CCTF Strategy Document
Updated: May 2016
Period covered: 2016-2026

1. General Information on CC Body (CC and CC WG):

CC Name: Consultative Committee for Time and Frequency (CCTF)

CC Working Groups: This report is being prepared by the CCTF Strategic Planning Working Group (WGSP) and generally covers the relevant activities of the CCTF and all of its Working Groups. The Working Groups have separate responsibilities that, taken together, include all of the issues that are addressed in this report. In 2012 there was a restructuring of the CCTF Working Groups with the creation of the CCTF Working Group on Algorithms (which was a sub-group of the WG TAI) and the transformation of the Working Group Global Navigation Satellite System Time Transfer Standards (CGGTTS) into the Working Group on GNSS Time Transfer (WG GNSS) with new terms of reference. In addition, the CCTF Working Group on Primary Frequency Standards extended its activities to cover reports on measurements of secondary representations of the second. This resulted in the adoption of a new name, CCTF Working Group on Primary and Secondary Frequency Standards (WGPSFS), an increase in membership and new terms of reference. The terms of reference and membership of the CCL-CCTF Frequency Standards Working Group (FSWG) have been approved by both Consultative Committees.

In March 2016, the Working Groups of the CCTF are:

- Working Group on International Atomic Time (WG TAI)
- Working Group on Algorithms (WG Algo)
- Working Group on Primary and Secondary Frequency Standards (WG PSFS)
- Working Group on GNSS Time transfer (WG GNSS)
- Working Group on Two-Way Satellite Time and Frequency Transfer (WG TWSTFT)
- Working Group on Coordination of the Development of Advanced Time and Frequency Transfer Techniques (WG ATFT)
    - ATFT Study Group on optical fibres for use in UTC (SGOF)
- Working Group on the CIPM MRA (WG MRA)
- Working Group on Strategic Planning (WG SP)
- CCL-CCTF Frequency Standards Working Group (CCL-CCTF FSWG)

Date of Establishment:

- CCTF: 1956, as CCDS, 1997, as CCTF
- WG TAI: 1985
- WG TWSTFT: 1989
- WG MRA: 1999
- CCL-CCTF FSWG: 2003 (formerly CCL-CCTF Joint Working Group)

- WG ATFT: 2006
    - SGOF: 2015
- WG SP: 2009
- WG Algo: 2012
- WG PSFS: 2012 (formerly WGPFS)
- WG GNSS: 2012 (formerly CGGTTS)

Membership:

- CCTF:
  Members: 24 institutes and 5 international organizations
  Observers: 3 institutes
- WG TAI: all laboratories contributing to UTC (74 in March 2016), 5 international organizations and 2 individuals
- WG Algo: Created in September 2012, membership is open to representatives of contributing laboratories and institutions with relevant activities, and relevant BIPM Time Department staff.
- WG PSFS: representatives of NMIs operating primary and/or secondary frequency standards reporting to TAI or planning to report, and representatives of the BIPM Time Department (approximately 25 individuals).
- WG GNSS: Created in September 2012, experts from laboratories contributing to UTC, from the International GNSS Service (IGS) and from the BIPM, one representative from the CCTF-WGTAI and one representative of the CCTF-WGATFT.
- WG TWSTFT: representatives from laboratories contributing TWSTFT data to UTC and those preparing their contribution (approximately 24 individuals).
- WG ATFT: one representative from each CCTF WG (TAI, ALGO, GNSS, TWSTFT, PSFS) two representatives from the WGFS, one representative from the BIPM Time Department, other experts in institutes members of the CCTF.
    - SGOF: created in September 2015, Members of the Study Group are experts from institutes where fibre links are in use and from the BIPM.
- WG MRA: Chairpersons of the RMOs T&F technical committees and experts (three in 2016, including one from the BIPM)
- WG SP: Chairpersons of the CCTF Working Groups
- CCL-CCTF FSWG: 8 institutes

Number of participants at last meeting:

- CCTF: 66 (2015)
- WG TAI: 53 (2015)
- WG Algo: 68 participants to the VI International Time Scale Algorithms Symposium and Tutorials (2015)
- WG PSFS22 (2015).

- WG GNSS: 14 (2016)
- WG TWSTFT: 27 (2015)
- WG ATFT: 25 (2015)
  - SGOF: 14 (2016)
- WG MRA: 9 (2015)
- WG SP: 7 (2016)
- CCL-CCTF FSWG: 16 (2016)

Periodicity of meetings:

- CCTF: every 3 years
- WG TAI: every 3 years, with CCTF
- WG Algo: no fixed schedule
- WG PSFS: no fixed schedule. Mostly done through correspondence.
- WG GNSS: no fixed schedule
- WG TWSTFT: annually
- WG ATFT: no fixed schedule
  - SGOF: no fixed schedule
- WG MRA: no fixed schedule
- WG SP: annually
- CCL-CCTF FSWG: every 1,5 years (at regular CCTF and CCL meetings and one meeting in between)

Date of last meeting:

- CCTF: September 2015
- WG TAI: September 2015
- WG Algo: no meeting as yet
- WG PSFS: April 2016
- WG TWSTFT: September 2015; next September 2016
- WG ATFT: September 2015
  - SGOF: April 2016
- WG MRA: September 2015
- WG SP: April 2016
- CCL-CCTF FSWG: April 2016

CC WG Chair (Name, Institute, and years in post):

- CCTF: L. Erard, LNE, 2007
- WG TAI: F. Arias (by interim), 2015

- WG Algo: Y. Hanado, NICT, 2012
- WG PSFS: S. Jefferts, NIST, 2012
- WG GNSS: P. Defraigne, ORB, 2012
- WG TWSTFT: V. Zhang, NIST, 2015
- WG ATFT: F-L. Hong, NMIJ, 2012
    - SGOF: D. Calonico, INRIM, 2015
- WG MRA: M. Lopez, CENAM, 2012
- WG SP: L. Erard, LNE, 2009
- CCL-CCTF FSWG: F. Riehle, PTB and P. Gill, NPL, 2003

Number of KCs organized (from 1999 up to and including 2015):

Only one key comparison defined by the CCTF and piloted by the BIPM: CCTF-K001.UTC. The comparison, at the BIPM under the name of BIPM *Circular T*, has been in existence since 1988 and was defined by the CCTF as a key comparison under the CIPM MRA in 2001. *Circular T* is calculated on a monthly basis, with degrees of equivalence calculated at five- day intervals for all participating laboratories (74 as in January 2016). Degrees of equivalence for CCTF-K001.UTC are published in the KCDB for 59 institutes (as on January 2016) in BIPM *Circular T* that are NMIs and DIs participants of the CIPM MRA.

Number of pilot studies organized (from 1999 up to and including 2015):

No pilot studies organized.

Number of CMCs published in KCDB supported by CC body activities (up to and including 2015):738

2. Terms of Reference of CCTF WGs

The BIPM provides the secretariat for the Working Groups.

WG TAI

Members

a) a representative from each of the following organizations:

- International Astronomical Union (IAU),
- International Committee for Weights and Measures (CIPM),
- International Union of Geodesy and Geophysics (IUGG),
- International Union of Radio Science (URSI),
- International Telecommunication Union, Radiocommunication Sector (ITU-R),

b) the Director of the BIPM,

c) the individual responsible for TAI at the BIPM, and

d) representatives of the laboratories contributing to TAI.

An expert from an organization or a laboratory contributing to TAI is appointed by the CCTF President as Chair of the Working Group.

Mission (Terms of Reference)

a) to review the requirements and comments received by users of TAI,

b) to prepare guidelines for the improvement of the TAI service and to report on these to the CCTF, and

c) to establish temporary *ad hoc* study groups to analyze specific problems, whenever necessary. These study groups should report to the Working Group.

The said mandate should be extended to Coordinated Universal Time UTC.

The Working Group should normally work by correspondence addressed to the Chair, and should meet annually at the Chair's request, if possible.

The Working Group on TAI should work closely with all other CCTF Working Groups to harmonize the overall contributions to TAI.

WG Algo

Members

a) representatives of the laboratories contributing to TAI expert or interested in algorithms,

b) the individual responsible for TAI at the BIPM,

c) the members of the BIPM time department devoted to the TAI algorithm,

d) members of other organizations or institutions interested in developing and using time algorithms.

An expert from an organization or a laboratory contributing to TAI is appointed by the CCTF President as Chair of the working group.

Mission (Terms of Reference)

a) to promote and support the development and improvement of the mathematical algorithms for the treatment of Time and Frequency measures used to establish a time scale, to characterize clock behavior, or to any other applications that may be arise,

b) to help the dissemination of the developed algorithm and tools to allow their correct use in the Time and Frequency metrology,

c) to support the modernization and the improvement, if necessary, of the TAI algorithm,

d) to assist developing or new laboratories in the correct understanding and implementation of the time and frequency algorithms,

e) to support the correct understanding and application of time algorithms also in other fields (eg navigation, telecommunication) were they may be necessary,

f) to establish temporary ad hoc study groups to analyze some specific problems, whenever necessary; these study groups should report to the working group,

g) to organize the “Time Scale Algorithm Symposium” as a mean to support the scientific community to identify new needs, to devise, develop, and disseminate algorithms.

The WG Algos should work closely with working group on TAI to harmonize the contributions to TAI, UTC, and its local representations.

WG PSFS

Members:

a) representatives of all NMIs operating PFS and/or SFS reporting to TAI,

b) representatives of NMIs planning to operate at least one PFS and/or SFS for reporting to TAI,

c) representatives of the BIPM.

Mission (Terms of Reference)

a) to develop and propose standards for the documentation of frequency biases and uncertainties, operational details, and frequency transfer uncertainties for primary and secondary frequency standards (PFS and SFS). Develop and propose standards for the reporting of the results of a PFS/SFS evaluation to the BIPM,

b) to provide a forum to evaluate and discuss the consistency among primary and secondary frequency standards,

c) to provide a forum to discuss and assess the overall knowledge of the accuracy of the SI second for use in establishing the frequencies of secondary standards (microwave and optical) and possibly an eventual redefinition of the second,

d) to interact with the BIPM on issues related to PFS and SRS contributions to the accuracy of TAI, particularly in the process of integration of the first reports of a standard,

e) to encourage and facilitate direct comparisons between primary and secondary frequency standards,

f) to encourage and support laboratories with new standards under construction.

WG GNSS

Members

a) one representative from the CCTF WG TAI,

b) one representative from the CCTF WG ATFT,

c) experts from laboratories contributing to UTC,

d) experts from the IGS,

e) members of the BIPM Time Department.

Mission (Terms of Reference)

a) to report to the CCTF on the state of the art in GNSS time and frequency transfer and to provide recommendations concerning receiving systems, calibrations and data processing,

b) in collaboration with the BIPM, to gather and share the information on equipment, calibration, and scientific results,

c) to maintain contacts with the receiver manufacturers in order to inform them about our needs,

d) to stimulate the collection and analysis of code and carrier phase data from all GNSS constellations,

e) to stimulate the development of calibration procedures in agreement with new GNSS receiving systems,

f) to establish contacts with the parallel scientific communities working on the definition of the receiver output standards,

g) to study the clock results formats in agreement with the user needs.

WG TWSTFT

Members

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.

Mission (Terms of Reference)

a) to perform coordination activities related to TWSTFT between participating and prospective institutes,

b) to act as a point of contact for BIPM on TWSTFT matters,

c) to organize the operation of TWSTFT links to support the production of TAI,

d) to perform calibration campaigns to reduce the time link uncertainties between participating institutes,

e) to observe and review the needs for remote frequency and time comparisons of frequency standards and atomic time scales,

f) to establish and maintain dedicated TWSTFT links to support remote clock comparisons,

g) to identify future needs of remote clock comparisons,

h) to undertake research for the improvement of TWSTFT and related techniques,

i) to follow and assess other techniques, including GNSS, optical fibers, optical satellite links which could be used for remote (optical) clock comparisons, and

j) together with BIPM, to foster the spread of information on technical achievements by suitable means, e.g. via BIPM webpage.

WG ATFT

Members

a) one representative from the CCTF Working Group on TAI,
b) one representative from the CGGTTS,
c) one representative from the CCTF Working Group on TWSTFT,
d) one representative from the CCTF Working Group on Primary Frequency Standards,
e) two representatives from the CCL-CCTF Working Group on Frequency Standards,
f) one representative from the BIPM, who will serve as the WG executive secretary,
g) other experts from laboratories members of the CCTF,
h) experts from other relevant bodies such as ITU, IGS, IUGG, URSI.

Mission (Terms of Reference)

a) to review the status and projected evolution of the characteristics of frequency standards, time scales and time and frequency transfer techniques,

b) to follow and assess the evolution of microwave links in current use, based on GNSS signals and TWSTFT,

c) to follow and assess other technical possibilities, including optical fibre links, optical satellite links, and transportable optical frequency standards, which could be used for comparison of high performance frequency standards,

d) to establish the relevant connections and facilitate consultations with other relevant bodies, such as IGS, IUGG, IVS, ITU, etc.

e) together with the BIPM, to foster the spread of information on technical achievements by suitable means, e.g. workshops, and multiple techniques (such as GNSS, TWSTFT, ACES microwave link, T2L2, optical fibre links).

SGOF

Members

Experts from institutes where fibre links are in use, or where experiments had been carried out, and representatives from the BIPM.

Mission (Terms of Reference)

a) to make a review of the present status of the various optical fibre links with applications in time and frequency metrology,

b) to study regulatory issues related to the availability of the services in a national context and the coordination between networks in different countries,

c) to propose technical directives for operating procedures, formats, including hardware, software and administrative issues,

d) to propose the appropriate recommendations for consideration of the CCTF and of the BIPM.

WG MRA

Members

a) the chairpersons of the RMO Technical Committees for time and frequency,

b) experts from time laboratories (two in March 2016),

c) an expert from the BIPM Time Department.

Mission (Terms of Reference)

a) authorization on a provisional basis for any action needed between meetings of the CCTF as indicated by the CIPM MRA, in consultation with the CCTF President,

b) to perform coordination activities relating to the MRA between RMOs,

c) to act as point of contact for the BIPM and JCRB on MRA matters,

d) to report actions to the next CCTF meeting, with the CCTF revising decisions as required,

e) to identify areas where additional key comparisons and supplementary comparisons are needed, and develop the necessary guidelines and procedures,

f) to provide guidance on the range of CMCs supported by particular key and supplementary comparisons,

g) to establish and maintain a list of service categories and, where necessary, rules for the preparation of CMC entries,

h) to agree on detailed technical review criteria,

i) to coordinate the review of existing CMCs in the context of new results of key and supplementary comparisons.

WG SP

Members

a) the President of the CCTF,

b) the chair persons of the CCTF WGs,

c) the Director of the BIPM Time Department, who will serve as the WGSP Executive Secretary,

d) experts that could be proposed by the WGSP chair person.

Mission (Terms of Reference):

a) to collect and make available information giving evidence of the importance and progress of time and frequency metrology,

b) to collect information from CCTF member laboratories on their long-term programmes of work with the aim of encouraging collaboration and cooperation, and to make this information available,

c) to propose to the CCTF long-term plans for the future activities of the relevant Department of the BIPM over the next ten to fifteen years, and regularly review and update these plans,

d) to review the activities of the relevant BIPM Department, and advise the CCTF on this by producing reports at its meetings,

e) to advise on the improvement of the structure of the CCTF and its WGs,

f) to monitor the evolution of new frequency standards and of techniques for their comparison with the aim of evaluating their impact on a possible future redefinition of the SI second,

g) to assure the liaison between relevant international organizations and the CCTF,

h) to establish the criteria for membership of the CCTF and its WGs.

CCL-CCTF FSWG

Members

In March 2016 members are the following institutes: INRIM, NIST, NMIJ/AIST, NPL, NRC, PTB, SYRTE, VNIIFTRI

Mission (Terms of Reference)

a) to make recommendations to the CCL for radiations to be used for the realization of the definition of the meter and to make recommendations to the CCTF for radiations to be used as secondary representations of the second,

b) to maintain, together with the BIPM, the list of recommended frequency standard values and wavelength values for applications including the practical realization of the definition of the meter and secondary representations of the second,

c) to take responsibility for key comparisons of standard frequencies such as CCL-K11,

d) to respond to future needs of both the CCL and CCTF concerning standard frequencies relevant to the respective communities.

3. Baseline (description status of activities and achievements up to and including 2015)

Support of comparisons and CMCs:

The CCTF has decided to define and support a unique key comparison in time and frequency identified as CCTF-K001.UTC. It has also been decided that the BIPM is the pilot of this key comparison, which is performed every month. Participants to CCTF-K001.UTC are a subset of the total contributors to BIPM *Circular T*.

CMCs on frequency, time interval and time scale differences are supported by the CCTF following the guidelines prepared by the CCTF WG MRA and approved by the CCTF.

Important achievements at the BIPM

BIPM Time Department activities and achievements:

- Maintenance of International Atomic Time (TAI) and Coordinated Universal Time (UTC):

About 500 industrial atomic clocks and a dozen primary frequency standards in 74 national contributing laboratories participate in the calculation of UTC at the Time Department of the BIPM in March 2016. Industrial clocks are mostly caesium industrial beams, plus an increasing number of hydrogen masers. The weighted average of the readings contribute to the calculation of the "free atomic scale" EAL (Echelle Atomique Libre), whose interval unit is not constrained to represent the SI second. TAI is then derived from EAL by applying (if necessary) a frequency correction for matching its unit interval to the SI second. Finally, UTC is derived from TAI by the application of the total number of leap seconds. Therefore, both the TAI and UTC scales are identical, except for the integral-number-of-seconds offset. The algorithm for the calculation of TAI used at the BIPM has been designed for optimal frequency stability of TAI at about one month with adequate weighting procedure and clock frequency prediction.

The algorithms for the computation of TAI has been improved since 2010 with the aim of detecting the origin of the drift observed in TAI with respect to the primary frequency standards, and eliminating it: the increasing number of hydrogen maser clocks had inadequate frequency prediction, and the caesium beam clocks are ageing. Studies conducted at the Time Department concluded that there was a need for a new model for clock frequency prediction and a new clock weighting algorithm. The new frequency prediction model was implemented in the algorithm for TAI in August 2011. This had the desired effect of stopping the drift of TAI. A new weighting strategy and algorithm was implemented in 2013. Its consequence has been to enhance the impact of the hydrogen masers on the scale, improving its frequency stability.

The calculation of UTC is based on clock comparisons between distant laboratories, which make use of various time transfer techniques to establish the time links. Improvement in time transfer directly affects the stability of the related time scales, and has an impact on their uncertainty. The BIPM developed methods of time transfer that maximize the benefits from upgraded equipment in the contributing laboratories.

Time links via global navigation satellite systems (GNSS) observations and by two-way satellite time and frequency transfer (TWSTFT) are currently used to compare clocks in TAI.

Most contributing laboratories have upgraded their GNSS equipment, and operate dual-frequency, multi-channel receivers that allow the observation of GPS and GLONASS satellites. The most recent receivers also observe the few operational Galileo satellites.

Typically 2-3 ns statistical time transfer uncertainty is possible with GPS single-frequency and multi-channel receivers. This limit has been decreased with the use of dual-frequency receivers, either by way of a "classical timing solution" using the CGGTTS format (1 ns statistical uncertainty), or by making better use of a combination of the code and the phase of the carrier (GPS PPP) with 0.3 ns statistical uncertainty in most links.

At the end of 2010 GLONASS satellites had begun to be used for clock comparisons in TAI.

It is well known that while the statistical uncertainty of GNSS time transfer can be as good as 0.3 ns, hardware constraints and other factors still prevent achievement of a systematic uncertainty of better than a few nanoseconds. This degrades the total uncertainty of UTC when GNSS time transfer is used. TWSTFT, when calibrated, allows 1 nanosecond or better systematic uncertainty to be achieved. To take better advantage of GNSS and TWSTFT, the Time Department developed a method for combining different kinds of links: the combination of GPS all-in-view with GLONASS common-views that open the way to GNSS multi-system time transfer; and the combination of GPS PPP links, with optimal statistical uncertainty, and TWSTFT where the systematic uncertainty can be 1 ns or better. During 2012 combined links have been in regular use in TAI and it is very likely this trend will continue.

With the aim of improving the component of the uncertainty coming from GNSS equipment calibration, the BIPM established a new organization in the Guidelines for GNSS calibrations, first published in 2013 (ftp://ftp2.bipm.org/pub/tai/publication/gnss-calibration/guidelines/). While keeping the ultimate responsibility for the calibrations, the BIPM shares with the RMOs the organization of regular calibration campaigns. The BIPM started in February 2016 the second measurement campaign on a selected group of laboratories in APMP, EURAMET and SIM. Similar trips are under organization or ongoing in RMOs. The results obtained between 2014 and 2016 demonstrate that the calibration uncertainty can be improved in a factor 2.5, with direct impact on the uncertainty of [UTC-UTC(k)].

The BIPM is not directly involved in the specific calibration of the TWSTFT links using a mobile station, but provides the necessary support through the CCTF WG on TWSTFT. In 2015 the BIPM and CCTF WG on TWSTFT developed the “TWSTFT Calibration Guidelines for UTC Time Links” for TWSTFT calibrations using a mobile station, a GNSS equipment and triangle techniques. The Guideline standardizes the procedures of calibration, uncertainty analysis and report (ftp://ftp2.bipm.org/pub/tai/publication/twstft-calibration/guidelines/).

As a contribution to the improvement of the TWSTFT technique, and at the proposal of the BIPM, the CCTF WG TWSTFT started in 2016 studies on the effectiveness of the “software designed receiver” (SDR) implemented in some observing stations. By using this new device and procedure, the diurnal signature which degrades the statistical uncertainty of most TW links could be minimized.

The accuracy of TAI is provided by the measurements of primary frequency standards reported regularly by contributing laboratories. The BIPM has implemented the strategy for the steering of the TAI frequency, and made improvements when necessary with the agreement of the CCTF.

Currently eight national metrology laboratories are reporting measurements to the BIPM from about ten cesium fountains on a more or less regular basis. There are also regular reports from measurements from two cesium thermal beam standards. Issues of *Circular T* in 2015 contains reports from two to seven cesium fountains, with an average of four per month. Typically combined type A and B fountain uncertainties are now in the mid to low 10^{-16} range so that the frequency uncertainty of TAI can be as low as 3×10^{-16}. (Dead time plays a significant role since most fountains reports are for time intervals of less than 30 days). In general, the situation regarding PFS’s is very healthy.

The first reports of a secondary frequency standard were presented to the BIPM in February 2012 for publication in *Circular T*. The secondary standard is the LNE-SYRTE FO2-Rb fountain. For review purposes, the reports were treated in the same way as if from a PFS, i.e., through the CCTF WG PFS. After approval of the frequency value by the WG and the CCL- CCTF FSWG, the BIPM started publishing the results of this secondary standard in *Circular T*, and using its results for improving the accuracy of

TAI since September 2013.

The BIPM Time Department is responsible for the single key comparison of time CCTF-K001.UTC. It is computed on a monthly basis, providing traceability to UTC to its local approximations UTC(k) in national laboratories. At the end of 2015, results for 74 laboratories world- wide are reported in *BIPM Circular T.* Following a request of some members of the CCTF, results for NMIs and DIs (59 in March 2015) are published at the BIPM KCDB.

Noting that the monthly computation of the differences [*UTC-UTC*(*k*)] in *Circular T* is not adapted to all applications, the Time Department, with the agreement of the CCTF (2012) put in place a rapid UTC solution computed on a weekly basis. Regular solutions have been published every Wednesday since June 2013. The number of participating laboratories at the end of March 2016 is 47. The major challenge in this activity for both the BIPM and the contributing laboratories is the real-time constraints.

Starting in January 2016, BIPM Circular T is published in a renewed format, allowing the link to the Time Department Data Base for getting more complete information on the local time scales, time links and calibrations (ftp://ftp2.bipm.org/pub/tai/publication/cirthtm/).

- International coordination

The Time Department is linked to many international organizations with activities related to timekeeping. The most significant activities up to the end of 2015 include:

International Telecommunication Union, Radiocommunication Sector (ITU-R): The BIPM is a sector member. The ITU-R is a member of the CCTF. The contribution of the BIPM Time Department is to Study Group 7 of the ITU-R (Science Services), and its Working Party 7A (time signals and frequency standard emissions). BIPM delegates participate actively in various relevant meetings as WP7A, Radiocommunication Assemblies and World Radiocommunication Conferences. The function of the BIPM is in particular providing guidance and expertise to the discussions on a future redefinition of UTC without leap seconds, to render it adequate to modern applications necessary for a continuous, non-stepped reference timescale.

The International Committee for GNSS (ICG): The ICG is the structure created by the United Nations (UN) for enhancing the interoperability and interchangeability of signals coming from the various GNSS, including in the future. The BIPM supported the establishment of the ICG by the UN in 2005 and is an observer. BIPM delegates provide guidance and expertise to the ICG with regard to the adoption of international references for time and geodetic references in GNSS. Thanks to these actions, recommendations have been accepted by GNSS service providers. The BIPM chairs the Task Force on Timing References.

The International Astronomical Union (IAU): The IAU cooperates with the BIPM on issues of common interest related to space-time references. The IAU is a member of the CCTF. BIPM Time Department staff actively cooperate with the IAU in dealing with Earth Rotation and References and Time and Relativity. Particular attention is given to coordinated actions contributing to the possible re-definition of UTC; the maintenance of timescales for astronomical applications (eg., TT(BIPM)) and linking the pulsar dynamical timescale. Staff of the BIPM Time Department are members of relevant IAU Commissions and Working Groups, with executive responsibilities in some cases.

The International Earth Rotation Service and Reference Systems Service (IERS): The BIPM is linked to two IERS activities. With regard to maintenance of UTC, the IERS is responsible for the announcement of the leap second application to UTC. Since 2001, under the framework of joint activities for the maintenance of standards and models for astro- geodynamical applications, the BIPM carries dual responsibility with the US Naval Observatory for the IERS Conventions. Maintenance of space references is also managed cooperatively.

The International GNSS Service: The IGS is the organization that provides the most complete set of parameters relevant to GNSS work. The BIPM is a member of the IGS Governing Board and the IGS is a member of the CCTF. The IGS relies on data provided by several hundred geodetic and timing stations world-wide as well as the work of analysis centres for the delivery of various IGS products. IGS's contribution to the realization of UTC includes: the provision of ionospheric corrections; satellite orbit and clock parameters; and the IGS timescale. The staff of the BIPM Time Department contribute to the IGS Working Group on Clock Products.

The European Space Agency (ESA): Cooperation with ESA relates to the development of the European global navigation satellite system, Galileo. Staff of the BIPM Time Department have been invited by ESA to contribute to different aspects of the preparation of the system including the Galileo timing interface (also included in the scope of work of the European Community), and the Galileo Science Advisory Committee. In 2012 ESA signed the CIPM MRA to formalize its interest in participating in the calculation of UTC at the BIPM.

The Civil GPS Service Interface Committee (CGSIC): The CGSIC is the recognized global forum for effective interaction between all civil GPS users and the U.S. GPS authorities. U Until mid-2014 the BIPM contributed to its Timing Subcommittee, which focuses on determining the requirements and needs of the civilian timing community for: GPS information, the sources of GPS timing information and the methods by which GPS timing data will be disseminated. In June 2014 the staff of the BIPM Time Department who provided the secretariat for the CGSIC Timing Subcommittee retired, and due to the workload of the Time Department no replacement in this representation was possible.

The International Union of Geodesy and Geophysics (IUGG): The IUGG is the international organization dedicated to advancing, promoting, and communicating knowledge of the Earth system, its space environment, and dynamical processes causing change. The IUGG is a member of the CCTF. The BIPM Time Department works with the International Association of Geodesy (IAG), whose mission is the advancement of geodesy. Of special interest to BIPM activities is the consistent representation of the figure, rotation, and gravitational field of the Earth and their temporal variations. As discussed at the CCTF in 2015, cooperation between the IUGG and the CCTF is expected on chronometric geodes. The BIPM contributes to the Global Geodetic Observing System of the IAG.

- BIPM Publications

Periodical publications

- *BIPM Annual Report on Time Activities*: Published since 1989 and available electronically since 2009, this contains information related to the maintenance of timescales at the BIPM over the year. The last issue (2014) was published mid-2015. Available at http://www.bipm.org/en/bipm/tai/annual-report.html.
- *BIPM Circular T*: Published monthly, BIPM *Circular T* provides traceability to

UTC to its local approximations in some74 national laboratories. This publication has been running for about 25 years. It has been renovated in January 2016 for providing more complete information on an interactive document (ftp://ftp2.bipm.org/pub/tai/publication/cirthtm/)

- CCTF-K001.UTC: Published monthly at http://kcdb.bipm.org/.
- Rapid UTC (UTCr): Published weekly since June 2013 (ftp://62.161.69.5/pub/tai/publication/utcr/

Other BIPM publications:

- *BIPM Reports*: These publications cover guidelines, comparisons and campaigns of measurement of relative delays in national laboratories.

Publications in scientific literature, including peer-reviewed journals and conference proceedings: the most extensive list is available on the BIPM web site at http://www.bipm.org/en/publications/scientif/tfg.html

Activities and achievements in NMIs

Time and frequency transfer

The comparison of remote clocks has always been an important part of time and frequency metrology and is also generally important to science. It allows *inter alia* assessment of the properties of (primary) frequency standards, e.g. to determine whether they agree within their assigned uncertainty. It is also needed for the calculation of time scales based on the readings of clocks located in different laboratories. In a perfect world, time transfer methods do not compromise the frequency stability and accuracy of clocks when at a remote site. In practice, this has not always been the case in the past, and today the comparison of remote optical frequency standards poses new challenges.

The quality of time comparisons has been substantially improved since the use of signals from the satellites of the Global Positioning System (GPS) – the first Global Navigation Satellite System (GNSS). With the completion of the GLONASS constellation, many metrology institutes upgraded their equipment with receivers tracking GPS and GLONASS satellites. Specific GNSS timing receivers have been developed for the purpose, but receivers and processing techniques initially developed in the geodesy context have found wide timing applications during recent years. Some receivers of thehe latest generation also track the few orbiting satellites of the Galileo and BeiDou constellations.

Two-Way Satellite Time and Frequency Transfer (TWSTFT) is the second time transfer method which has to date mainly been used by NMIs, other primary timing laboratories, but also for the synchronization of GNSS ground segments. This is a time transfer technique that is completely independent of GNSS but relies on commercial arrangements between laboratories and satellite providers, so increasing the risk of being able to provide perennial contributions. Dedicated TWSTFT satellites would address this and provide more stability for the observations, but these are not likely in the near future.

Aiming at improving the uncertainty of TW time transfer, new developments such as the “software designed receiver” (SDR) has been developed in Asia and is in use in some TW stations.

Time and frequency comparisons in national laboratories have different applications, such as:

- Contributing to the determination of UTC at the BIPM aimed at
    - Maintaining a local realization of UTC named UTC(*k*)
    - Maintaining a local timescale traceable to the SI second
- Comparing the local UTC(*k*) to an external reference, either a GNSS timescale or another local realization of UTC.

The uncertainty of the local UTC(*k*) depends on the quality of available clocks and the quality of the operating conditions of the time transfer equipment. All laboratories equipped with GNSS receivers upgrade these whenever possible, necessary for optimizing their contributions to the determination of TAI. Some NMIs maintain timescale-based clocks operated in different locations and use GNSS time transfer for comparison purposes.

About 15% of the laboratories contributing to TAI operate TWSTFT stations. Most of these maintain primary frequency standards that contribute measurements to improve the accuracy of TAI. TWSTFT and GPS PPP allow frequency transfer uncertainties of typically 2 x 10^{-16} to be reached with sufficiently long measurement durations, comparable with the uncertainties of current primary frequency standards.

In the last five years there has been a lot of progress in the development of optical standards. About a dozen groups (from NMIs and universities) are investigating various ion and atom species with indications of uncertainties approaching 10^{-17}. This will necessitate the use of frequency transfer techniques adapted to such accuracies. During the last few years, the transfer of stabilized optical carrier frequency signals through optical fibres has shown ultra- low instabilities at distances of up to > 1000 km. Very promising results have also been reported for frequency transfer of signals up to 1.5 GHz modulated on optical carriers. At a lower performance level, work is also ongoing to improve time and frequency distribution via internet data streams. Some NMIs are actively contributing to projects to achieve ultra- accurate time and frequency transfer over national and continental fibre networks.

Characterization of delays in time transfer equipment

Regional Metrology Organizations started organizing campaigns for calibrating GNSS equipment in national laboratories, with NMIs in different regions contributing travelling equipment and manpower. In particular, EURAMET and APMP have implemented measurement campaigns and provided results that can be used for maintaining calibration of world-clock comparison systems.

A TWSTFT station is calibrated using special equipment and services provided by external companies at non–negligible costs. Any evolution in calibration techniques that would reduce costs would be welcomed by NMIs. Calibration of time transfer equipment in UTC laboratories is essential since it impacts on the accuracy of time dissemination.

Primary frequency standards and secondary representations of the second

Eight national laboratories have regularly reported data from eleven cesium fountain and two thermal beam primary frequency standards (PFS) to TAI on a more or less regular basis. Several fountains have stated total uncertainties of approximately 4x10^{-16} for a 30-day run. Also, there is one secondary frequency standard (SFS) reporting.

The process of calibrating TAI with a PFS or SFS to a given uncertainty involves not only the uncertainties of the primary standard but also the frequency transfer uncertainty. In addition, if there is dead time (which there usually is), the stability of TAI or local flywheel frequency references must also be taken into account to calculate the total uncertainty. In the current situation the uncertainties contributed by each these three components are roughly of the same magnitude.

Comparisons of fifteen PFS fountains between 2008 and 2015 show an average frequency offset from the weighted mean of order of 4×10^{-16}, which is consistent with zero considering the combined uncertainties. The frequencies of all fountains agree with the weighted mean to within +/- 1×10^{-15}. If the individual fountain uncertainties are treated as uncorrelated (which may not be true) the uncertainty of the weighted mean of all fifteen is calculated to be about 1.6×10^{-16}. The Birge ratio for this data set is ~1.09. This indicates that there is slightly more scatter among the fountain frequencies than expected and the uncertainty of the mean should be about 10% larger. If there are correlations among the standards the uncertainty would need even further correction.

Table 1 shows information on the contribution of primary and secondary frequency standards to TAI during 2015, as published in the *BIPM Annual Report on Time Activities*. Reports of individual evaluations may be found at ftp://62.161.69.5/pub/tai/data/PFS_reports. Ref(*u*B) is a reference giving information on the value of *u*B as stated in the 2015 reports, uB(Ref) is the uB value stated in this reference. Note that current uB values are generally not the same as the peer reviewed values given in Ref(uB)

Primary Standard	Type /selection	Type B std. uncertainty/ 10^{-15}	u_B(Ref) /10^{-15}	Ref(u_B)	Comparison with	Number/typical duration of comp.
IT-CsF2	Fountain	(0.17 to 0.30)	0.18	[1]	H maser	7 / 15 d to 30 d
NIM5	Fountain	1.4	1.4	[2]	H maser	3 / 15 d to 20 d
NIST-F1	Fountain	0.31	0.35	[3]	H maser	2 / 15 d to 25 d
NIST-F2	Fountain	0.15	0.11	[4]	H maser	1 / 20 d
NPL-CSF2	Fountain	(0.22 to 0.37)	0.23	[5]	H maser	2 / 25 d
NPLI-CsF1	Fountain	2.82	2.5	[6]	H maser	1 / 10 d
PTB-CS1	Beam /Mag.	8	8.	[7]	TAI	10 / 30 d
PTB-CS2	Beam /Mag.	12	12.	[8]	TAI	12 / 30 d
PTB-CSF1	Fountain	(0.69 to 0.71)	1.4	[9]	H maser	8 / 20 d to 35 d
PTB-CSF2	Fountain	(0.30 to 0.33)	0.41	[10]	H maser	4 / 10 d to 30 d
SU-CsFO2	Fountain	0.25	0.50	[11]	H maser	11 / 25 d to 35 d
SYRTE-FO1	Fountain	(0.38 to 0.44)	0.37	[12]	H maser	2 / 30 d
SYRTE-FO2	Fountain	(0.25 to 0.30)	0.23	[12]	H maser	11 / 15 d to 35 d

Secondary Standard	Type	Type B std. uncertainty/ 10^{-15}	u_B(Ref) /10^{-15}	Ref(u_B)	Comparison with	Number/typical duration of comp.
SYRTE-FORb	Fountain	(0.28 to 0.32)	0.32	[13]	H maser	12 / 10 d to 30 d

Table 1: *Contribution of primary and secondary frequency standards to TAI during 2015.*

With the advent of several optical frequency standards that have reported systematic uncertainties below those of Cs fountain primary standards, the consideration of timescales for a future redefinition of the SI second is increased in importance. Those optical atomic reference transitions currently under study are subdivided between two generic categories of electromagnetically trapped single ions and multiple atoms trapped in optical lattices. Once Doppler broadening has been removed by laser cooling and suitable control of environmental fields achieved, cold ion or atom experimental linewidths in the region of 1 – 10 Hz can be observed. Natural linewidths for these systems range from 20 Hz – 1 mHz (with one octupole transition with a theoretical nHz linewidth). However, the effective linewidth is generally determined by the transform limit of the LO probe time (typically in the range 0.05 - 1 s). The optical frequency standard species now surpassing the Cs fountain capability include the $^{27}Al^+$, $^{199}Hg^+$, $^{171}Yb^+$ and $^{88}Sr^+$ trapped ion systems and ^{87}Sr, ^{199}Hg and ^{171}Yb atoms in optical lattices, with reported systematic uncertainties in the 10^{-16} to 10^{-18} range. Benchmark frequency instabilities for single cold ions confined within rf traps, and multiple atom systems

(~ 10^4 - 10^5 atoms) within optical lattices, are $3\text{x}10^{-15}\tau^{-1/2}$ and $\sim 3\text{x}10^{-16}\tau^{-1/2}$ respectively. Recent ^{87}Sr lattice clock results report a relative clock systematic frequency uncertainty of $2.1\text{x}10^{-18}$.

Various ion and atom candidate species under investigation at NMIs and research institutes are given in Table 2. The plurality of species highlights the need for further extensive evaluations of the comparative stability, uncertainty and reproducibility of each system, amongst other issues, before a redefinition of the second can be seriously considered. Later in this document, a roadmap for the redefinition of the second is given.

Atom / ion	**Clock type**	**Clock ν THz**	**Clock λ nm**	**Lowest published clock systematic uncertainty**	**Uncertainty of CIPM ν value**
^{87}Sr	Lattice	429	698	2.1 x10^{-18} [6]	5 x10^{-16}
^{171}Yb^{+}	Ion octopole	642	467	3.2 x10^{-18} [8]	6 x10^{-16}
^{27}Al^{+}	Ion, quantum logic	1121	267	8.6 x10^{-18} [9]	1.9 x10^{-15}
^{88}Sr^{+}	Ion quadrupole	445	674	1.2 x10^{-17} [10]	1.6 x10^{-15}
^{199}Hg^{+}	Ion quadrupole	1065	282	1.9 x10^{-17} [11]	1.9 x10^{-15}
^{40}Ca^{+}	Ion quadrupole	411	729	3.4 x10^{-17} [12]	1.2 x10^{-14}
^{199}Hg	Lattice	1129	266	7.2 x10^{-17} [13]	6 x10^{-16}
^{171}Yb^{+}	Ion quadrupole	688	436	1.1 x10^{-16} [14]	6 x10^{-16}
^{171}Yb	Lattice	518	578	3.4 x10^{-16} [15]	2 x10^{-15}
^{1}H	Cryogenic beam	1233	243	4.2 x10^{-15} [16]*	9 x10^{-15}

***Table 2**: Published systematic fractional frequency uncertainties of various optical clock species, and the fractional frequency uncertainties of the absolute frequency values adopted by the CIPM, following the 2015 Consultative Committee on Time & Frequency (CCTF); [16]*: the published uncertainty is that of the 2466 THz 1S-2S 2-photon transition, whereas the recommended CIPM value corresponds to the 1233 THz single photon frequency.*

The table shows the current status of published systematic uncertainties associated with these optical clock ion and atom species. The activities are very much a work in progress and the table will become more extensively populated, with further improved results. The lowest published systematic frequency uncertainties of the reference clock transition for each species are listed in column 5. These data have resulted from the derivation of estimated uncertainty budgets for the different species under development at various national measurement and research institutes. This has been achieved by means of measured or theoretically-calculated sensitivities of the clock frequency to environmental perturbations (eg Stark shifts including black-body radiation and light shifts, Zeeman shifts, same-species density shifts and collisions with background gas, and for ions, electric quadrupole shifts) and cold atom/ion residual motional perturbations (eg 2nd order Doppler shifts). Most of these optical candidate-species for a redefinition have already been accepted (with the exception of ^{1}H, ^{199}Hg and ^{40}Ca^{+} at this time) as secondary representations of the second (SRS) by the CIPM. The CIPM-adopted fractional frequency uncertainties of the updated absolute frequency values post-CCTF 2015 are given in column 6. Operational clock data (stability, reproducibility and uncertainty) for these secondary representations can now be reported to BIPM on a regular but preliminary basis in order to ascertain longer term performance prior to full contribution to UTC determination. Such contributions to UTC from optical clocks are seen as necessary criteria ahead of a redefinition. The CIPM-adopted uncertainties are larger than those published in the literature on two counts. First, the optical frequency absolute value has to be related to the current definition and its uncertainty, and, second, the Frequency Standards Working group (WGFS) of the CCTF adopts a cautious approach when determining universal frequency values from very small data sets such as a measurement from a single laboratory, or a few laboratories, where a normal distribution of results is not available. In such cases, typically an enlargement factor of a few is applied, dependent on circumstances. The basis for such treatment will be discussed in a publication in preparation.

Given the increasing number of optical clock species with systematic uncertainties lower than that for the Cs fountain clock, absolute determinations of their optical frequency values are at best constrained to that of the Cs fountain uncertainty. A more profitable approach is to directly compare optical frequencies ratios of the optical systems themselves. Here, all frequency comparisons can be quantified in terms of a matrix of frequency ratios, whether optical ratios, optical-microwave ratios (of which optical clocks measured relative to Cs are the most common case) or microwave ratios. Following the 2012 CCTF, the WGFS adopted this as a viable way forward to take advantage from the lower optical uncertainties. With a full matrix of frequency ratios, absolute frequency values for particular clock species may be derived by various routes eg from a single ratio or combinations of ratios, and this in effect over-constrains the determination of an optimised value for the clock transition frequency. A procedure to deal with this has been proposed recently [ref?] which should lead to a more statistically comprehensive approach. Nevertheless, at this time, an intermediate position is the case whereby several Cs-related determinations are combined with one or two all-optical ratios in order to determine CIPM values for some clock frequencies, with Cs uncertainties providing the limitation. An example of this is the absolute value of the $^{27}\mathrm{Al}^+$ clock transition, which is derived from both a Cs-related measurement of the $^{199}\mathrm{Hg}^+$ transition and a subsequent $^{27}\mathrm{Al}^+$/ $^{199}\mathrm{Hg}^+$ frequency ratio measurement. However, as the number of optical ratio determinations increase, one would expect that significance of the Cs-related values will be reduced within the matrix. It should be said it is still important to include the optical-to-caesium ratios to ensure that matrix values remain consistent with the Cs-related values in order that a discontinuity larger than the Cs uncertainty would not occur at redefinition.

At this time, it is not yet clear whether there is a preferred optical candidate for a future redefinition and further research needs to be carried out. It seems safe to conclude that 10^{-18} accuracy will be achievable with one or more such standards.

Major changes in needs, technologies or areas of interest during the period and the effect on the activities of the body:

Time transfer for clock comparison and dissemination:

- Generalization of TWSTFT as the most accurate time transfer method, notably including its extension to the Asia Pacific region.
- Studies on improving short-term instability using TWSTFT carrier-phase technique and software defined receiver (SDR) or digital MODEM equipment.
- Adoption of multi-channel, multi-frequency and carrier-phase capable GPS receivers, with the development of much more sophisticated data analysis methods. Extension to the GLONASS satellite constellation following its completion and use of multi-GNSS time links.
- Development of regional satellite augmentations and of new GNSS (Galileo, BeiDou): implications in the implementation of the respective time scales and strategies for synchronizing to UTC; preparations for the use of these systems.
- Studies on highly accurate time and frequency transfer, notably for optical standard comparisons: high-bandwidth and carrier-phase two-way microwave links, optical fibre links, free-space optical links, geodetic methods, etc.

Frequency standards:

- Generalization of cesium fountains as primary frequency standards and their improvement to the low 10^{-16} level; development of the rubidium fountain as a secondary representation of the second.
- Generalization of femtosecond optical frequency combs, contributing to a rapid advance in the development of optical clocks, leading to updated frequency values of 7 optical transitions already accepted as secondary representations of the second.
- Development of improved space clocks and preparation for their use.

Real-time products:

- Rapid UTC at the BIPM, in particular to support new, lower cost yet highly accurate time transfer and dissemination modes;
- Real-time scale monitoring for various applications;
- Improvement of timescale and comparison methods.

Information on repeat frequencies of any comparisons to date:

During its 19th meeting (2012), the CCTF confirmed that its unique key comparison is on time, CCTF-K001.UTC, and asked the BIPM Time Department to implement the publication of its results in the BIPM Key Comparison Data Base (KCDB). Regular monthly publication of the degrees of equivalence for NMIs and DIs contributing to UTC started in March 2015. The 20th meeting of the CCTF (2015) welcome this publication.

4. Stakeholders

There are stakeholders at several levels. At the highest level, any NMI that is a member of the MRA or that contributes to TAI is a stakeholder with considerable interest in the process, and already provides direct input direct through their CCTF representative and via the CIPM or CGPM.

Beyond the NMIs, important stakeholders include international organizations that have a strong interest in time scales or frequency measurements: the IAU (International Astronomical Union), IGS (International GNSS Service), ITU-R (International Telecommunication Union - Radiocommunication Sector), and IUGG (International Union of Geodesy and Geophysics).

Specific stakeholders are organizations managing Global Navigation Satellite Systems (GNSS) and related users, and basic science research laboratories.

The ultimate beneficiaries are in the following science fields: geodesy, radio-astronomy, space exploration, gravity wave detection, and fundamental physics. Other beneficiaries include industries that rely on the organizations listed above and consumers served by these industries.

When appropriate, non-NMI stakeholders can provide feedback through their NMI. NMIs are generally sensitive to stakeholders that describe time scale use and frequency measurement needs or have problems with existing measurement infrastructure. NMIs gather feedback through direct contact with individuals in industry and telecommunications, participation in standard organizations, or through workshops and conferences. In some cases, stakeholders sit on program formulation committees that guide NMI research activities.

5. Future Scan (2016-2026)

5.1 Time scale realizations, national and international levels

The definition of the SI second and its realization may be changed within the next ten years. This change will have an impact on the work at both the BIPM and NMIs and will improve the accuracy of UTC/TAI.

A variety of time scales co-exist for different applications, and more will appear in the future, particularly for global navigation satellite systems.

The international reference UTC will continue to be unique in the future. However, changes in UTC are to be expected, in addition to regular improvement in the algorithm and time links.

It is likely that a new definition of UTC without leap seconds will be adopted in 2023 at the International Telecommunication Union. If the new definition of UTC is accepted, changes will be necessary for different systems of time keeping and dissemination.

While UTC has optimal frequency stability over one month, some applications require long- term stability. For this purpose the BIPM publishes TT(BIPM) in the form of annual realizations and monthly predictions, mostly used by the astronomical community.

National institutes maintain local atomic timescales based on clocks located either in a laboratory or at various locations, requiring the use of techniques of clock comparison at a distance. These timescales are compared to UTC and their frequencies steered to agree with the international reference.

GNSS times are determined from the combination of clocks operated on Earth stations and on board the satellites. Some are synchronized to UTC through local representations UTC(*k*). This is the case for UTC(USNO) and UTC(SU) for GPS and GLONASS respectively. Other local timescales will serve as a reference for upcoming satellite systems, some of which are already under development. Clearly, the quality of the GNSS times relies strongly on the quality of these local timescales. At least two additional global navigation systems will be operational by the end of this decade: the European Galileo and the Chinese BeiDou.

Timescales are supported by algorithms that are adapted to their specific applications. In the case of UTC/TAI, the algorithm is designed for assuring optimal 30-day frequency stability and high frequency accuracy. In the case of TT(BIPM), long-term stability is required. The scale is mainly based on all the measurements of primary frequency standards reported in the past. Local atomic timescales are of a different quality, but most of them seek stability in the short-mean term, and steer their frequencies to match the SI second either by comparison with UTC or based on the frequency of the primary frequency standards they maintain.

To help reduce confusion and the consequent possibility of error, and to underpin the status of UTC as the primary international reference, it will be important to maintain clear and accessible statements, as far as possible, about the relationships between UTC and the diversity of time scales in use around the world for various purposes. A further way to reduce confusion will be to make UTC more accessible in real time, through the continued development of rapid products and low cost, continuously available, time dissemination modes. These measures will encourage the use of UTC for new applications, instead of the establishment of a plethora of new, special purpose time scales.

Furthermore, to support new applications for highly accurate time and to take advantage of developments in dissemination modes, it will be important to continue to develop more rapid predictions of UTC.

The use of GNSS times is different from that of local national timescales. They contribute to the internal synchronization of the system, and therefore the constraints on frequency stability and accuracy are looser.

5.2 Time and frequency transfer

Time and frequency transfer techniques can be distinguished as either ground-based or space- based techniques.

Over the past decade, the use of “ground-based” optical fibers has found wide usage, either dark fibers or fibers shared with data traffic in wavelength division multiplex access for the transfer of stabilized laser radiation and alternatively for RF signals and time codes modulated on the carriers. The feasibility has been demonstrated of frequency transfer with uncertainties of less than 10^{-17} for a distance of up to 900 km and of time transfer with uncertainties of 1 ns over a few hundred km. One goal is the establishment of regular services connecting major timing centers in Europe. The long-term vision is for a further improvement in accuracy and density of the links.

Space-based techniques are by their nature of more global usage: GNSS-based time transfer can be done virtually anywhere on earth. The current target is to establish time transfer with 0.1 ns uncertainty among sites contributing to TAI. Dedicated space-based techniques such as TWSTFT and the microwave link of the ACES (Atomic clock ensemble in space) mission require dedicated terminals of increasing sophistication. Nevertheless there is evidence that the frequency transfer uncertainty of 10^{-17} averaged over a few days could be realized even with the deployed equipment, provided that signals with sufficient bandwidth could be used. In the long-term the space-based comparison of optical clocks is aimed at tests of relativity and fundamental physics: only then can the scientific challenges of “testing of the theory of relativity, relativistic geodesy and others” be met on a global scale, not only on a point-to- point basis.

All of these time transfer and dissemination modes will need to be developed in terms of increased accuracy, reduced cost, easier accessibility and the ability of time transfer applications to coexist with other uses of the infrastructure or spectrum. “Turnkey” systems that provide cost-effective, reliable and ongoing access to precise time and frequency will be a key enabler of new applications.

5.3 Primary frequency standards

NMIs will probably continue to develop new cesium fountains. The CCTF WG PSFS will continue to make recommendations to the BIPM on new standards as reported by NMIs for improving the accuracy of TAI and, and in general, provide advice to the BIPM on PFS and SFS. Another major future task will be to assist in the decision on the possible redefinition of the second. If/when the second is redefined (probably using an optical transition) a priority task will be to determine the best value of the Cs SI second and its uncertainty (see *Metrologia*, **47**, 2010, pp. 1-10 and the *Proceedings of the 2011 Joint Conference of the IEEE International Frequency Control Symposium and the European Frequency and Time Forum*, pp. 596-599).

With the accuracy of primary standards challenging the best available time transfer techniques, it may be important to develop a range of portable yet highly accurate primary standards. These will confirm the performance of new, innovative long-distance clock comparison modes.

5.4 Algorithms for time scales

The development of algorithms for the treatment of time and frequency measures is expected to increase in the next ten years to fulfill the following aims:

1) Time scale realization: in order to improve stability, accuracy, and reliability the time laboratories are developing and maintaining more than one atomic clock. As much as the number of clocks increases, the laboratories have to harmonize their contribution for the realization of a single time scale. The availability of different type of atomic clocks from Cesium beam standards to Hydrogen maser, with different characteristics and performance, leads the laboratory to the development of algorithms able to optimize the contribution of each clock in the ensemble time scale. In addition the availability of different primary frequency standards, often working continuously as clocks, is increasing and the introduction of PFS in the ensemble time scale is being evaluated and realized in the laboratories;
2) Clock and time scale monitoring: the increase of demanding applications as national and international timekeeping and GNSS timing system ask for accurate and stable time reference but also for reliable services within certain specified performance limits. It is thus increasing the need of identification and solving of possible anomalies in the timing systems. Algorithms treating clock measures to monitor the level of performance and to identify possible misbehavior are thus getting more and more important and are to be developed either by the time metrology experts or by experts of other fields using clocks in their complex systems;
3) Real time applications: they are mostly driven by GNSS but also of important application in timekeeping, the real time availability of time signal, their monitoring, and evaluation will be crucial in the future. Algorithms able to run fast and to quickly identify failures and /or misbehavior will be needed in different filed of applications;
4) Other applications of clocks: in each system containing clocks or frequency standards the mathematical treatment of the time measure is mandatory. Sometimes the information to be obtained is similar but the context and the data availability is different. For example in space observation there may be long period of missing data, the clock measures may be indirectly obtained in correlation with other measures, the presence of different type of outliers may appear. In these context the traditional time and frequency algorithms may need to be adapted, improved, or in some case, completely devised based on the experience of previous applications;

These reasons ask for a certain effort of the timing community in disseminating the precise and correct use and understanding of time and frequency algorithms, as well as the support to the development of new, customized, powerful tools.

5.5 Optical frequency standards

A significant number of optical atomic reference transitions are currently being studied, within the two generic categories of electromagnetically trapped single ions and multiple atoms trapped in optical lattices.

Research is very much a work-in-progress and covers several ion species, but is concentrated primarily on 2 atom species (^{87}Sr and ^{171}Yb). This highlights the need for further extensive evaluations of the comparative stability, uncertainty and reproducibility of each system, amongst other issues, before a redefinition of the second is seriously considered.

Table 2 in section 3 shows the current status of development of the various optical clock ion and atom species. At this time, it is not yet clear whether there is a preferred candidate for a future redefinition and further research needs to be carried out. It seems safe to conclude that 10^{-18} accuracy will be achievable with one or more such standards.

5.6 New BIPM products adapted to new applications

The BIPM Time Department has implemented new strategies, tools and products in order to improve UTC and provide better services to NMIs. Part of the strategy is to put in place permanent actions to anticipate future needs arising from evolutions in technology.

The most significant recent products and applications together with future perspectives include:

Multi-technique time transfer

- Combined link solutions already implemented for GPS/GLONASS and TWSTFT/GPS PPP; direct combination of GPS and GLONASS observations with all-in-view solution to be implemented in 2016-2019.
- Studies of new GNSS solutions applied to time and frequency transfer, as GPS integer ambiguities, GLONASS PPP for implementation in 2016-2019.
- Future developments planned for implementing time transfer by Galileo and BeiDou making use of all available satellite systems (2016 onwards)
- Studies and calibration of new generations of GNSS receivers, based on guidelines for supporting regional calibration campaigns (ongoing).

Time scales

- Implementation of the “Rapid UTC”, a rapid UTC-solution calculated on a weekly basis. This has been conceived to support the ultimate reference UTC for short-term monitoring of national timescales. The Rapid UTC have an impact on the synchronization of the GNSS times to UTC that are obtained via local realizations UTC(*k*) (ongoing).
- In the next ten years, applications requiring more rapid solutions could result in the BIPM providing a more frequent evaluation of the key comparison CCTF-K001.UTC (*BIPM Circular T*).
- Since 2009 the BIPM has published monthly predictions of TT(BIPM), the timescale maintained for applications requiring long-term stability (ongoing).

5.7 GNSS, existing and upcoming, and their link to time scales

The global navigation satellite systems (GNSS) have been developed for obtaining precise positioning of the Earth and her close vicinity. These are rather complex systems. The space segment is formed by a number of satellites emitting signals, each satellite having an atomic clock on board. A number of stations on the Earth permanently track the satellite constellations, check their functioning, and provide input to the satellites. The International Telecommunication Union allocates the frequency bands to the systems. A navigation message contains information on the satellite itself, its position and the time corresponding to that position. The basic datum is the travel time of the signal between the satellite and the receiver, used to calculate the distance between the two.

GNSS provide the broadest means of time dissemination. The user has access to a timescale that is directly traceable to the international reference UTC.

Two essential elements in the functioning of the GNSS are the geodetic and time references. An internal time scale is maintained by each GNSS for time synchronization of the system. With the advent of multiple GNSS, the choice of these references is vital and has a direct impact on the interoperability and interchangeability of the systems. Recommendations adopted by the International Committee on GNSS (ICG) state that the internal GNSS times must be aligned to a realization of UTC.

The GNSS times are constructed from atomic clock ensembles that are aligned to an external reference for accuracy. This reference is, in all GNSS, steered on one or more local realizations of UTC in national laboratories.

The GNSS time scales must be continuous for correct functioning of the navigation systems. However, the reference UTC and its local approximations UTC(*k*) are affected by one-second discontinuities when a leap second is implemented on UTC to obtain a coarse approximation to rotational time UT1. Consequently, all GNSS except one do not incorporate the leap seconds in UTC; instead some epoch is arbitrarily adopted, the practice being called “a steering on UTC modulo 1 second”. Unfortunately, this procedure is not uniform for all GNSS times, and it jeopardizes the interoperability of the systems, potentially prejudicing different user communities.

GNSS	Reference for synchro to UTC	Tolerance of difference from UTC	Leap seconds	Epoch of alignment to UTC	Difference to UTC on Jan 2016 / s
GPS	UTC(USNO)	100 µs	No	6/01/1980	17
GLONASS	UTC(SU)	1 µs	Yes	Aligned to UTC	0
Galileo	Average of various European UTC(k)	50 ns	No	6/01/1980	17
BeiDou	UTC(NIM)	50 ns	No	1/01/2006	3

Table 4*: *Existing and coming GNSS times and their synchronization to UTC.

While new GNSS are under development, the issues about their interchangeability and interoperability have yet to be resolved. Simultaneous access to multiple GNSS systems will increase the precision of time comparisons. There is currently a proliferation of GNSS times with different relative offsets, most differing from UTC by changing and unpredictable values. When all four systems in table 4 are fully operational (hopefully in the next 5 to 10 years, and probably together with other newly developed GNSS), strategies will be necessary to determine and disseminate in real time the relative offsets between their time scales. This will probably leave ambiguities that could conspire against safety in case of a mismatch between the various GNSS times.

6. Rationale for various activities (2016-2023)

6.1 Time scale realizations, national and international levels

Ongoing development of time scales is essential to realize the benefits of improvements in the stability of primary frequency standards, other atomic clocks, time transfer and time dissemination methods. It is already clear that the short- and medium-term stability of the best primary frequency standards has surpassed the performance of the current long distance and international timing links used to compare them. As these links improve, time scale algorithms will need to develop with them. International participation in this work is obviously essential.

6.2 Time and frequency transfer

Operation of multi-GNSS receivers in laboratories or of various models of receivers tracking different satellite constellations started in 2014-2015.

Calibration of such receivers has been investigated and methods put in place for calibration campaigns organized by the BIPM and RMOs.

Redundant GNSS (or multi-GNSS) stations are be maintained by time laboratories. The BIPM will study and implement methods and procedures for performing multi- GNSS and multi/receivers links to make use of these redundant data. Comparisons between individual GNSS time links and also with TWSTFT will enable their individual qualities to be evaluated.

A few technological issues remain with regard to time and frequency transfer through optical fibres, but these are mainly associated with the ease and affordability of operations in a commercial telecommunication environment. A real challenge is the set-up of long-term dependable contractual relations with fiber network operators. Nevertheless, a continental-scale fiber network in Europe is being established and already partially in use for frequency comparison of the best optical clocks with highest stability. The financial support of some RMOs, such as EURAMET in the frame of the EMRP and EMPIR projects plays an important role in the progress of these technologies.

The BIPM shall follow this evolution closely, and participate in studies on the performance of time and frequency transfer through optical fibers, including the implementation of methods, programs and software for their integration in TAI. A Study Group on fiber links for UTC has been established within WGATFT to work closely with the BIPM on the issues of time and frequency transfer through optical fibers.

Several avenues for progress have been identified with regard to spaced-based time and frequency transfer. A very important issue is a follow-up mission to the agreed ACES mission. A dedicated mission on a geostationary satellite which would re-use part of the ACES ground and space equipment has been proposed to ESA. Currently 24 institutes world-wide undertake “conventional” TWSTFT. Ways to improve its performance have been identified, and works on using higher bandwidth, bi-modulated signals, carrier phase information and new equipment such as the SDR or digital MODEM are in progress. In all cases dedicated transponders are needed for continuous point-to-point connectivity rather than scheduled access for some minutes per hour per station pair.

The use of VLBI (and also optical techniques such as T2L2 and ELT) will be very likely limited to stations equipped with radio-astronomy quality terminals, but studies should be encouraged among selected sites.

The BIPM plans to participate in studies related to comparisons of atomic clocks in space, with particular interest in the ACES mission (anticipated to involve cooperative work with other institutes). This will be launched in 2016 and the studies will be ongoing based on the programme of work for 2016-2019.

6.3 Primary and secondary frequency standards

The development of new Cs fountains at national institutes continues, several new Cs fountains are anticipated to begin operation between 2016 and 2020. Comparisons will be needed between these fountains as well as those already operating, either directly by frequency transfer between laboratories, or via *BIPM Circular T*.

The BIPM will therefore continue comparing the fountains with TAI and TT(BIPM) and disseminating the results in *Circular T* and other publications. The number of fountains reporting data for TAI will increase as wills, most probably, their intervals of continuous operation. The uncertainty of the supplied frequency will also improve. These factors will improve the accuracy of TAI with respect to the SI second.

The development of optical standards will continue, and the recommendation of radiations as secondary representations of the second will serve to help decide which species should be studied by laboratories. This together with progress in techniques of highly accurate time and frequency transfer will allow comparisons between standards of the same kind.

Improved technology for flywheel frequency standards is also needed to handle issues of dead time. The stability of present day flywheel frequency standards would not even come close to maintaining a calibration from an optical standard at the $1x10^{-17}$ level. Optical techniques similar to those used for possible new primary frequency standards would have to be used for the flywheel function also, but these standards would need to be engineered as commercial products with very high reliability and at reasonable cost. These commercial products would need to have frequency stabilities of a few days comparable with the uncertainties of the optical PFS.

Time laboratories will work on validating the uncertainty budgets of these secondary standards and will operate them over reasonably long time intervals to enable adequate reporting of data to TAI.

The BIPM has implemented the method to include secondary standard measurements in the process of improving the accuracy of TAI and its frequency steering. As well, the CCTF will encourage and support the development of new primary and secondary frequency standards and promote high quality primary and secondary frequency standards operations. It will provide the group of experts on primary and secondary frequency standards for the BIPM Time Department to consult with, particularly with regard to new standards.

A SFS has an additional bias and associated uncertainty from the original calibration of the SFS relative to the SI second. As uncertainties are gradually reduced over time it may become clear that the defined frequency of an SFS needs to be changed. As long as the SFS error is within its stated uncertainty, and there are also a sufficient number of actively reporting PFS, this has no practical significance if the SFS frequency is used in the calculation of the rate of TAI. However, it is not inconceivable that a situation could arise when, in a particular issue of *Circular T*, there were no significant PFS reports but an SRS report (before the frequency could be redefined) which had a known bias error. Should the BIPM correct this before using the information in the calculation of the rate of TAI? This issue has to be resolved.

6.4 Algorithms for time scales

Not only for the institutional timekeeping, but also for the modern demanding applications as GNSS, it is very important that the statistical and mathematical algorithms and methods are correctly understood, used, and interpreted to estimate, appreciate, and take the maximum benefit of the utmost characteristic of atomic frequency standards.

6.5 The SI second, thoughts on its possible re-definition

The microwave cesium atomic clock has been the basis for the SI second over the last five decades, with a continuous reduction in the uncertainty of realizing the definition of the second by about an order of magnitude per decade. Today, the fractional uncertainty of the best primary cesium clocks can be as low as 2×10^{-16}. In parallel, optical atomic clock research has led to a number of optical clock systems based on different atomic species and different technologies. The performance of these optical clocks is improving at an even faster rate than the best primary cesium fountain clocks. After the first decade of the 3rd millennium there are several optical candidates that now achieve or exceed the performance of the Cs fountain primary standards used to realize the SI second, raising the issues of whether, how and when to re-define it.

The foreseeable progress with optical atomic frequency standards and clocks will have enormous impact on various fields in science, technology and is expected to continue in the next decades. More stable and accurate time scales will directly influence Global Navigation Satellite Systems with huge impact on novel services and future markets. Better clocks are the most accurate measuring systems and boost novel and more accurate tests of fundamental theories like special and general relativity, quantum electrodynamics, and the constancy of fundamental constants. These investigations have a high potential for unexpected discoveries and new science. The availability of better clocks will lead to new fields of research and applications such as relativistic geodesy where the Earth’s gravitational potential can be determined by the local change of a high accuracy clock when compared with a remote reference clock. Astronomy and space applications will benefit from better clocks by ultra-precise tracking of spacecraft, better reference systems, and eventually even from a master clock in space. It seems reasonable therefore to expect that progress with better clocks will also create the need for a definition of the second that will give the best realization of the unit.

The examples of the re-definition of other base units in the SI has shown that, for a limited period, science, society and industry could cope with a definition that does not give the best realization with respect to the achievable uncertainty provided and that there are stable and reproducible “ad hoc standards”. Examples are the Josephson or Quantum Hall standards for electric units, wavelength standards for length metrology before 1960, or the lunar movement during the ephemeris definition of the second before 1967/68. Such an “ad hoc standard” could be selected from the list of secondary representations of the second. In 2001 the CCTF considered the establishment of secondary representations of the second where such representations, whether optical or microwave, could be used to realize the second, provided that their accuracy was close to the Cs uncertainty. Even though their uncertainty could be no better than the Cs primary uncertainty, it was considered that the establishment of these representations would help with the detailed evaluation of reproducibility at the highest level, and significantly aid the process of comparing different standards in preparation for a future re-definition. Today, the secondary representations already have considerable impact in metrology.

Even though the Cs definition will serve industry’s needs for the next few years and the secondary representations will serve science’s needs, significant effort is required for specific issues underpinning a new definition of the second in due course. For example, the full potential of optical frequency standards and clocks can only be utilized if the means to compare remote clocks and disseminate optical frequencies in a simple and reliable way without degradation of stability and accuracy over long distances are developed in parallel. Due to the relatively low frequency in the microwave domain the currently established methods for time and frequency transfer via microwave satellite links cannot support the achievable stability of optical clocks where a fractional instability in the 10^{-16} range at one second is envisaged. Advanced methods of time and frequency transfer in the microwave region with increased chip rate will be investigated in the forthcoming ACES project on the ISS. Optical laser links to satellites can transfer time and frequency of optical clocks within shorter times. A particular interesting method of transferring optical frequencies over large distances is to compare clocks with fractional uncertainties in the 10^{-18} regime within a few hours or less by the telecommunication fiber network. Transportable optical frequency standards represent another promising way to compare remote optical clocks. Scientific, technical and political activities will need to be improved, harmonized and coordinated to fully explore and utilize these methods.

On the way to a new definition of the second via optical frequencies it is necessary to further extend the investigations of the best optical frequency standards in the framework of secondary representations of the second. The current status of these secondary representations is such that existing optical clocks could improve TAI if they were operated on a more regular basis for this purpose. On the other hand, the uncertainty of the recommendations of standard frequencies is soon going to be limited by the uncertainty of the realization of the primary caesium fountain clocks themselves. Hence, the performance of optical frequency standards can be evaluated at best by relating their frequency to that of another suitable optical frequency standard e.g. by reporting the measured frequency ratio. Combining these ratios together with direct frequency measurements will eventually lead to a better understanding of the different standards and their uncertainties.

There are a number of supporting measures that would help pave the way to a re-definition of the second. Among these are demonstrating improved reliability of different optical clocks allowing for continuous operation, comparison of remote optical clocks by fibre links and transportable optical frequency standards, and use of optical clocks in different areas where their superior performance allows for novel applications. As the time for a re-definition approaches, procedures for the transition of the time scale also have to be developed. The exact knowledge of the geoid at a level of 1 cm or better (equivalent to 10^{-18} fractional uncertainty) is mandatory. Furthermore investigation is needed of the fundamental and technical limits imposed by the application and calculation of general relativistic corrections for the clocks and their comparisons.

Given the current rapid evolution of optical clocks, increased knowledge of their performance and novel methods for their validation, it seems likely the few best candidates will be identified in coming years so that a re-definition of the second is possible in the medium term, although it does not seem likely as early as the 2018/2019 CGPM. The roadmap related to the redefinition of the second is appended in Annex 1.

Apart from optical frequency standards leading to a re-definition of the second, there are also possibilities of completely different approaches to a re-definition of the second. There are promising investigations of clock transitions of even higher frequencies, including nuclear transitions. There is still a dream of a calculable transition frequency related directly to fundamental constants such as the Rydberg constant and the speed of light. Even though the current accuracy and reproducibility of optical transitions is many orders of magnitude higher than the present best theories can deliver, these and other developments have to be followed carefully.

6.6 BIPM activities

Algorithms

- Major revision of the algorithm for UTC (starting 2016)
- Maintenance of the algorithm for calculation of TT, changes to include secondary representations of the second (started 2013).

Time and frequency transfer

- Multi-GNSS time transfer (two-system combined observations, four-system solutions 2016 onwards).
- New GNSS (GPS integer ambiguities, GLONASS PPP) starting 2016.
- Optical fibre links for time and frequency transfer in TAI, studies and implementation depending on progress in national institutes (ongoing).
- Time and frequency transfer through space techniques; microwave links (ACES, 2016 and onwards), studies on feasibility of other techniques (2017-2019).

Accuracy of TAI

- Use of secondary representations of the second to steer EAL. Rb has been included from 2013.
- Studies on using optical standards to steer TAI, with application depending on progress on uncertainty evaluation and intervals of continuous operation (2016-2017).

Measurement of delays in GNSS equipment

- Application of the absolute calibration method and equipment developed with the CNES (from 2016)
- Studies and calibrations of new generations of GNSS receivers, coordination with RMOs, support to regional calibration campaigns (ongoing, with peaks of activity when new multi-system receivers are commercialized).

Time scales

- UTC solution via monthly *BIPM Circular T*, ongoing.
- Regular publication of "Rapid UTC" (starting in 2013 and ongoing).
- Studies to shorten the frequency of publication of *Circular T*
- Annual publication of TT (BIPM) and monthly publication of predictions (ongoing).

New definition UTC

- Work at the ITU-R with a decision due in 2023. Implementation of definitions of metrological time scales for adoption at the CGPM 2018.

Redefinition of the SI second

- In the next five years, progress on optical clock development and comparison should open discussion on possible candidate(s) for a redefinition of the second. The BIPM will have an active role in this discussion, mostly contributing to the comparison of candidate radiations (2016-2020).

Knowledge transfer

- Training on calculation of time scales,
- Assistance to developing laboratories.

7. Required key comparisons and pilot studies 2016-2023 with indicative repeat frequency

No specific new key comparisons and pilot studies are foreseen.

How far the light shines:

Extending to all time (and frequency) laboratories in the world.

Impact of lengthening the repeat frequency or stopping the comparison:

Stopping the key comparison in time will mean interrupting the production of UTC and, thereby, not having a reliable universal reference time scale. The current tendency is to shorten the periodicity of publication of UTC to allow more frequent assessment of local clocks and timescale prediction.

8. Resource implications for laboratories for piloting comparisons

The key comparison CCTF-K001.UTC is the result of permanent contribution of data from NMIs and other institutes to the BIPM, the pilot laboratory.

Resources for this key comparison are located in the contributing laboratories and at the BIPM. This section does not include an estimate of the resources at the 74 participating laboratories. In each laboratory this depends on the number and quality of clocks, the time transfer techniques and manpower. The equipment involved is different and operated in different locations. The NMIs maintain atomic clocks and primary standards, operate time transfer devices (GNSS receivers, TWSTFT stations), and communicate data to the BIPM on a daily basis.

We only present the resource implications at the BIPM.

Piloting CCTF-K001.UTC must be considered as the result of several processes:

a) A permanent activity involving development, maintenance and improvement of algorithms, programmes, methods and studies;

b) Day-by-day communication with contributing laboratories;

c) Establishment of procedures for data exchange and other information;

d) Calibration of time transfer equipment. The BIPM organizes calibration campaigns of GNSS equipment with travelling receivers sent to laboratories. Since 2015 this is supported by regional campaigns organized by RMOs.)

e) Calculation of *BIPM Circular T*. The calculation of each key comparison and its publication in BIPM *Circular T* is a process that includes the calculation of a redundant number of time links and their analysis and comparison for making optimal use, the application of corrections to compensate for calibration whenever necessary, the calculation of weights and rates to characterize participating clocks, the computation of the atomic free scale (EAL), the treatment of data of primary standards to calculate their average frequency applied in the process of steering the frequency of EAL to transform it into TAI, and finally into UTC. Procedures for validation of results have been implemented and are regularly applied.

f) Studies post-publication (comparison of time links, statistical analysis of data and results);

g) Publication of data and results. Comparisons between different techniques/methods of time transfer are made and data plus results are published on the ftp server of the Time Department, also available through the BIPM web site.

The basis for the key comparison consists of the calculation of the degrees of equivalence as the values of the differences [*UTC-UTC*(*k*)] every five days for more than 74 laboratories. The key comparison is undertaken on a monthly basis. The staff of the BIPM Time Department who work on a full-time basis to calculate the key comparison are (beginning of 2016) three scientists, an engineer, two technicians and the department director.

Equipment and other elements at the BIPM involved in the key comparison:

- Servers for data exchange (redundant)
- Computers connected to the internet
- Non-commercial software developed at the BIPM
- Commercial software commonly used in laboratories and calculation centres
- Atomic clocks (industrial Cs and H-masers)
- GNSS receivers of different kinds used in calibrations, some kept at the BIPM to provide a reference, others used for travelling
- Webmaster and publications officers' support
- Access to relevant journals and publications

The report of CCTF-K001.UTC is a subset of the monthly *BIPM Circular T*. A report of all operations, incidents, changes, and data is prepared and circulated within the department to support the computation. Technical Memoranda are issued to support changes in the algorithm, programs, software, analyses and results. Publications are submitted to peer-review journals and conference proceedings; some analyses are published in BIPM Monographs and Reports. An ftp site is permanently updated for disseminating data, intermediate and final results, comparisons, etc.

An annual report (http://www.bipm.org/en/bipm/tai/annual-report.html) is issued and published at the BIPM web site on activities in the laboratories and at the BIPM.

Staff receives different kinds of training: formal courses and participation in workshops, seminars and meetings. Staff also provide training on request, including seminar lectures, and courses at metrology schools, etc.

Travelling takes a non-negligible part of the working time of the staff. Participation in meetings at different levels is essential to the dissemination of the quality of UTC, presentations on progress of the work, and discussion of novel techniques under analysis.

Representation in international organizations with relevant activities is also part of the activity.

BIPM time department: 8 man-days (when activities from (a) to (g) are included)

3 man-days (when only activity (e) is considered)

9. Summary table of comparisons, dates, required resources and the laboratories already having institutional agreement to pilot particular comparisons

Ongoing comparison: BIPM comparison: BIPM.CCTF-K001.UTC

10. Document Revision

Schedule 1 year for exceptions
2 year updating of all lists
4 year major revision with extension of period covered by rolling programme

The document will be updated, if relevant, at each yearly meeting of the CCTF WG SP.

The major revision is expected to be performed at the occasion of the formal meeting of the CCTF, usually every three years.

Annex 1

Fritz Riehle April 2016

Towards a new definition of the second in the SI

Introduction

In the International System of Units (SI) the base unit “second” for time and frequency has been defined by the 13th General Conference on Weights and Measures (CGPM) in 1967 as

- The second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium 133 atom [1].

This definition is realized in the primary caesium atomic clocks whose fractional uncertainties decreased over the last fifty years by about an order of magnitude every decade (Fig. 1).

Since about 2005 optical frequency standards, where a laser interrogates an optical transition line in a suitable atom or ion, can realize the unperturbed line center with better accuracy than it can be achieved by using the caesium hyperfine transition (Fig. 1).

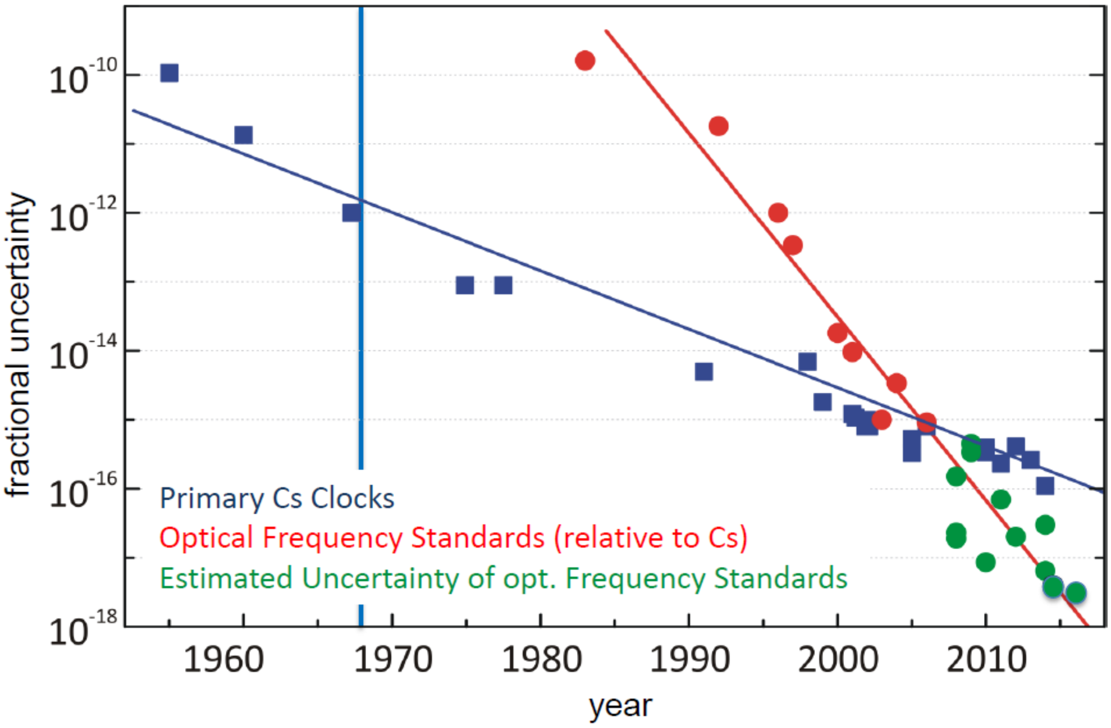

Fig. 1: Temporal evolution of the fractional uncertainty of the realization of the second with caesium atomic clocks and of optical frequency standards. The vertical line indicates the time of introducing the current definition of the second.

However, the frequencies of such transitions can never be determined in the SI better than the best caesium atomic clocks they are compared with. Such a situation is not uncommon in the SI; e.g. over many years, the base unit “ampere” could be realized with a two orders of magnitude lower uncertainty than the electrical units of resistance and voltage could be reproduced by using the von Klitzing effect or the Josephson effect, respectively. Nevertheless, after some time such a situation will become uncomfortable and a new definition will be established as it is planned for the year 2018 [2].

In 2001, the Consultative Committee for Time and Frequency (CCTF) foresaw this trend. One of the optical frequency standards could provide the basis for a future definition of the second, and the CCTF emphasized the need to review accurate frequency measurements of such atom and ion transition frequencies made relative to the caesium frequency standard. As a result, the Recommendation CCTF 1 (2001) [3] promoted the establishment of a list of "secondary representations of the second". The documentation of uncertainty to be applied to these secondary representations would be the same as those for primary caesium standards used to contribute to International Atomic Time (TAI). Later, the CIPM concluded in its Recommendation CI 1 (2006) [4] 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" should be established. This list has been frequently updated by the CIPM on proposition of the CCTF and CCL and can be found on the website of the BIPM [5].

Another advantage of the optical frequency standards results from the about five orders of magnitude higher optical than microwave frequency used to interrogate the respective transitions. In general, this leads to a higher stability of the realized frequency in the optical case and the frequencies of optical standards can be compared in a much shorter time with higher accuracy.

Current status of optical frequency standards

The lowest estimated uncertainties have been reported in the 10^{-18} range for the Sr optical lattice clock [6,7], the Yb^+ single ion clock [8] or the Al^+ quantum logic clock [9]. Direct optical frequency ratios between the different optical frequency standards have been determined within the 10^{-17} range for Al^+/Hg^+ [10], $^{199}Hg/^{87}Sr$ [11], Yb/Sr [12], or Yb^+/Sr [13]. Such frequency ratios have been used already to determine new recommended values for the frequencies of optical frequency standards and secondary representations of the second [14]. The ^{87}Sr lattice clock is the frequency standard whose frequency has been determined most often directly by comparison with the Cs atomic fountains (Fig. 2).

Consequently, in the 2015 CCTF meeting a fractional uncertainty of 5×10^{-16} has been assigned to the ^{87}Sr lattice clock which is only roughly a factor of two higher than the fractional uncertainty to realizing the unperturbed Cs hyperfine frequency with Cs fountains [15]. If remote optical frequency standards are compared by using the conventional two-way satellite time and frequency transfer (TWSTFT), the uncertainty of such a comparison over transcontinental distances has been shown to be limited to about 10^{-15} [16]. With increased bandwidth, a campaign in the framework of a European project [17] has been performed aiming slightly below 10^{-15} and with the ACES project [18] 10^{-17} for several days of averaging is aimed at. With dedicated optical fiber links the frequency of different optical clocks in different laboratories can be compared [19,20] or even continental distances can be spanned. A first transnational link has been used to compare the Sr optical lattice clocks of LNE-SYRTE and PTB in Paris and Braunschweig, respectively, showing agreement within fractional uncertainties of 5×10^{-17} [21].

Benefits of a new definition

"The present definition of the second based on the caesium transition is well suited for most industrial applications but the first high-tech companies are now asking for access to fibre optical links with optical frequencies since the current microwave technology does no longer satisfy their needs. The current drivers for better optical atomic clocks are mainly basic research, time and frequency metrology and novel applications. The search for better limits for the constancy of the constants [22,23], secondary representations of the second, and a future *Relativistic Geodesy* represent examples from each of these fields. As it is well known according to General Relativity, two optical clocks in a different gravitational potential show different frequencies [24] when compared, and this effect has been taken into account for a long time when comparing atomic clocks in the international time scales TAI and UTC.

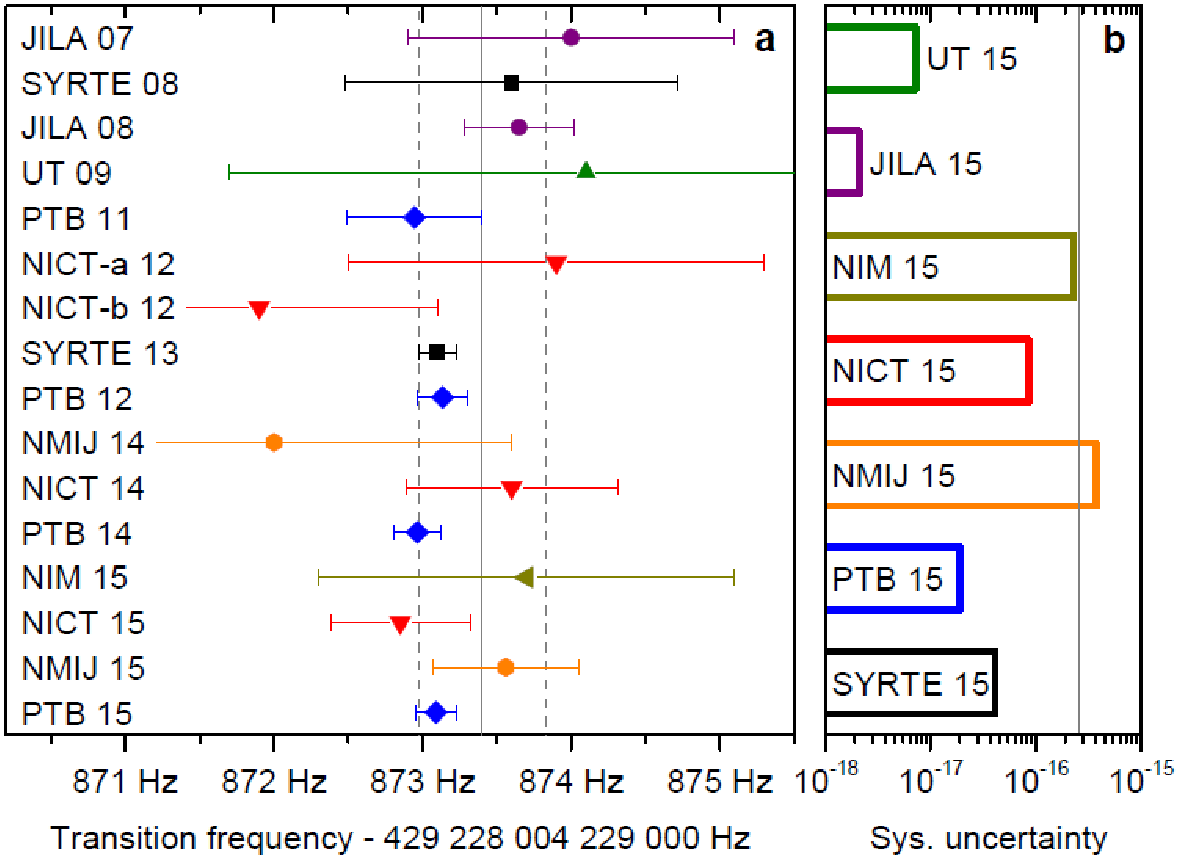

Fig. 2: taken from [25]. a: Comparison of measured absolute frequencies of the $5s^2\ {}^1S_0$ - $5s5p\ {}^3P_0$ transition in ^{87}Sr. The values have been obtained from various references (see [25]). The vertical line indicates the frequency recommended by the CIPM in 2013 for the secondary representation of the second by Sr lattice clocks [26], the dashed lines show the assigned uncertainty. b: Listing of the systematic uncertainty u_B of the best Sr clocks worldwide [7,27,28,29,30,21]. The gray line indicates the Cs systematic uncertainty of the absolute frequency measurement with the smallest overall uncertainty published so far [15].

With a difference of the fractional frequency $\delta\nu/\nu \approx 10^{-16}$ per meter of height difference near the surface of Earth, the expected 10^{-18} fractional uncertainty of the best optical clocks requires the determination of the exact gravitational potential equivalent to 1cm in height. On the other hand, it allows one to determine the difference in the gravitational potential at the locations of the two clocks. The potential of such a *Relativistic Geodesy* has been recognised a long time ago [31], but it now can be realised given that suitable transportable clocks and fibre links are available.

If the already available and planned fibre links for dissemination of optical frequencies with unprecedented frequency stability and accuracy described above can be financially secured, they will serve as a metrological fibre backbone e.g. in Europe or elsewhere. Such a backbone - mostly used to compare the best optical clocks - would then allow, in a second stage, the connection of national networks that can deliver these frequency and time resources to virtually all interested customers and clients. This opportunity will definitely boost novel applications and services from the very beginning.

A wider use of optical clocks in this and in other fields will depend strongly on a higher degree of compactness, reliability, and increased operation time and commercial availability. Even though the basic building blocks for such clocks are currently under development, e.g., for transportable optical clocks or for space applications, there are further engineering steps required. Optical clocks for special applications like *Relativistic Geodesy* and other ground and space applications will then immediately find application in the well-established fields where atomic clocks are used today, e.g., for time keeping and all other fields of frequency metrology.

After a redefinition, time scales would benefit directly from the availability of more stable and more accurate clocks that could be included in the generation of TAI and UTC and gradually replace the caesium clocks. The first steps along this road have been undertaken already [15, 32, 25]. Towards and after a new definition, the more optical clocks that contribute to TAI will make TAI and UTC more stable in the long-term [25] and more robust. A redefinition in conjunction with optical telecommunication fibre networks allows the much higher accuracy and stability to be delivered to virtually all places where phase-coherent fibre links are available or can be installed. Fibre networks will need replacement and maintenance of amplifier equipment within given cycle times when a refurbishment would allow installation of phase-coherent components step-by-step on a broader scale. Such an opportunity will immediately lead to novel applications and services." (The previous paragraphs in quotation marks have been copied mainly from [33]).

When will be the right time for a new definition? – Tentative roadmap

To answer this question we consider a few conditions, some of which have already been addressed before [33, 34, 35, 36]. From an industry and society perspective, there is no pressure for a new definition since their needs can be served with the current definition and caesium clock uncertainties achieved so far, and associated microwave dissemination. Science´s needs can be served for the time being by the secondary representations of the second, since their frequencies could be linked without loss of accuracy to the new transition after a redefinition. To set up a roadmap towards a new definition of the second a number of different and sometimes contradicting requirements have to be taken into account. Here we propose to define **necessary milestones** to be fulfilled.

As can be seen from Fig. 1, the progress with optical frequency standards still seems to continue with unbroken speed. From this point of view, there is a risk that a new definition might be premature because the current research and development could give new insight and would help to establish the best candidate. If this argument would have the only priority, it would prevent a new definition almost for good. Another criterion for the right time will occur when such an ongoing improvement would lose its impact for practical applications. The most practical application of the definition of the second is to establish a time scale. With a new definition and the novel means to compare optical clocks, the current time scale will improve immediately. However, in the 10^{-18} to 10^{-19} regime there seems to be a natural limit for better time scales on Earth. With fractional inaccuracies in the 10^{-18} regime, the geopotential has to be determined to the cm-level to account for the gravitational redshift. The best geodetical methods seem to be limited near this level. Following this argument, the time would be right for a new definition when the optical clocks have furnished proof that they solidly reach a fractional uncertainty of around 10^{-18}. Such a fractional uncertainty would be roughly two orders of magnitude lower than that of the best Caesium fountains of that time. Solid proof for such an achievement could be furnished in different ways: One possibility might be to connect optical clocks of the same type in different laboratories via optical fibers e.g. the Sr lattice clocks of SYRTE, NPL and PTB via the currently established fiber links. Similar links are available e.g. in Japan [20]. Such a clock could then either be a strong candidate for the new definition or be an anchor for other optical frequency standards that one would have a choice. A second possibility would rely on transportable optical atomic clocks if they will provide the required accuracy through the transportation. Such transportable clocks might even be necessary for comparison on a regular basis [[37]] en pointed out [`Another milestone that should be considered is the requirement that a means be developed to compare, on a regular basis and at a level of 5x10-18, optical clocks in laboratories throughout the world`]. Another option would use different measured frequency ratios and the associated evaluations [38] between remote optical clocks. From these considerations, one could define the first two milestones to be reached before a new definition will take place:

The time for a new definition is right when …

1. ... at least three different optical clocks (either in different laboratories, or of different species) have demonstrated validated uncertainties of about two orders of magnitude better than the best Cs atomic clocks at that time.

2. … at least three independent measurements of at least one optical clock of milestone 1 were compared in different institutes (e.g. $\Delta\nu/\nu < 5 \times 10^{-18}$) either by transportable clocks, advanced links, or frequency ratio closures.

The next important step would be to assure continuity between the present definition and the new definition. To this end the frequencies of the frequency standards considered in milestone 1 have to be measured (via an unbroken traceability chain) with an uncertainty essentially limited by the uncertainty of the best Cs fountain atomic clocks. It will be necessary to include several independent primary Cs clocks to obtain the best link between the new and the present definition.

The time for a new definition is right when …

3. … there are three independent measurements of the optical frequency standards listed in milestone 1 with three independent Cs primary clocks, where the measurements are limited essentially by the uncertainty of these Cs fountain clocks (e.g. $\Delta\nu/\nu < 3 \times 10^{-16}$).

To ensure that the new definition has a practical value, optical clocks that have been assigned the status of secondary representations of the second should contribute regularly to TAI in order to improve the time scale and to develop further the technology and protocols of improved methods for comparisons. From this consideration, one can ask for another important milestone.

The time for a new definition is right when …

4. … optical clocks (secondary representations of the second) contribute regularly to TAI.

With more than a dozen different optical frequency standards currently investigated or proposed, the achievement of a consensus for a new definition based on a particular transition will meet with difficulties since a lot of effort has been devoted to the other standards. Several of the other candidates will have similar low uncertainties as the one selected for the new definition. It would therefore be most desirable to use these existing standards and the associated competence and infrastructure also after a redefinition for time and frequency metrology and basic research. Such a procedure could be expected also to ease the approval of the new definition. To allow closures and links between the different optical standards and their continuous use, a fifth milestone would thus be desirable:

The time for a new definition is right when …

5. … optical frequency ratios between a few (at least 5) other optical frequency standards have been performed; each ratio measured at least twice by independent laboratories and agreement was found (with e.g. $\Delta\nu/\nu < 5\text{x}10^{-18}$).

After a redefinition the present standard of time and frequency would serve as a secondary representation of the second where the uncertainty to realize the second would be the same as before. Improvements of the caesium atomic clocks would be evaluated regularly in the established framework and rules used to recommend today “secondary recommendations of the second”. In essence, the full infrastructure of the current system would be used further without any need for modification, but would allow one also to re-think the current procedures [39].

Sometimes the question has been raised as to whether a combination of selected optical clocks via a “matrix” value algorithm [34] would be an alternative to the selection of a single transition. There, it was pointed out that “the drawback to this idea is that the matrix value would have no physical significance. It also would require regular updating, and acquire significantly different values with the introduction of new frequencies”.

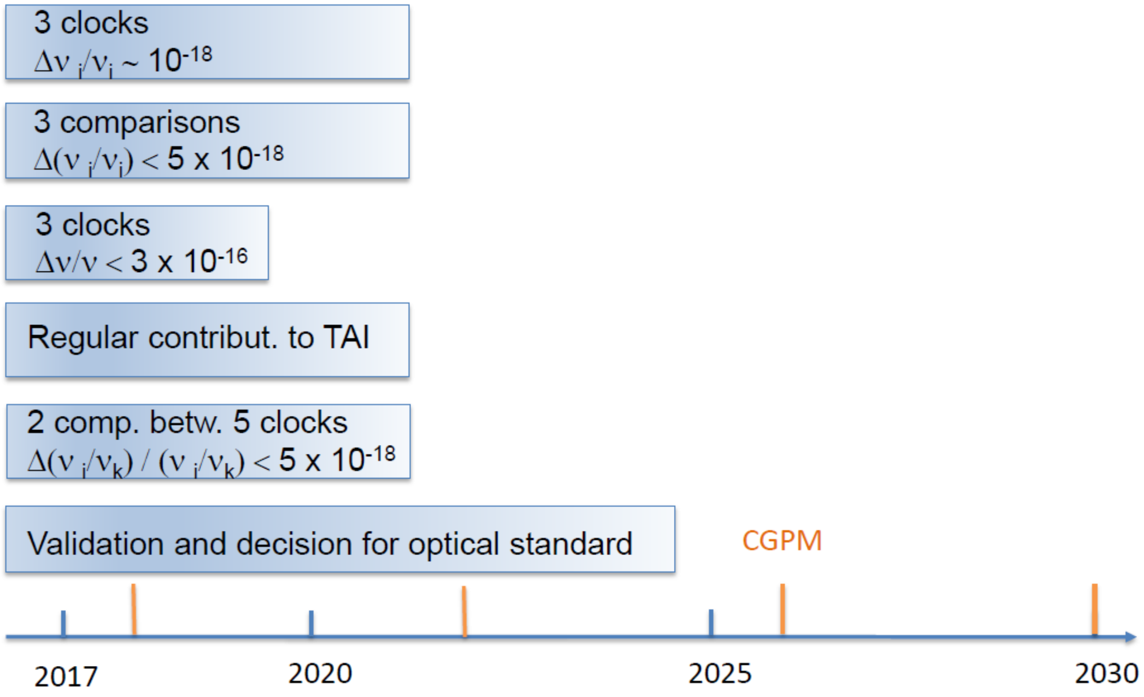

Fig. 3: Tentative schedule towards a new definition of the second. The first five bars represent the five milestones discussed above.

Even though roadmaps – as we know from everyday life - do not tell the user when the destination is reached, it might be also useful to get a feeling when different milestones along the road could be reached. Currently, there are no hints of any showstoppers. The time needed to arrive at a new definition will largely depend on the expended effort, the results emerging in the near future, and the good will for a consensus. A new definition should therefore take place **as early as possible and as late as necessary**. From the current pace one could make a rough estimate of the time needed (Figure 3).

Given that the five milestones are reached at 2022 (about 5 years after a consensus on the procedure and the milestones for a redefinition), one has to assume another four years for discussion in the CCs and the CIPM, the liaising with the stakeholders and arriving at a consensus. Given that the CGPM follows its previous four-year cycle, the new definition could be established as early as 2026. This estimate does not differ so much from the expected date given in [17].

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