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DIVISION A COMMISSION 31 — TIME

LE TEMPS

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Recent time-related topics in astronomy and metrology

Time is an essential element of fundamental astronomy. In recent years there have been many time-related issues, in scientific and technological aspects as well as in conventions and definitions. At the Commission 31 (Time) business meeting at the XXIX General Assembly, recent progress and many topics, including Pulsar Time Scales WG and Future UTC WG activities, were reviewed and discussed. In this report, we will review the progress of these topics in the past three years. There are many remarkable topics, such as Time scales, Atomic clock development, Time transfer, Future UTC and future redefinition of the second. Among them, scientific highlights are the progress of pulsar time scales and the optical frequency standards. On the other hand, as the social convention, change in the definition of UTC and the second is important.
In this report, we will discuss these topics and the future plans discussed in the C31 business meeting.

1. Time scales

Generation and dissemination of time scales are the fundamentals of the time service. Since the current definition of the second was accepted in 1967, International Atomic Time (TAI) and Coordinated Universal Time (UTC) have been used world-wide. Many national metrology institutes generate their own time standards using their own data, whereas TAI and UTC are determined by BIPM. Here, we describe the activities in BIPM and National Metrology Institutes.
Major achievements in the generation of time scales at the BIPM have been:

- The implementation of a new algorithm in the regular calculation of TAI and UTC. This algorithm is based on a parabolic model for the prediction of the participating clocks' frequencies, and a weighting procedure which uses the clock predictability as the criteria. The time scale computed with the new algorithm has an improved stability of about 20 % in both the short and long term.
- Five new caesium fountains were incorporated in the period of this report to improve the frequency accuracy of TAI/UTC. In total, 17 primary frequency standards,

including 15 caesium fountains, and one secondary representation of the second (rubidium fountain) contributed to TAI/UTC, with an average of about four caesium fountains reporting measurements each month. The increasing number of measurements reported for these standards reinforces the accuracy estimation of TAI. The frequency stability of TAI is estimated to be 3 parts in 10^{-16} for averaging times of one month, and its frequency accuracy is in the low 10^{-16}.

- A rapid UTC solution (UTCr) has been implemented at the BIPM published every week since July 2013. About 70% in the clocks in UTC are in UTCr, providing a prediction of UTC with a monthly stability of 4×10^{-16}. This rapid solution should impact the quality of the representations of UTC in national laboratories and facilitate the steering of the Global Navigation Satellite Systems' times to local representations of UTC.
- Time transfer methods used for clock comparison are the major component in the uncertainty of UTC realizations in national institutes. Improving time transfer with the study and implementation development of new methods has been a substantial part of the work programme of the Department, with the goals of reducing the statistical uncertainty of time transfer to a few hundred ps and to improve the accuracy of time transfer at least in a factor two by more refined and frequent calibrations.
- BIPM Circular T is the monthly publication which gives traceability to the SI second via Coordinated Universal Time (UTC) to its local realizations in more than 70 national laboratories.
- TAI is a realization of Terrestrial Time computed "in real time" and never corrected in retrospect; thus it is not optimal. The BIPM computes a post-processed time scale TT(BIPMxx) for year 20xx, using all data available from primary frequency standards. Each new version of TT(BIPMxx) is a complete reprocessing of data since 1993 which updates and replaces the previous version. Since the introduction of constantly-improving caesium fountains in 1999 the frequency accuracy of TT(BIPMxx) has regularly decreased from 2.5×10^{-15} to about 2×10^{-16} in 2015.
- The BIPM, along with other laboratories, has participated in the ICG, whose goal is to coordinate the several Global Navigation Satellite Systems expected to be operational by 2020. This has led to modifications of several procedures, along with format modifications including that of the Circular T itself.

Time scales in institutes and observatories:

- Frequency standards have been developed and are maintained in cooperating institutes, including caesium fountains and fountains based on transitions adopted as secondary representation of the second. Three caesium fountains from LNE-SYRTE, in Paris Observatory, have contributed 40% of all TAI frequency calibrations in 2014; the double Cs-Rb fountain is the only secondary representation of the second to contribute to the accuracy of TAI. The cold-atom space clock PHARAO, constructed at Paris Observatory, will be launched in 2016 as part of the ACES space clock ensemble on the International Space Station (ISS).
- The realization of UTC at Paris Observatory has since October 2012 been based on a hydrogen-maser clock steered on the atomic fountains; since then, the departure of UTC(OP) has remained below 10 ns.
- Lattice clocks of different species are under development at Paris Observatory and at Riken-Tokyo University in Japan, with demonstrated accuracy at the 10^{-17} - 10^{-18} level. In parallel, accurate methods for enabling the comparison of clocks of these types are being implemented, and among them optical fibres between various institutes in Europe and in China.

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- The US Naval Observatory maintains the largest ensemble of clocks contributing to UTC/TAI, including more than one hundred atomic clocks and six rubidium fountains. These clocks enable tests of time-variation of fundamental constants, of the principle of equivalence and with the next generation clocks, the gravitational redshift. Their rubidium fountains are stable enough to be routinely used as the standard by which to evaluate time scale innovations.
- Four laboratories (USNO, PTB, OP, and SU) have adopted fountain-based time scales which resulted in noticeable improvements in their ability to realize UTC, and many laboratories have begun using UTCr to improve their performance as well.
- Experimental time transfer techniques involving optical fibers, carrier-phase Two Way Satellite Time Transfer (TWSTT) and Dual Pseudo-Random Noise "DPN" TWSTT show promise of achieving time transfer to the level of a few ps, while portable rubidium fountains may provide a highly accurate means of frequency transfer calibration.
- Precise Point Positioning is now fully operational; investigations to improve it with integer ambiguity resolution are underway.

2. Pulsar time scales

Pulsar Timing Array (PTA) projects, whose primary objective is the detection of low-frequency gravitational waves, also have the ability to define an independent reference time scale. Currently there are three main PTA projects around the world: the European Pulsar Timing Array (EPTA) based on five large radio telescopes in Europe, the North American PTA (NANOGrav) based on observations made with the Green Bank and Arecibo radio telescopes, and the Parkes Pulsar Timing Array (PPTA) which uses data from the Parkes radio telescope in Australia. These three PTAs have formed a collaboration known as the International Pulsar Timing Array (IPTA) in order to optimize sensitivity for all PTA scientific goals.

Recent implementations of the pulsar time scale have a stability over intervals of months and years that is comparable to that of the best atomic time scales. The pulsar time scale is based on entirely different physics (macroscopic rotation) to the atomic time scales and will be continuous for millions of years. It is therefore a valuable complement to the atomic time scales. The pulsar time scale is not absolute because pulsar periods are a priori unknown. Furthermore, since pulsars also have an a priori unknown slowdown rate, only fluctuations in the rate of atomic timescales that are second order or above can be detected.

Data from the PPTA, analysed by Hobbs *et al.* (2012, MNRAS, 427, 2780), define a pulsar time scale known as TT(PPTA11) over the interval from 1994 to 2011. The time scale has a time or phase uncertainty relative to TT(TAI) of less than or about 100 ns after 2005 and a few hundred nanoseconds prior to that. Comparison of this time scale with TT(BIPM11) show that deviations of TT(BIPM11) from TT(TAI) over the 15 years are largely reproduced, verifying that TT(BIPM11) is a much improved time scale over TT(TAI). While there are some deviations of TT(PPTA11) from TT(BIPM11), at present these are of marginal significance. The IPTA combined data set and improved signal-processing algorithms offer the promise of much improved stability and also longer duration for the pulsar time scale. Efforts are currently under way to realize this potential.

3. Atomic clock development

Current definition of the second is based on the frequency of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium

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133 atom. Atomic fountain is the type of primary frequency standards that realize the definition most accurately. Since 2006, every primary standard has been required to pass in the review by Consultative Committee for Time and Frequency (CCTF) WG on primary frequency standards to join the standards that contribute to the accuracy of TAI. For these two years, five standards have been newly accepted by the WG and at present, fifteen atomic fountains are accepted by the WG. The combined accuracy of these standards has been slowly improved, in low parts in 10^{-16}. Recently, several laboratories have implemented quasi-continuous operation of their atomic fountains, to realize exceptionally good UTC representations in those laboratories.

Since the beginning of this century, we have seen a remarkable progress in the development of the optical frequency standards. It can be seen in the fact that this field has brought two Novel prize winning results, development of optical comb systems, awarded in 2005, and the measurement and manipulation of individual quantum systems and the development of single ion standards, awarded in 2012.

The optical frequency standards can be categorized into two types, single ion optical clocks and neutral atoms lattice clocks. In both type, originally expected goal of the accuracy, the level of 10^{-18}, are within reach. The limit of the frequency uncertainty was considered to come mainly from the black body radiation and gravitational red shift. A few years ago, Al^+ single ion clocks in NIST, US showed their uncertainty on the order of 10^{-18}. In 2015, a comparison of two "cryogenic" strontium lattice clocks in Riken, Japan demonstrated that the uncertainty due to black body radiation was well suppressed, achieving the frequency uncertainty of lattice clocks at the 10^{-18} level.

In this level, gravitational red shift, 10^{-16} frequency shift by 1m height change, would be serious problem when we compare the standards located in long distance. Therefore, it becomes important to have a close relation with Geodesy. As for the absolute frequency values, to determine those of these standards, the accuracy of caesium standard, current realization of the definition of the second, has set the practical limit.

Another technical limit is the stability of the clock lasers. Currently, the largest instability of the lasers comes from the thermal noise of the optical cavity mirrors. On this problem, many research have been conducted. One is the cooling mirrors as is used in Gravitational wave detection systems, ant the other is the development of new mirror coating materials whose thermal noise is lower than the current dielectric coat. When large improvement is attained, this technique will give impacts, not only on the optical frequency standards, but also on many precise measurement applications.

In CIPM, considering current progress in this field, Consultative Committee for Length (CCL)-CCTF Frequency Standard WG has been made a list of recommendations for the radiations to be used as secondary representations of the second. In September 2015, the recommended values and uncertainties in the list was updated. In the updated list, recommended uncertainty of some radiations, ^{87}Sr, ^{199}Hg and ^{171}Yb lattice clocks, and $^{171}Yb^+$ single ion clock, are on the order of 10^{-16}, whose uncertainties are essentially limited by Cs clocks.

On the other hand, in some institutes, they have been developing two or more different optical standards. In such institutes, they have measured the optical frequency ratio of the different standards directly. The uncertainties of these ratios are not limited by Cs clocks. In the WG, these results are used for the 2015 update to provide valuable information about relative performance of different optical frequency standards and to determine optimized values and uncertainties for absolute frequencies of each optical standard relative to the current definition of the SI second.

Considering the rapid progress in this field, redefinition of the second by using optical frequency standards has been discussed for more than ten years. The roadmap to the redefinition is now under discussion. This redefinition is not so easy and it will take around ten more years.

There are two issues to be noted. One is, the development of the standards is still on going. We should better watch carefully which standard is best for the next definition. The other is the problem on the time transfer technique. Compared to the caesium standards, optical frequency standards show the higher accuracy in shorter period. Therefore current time transfer techniques are far not enough for the comparison of the standards to see the accuracy limit. For the redefinition of the second, at least to obtain some prospect for these two issues will be needed. Recent aspect on the latter problem is shown in the next section.

4. New time transfer technology

For the construction of TAI and UTC, GNSS Precise Point Positioning (PPP) and Two Way Satellite Time and Frequency Transfer (TWSTFT) are regularly used. Its official time transfer uncertainties are 0.3 ns and 0.5 ns, respectively. These uncertainties, enough for 10 days with 10^{-16} level accuracy evaluation of atomic fountain, are quite insufficient for the evaluation of optical frequency standards with 10^{-18} level at a few hours, as is mentioned in the previous section. Therefore, a large improvement on the time transfer uncertainly is required to evaluate the new standards.

Optical fiber link is one of the most promising techniques. In some short distance cases, such as NIST- JILA 5km link in Boulder, US and NICT-Tokyo University 50 km link in Tokyo, Japan, already in several years ago, 10^{-18} frequency transfer uncertainty level at one day are demonstrated. For a long distance comparison, this technique had some difficulties. Recent development shows this difficulty has been gradually overcome. In 2015, PTB in Germany and SYRTE in France reported a 1440 km optical fiber link frequency transfer with uncertainty of 10^{-20} in one day. Including this experiment, there are many experiments and plans on the optical fiber time and frequency transfer in the world.

In an ESA space mission, ACES (Atomic Clock Ensemble in Space) project, time and frequency transfer technique play an important role. Its time and frequency transfer system is under development aiming at 10^{-17} frequency resolution at one week of measurements. The satellite is planned to launch in 2017.

Another candidate technique is a carrier-phase TWSTFT (TWCP), development leaded by NICT. This technique has the potential to compare the frequency better than 10^{-16} in a few hours. Under cooperation between NICT and PTB, in 2013, a TWCP measurement was performed in the baseline of 9000 km. In this intercontinental baseline, a short-term instability for frequency transfer of 2×10^{-13} at 1 s was obtained. This shows the potential of this technique for a precise intercontinental time and frequency transfer. In this NICT - PTB link experiment, the demonstration of a direct frequency comparison of two Sr lattice clocks was successfully performed by TWCP technique, and a frequency agreement of the two Sr clocks in 10^{-15} level was confirmed on an intercontinental scale.

VLBI time transfer has the potential to attain the frequency transfer uncertainty of around 10^{-16} in a day, when broadband observation system is developed. Recently, NICT has succeeded to develop a new VLBI observation system which enable over 10 GHz total bandwidth, by capturing four 1GHz bandwidth signal in 3-14GHz frequency range. So far, using only 1GHz bandwidth, this system has shown a frequency transfer uncertainty with the same level as GNSS PPP. Recently, the bandwidth synthesis software was completed. When this software is applied, this broadband VLBI system is expected to make 10^{-16}

level frequency transfer uncertainty in one day, by using not expensive satellite signals, but only the free space radio signals.

It is worth noting that currently some transportable optical clocks are under development, aiming at 10^{-17} accuracy level at a few hours. When such transportable clocks are completed, they will open a new way for the frequency comparison of remote optical clocks.

5. Future of UTC

The Working Group on the redefinition of Coordinated Universal Time was formed following the XXVIIIth IAU General Assembly in Beijing in 2012. Its mission was to prepare a proposal for the response of the IAU to the Radio-communication Sector of the International Telecommunication Union (ITU-R) in reply to that organization's request to the IAU for comments regarding the possible redefinition of Coordinated Universal Time (UTC). The 2015 World Radio-communication Conference (WRC-15) agenda item 1.14 is scheduled to "consider the feasibility of achieving a continuous reference time scale, whether by modification of UTC or some other method".

The WG was chaired by Dennis McCarthy and Felicitas Arias and had a membership of twelve. In order to make a timely contribution to the ITU-R a report from the WG was to be concluded by April 2014.

The WG worked by correspondence and had difficulties in reaching a consensus because of the different opinions of its members. However, a report was submitted to the IAU General Secretary in April 2014.

This described the lack of consensus between its members, and in consequence recommended that the IAU can neither favor nor oppose the cessation of the leap-second insertion in UTC. It suggested that, if a continuous reference time scale were to be adopted, at least five years of lead time is required for re-education and changes to legacy software and data storage formats; that a different name be considered for the new time scale, and requested that the IAU continue to be represented in future discussions relating to time scales. The Working Group in its report urged IAU members to develop astronomical software that requires precise Earth orientation information to use Earth orientation data provided by the International Earth Rotation and Reference Systems Service (IERS), and requested that the IERS investigate more widely and technologically useful means of providing Earth orientation information. On this last issue, it was reported at the IAU XXIX General Assembly in Honolulu, that the National Institute of Standards and Technology (NIST, USA), in cooperation with the IERS, has started a NTP server service that disseminates UT1.

The Working Group was disbanded after the conclusion of its report. The future UTC issue has been discussed in ITU-R Study Group (SG) 7 and member countries. Some conclusion is expected in WRC-15.

6. Commission 31 business meeting report and future plan

The Commission 31 business meeting was held on 6 August 2015, at the IAU XXIX General Assembly in Honolulu, with around twenty attendees. There, the recent time-related activities described above were reviewed and the importance of the cooperation between astronomy and time metrology was confirmed. Unfortunately, a new Commission on Time, proposed mainly by current OC members, was not accepted by the IAU Executive Committee.

The second half of the business meeting was devoted to the discussion on the plan for future activity in this field. Based on a draft prepared by Commission President and OC members, some discussion was held, and a proposal to create a new Working Group on the link to time metrology standards within Division A was agreed. This proposal was supported by Division A in its business meeting held on 13 August. It is expected that many of the activities conducted in the Commission 31 will be taken over to the new WG, as well as to the Division A and its new Commissions.

To see the metrological aspect on time and frequency, the activities of CCTF and its WGs are useful. CCTF WG on Primary Frequency Standards and CCL–CCTF Frequency Standard WG are mentioned above. In the field of timescales, two Working Groups, WG on TAI and WG on Time Scale Algorithms, have been established. For time and frequency transfer, three, WG on Two Way Satellite Time and Frequency Transfer, WG on GNSS Time Transfer and WG on Coordination of the Development of Advanced Time and Frequency Transfer Techniques have been established.
The activities of these WGs can be seen in a lot of informative open documents at the CCTF web site (`http://www.bipm.org/en/committees/cc/cctf/`).