the uncertainties of [UTC-UTC(k)] is presented and correctly takes into account the correlations in uncertainty propagation. Two major changes are envisaged for its application:

- The pivot for GNSS time links is an auxiliary time scale instead of the PTB
- The correlations are added.

It is planned to introduce this new algorithm within a few months, and consequently to modify the information in Section 5 of *Circular T*. The future development of this work is the introduction of redundant links in UTC calculation, starting from TWSTFT measurements.

Dr Tavella commented that a choice of the correlation explicitly put the bias in the computation and asked if the bias is estimated. Dr Panfilo answered the biases are equal to zero because the redundant time links are not yet introduced in the calculation. The calibration is not checked by the moment.

Studies on the status of UTC

A key point of the UTC algorithm is the prediction of clock frequency drift; a feature introduced recently. The least square technique is applied on the frequency difference (TT-Hi) to evaluate the drift. The least squares are evaluated on a 6 months interval. Two analyses have been done:

- A different evaluation interval (3, 4, 5, 6 and 8 months)
- A different interval for each clock, optimized with respect to clock predictability.

The drift prediction interval has been set to be equal to 3 months to avoid the possibility that some clocks with an unpredictable drift could spoil the long-term frequency stability of EAL and UTC.

The Hadamard Variance has been used to evaluate the best prediction interval for each clock and the results are promising for improving the stability of UTC.

In the future, the characterization of each single clock with respect to their drift predictability will be developed to rapidly detect clock anomalies and prevent their impact on UTC.

Constrained least square solution applied to the calculation of TT

TT is calculated with the PSFS, the algorithm solves a least square (LS) problem. The LS solutions give the “weights” (called “filters”) of the PFS and SFS in TT calculation. The filters can be negative and this has no meaning from a physical point of view.

The proposed Constrained Least Squares (CLS) method can be used to overcome this problem. The goal of this new proposal is to reach a solution in close agreement with the physical reality.

The CLS algorithm allows only positive (or null) filters but more detailed studies are necessary to validate the results.

5.3 Report on Rapid UTC (G. Petit, BIPM) (CCTF/17-15) and (CCTF/17-39)

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 (2012), for the BIPM to continue its work on the rapid UTC (UTCr) project.

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.

As of July 2013, UTCr became an official BIPM product, following approval by the WGTAI. UTCr is a weekly solution of daily clock data and time transfer data. The computation interval is 26 to 30 days (sliding solution). The weekly publications of UTCr provide daily values of [UTCr-UTC(k)]. The stability of UTCr is expected to be about similar to UTC since participating laboratories represent at least 70 % of the clocks in UTC.

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

- Data checking (on daily data reported daily)
- Computation of time links (TWSTFT, GPS P3 or GPS MC)
- Stability algorithm (prediction, weighting)
- Steering to UTC.

The differences between UTCr and UTC show a significant degradation of [UTCr-UTC] starting from 2014 and this is also visible when UTCr has just been reset to UTC. Several possible causes were identified and tested: different data in UTCr and UTC, UTCr sliding computation interval and weighting algorithm. The problem was addressed by implementing two simple changes in the short term: adapt computation interval and adopt weight based on latest UTC computation. Also, participating laboratories have been requested to check the consistency of their data reported to UTCr and to UTC.

Dr Levine indicated that when using UTCr to steer UTC(NIST), steps appear, which are caused by a white noise process (an example is given over the MJD period from 57800 to 57900 showing several nanoseconds' steps).

In reply to concerns about different data being used by the BIPM in calculating UTC and UTCr, respectively, Dr Bauch suggested that the BIPM should consider using the data submitted from the (approximately) 50 laboratories that contribute to UTCr daily and extract the data for the days required for calculating UTC in an automated way. It is noted that this contains the risk that data submitted daily in an automated way by the laboratories may contain flaws. If the practice were to be adopted at a later time, the laboratories contributing to UTCr need to be alerted about this issue and invited to check the daily data with as much as care as is practical.

Dr Arias said that the BIPM clearly will converge towards the solution proposed by Dr Bauch.

5.4 Reports on progress on other time scales (Delegates)

Dr Bize reported that UTC(CNES), which is the realization of coordinated universal time of the French space agency CNES, has been available since May 2016. Since then, [UTC-UTC(CNES)] has been published regularly in *CircularT*.

Dr Ido reported that in order to maintain the continuity of Japan Standard Time, even if Tokyo is affected by an earthquake, the space time standards laboratory of NICT has recently built a second laboratory in Kobe, which is in western Japan, away from Tokyo. An additional ensemble time scale is available there, using two hydrogen masers and five commercial Cs clocks. The start of the official service is scheduled for April 2018.

Following a proposal from the President, Mr Erard, the draft recommendation on time scales definitions was introduced by Dr Arias. The text has been prepared by the Task Group on Time Scales Definitions created at the CCTF WG TAI, taking into consideration suggestions from the IAU delegate:

- Recommendation on the Definition of time scales (CCTF/17-04)

  At the meeting, representatives and delegates from the IUGG, BIPM, LNE-SYRTE and INRIM commented. The comments were not focused on the content of the recommendation, but on vocabulary (use of “systems” rather than “frames”, clarification of nomenclature, etc). All comments were considered and a new version was prepared.

6 TIME AND FREQUENCY TRANSFER METHODS

6.1 Report of the CCTF Working Group on TWSTFT (V. Zhang, NIST) (CCTF/17-23) and (CCTF/17-40)

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

The members of this working group are representatives and especially experts of the participating institutes as well as representatives of prospective participating institutes.

Representatives of institutes interested in this field are encouraged to follow the activities as observers. The chairman of this group is Dr Zhang (NIST) and the secretary is Dr Jiang (BIPM).

Since the previous CCTF meeting, TWSTFT annual meetings have been held in Boulder (2016) and in Xi'an (2017). Several meetings of the participating stations have also been held at European Frequency and Time Forum (EFTF) and Precise Time and Time Interval Systems and Applications (PTTI) conferences.

A number of calibration campaigns during 2015-2017 have been carried out and the TWSTFT calibration guidelines for UTC time links have been updated (2016).

A number of activities were reported:

- The Task Group Study on "Long-Term Instability of UTC Time Links" was set up by the WGTWSTFT, in coordination with the WG on GNSS, in early 2016. The study was triggered by observations reported by NIST and OP during the 23rd annual meeting that the TWSTFT difference and GPS difference of the NIST-PTB and OP-PTB links drifted apart significantly with respect to the estimated link uncertainty over the years. The task group members come from the WGs on TWSTFT and on GNSS time transfer. The study was published in the BIPM TM263 and in a 2017 ION-PTTI paper.
- The daily variation (diurnal) in the TWSTFT difference is the main instability for most of the TWSTFT links. Over the past few years, several studies have been conducted to find the causes of the diurnal, but no dominant cause could be identified. In early 2016, the BIPM and the WGTWSTFT started a pilot study "on Using Software Defined Radio (SDR) Receivers for TWSTFT". The aim of the pilot study is to investigate the impact of SDR TWSTFT on using different satellites for the Asia/Europe, Europe/Europe and Europe/USA links. All of the laboratories operating TWSTFT showed great interest in the study. As of May 2017, twelve laboratories have installed the SDR system and participated to the regular daily SDR TWSTFT. The pilot study demonstrated that the SDR TWSTFT can significantly reduce the diurnal in most of the intra-continental TWSTFT links and reduce the short-term TWSTFT time transfer noise in all TWSTFT links. The SDR TWSTFT results were recently published in the proceedings of the 2017 ION-PTTI meeting.
- In TWSTFT networks, there are UTC time links (the links to PTB) and many non-UTC time links that are redundant links in the view of UTC generation. Other redundant time transfer data, such as TWSTFT+GPSPPP, have been used for UTC generation to improve the stability of UTC time links. Two studies have found that instabilities of the Europe-to-Europe UTC TWSTFT links can be reduced with the transatlantic indirect TWSTFT links. More studies are necessary for using the redundant TWSTFT data in UTC generation.
- Some TWSTFT participating laboratories are developing and testing digital TWSTFT modems for Pseudo-Random Noise (PRN) coded and carrier-phase TWSTFT. Because the Ku-band carrier frequency is much higher than the GPS L-band carrier frequency, in theory, the carrier-phase TWSTFT could achieve a measurement resolution much higher to that of the GPS carrier-phase.

Based on the SDR pilot study results, the studies on using redundant TWSTFT data and the development of digital modems, the WG on TWSTFT has prepared a recommendation, which was introduced by Dr Zhang:

- Recommendation on Improving Two-Way Satellite Time and Frequency Transfer for UTC-Generation (CCTF/17-06).

  Delegates and representatives from the PTB and the BIPM commented.

6.2 Report of the CCTF WG on GNSS Time Transfer (P. Defraigne, ORB) (CCTF/17-12) and (CCTF/17-41)

The members of this working group are a representative of the WGTAI, a representative of the WGATFT, experts from laboratories contributing to UTC, a representative from the International GNSS Service (IGS), experts from time/frequency sections of NMIs and members of the BIPM Time Department. The chairman of this group is Dr Defraigne (ORB) and the secretary is Dr Petit (BIPM).

A brief summary of the objectives of the WGGNSS is presented. Two main subjects have been developed during the period 2015-2017: the development of calibration procedures, and the study of long-term variations between TWSTFT and GPS time transfer for stations of the TAI network. Some progress by the WG members in terms of time/frequency transfer performances was also reported.

- A new version of the calibration guidelines (version 3.2) was reviewed by the WG before being made available on ftp://tai.bipm.org/TFG/GNSS-Calibration-Results/Guidelines/ and http://www.bipm.org/wg/AllowedDocuments.jsp. A summary of calibration campaigns carried out during the period, either by the BIPM or by the G1 laboratories is presented.
- While the CGGTTS results are by convention corrected for the GNSS station hardware delays, the PPP software tools generally provide a clock solution, which still contains the hardware delays. In order to allow easy access to the calibration results for the correction of hardware delays in the PPP clock solutions, the WG proposed the use of a unique file reporting all the calibration results of all the stations involved in the TAI network. This file, known as Calex, contains the whole history so that it can be used when processing any Rinex file. An evaluation version of the Calex file has been created with the available G1 and G2 calibrations and made available to the community on the BIPM ftp server.
- ORB developed and distributed new R2CGGTTS software (version 7.1) to the time laboratories, allowing analysis of RINEX3, for GPS, GLONASS and Galileo. This software provides CGGTTS results in the format version V2E.
- Some members of the WG continued with progress in using the PPP technique for remote clock comparisons. The major goal is to get a continuous solution and to mitigate, as much as possible, the discontinuities appearing at the boundaries between batch solutions. Several options have been studied, such as the use of longer batches or moving overlapping batches; all show similar performance to the monthly solutions used by the BIPM for the realization of UTC. Another proposed improvement to the PPP algorithm is to solve the carrier phase ambiguities as integer numbers. This requires the availability of dedicated satellite clock products and hence a strong collaboration has started with the geodetic community that provides such products. Studies at the BIPM show that a frequency transfer accuracy of 1×10^{-16} is obtained at a few days averaging and that the performance still improves at longer averaging time.

The study on “Long-Term Instability of UTC Time Links” is reported above by the WGTWSTFT. The findings resulting from the task group study are reflected in the proposal of a recommendation prepared jointly by the WGs on GNSS Time Transfer and on TWSTFT, and introduced by Dr Defraigne:

- Recommendation on the Utilization and Monitoring of Redundant Time Transfer Equipment in the Timing Laboratories Contributing to UTC (CCTF/17-05).

6.3 GNSS calibrations for UTC (G. Petit, BIPM, RMOs, delegates) (CCTF/17-42)

A new GNSS calibration scheme was put in place in 2015. The BIPM calibrates the systems in G1 laboratories while RMOs are responsible for calibrations of G2 laboratories in the regions, and for submitting reports to the BIPM.

The BIPM maintains a database of all calibration results, in which each calibration is identified by a unique calibration identifier (Cal_Id). From the equipment calibrations, the BIPM will determine the UTC link uncertainties. All reports for UTC calibrations are available via the website: http://www.bipm.org/jsp/en/TimeCalibrations.jsp. The contents can also be accessed through the BIPM Time Department database (http://webtai.bipm.org/database/index.html).

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 v3.2 from February 2016. Many details covering operation, computation and reporting are provided in the annexes. Transfer of calibration and alignment cases are also addressed.

The status of G1 calibrations indicates that the BIPM carried out nine calibrations in 2016 (APMP and EURAMET results were published in January 2017, SIM results will be published soon). For G2 calibrations, 21 Cal_Id were attributed.

From January 2016, a new form of *Circular T* has been produced including additional information on the time link calibrations. Definitions of different contributions to the uncertainties were updated. The equipment involved are identified and calibration identifiers are included. Where applicable, calibration alignment of the equipment is added.

Dr Arias indicated that G1 laboratories provide much support for the calibration process in terms of equipment and staff. She added that records of any change in the equipment must be reported to the BIPM by the laboratory and concluded that, for the moment, a periodicity of calibration of two years must be kept.

Dr Bauch mentioned that the Galileo calibration campaign had very consistent results.

6.4 GNSS processing techniques (BIPM, delegates)

There was no input as the topic was covered under the report of the WG on GNSS.

6.5 Report on activities at the International Committee for GNSS (ICG) (G. Petit, BIPM) (CCTF/17-43)

The International Committee on Global Navigation Satellite Systems (ICG), established in 2005 under the umbrella of the United Nations, promotes voluntary cooperation on matters of mutual interest related to civil satellite-based positioning, navigation, timing, and value-added services.

The BIPM has Observer status and chairs the Task Force on Timing References of Working Group D: Reference Frames, Timing and Applications.

The WG-D main products include templates describing GNSS references (e.g. templates on geodetic and timing references) and recommendations mostly to GNSS service providers (e.g. GNSS Times offsets) or to the BIPM (e.g. publication of [UTC-GNSS times] and Rapid UTC).

Dr Arias recalled that within the timing community, the point of contact for this activity is provided by the BIPM.

16 h: Lecture in commemoration of the 50th anniversary of the atomic definition of the second by the CGPM: “The History of the Second” by Dr Dennis McCarthy (CCTF/17-03)

After being introduced by Dr Arias, Dr McCarthy, who is currently serving as a contractor with the US Naval Observatory, where he was Science Advisor, Director of the Directorate of Time, and Head of the Earth Orientation Department, gave a lecture on the history of the second (past, present and future).

Dr McCarthy described in a structured manner the various steps and important events on timekeeping, since the 3rd millenium BCE and the use of the Sexagesimal numbering system until the invention of the first caesium atomic clock in 1955. He spoke about the adoption of TAI and UTC before the late 20th century, having mentioned the intermediate and fundamental steps, notably with subdividing the day (around 2000 BCE) and the hour (in Antiquity), the early use of the term "second" towards the end of the 10th century, the development of clocks in the 13th and the 14th century in Europe, and subdividing the minute (in the 16th century) although minute hands only came into regular use around 1690, after the pendulum and anchor escapement improved timekeeping enough to justify it. Dr McCarthy also mentioned astronomical timekeeping, the signature of the Convention du mètre in 1875 and the adoption of the Système International d’Unités (SI) by the CGPM in 1960. He concluded by presenting the optical frequency standards of today for the future, re-definition issues and what is expected to come next in the field of time and frequency (e.g. Single atom clocks and Pulsars).

7 NEW STANDARDS AND ACCURATE COMPARISON TECHNIQUES

7.1 Report of the CCL/CCTF Working Group on the Secondary Representations of the Second (F. Riehle, PTB and P. Gill, NPL) (CCTF/17-16) and (CCTF/17-44)

The members of this working group are INRIM, LNE-SYRTE, NIST, NMIJ/AIST, NPL, NRC, PTB and VNIIFTRI. The chairmen of this group are Prof. Patrick Gill (NPL) and Prof. Fritz Riehle (PTB) and the secretaries are Dr Felicitas Arias (BIPM) and Dr Lennart Robertsson (BIPM).

Since the CCTF 2015, the WGFS has met twice. The first meeting took place at the EFTF 2016 in York on 7 April 2016 and the second on 3 May at the BIPM. A third meeting on 6 June 2017 at the BIPM, prior to the CCTF 2017 has taken place.

A WGFS subgroup was established in 2016 to study the new schedule for preparing recommendations.

A new approach to include frequency ratios and absolute frequency measurements into the CIPM List of Recommended Frequencies (LoF) has been applied.

The following frequencies have been discussed within the WGFS but no update is suggested because no new data were available: ^{1}H, $^{27}Al^{+}$, $^{199}Hg^{+}$, $^{171}Yb^{+}$ (E2 or quadrupole), $^{171}Yb^{+}$ (E3 or octupole) and ^{40}Ca. However, the following frequencies are recommended for an update: $^{115}In^{+}$, ^{199}Hg, ^{171}Yb, $^{88}Sr^{+}$, ^{88}Sr, ^{87}Sr, $^{40}Ca^{+}$ and ^{87}Rb.

A new SRS was introduced, based on the ^{199}Hg lattice clock transition, for which the recommended frequency has now an uncertainty that is comparable to that of primary caesium fountain clocks. The CCTF therefore recommends this standard as a new SRS with a fractional standard uncertainty of 5×10^{-16}.

The WGFS discussed the influence of correlations between the different measurements used for the recommendations that could underestimate the final uncertainty. Several test examples have been calculated and it was found that this influence is currently small but already detectable and will become more and more important in the future. Hence, the WGFS will prepare a guideline on how to report on measurements of optical frequencies and frequency ratios.

The CCL-CCTF WGFS presented the procedure for updating the CIPM List of Frequencies.

The WGFS has prepared two recommendations. They were introduced by Prof. Riehle:

- Recommended frequency standard values for applications including the practical realization of the metre and secondary representations of the second (CCTF/17-17) (Note that the title of this recommendation has been modified to “Recommendations for operating, comparing and reporting frequency standards as secondary representations of the second in preparation for a redefinition of the second by optical transitions”)
- Recommendation on Updates to the CIPM list of standard frequencies.

7.2 Report of the CCTF WG on Coordination of the Development of Advanced Time and Frequency Transfer Techniques (WGATFT) (F.-L. Hong, NMIJ) (CCTF/17-45)

The members of this working group are a representative of the WGTAI, a representative of the WG-ALGO, a representative of the WGGNSS, a representative of the WGTWSTFT, a representative of the WGPSFS, two representatives of the WGFS, one representative from the BIPM, other experts from laboratory members of the CCTF. The chairman of this group is Dr Hong (NMIJ) and the secretary is Dr Robertsson (BIPM).

A brief overview of the terms of reference of this WG was presented.

During the period 2015-2017, the WG has held two meetings at the BIPM in September 2015 and June 2017. Under the WGATFT, the Study Group on Optical Fibre links for UTC (SGOF), created in 2015 under the chairmanship of Dr Calonico (INRIM), met once in April 2016 at York during the EFTF.

The topics discussed in the 2017 meeting were:

- Transportable optical clocks;
- Fiber links;
- Discussion about the ongoing campaign of clock comparisons between SYRTE, PTB, and NPL using fibre links, with the transportable clock coming to SYRTE from the PTB.

From 2012 to 2017, Dr Feng-Lei Hong from NMIJ has been the chairman of this group. Dr Davide Calonico from INRIM is proposed as the new chairman to commence his appointment after this CCTF meeting. The members of the working group supported this proposal.

7.2.1 Report on the status of fibre links (D. Calonico, INRIM) (CCTF/17-31) and (CCTF/17-46)

In April 2015, the Study Group on the Optical Fibre links for UTC (SGOF) under the WGATFT was created. The SGOF focuses on developments and achievements in the field of frequency and time transfer using optical fibres, aiming at the comparison of atomic clocks, the comparison of timescales, the dissemination of TF standards and of UTC to users.

The optical fibre link techniques have grown fast and offer unprecedented performance in terms of stability and accuracy, both for time and frequency transfer. Over thousands of kilometres, a coherent fibre link can compare clocks with an instability of few parts in 10^{18} at 1000 s – 10000 s. Also time transfer using fibre has reported significant advances, with different techniques, that today can offer a sub-ns inaccuracy.

Only one laboratory in Europe regularly reports data to the BIPM by connecting a remote atomic clock by optical fibre, however this link does not contribute to UTC.

The fibre link comparisons demonstrated today are the only suitable means to compare remote optical frequency standards. More comparisons will now be carried out in order to achieve the milestones identified in the roadmap for the possible redefinition of the SI second, collecting more-and-more comparisons of optical frequency standards.

Nonetheless, there are currently no projects for an intercontinental fibre link. In the coming years, the remote intercontinental comparison of optical frequency standards will become an issue. The use of advanced satellite techniques as an alternative solution will be pursued to compare optical frequency standards at the right level of inaccuracy and instability.

Fibre links have been demonstrated to be beneficial to stakeholders other than just primary metrology and NMIs. Different stakeholders have started to use optical fibre links to synchronize their equipment and/or to have traceability to UTC (financial market timestamping, radio-astronomy facilities and particle physics facilities). The engagement of the time and frequency metrology community with those stakeholders will be strengthened.

Optical fibre links have enabled new scientific possibilities, and the demonstration of chronometric geodesy, for the precise measurement of punctual gravity potential differences between remote sites, was reported.

The SGOF does not propose new recommendations, because even if large advances have been achieved, the Recommendation CCTF 6 (2015) is still valid, which highlights the requirements to be pursued.

8 CIPM MRA AND RMOs

8.1 Report of the work of the CIPM *ad hoc* WG on implementing the recommendations from the review of the CIPM MRA (L. Erard, CIPM) (CCTF/17-10)

The members of this WG are Ismael Castelazo (Mexico), Wynand Louw (South Africa), Gert Rietveld (the Netherlands), Takashi Usuda (Japan), Luc Érard (France), Hector Laiz (Argentina), Andy Henson (BIPM) and Willie May (USA). The chairman of the WG is Barry Inglis (Australia). The Director of the BIPM, Martin Milton, participates as an observer.

The terms of references and objectives of the WG were reported.

The CIPM *ad hoc* WG met in March 2017. At its meeting, the *ad hoc* WG agreed a number of actions that it requests the CC Presidents to expedite for reporting and discussion at their next meeting in order to promote best practice, and where appropriate harmonization, of the approaches. The following summary actions are reported:

- Progress on CC strategy updates particularly related to defining the long-term timetable for CC KCs (including the policy on repeat cycles)
- The approach adopted to limiting participation in CC KCs that use sequentially travelling standards
- Progress towards better consistency in the expression of CMCs (e.g. units, uncertainty ranges) within their CC
- The approach adopted or planned to clarify ‘how far the light shines’ such that KCs and SCs are interpreted as widely as reasonably applicable to indicate coverage of CMCs
- The approach taken to ensure CMCs cover as many services as is technically justified, constrain the proliferation of CMCs and express CMCs as concisely as practical. It was recalled that the objective is to manage workload rather than CMC numbers
- The approach adopted (or planned) to implement a ‘risk-based’ approach to CMC review

- The CC approach to CIPM MRA-D-04 section 3 (which addresses the evidence needed to support CMC claims when not supported by comparison) with a view to harmonizing the approaches across CCs
- The availability of CCs specific methodologies for carrying out comparisons, including evaluation tool templates (including reporting) guidance/templates, and guidance materials to ensure "right first time" CMCs.

A summary of actions for the JCRB/RMO were also presented.

8.2 Report of the CCTF WG on the CIPM MRA (M. Lopez Romero, CENAM) (CCTF/17-11) and (CCTF/17-47)

The members of this working group are the chairpersons of the RMO technical committees for time and frequency: Peter Whibberley (EURAMET), Chris Matthee (AFRIMETS), Michael Wouters (APMP) until the end of 2017, Aimin Zhang (APMP) since January 2018, Raul Solis (SIM), Jon Bartholomew (GULFMET) and Vitaly Palchicov (COOMET). Expert members, from time laboratories: Marina Gertsvolf (NRC), Joseph Achkar (LNE-SYRTE), Erik Dierikx (VSL) and Huang-Tien Lin (TL). The chairman is Dr Lopez (CENAM) and the secretary is Dr Panfilo (BIPM).

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

The WGMRA met via a videoconference meeting hosted by the Observatoire de Paris in February 2017. During this meeting the Time and Frequency Supplementary Guide for Appendix B and C of the CIPM MRA document was discussed and commented. Several suggestions were made to guidelines 6, 8 and 9. A second meeting of the WG was held at the BIPM on 6 June 2017 immediately before the present CCTF meeting.

As of May 2017, a total of 50 countries were listed in the BIPM KCDB as suppliers of calibration services for Time and Frequency, provided as follows: Time scale difference (38 countries), Frequency (50 countries) and Time Interval (43 countries). The total of CMCs in Time and Frequency recorded in the KCDB are 761. The dates of approval of these CMCs range from 2005 to 2016. It is common practice for RMOs to have a periodic review of CMCs on a 5-year basis.

Following the decision taken at the 20th meeting of the CCTF (2012), the single key comparison CCTF-K001.UTC is published monthly in the BIPM KCDB starting from March 2015. A new supplementary comparison, GULFMET.TF-S1, has been declared in the KCDB.

The main activity of the CCTF Working Group on the CIPM MRA (WGMRA) during the period 2015-2017 concerned the implementation of the recommendations made by the "Working Group on the Implementation and Operation of the CIPM MRA". To deal with these recommendations, several actions have been undertaken. The work has been organized with the support of a Task Group (TG), the members of which were nominated for having broader expertise.

The following actions have been identified by the CCTF for accomplishing the recommendations made by the "Working Group on the Implementation and Operation of the CIPM MRA":

- Time and Frequency Supplementary Guide for Appendix B and C of CIPM MRA
- Guideline on the CCTF criteria for obtaining traceability in time and frequency
- A report on the state of the relationship between the List of Services and the CMCs declared
- Consolidate the relationship between the CCTF WG on MRA and the RMOs.

The WG has prepared a new document and three guidelines (two revisions and one new guideline):

- Guideline 6 gives the rules for the participation to the computation of UTC at the BIPM. The proposed revision removes the aspects that deal with traceability since a new guideline dealing with this subject is proposed by the working group.

Dr Tavella asked why, in Guideline 6, the technical requirements for accepting a new contribution are not described. Dr Bauch indicated that the criteria for acceptance to participate are not mentioned at all. Dr Milton commented that the BIPM Time Department will clarify these two points.

Mr Erard and Dr Arias proposed that the CCTF should approve this updated guideline and corrections will be added and approved by correspondence within the CCTF Working Group on the CIPM MRA (WGMRA), before the end of 2017. However, the technical requirements for participation are presented in Guideline 8 (next item in the report).

The members of the CCTF agreed and Guideline 6 was approved under the conditions above.

- The Guideline 8 gives the conditions for the contribution of time laboratories to UTC. The proposed revision concerns minor changes to the text.

Dr Hamid proposed the incorporation of *caesium* clocks into the text. Dr Arias clarified this point by saying that the term *atomic* will be added.

The members of the CCTF agreed and Guideline 8 was approved.

- The new Guideline 9 gives the CCTF criteria for obtaining traceability in time and frequency.

Delegates and representatives from the PTB, NIST and the BIPM commented. The members of the CCTF agreed the document and Guideline 9 was approved.

- A new document entitled “Time and Frequency Supplementary Guide for Appendix B and C of CIPM MRA” was prepared by the WGMRA in response to the requirements of the “Working Group on the Implementation and Operation of the CIPM MRA”.

This Supplementary Guide reports information on how to draw up Calibration and Measurement Capability (CMC) Excel files in the field of Time and Frequency and sets out the CMC review procedure to be followed. The Guide is intended to be used world-wide, but makes provision for specific requirements of each Regional Metrology Organization (RMO), particularly concerning the way the information supporting CMCs is gathered and the detailed CMC intra-regional review process.

For general information related to the CMC review process, acceptance criteria, support by key and supplementary comparisons etc. the reader should refer to the JCRB documents, available at: http://www.bipm.org/en/committees/jc/jcrb/documents.html.

This Guide is addressed to both the NMIs that have not yet submitted their capabilities and the NMIs that would like to add to or modify their already published CMCs.

Mr Erard proposed that delegates should send their comments on the document to the WGMRA chair and secretary by the end of June 2017. The WG will then take the comments received into account and a new version will be issued by September 2017.

The members of the CCTF agreed and the new supplementary guide was approved.

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

8.3 Reports from RMOs Technical Chairs

8.3.1 SIM region (M. Lopez, CENAM, on behalf of R.F. Solis Betancur, CENAMEP) (CCTF/17-50)

The SIM region includes 34 NMIs, 20 DIs and three organizations as observers. Under the terms of the CIPM MRA, SIM has 20 NMIs and four DIs operating time and frequency laboratories. From these laboratories, 12 contribute to the realization of UTC of which eight participate in CCTF-K001.UTC. Nine countries have their CMCs for time and frequency registered in the BIPM KCDB.

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.

NIST and USNO, both from the SIM region, are Group 1 (G1) laboratories whose GNSS equipment contribute to UTC and are calibrated by the BIPM. NIST is carrying out a calibration campaign divided into two rounds: Round-1 involving NIST, NRC, CENAM and CENAMEP is complete. Round-2 involving NIST, ONRJ, INMETRO and INTI is expected to start in July 2017.

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.

8.3.2 APMP region (M. Wouters, NMIA and A. Zhang, NIM) (CCTF/17-26) and (CCTF/17-48)

The APMP Technical Committee for Time and Frequency (TCTF) has working groups on the CIPM MRA, GNSS, TWSTFT and TC (Test and Calibration). With the Technical Committee for Length (TCL), there is a joint TCL/TCTF working group on Optical Frequency Metrology (OFM). The TCTF meets annually, in conjunction with the APMP General Assembly.

The APMP WG MRA handles the intra- and inter-regional CMC reviews. This WG 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 carried out three calibrations of G2 receivers, two of them organized by NIM and one by TL. Under the framework of a 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. This is now almost complete. The system's hardware design and software will be openly available.

The APMP WG TWSTFT is responsible for the TW links in this region. Research on TWSTFT includes: link calibration; the use of dual pseudo-random noise codes; software-defined radio receivers; and the use of a carrier-phase.

The APMP WG OFM's main area of research includes: optical clocks; optical frequency combs; dissemination of microwave and optical frequency standards over optical fibres.

The APMP WG TC is a new WG focusing on practical test and calibration issues and addressing the interests of NMIs in developing economies. A stopwatch calibration comparison is currently being organized, since this is a common activity in many working laboratories.

A workshop on GNSS time-transfer and receiver calibration techniques was held in Chinese Taipei and hosted by TL in 2016. The workshop consisted of lectures and practical demonstrations using the time-transfer systems that are being used within the APMP for GNSS receiver calibrations. The workshop has been followed up with a limited GNSS receiver calibration campaign: three NMIs whose receivers have never been calibrated were visited. There will also be on-site visits to several NMIs and a concluding workshop later in 2017.

8.3.3 EURAMET region (P. Whibberley, NPL) (CCTF/17-49)

The EURAMET TCTF currently has 28 contact persons and one WG for CMC reviews. Ramiz Hamid (UME) was the chair for 2013-2017 and since May 2017, Peter Whibberley (NPL) has been the chairman.

The EURAMET TCTF held its annual meeting in March 2017 at ROA in Spain.

Different projects are carried out within the TCTF:

- GNSS receiver performance coordinated by GUM since 2010, is continuing;
- Time interval comparison using delay standards of two types has been initiated and coordinated by GUM; the first inter-comparison campaign is in preparation;
- The preparation of a EURAMET technical guide on the use of GPS disciplined oscillators (GPSDOs) by calibration laboratories. The guide was published in March 2016. It is available for free download from the EURAMET website.

On-site peer review visits carried out in late 2015 - early 2016: IMBiH (Bosnia-Herzegovina) carried out by SIQ (Slovenia) and FTMC (Lithuania) carried out by GUM (Poland). IMBiH had CMCs reviewed and published in the BIPM KCDB in September 2016. Some updated CMCs are in preparation (e.g. ROA, LNE).

PTB, ROA and OP from the EURAMET region, are part of the Group 1 (G1) laboratories whose GNSS equipment contributing to UTC are calibrated by the BIPM. Several G1-G2 campaigns were completed in 2015-2016: OP for CNES; PTB for BEV, DLR, METAS and VSL; ROA for BIM, UME, BOM, DMDM, IMBiH and INRIM.

EURAMET receives funding from the European Union and redistributes it through competitive research programmes. The current funding programme is EMPIR – the European Metrology

Programme for Innovation and Research, launched in 2014, which will run until 2020. The Time and Frequency community has been successful in winning funding for a series of projects:

- Optical clocks with 10^{-18} uncertainty. The NMI partners are: NPL, PTB, INRIM, LNE, OBSPARIS, TUBITAK UME and VTT. Some industrial partners are involved.
- Optical Frequency Transfer – a European Network: this EMPIR project follows on from the EMRP project NEAT-FT. The participants are: PTB (coordinator), CMI, OBSPARIS, INRIM, SP, UME, NPL, CNRS-LPL, AGH, PSNC and Chalmers.

For finance sector regulation in Europe, the European Securities and Markets Authority (ESMA) Markets in Financial Instruments Directive II (MiFID II) regulations will come into effect on 3 January 2018. The directive includes a regulatory technical standard RTS 25 which deals with clock synchronization.

The BIPM and NPL responded to the ESMA consultation in March 2016. The NPL hosted a EURAMET workshop on the subject with the aim to develop cooperation and encourage NMIs to engage with their national finance sectors. Today, the NPL and INRIM are offering fibre-based time delivery to users.

8.3.4 COOMET region (N. Koshelyaevsky, VNIIFTRI)

Dr Koshelyaevsky reported briefly on the COOMET activities. *There was no report submitted by COOMET.*

8.3.5 GULFMET region (K. Aldawood, SASO) (CCTF/17-27)

The Gulf Association for Metrology (GULFMET) was granted provisional acceptance as an RMO at the 34th meeting of the JCRB in September 2015. The GULFMET TC-EMTF covers the fields of electricity, magnetism, time and frequency. The TC-EMTF meets twice a year.

Saudi Arabia and United Arab Emirates currently have time and frequency capabilities. An overview of the time and frequency capabilities for SASO-NMCC and ADQCC-EMI were given. Current and future inter-comparisons were presented.

9 SPACE-TIME REFERENCES AND GENERAL RELATIVITY

9.1 Report on the IERS Conventions Product Centre (G. Petit, BIPM) (CCTF/17-51)

Since 2001, the IERS Conventions Centre has been provided jointly by the BIPM and the US Naval Observatory (USNO). Since 2015, minimal work towards updating the existing web documents and software has been provided.

The co-responsibility of the Conventions Centre was transferred to the Observatoire de Paris in July 2016 (still with the USNO team). More information can be found here: http://iers-conventions.obspm.fr/.

9.2 News on the IAG Working Group on Relativistic Geodesy (G. Petit, BIPM) (CCTF/17-51)

Under the auspices of IAG Commission 2 (Gravity Field), a new joint WG 2.1 was established dealing with relativistic geodesy: first steps towards a new geodetic technique. The JWG is chaired by Jakob Flury (Leibniz Universität) and co-chaired by Gérard Petit (BIPM). The objectives of the JWG were presented.

The kick-off meeting was held in Hannover on May 2017. The main topics reviewed were:

- Theory
- Reference frames, geoid, mean sea level, height networks, time
- Classical gravity potential determination
- Frequency transfer, fibre links, campaigns
- Optical atomic clocks, calibration, comparisons
- Use of accurate clocks for gravity potential determination.

The JWG plans to prepare a “mise en pratique” for time and frequency laboratories to compute relativistic shift to 10^{-18} based on several recent publications by WG members.

9.3 News from the international organizations

9.3.1 IGS report (M. Coleman)

Two points were presented:

- The IGS rapid products are now produced by solutions that realize International Terrestrial Reference System (ITRF) 2014 rather than ITRF 2008 (effective from 29 January 2017 equivalent to GPS week 1934). No substantial change to the precision of the products resulted from this change
- Clock Rinex 3 format will be updated to version 3.04, which is expected to be released in July 2017.

A request to Dr Petit for information on the IGS workshop to be held in July 2017 in Paris was provided.

9.3.2 ITU-R report (R. Beard)

Mr Beard reported briefly on ITU-R activities related to the UTC issue, in particular the outcome of the WRC-15.

Given the difficulty in reaching consensus on a common vision of the future of UTC by the ITU member states, the WRC-15 adopted Resolution 655 on the Definition of time scale and dissemination of time signals via radiocommunication systems.

The WRC-15 resolves to invite ITU-R:

- to strengthen the cooperation between ITU-R and BIPM, CIPM, CGPM, as well as other relevant organizations, and to carry out a dialogue concerning the expertise of each organization;
- to further and more widely study the various aspects of current and potential future reference time scales, including their impacts and applications, in cooperation with the relevant international organizations, concerned industries and user groups, and through the participation of the membership;
- to provide advice on the content and structure of time signals to be disseminated by radiocommunication systems, using the combined expertise of the relevant organizations;
- to prepare one or more reports containing the results of studies that should include one or more proposals to determine the reference time scale and address other issues mentioned above.

The WRC-15 instructs the director of the Radiocommunication Bureau to invite the relevant organizations to participate in the work mentioned above, and to report on the progress of this resolution to WRC-23.

The WRC-15 resolves that until WRC-23, UTC as described in Recommendation ITU-R TF.460-6 shall continue to apply.

Mr Beard added that working party 7A will prepare a report for WRC-23.

9.3.3 IUGG report (C. Boucher)

The International Union of Geodesy and Geophysics (IUGG) is the international organization dedicated to advancing, promoting, and communicating knowledge of the Earth system, its space environment, and the dynamic processes causing change.

Mr Boucher reported briefly on IUGG activities, in particular the international recognition of the international terrestrial system and frame. He informed the CCTF on the establishment by ISO of a working group devoted to geodetic references – the International Terrestrial Reference System (ITRS).

The WG is chaired by Mr Boucher with the following scope: to prepare a technical report on a standard providing the basic information and the requirements related to the ITRS, specifically its definition, realizations and access. The WG will:

- Endorse definition(s) and terminology adopted by the IUGG, the IAG and the IAU
- Describe various realizations (such as ITRF, WGS-84, ETRS89, etc.)
- Provide required methods of realizing the ITRS
- Describe various ways of getting positions expressed in a realization of the ITRS.

9.3.4 IAU report (D. McCarthy)

The International Earth Rotation and Reference Systems Service (IERS), as a service sponsored, in part by the IAU, called for the insertion of a leap second in the UTC time scale on 31 December 2016, which was successfully implemented world-wide.

With the re-organization of the IAU, the responsibility for matters relating to time previously considered by IAU Commission 31, have been transferred to Commission A3 (Fundamental Standards) within IAU Division A (Fundamental Astronomy).

The draft of the proposed CCTF recommendation regarding the definition of TAI and UTC was distributed to the IAU General Secretary, the President of IAU Division A and to the President and members of IAU Commission A3 for comments. Comments were received and many were incorporated in a proposed revised version of the draft returned to the Chair of the Working Group on TAI. Other comments were transmitted directly to the Chair of the CCTF Working Group on TAI.

9.3.5 URSI

There was no report from URSI.

10 STRATEGIC PLANNING

10.1 Proposal for the BIPM Time Department programme of work for 2020-2023 (F. Arias, BIPM) (CCTF/17-52)

The BIPM Time Department's strategic planning was presented. It included the detailed strategy with respect to time metrology, the related plans for the period 2018 to 2019 and proposals for long-term work (2020-2025).

Based on the proposals for the long term with a trend for continuity, the new programme of work (PoW) to be developed for the BIPM Time Department, will be presented to the CIPM for approval and will be available by the end of 2017. The new PoW will be established through interactions with NMI Directors and representatives from BIPM Member States.

The proposed strategy for the long-term PoW of the Time Department are:

1. To support the needs of the global time community by providing UTC of sufficient accuracy to progress the state of the art;
2. To coordinate and support a redefinition of the second, based on optical transitions and, to adapt the infrastructure for time scale maintenance and dissemination to the new definition of the second;
3. To provide the unique, continuous time scale for world time coordination.

A comprehensive view of the detailed strategy was presented, both for the 2018-2019 plans and for the long-term work (2020-2025).

10.2 Report of the Strategic Planning Working Group

The members of this working group are: the chairpersons of the CCTF working groups, the director of the BIPM Time Department and experts proposed by the WGSP chairperson. The chair of the group is Mr Erard (LNE) and the secretary is Dr Arias (BIPM). Discussions by the group are usually made by correspondence; a meeting was held at York in 2016.

The CCTF strategy document developed by the WGSP was updated in 2016 including a draft revision of the roadmap for the re-definition of the second. The last version was issued in May 2016 and is available on the BIPM website.

A meeting is planned (probably in 2018), at the BIPM or by videoconference.

10.3 CCTF Working Group structure and chairs

Since 2015, Dr Arias has been acting as the interim chairperson of the CCTF Working Group on TAI (WGTAI). Dr Arias recalled that at the previous meeting of the CCTF, proposals to change this WG were discussed: to create *ad hoc* groups for different issues was not accepted and a forum does not seem appropriate. It was again requested that, for this WG, its name, terms of reference, members and chairperson be discussed, and a new proposal will be presented at the next CCTF meeting.

Working Group chairs who will continue their term, until the next meeting of the CCTF are: Dr Hanado (WG-ALGO), Dr Defraigne (WGGNSS) and Dr Zhang (WGTWSTFT). Mr Erard will continue as chair of the WGSP.

Newly proposed WG chairs who have been accepted by the CCTF are: Dr Weyers (WGPSFS), Dr Matthee (WGMRA) and Dr Calonico (WGATFT). The SGOF is therefore dissolved and its activities fully taken over the WGATFT.

For the CCL-CCTF Frequency Standards Working Group (WGFS), Dr Bize has been proposed as a new co-chair to replace Prof. Riehle by the end of 2017. Prof. Gill will be replaced by a new person to be nominated by the Consultative Committee for Length (CCL) as co-chair of this joint working group.

11 RECOMMENDATIONS

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

- RECOMMENDATION CCTF 1 (2017): Recommendations for operating, comparing and reporting frequency standards as secondary representations of the second in preparation for a redefinition of the second by optical transitions;
- RECOMMENDATION CCTF 2 (2017): Updates to the CIPM list of standard frequencies;
- RECOMMENDATION CCTF 3 (2017): Recommendation on the definition of time-scales;
- RECOMMENDATION CCTF 4 (2017): On the utilization and monitoring of redundant time transfer equipment in the timing laboratories contributing to UTC;
- RECOMMENDATION CCTF 5 (2017): On improving the uncertainty of Two-Way Satellite Time and Frequency Transfer (TWSTFT) for UTC Generation.

The members of the CCTF agreed on the proposed recommendations. Mr Erard will inform the CIPM of these recommendations and in particular Recommendation 3 (2017) will be submitted to the CIPM in October 2017 for approval. Recommendation 3 (2017) will be forwarded to the CGPM in 2018 for possible inclusion in a resolution.

12 NEW RULES FOR CCs MEMBERSHIP (L. Erard, CIPM)

The president reported briefly on the Decisions of the 105th CIPM (October 2016). In particular, he provided some important information of particular interest to the CCTF on certain decisions of the CIPM, hereinafter (non-exhaustive):

- The CIPM welcomed the recommendations of the Working Group on the Implementation and Operation of the CIPM MRA and thanked the participants for their contributions. The CIPM agreed to establish an *ad hoc* Working Group to oversee the implementation of the recommendations with agreed terms of reference.
- The CIPM requested a short description of the “risk-based approach to CMC review” adopted by the CCQM, CCEM and CCT and to provide these examples for consideration to other Consultative Committees.
- The CIPM requested from all Consultative Committees an update of the *mises en pratique* (current online Appendix 2) to be ready on 31 July 2017. This Appendix will continue to be an online Appendix in the context of the new Brochure.
- The CIPM decided to revise the Rules for Membership of the Consultative Committees as follows; all Member States will have the right for one national laboratory charged with establishing national standards in the field to be an Observer at the applicable Consultative Committee and to send one person (only) and following their request for each meeting. Document CIPM-D-01 will be updated accordingly.
- The CIPM decided that for all Consultative Committee meetings in 2017 and thereafter: i) International organizations will be referred to as « liaisons » and will not be offered membership. ii) Named individuals will be « guests » or « experts » and will not be offered membership. Document CIPM-D-01 will be updated accordingly.
- The CIPM agreed that the 26th meeting of the CGPM will be held at the Palais des Congrès de Versailles on 13-16 November 2018 with informal meetings planned on 12 November.

Dr McCarthy noted that the status of the international organizations in Consultative Committees had been changed from “members” to “liaisons”, without any notice or concertation, in particular in the case of the IAU. The role of “liaisons” has not been defined, and suggested that this point should be stated clearly for the international organizations.

12.1 Consideration of requests for membership/observership

12.1.1 INMETRO

The BIPM received a formal request from INMETRO (Brazil) to become a member of the CCTF as an observer. No representative from INMETRO was able to attend the meeting and no report was submitted.

In consequence, the application could not be considered at this meeting.

12.1.2 TL (CCTF/17-53)

The BIPM received a formal request from TL (Chinese Taipei) to become a member of the CCTF as an observer. Mr Erard invited Mr H-T Lin to make a presentation on the activities of TL in the field of time and frequency.

TL is responsible for the time and frequency standard of Chinese Taipei. Chinese Taipei is an associate member of the CGPM, and TL has attended CCTF meetings as a guest since 1999.

The reference clocks of TL are composed of ten Microsemi 5071A caesium clocks with high-performance tubes and four active Hydrogen masers. TL is maintaining two time scales: UTC(TL) generated from the output frequency of a Master hydrogen maser, which is steered by a micro-phase-stepper and TA(TL), which is a weighted result of the caesium-clocks ensemble.

TL contributes in the generation of TAI and UTC. TL has CMCs published in the BIPM KCDB and UTC(TL) is published monthly in *Circular T*.

TL developed precise time and frequency transfer using GPS, TWSTFT and optical fibres. TL is one of the “G1” laboratories in the APMP region for GNSS calibration campaigns. TL has been devoted to the TWSTFT activities since 2002, and established the first Europe to Asia (VSL-TL) link in 2003. TL is maintaining four earth stations for the TWSTFT experiments: Asia to Pacific link, Europe to Asia link, and North America to Asia link. TL has been working on the development of a TWSTFT SDR receiver since 2014 and participated actively in the pilot study established by the BIPM and the CCTF WG on TWSTFT in 2016, with the target to evaluate the feasibility of contributing SDR technology to UTC generation. TL operates time dissemination services through NTP and speaking clocks.

TL regularly participates in CCTF related activities (e.g. WG on TAI, MRA, GNSS, TWSTFT and ATFT). TL is a full member of APMP, and is strongly involved in TCTF activities including support to the intra- and inter- RMO CMCs reviews for APMP WGMRA.

Over the past six years, TL has published or contributed to about 15 scientific papers related to the field of time and frequency.

The CCTF welcomed the report by TL, and the President of the CCTF will make a proposal to the CIPM in October 2017 to accept TL as an Observer to the CCTF.

13 OTHER BUSINESS

13.1 Next meeting of the CCTF

It was proposed that the next meeting of the CCTF should be held in 2020. As usual, the WGs meetings will be held in the days prior to the CCTF meeting.

14 CONCLUSIONS

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

- Five new recommendations were adopted by the CCTF, one of them will be submitted to the CIPM for approval, and will be forwarded to the CGPM for possible inclusion in a resolution;
- Three CIPM MRA guidelines and a Supplement guide were adopted;
- All presentations will be published on the BIPM website, unless the presenter explicitly disagrees;
- The group photo will be published on the BIPM website.

The President summarized the actions taken during that meeting:

- Action 1 (2017): To define milestones for the roadmap for the re-definition of the second that was drafted by the WGSP.
- Action 2 (2017): To update the "*mises en pratique*" (currently online as Appendix 2 of the SI brochure) to be ready on 31 July 2017. It is to be noted that the "*mises en pratique*" are prepared by the relevant Consultative Committees, and, after approval by the CIPM, are published in electronic form on the BIPM website, where they may be revised more frequently than if they were printed in the SI Brochure.
- Action 3 (2017): To provide the terms of reference and membership list of the "new" WGTAI.
- Action 4 (2017): To discuss and possibly update the CIPM MRA document on Classification of services in Time and Frequency by including an additional branch that deals with phase noise measurements.
- Action 5 (2017): To complete and correct CCTF WGMRA Guideline 6 according to the member's request and ask approval by correspondence before end 2017.

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

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

Special thanks were expressed to Dr Arias as the local host for this meeting. This is her last CCTF meeting as she will retire in November 2017. To mark this special occasion, speeches were delivered by the President of the CCTF, a representative from VNIIFTRI and one representative from the CIPM.

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 16:00 h.

RECOMMANDATION CCTF 1 (2017)

Recommandations sur l’utilisation et la comparaison des étalons de fréquence comme représentations secondaires de la seconde, ainsi que sur la communication de leurs résultats, en vue d’une redéfinition de la seconde fondée sur des transitions optiques

Le Comité consultatif du temps et des fréquences (CCTF), à sa 21e session en 2017,

considérant que

- la liste des représentations secondaires de la seconde est maintenue selon les recommandations du CIPM,
- différentes représentations secondaires optiques de la seconde permettent d’obtenir des incertitudes relatives de fréquence estimées d’environ deux ordres de grandeur inférieures à celles obtenues à l’aide des meilleurs étalons primaires à césium,
- l’incertitude associée aux étalons de fréquence optique continue d’être améliorée,
- le CCTF a approuvé une feuille de route concernant une future redéfinition de la seconde fondée sur des étalons de fréquence optique,

recommande

- aux laboratoires de porter leurs efforts sur l’utilisation de leurs étalons de fréquence comme réalisation de représentations secondaires de la seconde de façon à ce qu’ils soient couramment transmis au BIPM et inclus au calcul du TAI,
- de comparer les étalons optiques avec des incertitudes comparables à celles estimées pour les étalons eux-mêmes,
- aux laboratoires de mesurer les fréquences des réalisations de leurs représentations secondaires de la seconde par rapport aux meilleurs étalons primaires à césium, ce qui constitue une condition indispensable pour une éventuelle future redéfinition de la seconde fondée sur des transitions optiques,
- aux groupes de travail du CCTF concernés de finaliser les étapes majeures requises pour redéfinir la seconde et d’informer régulièrement le CIPM des progrès effectués en la matière.

RECOMMANDATION CCTF 2 (2017)

Mises à jour de la liste des fréquences étalons du CIPM

Le Comité consultatif du temps et des fréquences (CCTF), à sa 21^{e} session en 2017,

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,

recommande

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

- la transition optique non perturbée $5s^2\ {}^1S_0 - 5s5p\ {}^3P_0$ de l'ion de $^{115}In^+$, à la fréquence de f_{115In+} = 1 267 402 452 901 050 Hz avec une incertitude-type relative estimée de $1{,}6 \times 10^{-14}$;
- 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} = 1 128 575 290 808 154,4 Hz avec une incertitude-type relative estimée de 5×10^{-16} ;

  Cette radiation est désormais approuvée 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} = 518 295 836 590 863,6 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 $5s\ {}^2S_{1/2} - 4d\ {}^2D_{5/2}$ de l'ion de $^{88}Sr^+$, à la fréquence de f_{88Sr+} = 444 779 044 095 486,5 Hz avec une incertitude-type relative estimée de $1{,}5 \times 10^{-15}$ (cette radiation a déjà été approuvée par le CIPM comme représentation secondaire de la seconde) ;
- la transition optique non perturbée $5s^2\ {}^1S_0 - 5s5p\ {}^3P_0$ de l'atome neutre de ^{88}Sr, à la fréquence de f_{88Sr} = 429 228 066 418 007,0 Hz avec une incertitude-type relative estimée de 6×10^{-16} ;
- 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} = 429 228 004 229 873,0 Hz avec une incertitude-type relative estimée de 4×10^{-16} (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+} = 411 042 129 776 399,8 Hz avec une incertitude-type relative estimée de $2{,}4 \times 10^{-15}$;

- la transition hyperfine non perturbée de l'état fondamental de l'atome de 87Rb, à la fréquence de f_{87Rb} = 6 834 682 610,904 312 6 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) ;

et en informe le CIPM.

RECOMMANDATION CCTF 3 (2017)

Recommandation sur la définition des échelles de temps

Le Comité consultatif du temps et des fréquences (CCTF), à sa 21e session en 2017,

considérant

- que la Résolution 1 adoptée par la CGPM à sa 14e réunion (1971) demande au CIPM de donner une définition du Temps atomique international (TAI),
- qu'aucune définition exhaustive et autonome du TAI n'a été établie de façon officielle par le CIPM,
- que le Comité consultatif pour la définition de la seconde (CCDS) a proposé dans sa Recommandation S2 (1970) une définition du TAI qui a été complétée en 1980 par une déclaration du CCDS,
- que la CGPM lors de sa 15e réunion (1975) a constaté que le Temps universel coordonné (UTC), dérivé du TAI, est à la base du temps civil et qu'elle a estimé son emploi parfaitement recommandable,

reconnaissant

- que la mission du BIPM est d'assurer et de promouvoir la comparabilité mondiale des mesures, en fournissant notamment un système international d'unités cohérent,
- que l'Union astronomique internationale (UAI) et l'Union géodésique et géophysique internationale (UGGI), ainsi que l'Association internationale de géodésie (AIG), ont pour responsabilité de définir des systèmes de référence pour les applications spatiales et terrestres,
- que l'Union internationale des télécommunications – Secteur des radiocommunications (UIT-R) a pour responsabilité de coordonner la dissémination des signaux de temps et de fréquence et de formuler des recommandations pertinentes,
- que le Service international de la rotation terrestre et des systèmes de référence (IERS), un service de l'UAI et de l'UGGI, est responsable de fournir les informations requises afin de relier les systèmes de référence terrestre et céleste, parmi lesquelles : les mesures variant dans le temps de l'angle de rotation de la Terre, UT1-UTC ; la prédiction de faible précision d'UT1-UTC transmise par les signaux de temps, DUT1 ; et les données permettant de décider et d'annoncer l'insertion des secondes intercalaires,

notant

- que la Résolution A4 (1991) de l'UAI définit, dans ses Recommandations I et II, le Système de référence géocentrique comme un système de coordonnées spatio-temporelles pour la Terre dans le cadre de la théorie de relativité générale, et nomme, dans sa Recommandation III, le temps-coordonnée de ce système de référence le « Temps-coordonnée géocentrique (TCG) »,
- que la Résolution A4 (1991) de l'UAI définit en outre, dans sa Recommandation IV, le Temps terrestre (TT) comme un autre temps-coordonnée dans le Système de référence géocentrique, différant du TCG par une marche constante, l'unité d'échelle de TT étant choisie de sorte qu'elle s'accorde avec la seconde du SI sur le géoïde,

- que la Résolution B1.9 (2000) de l'UAI redéfinit TT comme une échelle de temps qui diffère du TCG par une marche constante : $d\mathrm{TT}/d\mathrm{TCG} = 1 - L_\mathrm{G}$, où $L_\mathrm{G} = 6{,}969290134 \times 10^{-10}$ est une constante de définition[1],
- que la redéfinition de TT en 2000 a introduit une ambiguïté entre TT et le TAI car le CCDS avait déclaré en 1980 que le TAI avait « comme unité d'échelle la seconde du SI telle qu'elle est réalisée sur le géoïde en rotation » alors que la définition de TT ne fait pas référence au géoïde,

déclare

- que le TAI est une échelle de temps continue produite par le BIPM à partir des meilleures réalisations de la seconde du SI et que c'est une réalisation de TT comme défini dans la Résolution B1.9 (2000) de l'UAI,
- que pour la conversion du temps propre d'une horloge en TAI, le décalage relativiste de fréquence est calculé par rapport à la surface équipotentielle $W_0 = 62636856{,}0\ \mathrm{m}^2\mathrm{s}^{-2}$ du potentiel de gravité de la Terre, adoptée de façon conventionnelle, en conformité avec la constante L_G définissant la marche de TT,
- que, tel qu'indiqué dans la Résolution A4 (1991) de l'UAI, TT-TAI est égal à 32,184 s exactement au 1er janvier 1977, 0h TAI au géocentre, pour assurer une continuité de TT avec le temps des éphémérides,
- que l'UTC produit par le BIPM, fondé sur le TAI, est l'unique échelle de temps recommandée comme référence internationale et qu'il est à la base du temps civil dans la plupart des pays,
- que l'UTC diffère du TAI seulement par un nombre entier de secondes, tel que publié par le BIPM,
- que les utilisateurs peuvent dériver l'angle de rotation de la Terre en appliquant à l'UTC les valeurs observées ou prédites de UT1-UTC telles que fournies par l'IERS,
- que l'UTC fournit un moyen de mesurer les intervalles de temps et de disséminer l'étalon de fréquence pendant les intervalles qui ne comprennent pas de secondes intercalaires,
- que la traçabilité à l'UTC est obtenue par l'intermédiaire des réalisations locales en temps réel maintenues par les laboratoires participant au calcul de l'UTC, dénommées UTC(*k*) où « *k* » identifie un laboratoire particulier,

recommande que les définitions suivantes du TAI et de l'UTC soient adoptées par le CIPM

- le Temps atomique international (TAI) est une échelle de temps continue produite par le BIPM à partir des meilleures réalisations de la seconde du SI. Le TAI est une réalisation du Temps terrestre (TT) ayant la même marche que TT, tel que défini par l'UAI dans sa Résolution B1.9 (2000),
- le Temps universel coordonné (UTC) est une échelle de temps produite par le BIPM ayant la même marche que le TAI mais différant du TAI par un nombre entier de secondes seulement,

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[1] La valeur numérique de L_G a été choisie pour se conformer à la valeur de $W_0 = 62636856{,}0\ \mathrm{m}^2\mathrm{s}^{-2}$ pour le potentiel de gravité sur le géoïde tel que recommandé par la Commission spéciale 3 de l'AIG en 1999.

recommande par ailleurs

- à toutes les organisations et unions concernées de prendre en compte ces définitions et de travailler ensemble afin de parvenir à une compréhension commune des échelles de temps de référence, de leur réalisation et de leur dissémination, l'objectif étant d'examiner à nouveau les limites actuelles de l'amplitude maximale de UT1-UTC afin de répondre aux besoins des communautés d'utilisateurs actuelles et à venir,
- à toutes les organisations et unions concernées de travailler ensemble pour améliorer davantage l'exactitude de la prédiction d'UT1-UTC et sa méthode de dissémination afin de satisfaire les futures exigences des utilisateurs.

RECOMMANDATION CCTF 4 (2017)

Sur l'utilisation et le contrôle des équipements de comparaison de temps redondants dans les laboratoires de temps participant au calcul de l'UTC

Le Comité consultatif du temps et des fréquences (CCTF), à sa 21e session en 2017,

réalisant

- que les étalons atomiques de fréquence ont atteint un niveau d'exactitude inégalé et que d'autres progrès rapides sont en cours dans ce domaine,
- que l'aptitude à comparer ces étalons pour réaliser l'UTC est limitée par l'exactitude et la stabilité des équipements de comparaison de temps,

considérant

- que les données de comparaisons de temps et de fréquences obtenues à partir des signaux des systèmes globaux de navigation par satellite (GNSS) et des systèmes de comparaison de temps et de fréquences par aller et retour sur satellite (TWSTFT) jouent un rôle important dans la réalisation de l'UTC,
- que des étalonnages réguliers des liaisons TWSTFT et des étalonnages des équipements GNSS, effectués dans le cadre d'une coopération entre le BIPM, les organisations régionales de métrologie et les laboratoires participant au calcul de l'UTC, ont permis d'obtenir des incertitudes d'étalonnage de l'ordre de 1 ns à 1,5 ns,
- que les variations des retards électriques des équipements limitent la validité des résultats d'étalonnage et que des variations aléatoires des mesures limitent également l'aptitude à combiner les données obtenues à partir de techniques complémentaires et redondantes,

notant

- que la Recommandation CCTF 4 (2012) recommandait aux laboratoires participant au calcul de l'UTC de mettre à niveau leurs équipements GNSS afin de passer à des systèmes de réception multifréquences et multiconstellations permettant d'effectuer des mesures de code et des mesures de phase des porteuses et leur demandait de fournir des données obtenues à partir d'au moins trois récepteurs,
- que l'étalonnage des récepteurs GNSS des laboratoires du Groupe 1 (G1) désignés par les organisations régionales de métrologie revêt une importance particulière car ces récepteurs ont une influence significative sur les étalonnages ou les liaisons de nombreux autres laboratoires,
- qu'ont été observées des variations des mesures CCD (Common Clock Differences) entre les systèmes GNSS et des variations des mesures DCD (Double Clock Differences) entre les liaisons obtenues par le Global Positioning System (GPS) et les liaisons TWSTFT qui dépassent l'incertitude composée des étalonnages les plus récents,
- que plusieurs études en cours étudient comment réduire les effets des variations de l'étalonnage de systèmes de comparaison de temps,

recommande aux laboratoires participant au calcul de l'UTC

- de maintenir au moins deux (trois dans le cas des laboratoires G1) systèmes GNSS indépendants, dont un système représentant l'état de la technique si les ressources le permettent,
- de fournir au BIPM l'ensemble des données obtenues à partir de systèmes GNSS redondants,
- de contrôler leurs mesures CCD et les caractéristiques internes des signaux de référence de leur laboratoire, telles que la forme du signal de pulsation par seconde au niveau de leurs systèmes de comparaison de temps, tous les ans ou à une périodicité plus adéquate,
- de documenter tous les changements de paramètres et de configuration concernant les comparaisons de temps et les transmettre aux BIPM,
- d'enregistrer les informations pertinentes concernant la température et l'humidité, extérieures et intérieures, et de les transmettre au BIPM,
- d'évaluer la corrélation entre les solutions de comparaison de temps et les mesures locales de température et d'humidité,
- d'étalonner au moins une liaison opérationnelle tous les deux ans,

recommande au BIPM, au Groupe de travail du CCTF sur les comparaisons de temps et de fréquences par aller et retour sur satellite et au Groupe de travail du CCTF sur les comparaisons de temps à l'aide de systèmes GNSS

- de coordonner les étalonnages des liaisons horaires par aller et retour sur satellite et ceux des équipements GNSS de façon à ce qu'ils soient comparables et à ce que les impacts saisonniers puissent être étudiés afin d'en réduire les effets,
- d'étudier l'impact de l'introduction des résultats d'étalonnage sur les séries de mesure CCD et DCD à long terme,
- de définir le format pour soumettre les informations concernant la température et l'humidité,

recommande au BIPM

- de continuer à publier sur ses pages internet les différences de comparaison de temps qu'il calcule (liaisons horaires et comparaisons de liaisons) sous la forme de fichiers informatiques portant des noms explicites,
- de continuer à publier sur ses pages internet des informations sur les configurations des systèmes et les résultats d'étalonnage, accompagnées des rapports associés,
- de continuer à étudier l'utilisation de systèmes de comparaison de temps redondants pour calculer l'UTC,
- d'ajouter dans la base de données du Département du temps les informations concernant la température et l'humidité et de mettre ces informations à la disposition des groupes de travail,
- d'ajouter dans la base de données du Département du temps les changements de paramètres et de configuration de la station pertinents pour les comparaisons de temps.

RECOMMANDATION CCTF 5 (2017)

Sur l'amélioration de l'incertitude des comparaisons de temps et de fréquence par aller et retour sur satellite (TWSTFT) dans le cadre du calcul de l'UTC

Le Comité consultatif du temps et des fréquences (CCTF), à sa 21e session en 2017,

réalisant

- que les étalons atomiques de fréquence ont atteint un niveau d'exactitude inégalé et que d'autres progrès rapides sont en cours dans ce domaine,
- que les données de comparaisons de temps et de fréquences obtenues à partir des systèmes TWSTFT jouent un rôle important dans la réalisation de l'UTC,
- que l'incertitude des données obtenues à l'aide des systèmes TWSTFT actuels pour la réalisation de l'UTC est limitée par des contraintes techniques, ce qui peut générer une variation quotidienne (diurne) des résultats des comparaisons de temps,

considérant

- que l'utilisation à titre expérimental de récepteurs SDR (Software Defined Radio) dans la région Asie-Pacifique (les récepteurs SDR mesurent les signaux horaires générés par les équipements TWSTFT actuellement utilisés) a montré que les récepteurs TWSTFT SDR réduisent de façon significative le bruit diurne et le bruit des mesures,
- qu'une étude pilote sur l'utilisation de la technique TWSTFT SDR pour l'UTC a été organisée en février 2016 par le BIPM et le Groupe de travail du CCTF sur les comparaisons de temps et de fréquences par aller et retour sur satellite afin d'étudier l'impact de cette technique sur les liaisons Asie-Asie, Asie-Europe, Europe-Europe, Europe-États-Unis et États-Unis-États-Unis à l'aide de différents satellites géostationnaires,
- que tous les laboratoires participant au calcul de l'UTC qui effectuent des comparaisons de temps et fréquences par aller et retour sur satellite se sont montrés intéressés à participer à cette étude pilote et que douze stations en Asie, en Europe et aux États-Unis ont installé des systèmes SDR puis effectué des mesures qui ont contribué à l'étude,
- que la validation par le BIPM des résultats de comparaisons à l'aide de la technique TWSTFT SDR a montré une réduction significative du bruit diurne et de mesure dans les liaisons TWSTFT intracontinentales avec un facteur de gain de deux à trois concernant la stabilité des liaisons horaires par rapport aux résultats de comparaisons fondées sur les équipements TWSTFT actuellement utilisés,
- que des modems TWSTFT numériques sont en cours de développement depuis quelques années et que certains peuvent supporter à la fois des mesures de code et des mesures de la phase des porteuses, ce qui pourrait améliorer davantage l'incertitude des comparaisons de temps et de fréquence par aller et retour sur satellite,

recommande aux laboratoires disposant de stations TWSTFT

- de continuer à étudier la technique TWSTFT SDR en maintenant des opérations fondées sur des récepteurs SDR ou en installant des systèmes SDR dans les stations, et en fournissant au BIPM des résultats de comparaisons réalisées à l'aide de la technique TWSTFT SDR en plus des données obtenues à partir des équipements TWSTFT actuellement utilisés, l'objectif étant d'améliorer par une réduction du bruit diurne l'incertitude des liaisons horaires obtenue lors des comparaisons TWSTFT actuelles,
- de soutenir et de participer au test de nouveaux modems TWSTFT numériques lorsqu'ils seront disponibles dans le but d'améliorer davantage l'incertitude des comparaisons de temps et de fréquence par aller et retour sur satellite, potentiellement en les rendant utilisables pour la comparaison d'horloges optiques au niveau de leur exactitude,

recommande au BIPM

- de poursuivre les travaux visant à utiliser des données obtenues à l'aide de la technique TWSTFT SDR pour le calcul de l'UTC,
- de soutenir les études visant à améliorer la technique TWSTFT par des mesures redondantes au sein du réseau TWSTFT et par des modems numériques lorsque les données seront disponibles.

RECOMMENDATION CCTF 1 (2017)

Recommendations for operating, comparing and reporting frequency standards as secondary representations of the second in preparation for a redefinition of the second by optical transitions

The Consultative Committee for Time and Frequency (CCTF), at its 21st session in 2017,

considering that

- a list of secondary representations of the second (SRS) has been maintained following the recommendations of the CIPM,
- different optical SRS have estimated fractional frequency uncertainties nearly two orders of magnitude lower than those of the best caesium primary standards,
- improvements in uncertainty associated with optical frequency standards are ongoing,
- a roadmap for a future redefinition of the second using optical frequency standards has been agreed by the CCTF;

recommends that

- the institutes put effort into operating their frequency standards to realize SRS in such a way that they routinely contribute to TAI via reporting to the BIPM,
- the optical standards be compared with uncertainties that are comparable to the estimated uncertainties of the standards themselves,
- the institutes measure the frequencies of the realizations of their SRS with respect to the best primary caesium standards as a necessary requirement for a possible future redefinition of the second in terms of optical transitions,
- the relevant CCTF working groups finalize the milestones for a redefinition and regularly inform the CIPM about the progress towards meeting these milestones.

RECOMMENDATION CCTF 2 (2017)

Updates to the CIPM list of standard frequencies

The Consultative Committee for Time and Frequency (CCTF), at its 21st session in 2017,

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;

recommends

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

- the unperturbed optical transition $5s^2\ {}^1S_0 - 5s5p\ {}^3P_0$ of the $^{115}In^+$ ion with a frequency of f_{115In+} = 1 267 402 452 901 050 Hz and an estimated relative standard uncertainty of 1.6×10^{-14};
- the unperturbed optical transition $6s^2\ {}^1S_0 - 6s6p\ {}^3P_0$ of the ^{199}Hg neutral atom with a frequency of f_{199Hg} = 1 128 575 290 808 154.4 Hz and an estimated relative standard uncertainty of 5×10^{-16};

  This radiation is now endorsed 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} = 518 295 836 590 863.6 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 $5s\ {}^2S_{1/2} - 4d\ {}^2D_{5/2}$ of the $^{88}Sr^+$ ion with a frequency of f_{88Sr+} = 444 779 044 095 486.5 Hz and an estimated relative standard uncertainty of 1.5×10^{-15} (this radiation is already endorsed by the CIPM as a secondary representation of the second);
- the unperturbed optical transition $5s^2\ {}^1S_0 - 5s5p\ {}^3P_0$ of the ^{88}Sr neutral atom with a frequency of f_{88Sr} = 429 228 066 418 007.0 Hz and an estimated relative standard uncertainty of 6×10^{-16};
- the unperturbed optical transition $5s^2\ {}^1S_0 - 5s5p\ {}^3P_0$ of the ^{87}Sr neutral atom with a frequency of f_{87Sr} = 429 228 004 229 873.0 Hz and an estimated relative standard uncertainty of 4×10^{-16} (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+} = 411 042 129 776 399.8 Hz and an estimated relative standard uncertainty of 2.4×10^{-15};

- the unperturbed ground-state hyperfine transition of ^{87}Rb with a frequency of f_{87Rb} = 6 834 682 610.904 312 6 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);

and informs the CIPM accordingly.

RECOMMENDATION CCTF 3 (2017)

Recommendation on the definition of time-scales

The Consultative Committee for Time and Frequency (CCTF), at its 21st session in 2017,

considering that

- Resolution 1 of the 14th CGPM (1971) requested the CIPM to define International Atomic Time (TAI),
- no complete self-contained definition of TAI has been provided officially by the CIPM,
- the Consultative Committee for the Definition of the Second (CCDS) proposed in its Recommendation S2 (1970) a definition which was extended by a Declaration of the CCDS in 1980,
- the 15th CGPM (1975) noted that Coordinated Universal Time (UTC), derived from TAI, provides the basis of civil time, and strongly endorsed this usage;

recognizing that

- the mission of the BIPM is to ensure and promote the global comparability of measurements, including and providing a coherent international system of units,
- the International Astronomical Union (IAU) and the International Union of Geodesy and Geophysics (IUGG) with the International Association of Geodesy (IAG) are responsible for defining reference systems for Earth and space applications,
- the International Telecommunication Union Radiocommunication Sector (ITU-R) is responsible for coordinating the dissemination of time and frequency signals and making relevant recommendations,
- the International Earth Rotation and Reference Systems Service (IERS), a service of the IAU and IUGG, is responsible for providing information required to relate terrestrial and celestial reference systems, including time-varying measurements of the Earth’s rotation angle, UT1-UTC, the low-precision prediction of UT1-UTC for time signal broadcasts, DUT1, and for deciding and announcing leap second insertions;

noting that

- Resolution A4 (1991) of the IAU defined, in Recommendations I and II, the Geocentric Reference System as a system of space-time coordinates for the Earth within the framework of general relativity, and, in Recommendation III, named the time coordinate of that reference system “Geocentric Coordinate Time” (TCG),
- Resolution A4 (1991) of the IAU further defined, in Recommendation IV, Terrestrial Time (TT) as another time coordinate in the Geocentric Reference System, differing from TCG by a constant rate; the unit of measurement of TT being chosen to agree with the SI second on the geoid,

- Resolution B1.9 (2000) of the IAU redefined TT to be a time scale differing from TCG by a constant rate: $d\mathrm{TT}/d\mathrm{TCG} = 1 - L_G$, where $L_G = 6.969290134 \times 10^{-10}$ is a defining constant[2],
- the redefinition of TT in 2000 introduced an ambiguity between TT and TAI as the CCDS had stated in 1980 that TAI was to have "*the SI second as realized on the rotating geoid as the scale unit*" while the definition of TT does not refer to the geoid;

states that

- TAI is a continuous time scale produced by the BIPM based on the best realizations of the SI second, and is a realization of TT as defined by IAU Resolution B1.9 (2000),
- in the transformation from the proper time of a clock to TAI, the relativistic rate shift is computed with respect to the conventionally adopted equipotential $W_0 = 62636856.0\ \mathrm{m^2 s^{-2}}$ of the Earth's gravity potential, which conforms to the constant L_G defining the rate of TT,
- as stated in the IAU Resolution A4 (1991), TT-TAI = 32.184 s exactly at 1 January 1977 , 0h TAI at the geocentre, in order to ensure continuity of TT with Ephemeris Time,
- UTC produced by the BIPM, based on TAI, is the only recommended time scale for international reference and the basis of civil time in most countries,
- UTC differs from TAI only by an integral number of seconds as published by the BIPM,
- users can derive the rotation angle of the Earth by applying to UTC the observed or predicted values of UT1-UTC as provided by the IERS,
- UTC provides a means to measure time intervals and to disseminate the standard of frequency during intervals in which leap seconds do not occur,
- traceability to UTC is obtained through local real-time realizations UTC(*k*) maintained by laboratories contributing data to the calculation of UTC, identified by "*k*",

recommends the following definitions of TAI and UTC be adopted by the CIPM

- International Atomic Time (TAI) is a continuous time scale produced by the BIPM based on the best realizations of the SI second. TAI is a realization of Terrestrial Time (TT) with the same rate as that of TT, as defined by the IAU Resolution B1.9 (2000),
- Coordinated Universal Time (UTC) is a time scale produced by the BIPM with the same rate as TAI, but differing from TAI only by an integral number of seconds,

and further recommends that

- all relevant unions and organizations consider these definitions and work together to develop a common understanding on reference time scales, their realization and dissemination with a view to reconsider the present limitation on the maximum magnitude of UT1-UTC so as to meet the needs of the current and future user communities,
- all relevant unions and organizations work together to improve further the accuracy of the prediction of UT1-UTC and the method for its dissemination to satisfy the future requirements of the users.

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[2] The numerical value of L_G was chosen to conform to the value $W_0 = 62636856.0\ \mathrm{m^2 s^{-2}}$ for the gravity potential on the geoid as recommended by Special Commission 3 of the IAG in 1999.

RECOMMENDATION CCTF 4 (2017)

On the utilization and monitoring of redundant time transfer equipment in the timing laboratories contributing to UTC

The Consultative Committee for Time and Frequency (CCTF), at its 21st session in 2017,

realizing that

- atomic frequency standards have achieved unprecedented accuracy, and that further rapid advances in this field are under way,
- the ability to compare these standards for the realization of UTC is limited by the accuracy and stability of time transfer equipment;

considering that

- time and frequency transfer data from the use of Global Navigation Satellite Systems (GNSS) signals and from Two-Way Satellite Time and Frequency Transfer (TWSTFT) systems play an important role in the realization of UTC,
- regular TWSTFT time link calibrations and GNSS equipment calibrations have been carried out through cooperation of the BIPM, the Regional Metrology Organizations (RMO) and the UTC contributing laboratories resulting in calibration uncertainties at the level of order of 1 ns to 1.5 ns,
- hardware delay variations limit the validity of calibration results, and random variations in measurements also limit the ability to combine data from redundant and complementary techniques;

noting that

- Recommendation CCTF 4 (2012) recommended laboratories that contribute to UTC to upgrade their GNSS equipment towards multi-frequency multi-constellation receiving systems providing code- and carrier-phase measurements and to supply data from at least three receivers,
- the calibration of GNSS receivers of the Group One (G1) laboratories designated by the RMOs has special importance as they influence the calibrations or links of other multiple laboratories in a significant manner,
- variations of the common clock differences (CCD) between GNSS systems and variations of the double clock differences (DCD) between Global Positioning System (GPS) and TWSTFT links, which exceed the combined calibration uncertainty of the most recent calibrations, have been observed,
- several ongoing studies consider ways to mitigate the effects of time transfer systems' calibration variations;

recommends that laboratories participating in UTC generation

- maintain at least two (three in the case of G1 laboratories) independent GNSS systems, some of which being state-of-the-art if resources are available,
- provide all data from redundant GNSS systems to the BIPM,

- monitor their CCDs and the internal characteristics of their laboratory reference signals, such as the shape of their pulse-per-second signal as seen at their time transfer systems, on an annual or other appropriate basis,
- document all setup and configuration changes relevant to time transfer and report this data to the BIPM,
- record and maintain both external and relevant internal temperature and humidity information and report this data to the BIPM,
- evaluate the correlation between the time transfer solutions and the local temperature and humidity measurements,
- calibrate at least one operational link every two years;

recommends that the BIPM and the CCTF WGs on TWSTFT and on GNSS Time Transfer

- coordinate TWSTFT and GNSS calibrations so that they can be compared and that the seasonal impacts can be studied and their effects minimized,
- study the impact of introducing calibration results on the long-term CCD and DCD series,
- define the format for the submissions of temperature and humidity information;

recommends that the BIPM

- continue to publish its computed time transfer differences (links and link comparisons) on its web pages in computer files with self-explanatory names,
- continue to publish the information about system configurations and calibration results on its web pages, along with the associated reports,
- continue to study the use of redundant time transfer systems in UTC generation,
- add the station temperature and humidity information to the Time Department database and make these data available to the WGs,
- add the station setup and configuration changes relevant to time transfer to the Time Department database.

RECOMMENDATION CCTF 5 (2017)

On improving the uncertainty of Two-Way Satellite Time and Frequency Transfer (TWSTFT) for UTC Generation

The Consultative Committee for Time and Frequency (CCTF), at its 21st session in 2017,

realizing

- that atomic frequency standards have achieved unprecedented accuracy, and that further rapid advances in this field are under way,
- that time and frequency transfer data from the use of TWSTFT systems plays an important role in realization of UTC,
- that the uncertainty of current TWSTFT systems for the realization of UTC is limited by technical constraints that can result in a daily variation (diurnal) in time transfer results;

considering

- that the experimental use of Software Defined Radio (SDR) receivers in the Asia-Pacific region (SDR receivers measure the timing signals generated by the currently used TWSTFT equipment) demonstrated that SDR TWSTFT significantly reduced the diurnal and measurement noise,
- that a pilot study on using SDR TWSTFT for UTC was organized by the BIPM and the CCTF Working Group on Two-Way Satellite Time and Frequency Transfer (WGTWSTFT) in February 2016 to investigate the impact of SDR TWSTFT for the Asia-Asia, Asia-Europe, Europe-Europe, Europe-US and US-US links using different geostationary satellites,
- that all UTC laboratories engaged in TWSTFT expressed their interest in participating in the pilot study and that twelve stations in Asia, Europe and the USA have installed SDR systems and carried out measurements contributing to the pilot study,
- that the BIPM global validation of the SDR TWSTFT results has revealed a significant reduction of the diurnal and measurement noise in the inner-continental TWSTFT links with a gain factor of two to three in the time link stability as compared to the currently used TWSTFT results,
- that a few digital TWSTFT modems have been under development in recent years, some of which are capable of supporting both code-phase and carrier-phase measurements, which could further improve the uncertainty of TWSTFT;

recommends that laboratories operating TWSTFT stations

- continue to study the SDR TWSTFT technique by maintaining SDR operation or installing SDR systems in stations, and providing SDR TWSTFT data to the BIPM in parallel to the data from the currently used TWSTFT equipment, with the aim of improving the uncertainty of time links with the current TWSTFT by a reduction of the diurnal noise,

- support and participate in the test of new digital TWSTFT modems as they become available with the perspective of further improving the uncertainty of TWSTFT, potentially making it practical for the comparison of optical clocks at the level of their accuracies;

recommends that the BIPM

- work towards implementing the use of SDR TWSTFT data in UTC generation,
- support studies to improve TWSTFT with redundant measurements in the TWSTFT network and with digital modems when data becomes available.