The 50th Anniversary of the Atomic Second

E. Felicitas Arias, Demetrios Matsakis, Terry J. Quinn, and Patrizia Tavella, *Senior Member, IEEE*

***Abstract*— This paper gives a brief account of the history of time standards and timekeeping beginning with John Harrison's seagoing clocks for navigation up to today's optical frequency standards and prospects for the future definition of the second.**

***Index Terms*— Frequency measurement and statistics, timing and time distribution.**

I. Introduction

At about 4:30 p.m. of October 13, 1967, the 13th General Conference on Weights and Measures (CGPM) made the historic decision to define the second in terms of a hyperfine transition of the atom of cesium 133. At this moment, the measurement of time ceased to be based on the movement of the earth but on the period of vibration of an atom of cesium. Now, some 50 years later, that revolution remains perpetually young due to an unceasing series of innovations. The history of those innovations is in itself becoming a field of study, but the future promises even greater advancement, both in the measurement techniques and in the fundamental understanding of time.

II. History of the Definition of the Second and Responsibility for Time

Since the dawn of human existence, and as long as time was purely local, the passage of time was set by the rising and setting of the sun with the solar day being the basic unit divided into 12 or 24 hours. No one really had need for accurate time measurement until long sea voyages far from the land became common and the determination of longitude became critical.

In the middle of the 18th century, John Harrison transformed navigation at sea by his accurate seagoing clocks. His famous H4 was taken from Great Britain to the West Indies keeping time to about 5 s, equivalent to an error in longitude of about one nautical mile. This performance set the scene for marine navigation up until the Second World War, after which radio navigation at sea was developed.

The French Revolution inspired the metric system, which included units for length, mass, and volume. New units for time and the calendar were also defined then, but they were rapidly abandoned due to practical considerations of navigation using charts following the conventional system, and in dating commercial transactions. In 1832, Gauss introduced his millimeter/milligram/second system and in 1874 the British Association for the Advancement of Science (BAAS) created the centimeter/gram/second (CGS) system, and later the meter/kilogram/second (MKS) system. The second, as the unit of time, remained defined as 1/86 400 of a mean solar day, and therefore time remained, and continued to remain for another century, firmly in the hands of the astronomers.

In the 19th century, the building of railways and the invention of the electric telegraph led to the need for time coordination within individual countries. The 1884 International Meridian Conference in Washington established Greenwich as the prime meridian and Greenwich Mean Time (GMT) became a universal reference for worldwide navigation and timekeeping.

The first formal treaty concerning measurements was the Metre Convention of 1875 whose mission was "*to assure the international unification and perfection of the metric system*"—thus it did not include any responsibility for the unit of time. At the beginning of the 20th century, radio transmissions of time and frequency led to the creation in 1912 of the *Bureau International de l'Heure* (BIH) at the Paris Observatory. The scope of the Metre Convention of 1875 was enlarged by a second Convention in 1921, but this still did not include any specific responsibility for the unit of time but it left it open to Member States to extend its range of responsibilities as necessary in the future.

This first observational hint that earth's rotation rate was variable was made using high-grade pendulum clocks [1], [2], and confirmed following the development of crystal clocks in the 1930s by Scheibe and Adelsberger [3] and Pavel and Uhink [4] of the Physikalisch-Technische Reichsanstalt (PTR) in Germany. The next step from mechanical clocks to atomic clocks began with the linking of a resonating quartz crystal to an ammonia spectral line at a frequency of 24 GHz by Lyons [5] in 1949 at the National Bureau of Standards (NBS) at the United States of America. The accuracy was limited, however, to some parts in 10^7. The move to cesium as the reference came through theoretical work of Rabi and Ramsey and a program toward a cesium atomic clock was begun at the NBS, but was not completed. It was in 1955 that Essen and Parry [6] at the National Physical Laboratory (U.K.) made the first operational cesium atomic clock. It was calibrated with respect to Universal Time (UT) (which will be discussed in Section II-A) by comparisons using quartz clocks at the Royal Greenwich Observatory, and later calibrated with respect to the Ephemeris second by

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E. F. Arias is with SYRTE, Observatoire de Paris, Université PSL, Paris, France, and also with CNRS, Sorbonne Université, 75014 Paris, France.

D. Matsakis is with U.S. Naval Observatory, Washington, DC 20392 USA.

T. J. Quinn, retired, was with the International Bureau of Weights and Measures, 92312 Sèvres, France. He resides in 92310 Sèvres, France.

P. Tavella is with the International Bureau of Weights and Measures, 92312 Sèvres, France (e-mail: patrizia.tavella@bipm.org).

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observations of the moon made in collaboration with Markowitz of the U.S. Naval Observatory [7]. This latter calibration took some three years and led to the value of the cesium frequency of 9 192 631 770 Hz with which we are all now familiar.

The Metre Convention first took formal responsibility for the unit of time only in 1960 when the 11th CGPM created the International System of Units (SI), considered to be the modern form of the metric system. The SI included the second, which had been provisionally redefined by the International Committee for Weights and Measures (CIPM) in 1956 as the Ephemeris second following a proposal of the International Astronomical Union (IAU). The Ephemeris second was defined as a certain fraction of a year—the period of the movement of the earth around the sun. This was done because by then improved mechanical clocks had shown that the rotation of the earth was not perfectly stable.

In 1985, the Metre Convention took over responsibility for the world's time scale from the BIH. Since then, the BIPM has been responsible for calculating the world's atomic time scale, International Atomic Time (TAI). This is disseminated to the world through the many National Metrology Institutes as Coordinated Universal Time known as UTC, which is TAI to which is added the occasional leap second. Due to the need to coordinate worldwide radio time signals, the World Radio Congress in 1959 asked the Radio Consultative Committee [International Radio Consultative Committee (CCIR)] to study the problem. UTC was first formalized in CCIR Recommendation 374 in 1963 and later approved by the IAU in 1967. The suggestion of leap seconds was made at about the same time by a commission under the CIPM (Metre Convention) and a CCIR Study Group. The definition of UTC soon ceased to be a question of time signal formulation and wholly a question of a world practical time scale for which the Metre Convention is responsible. Therefore, in our view, it would have been more appropriate for the CIPM to have assumed full responsibility for UTC at the onset, and we suggest that this should once again be considered.

A. Universal Time

As early as 1956, the IAU recognized three forms of UT. "UT0" corresponded to the Greenwich mean solar time as observed at any location of the earth, "UT1" is UT0 corrected for the motion of the earth's polar axis, so that it is proportional to the rotation angle of earth in inertial space. Thus, UT1 suffers from the irregularities of the rotational rate of the earth, including a secular deceleration and decadal fluctuations. The third form of UT, "UT2," is UT1 corrected for seasonal variations of the speed of rotation of the earth.

B. Ephemeris Time

The irregularities of UT1 had been demonstrated by its shortcomings in modeling the motion of the solar system bodies. Before 1956, there had been no definition of the second by a body of the Metre Convention; the SI second was still defined tacitly as the second of mean solar time. To avoid its variations of 10^{-7} to 10^{-8} in relative value, the astronomers suggested a new definition of the second to be based on the orbital motion of earth. The IAU, in 1952 and 1955, decided on the definition of the Ephemeris second as a fraction of the tropical year for January 0, 1900 at 12-h ephemeris time according to a calculation made in 1895 by Simon Newcomb of the United States Naval Observatory (USNO). The Resolution 9 of the 11th CGPM in 1960 formally validated this new definition.

Ephemeris Time was far from representing a real improvement. There were two problems with the Ephemeris second. The first was that accurate clock calibrations would have to last a number of years, and this was very inconvenient. The second problem resulted from the numerical value chosen for the length of the Tropical Year 1900, which in fact was based on the average of a few centuries of astronomical observations having a mean date around 1840. The earth rotation rate was known to be reducing, mainly due to tidal friction, with the length of the day thus increasing, by about 1.7 ms per century. By 1960, when the new Ephemeris definition of the second was adopted, the length of the day had increased by some 2.2 ms compared with its value in 1840. In a year, this amounted to nearly ¾ of a second. The result was that when in 1967 the atomic definition of the second was adopted—and set to be consistent with the Ephemeris second in use since 1960—the atomic second was set to be too short by the equivalent of about ¾ of a second per year, at the year of its introduction!

While in the long run the rate of leap second insertions should grow to once a month in approximately 2000 years, the unfortunate result in the short run has been that more leap seconds have had to be introduced to keep atomic time in phase with the rotation of the earth. To date, the difference between TAI and UTC is 37 s, 27 of them inserted since the system was put into operation in 1972. The introductions of leap seconds increasingly cause practical difficulties in timing applications, particularly with the less technically savvy public and commercial sectors. The adoption of the Ephemeris second can be seen today as an unnecessary and unwise step toward the atomic second.

C. Atomic Time

By 1967, the precision and the stability of the cesium frequency standards had so demonstratively exceeded what was available from astronomical observations that it was decided to define the SI second in terms of the measured period of a specified transition of the cesium 133 atom. The definition of the Ephemeris second was at the same time abandoned.

A timescale based upon integration of the SI second was then defined and termed International Atomic Time (TAI). Initially Coordinated Universal Time (UTC) was generated by a combination of 100-ms time steps and frequency steers; however, the current system of leap seconds was established in 1970 by mutual agreement of the CIPM (succeeded by CGPM), the IAU, the International Union of Radio Science (URSI), and the use of UTC in radiocommunications was agreed to by the CCIR, whose successor is the International Telecommunications Union [8]. At that point the world's time, in effect if not always in law, switched from being based on GMT to being based on UTC; from the motion of the earth to the frequencies of atoms. As we have seen, the UTC algorithm had to incorporate the occasional addition of leap seconds to TAI so as to keep step with the variations in the earth's rotation; however, if proper account is made of leap seconds, the SI second can be realized using UTC as well as TAI. As of this writing TAI-UTC is 37 s; predictions based on trends over the last 50 years indicate that the number of new leap seconds expected to be inserted by 2100 would be significantly less than 60, although decadal fluctuations of the rotational rate of the earth make accurate predictions difficult.

Modern cesium primary frequency standards have accuracies of a few parts in 10^{16}, six orders of magnitude better than that achieved by Essen and Parry [6]. Two thermal cesium beams developed by the Physikalisch-Technische Bundesanstalt (PTB) are maintained in continuous operation and have for decades been contributing to the realization of the SI second, with current uncertainty values of order 10^{-14} [9]. The best primary standards are cesium fountains, which contribute regularly to improve the accuracy of TAI. In the new generation of fountains, the noise has been controlled using optically stabilized microwave oscillators [10]. The dominant type B uncertainty has been progressively reduced through better treatment of systematics and evaluation of corrections; cesium fountains are for example calibrated for the blackbody radiation shift at cryogenic temperatures [11], [12].

Worldwide time consistency is today assured through the monthly BIPM *Circular T* [13]. This gives the differences between UTC and its real-time realizations by each of the world's time laboratories, denoted UTC(k). UTC is computed by the BIPM through ongoing (mostly) satellite-based comparisons of these laboratories' unsteered clocks.

III. Promise of Optical Techniques

As will be described elsewhere in this issue, many groups are actively and successfully developing all aspects of the optical clock technology. A key enabler for optical technology was the development of the optical comb, which allows the generation of a microwave signal locked to an optical one, so that frequencies can be compared to high accuracy between these two domains.

It is clear that lower uncertainty and higher relative stability can be obtained with a clock operating on an optical transition rather than a microwave transition. It is also striking that cesium clocks improved their accuracy by a factor of a million over 50 years, while optical clocks have had identical progress in 20 years!

Fig. 1 shows the accuracy of frequency measurements involving a total of 14 optical atomic transitions that have been published to date. See also [14].

The progress in the development of these new clocks motivated in 2001 the creation of a list of recommended transitions to provide secondary representation of the second (SRS) with the aim of investigating their stability in view of a possible future redefinition of the SI second, and of supporting the institutes to work on their development. Nine SRS are at present included in the list of standard reference frequency values of the CIPM [15]. Beginning in 2012, some of these have been used along with the cesium primary standards

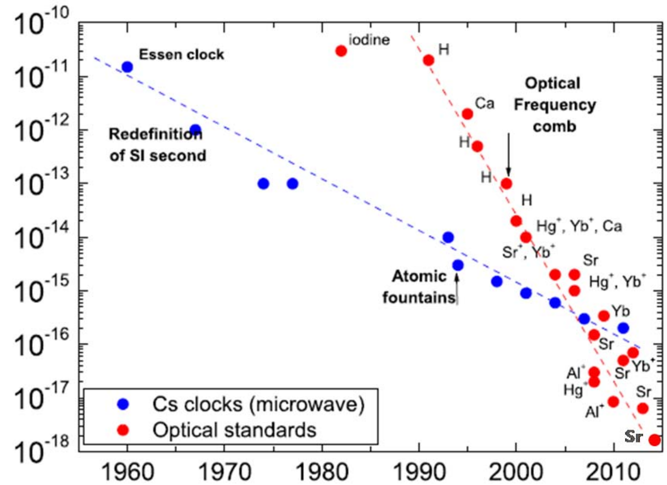

Fig. 1. Reported accuracy of atomic transitions (from BIPM website).

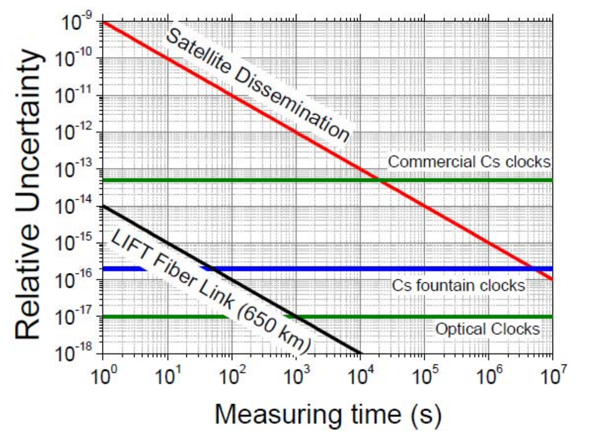

Fig. 2. Relative uncertainty of microwave and optical clocks compared to satellite and fiber time-transfer techniques as a function of measuring time. (From D. Calonico, report "Towards a European optical fibre network," 2015).

in calibrating the frequency of TAI. One is a microwave transition ^{87}Rb reported by the French metrology institute LNE-SYRTE [16]. Of the eight optical transitions, ^{87}Sr was also reported in 2017, by the LNE-SYRTE [17].

The creation of extremely precise and accurate frequency standards has brought about a need for a corresponding improvement in time and frequency transfer, including often-subtle relativistic and geodetic effects [18]. As illustrated in Fig. 2, long-distance time and frequency transfer using optical techniques has surpassed even carrier-phase-based microwave techniques, in both accuracy and precision, although cost remains a serious issue. A permanent 420-km fiber link in Poland is currently being used in the generation of the Polish atomic time scale and reported to the BIPM [19]. Extensive campaigns have been initiated among a group of European institutes to assess the accuracy of optical links over long distances, such as the successful comparison of cesium fountains over a 1400-km fiber linking the LNE-SYRTE in Paris to the PTB in Braunschweig [20]. Two optical clocks were compared by both fiber and experimental two-way satellite links in Japan [21]. However, comparing these clocks along distances beyond the limits of fibers, where the current satellite techniques are not sufficiently accurate and the cost of experimental techniques may prove unaffordable, is still an issue. It may be partially addressed through the development of transportable clocks [22].

IV. Roadmap Toward a Redefinition of the SI Second

A procedure to implement a change in the definition of the SI second was agreed upon at the 21st meeting of the consultative committee for time and frequency (CCTF) in 2017 [23], [24].

In order to change the basis of the SI second to a new transition, it is requested from the CCTF Working Groups that the following have been met.

1) At least three different optical clocks (either in different laboratories, or of different species) have demonstrated validated uncertainties two orders of magnitude better than the cesium transition (i.e., a fractional frequency uncertainty of order 10^{-18}).
2) At least three optical clocks, in different institutions, are measured to be in agreement at this same level.
3) The optical standards are compared to at least three cesium fountains and the uncertainty of the measure is limited essentially by the uncertainty of the fountains. This is requested to preserve the continuity between the present and the future definitions.
4) For secondary optical frequency standards, at least five measured ratios with the new primary frequency standard should be in agreement, with those ratios being measured twice by independent laboratories.
5) Optical clocks, recommended as SRS, should contribute regularly to TAI. This means they should comply with a robustness criterion that their series of monthly continuous frequency measurements would span periods of at least ten days, with nonsignificant dead times.

After the redefinition, the current standards would serve as secondary representations of the second.

In parallel to and in coordination with this process, the Consultative Committee for Units (CCU) will shortly start discussions on the new definition, and it is expected that the CGPM will officially open a discussion in 2018, and it is anticipated that the new definition could be adopted by the CGPM in 2026 or 2030.

The new SI second will be a landmark to possible future changes in Metrology.

From a technical point of view, there might be a reconsideration of whether the SI second should still be defined via a single transition, or via a weighted average of optical transitions or even by a small number of specified transitions each having equal weight. While TAI could be defined by a single frequency standard, the fallibility of individual clocks makes it imperative to use a weighted average. In a similar manner, while we do not anticipate the fallibility of a single transition, it may be that a weighted average would naturally allow for improvements as optical standards based upon new frequencies are developed, some of which would undoubtedly be more stable and capable of more precise measurements. The decision to change the algorithm in this way would require as much care as is going into the anticipated change; the theoretical work has not even begun.

A second issue is related to the optimal introduction of new Primary and Secondary frequency standards in TAI/UTC, and in the national realization UTC(k). There are already studies on how this can be optimized considering that an optical standard may initially operate with a significant dead time [25]–[27]

In addition, once the relative accuracy of the frequency values will be consolidated at 10^{-18} level, it will be necessary to refine the earth gravity potential representation at the centimeter level as necessary for the comparison of optical frequency standards and for the realization of Terrestrial Time.

A deeper question would be whether to invert the process by which the SI second is used to define fundamental constants, as they have already demonstrated the constancy of certain combinations of them [28], [29]. Perhaps someday the frequency of a transition can be considered a fixed function of the relevant physical constants (fine structure constant and electron-to-proton mass ratio), much as the unit of length is a function of the fixed speed of light. This change was made to the meter because the speed of light could be measured much more accurately than that of the length of a meter bar, and a similar consideration is driving the pending redefinition of the kilogram. We do not envision such a change being needed for the SI in the next 20 years at least, because the SI second can be measured more precisely than the physical constants. In addition, different atomic transitions depend upon different combinations of the physical constants and this has been used to test for variation of these physical constants over time on both astronomical and decadal scales [29], as well as in different solar gravitational potentials.

V. Great Technology Developments Based on Atomic Clocks

The effects of improved timekeeping upon our society are certainly foreseeable. Global Navigation Satellite Systems (GNSS) are based upon atomic clocks broadcasting their time; their original military purposes have been vastly superseded by an ever-growing number of civilian applications. A generation now exists that has no memories of daily life without GNSS. In metrology as well, the impact of GNSS has been matched by GNSS's need for improved and more rapid UTC, and better time transfer. More precise techniques would also allow for more rapid computations due to the decreased time that would be necessary to acquire an acceptable signal-to-noise ratio. The BIPM's development of the UTC-predictor known as UTCr [30] is one effort that was made to address this need. Another is the development of better space-qualified clocks for GNSS satellites.

The accuracy of local realizations of UTC can be improved by steering their frequency to primary frequency standards. Cesium fountain-based timescales are maintained at a few institutes contributing to UTC. With algorithms combining H-maser clocks and atomic fountains, PTB in Germany [31], LNE-SYRTE in France [32], and USNO in the USA [33] generate UTC realizations that have stayed within 2.5 ns RMS of UTC since 2014.

The most accurate atomic clocks constitute a key element in the development of new gravitational measurement techniques. A new emerging field, "chronometric geodesy," makes use of remote comparisons of optical clocks for a relativistic determination of the differences in gravitational potential and height between the locations where the clocks are operated [34].

VI. Conclusion

Time and frequency metrology remains a fascinating field where each step in the improvement of standards or in the refinement of time and frequency comparison methods brings new insight on physics and technological applications. The second was the first SI unit based on quantum physics; along these 50 years, it has given inspiration to more than ten Nobel Prize awarded scientists and it has allowed the development of GNSS, certainly the technological tool with the highest impact on today's society.

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E. Felicitas Arias received the bachelor's degree in astronomy from the University of La Plata, Buenos Aires, Argentina, and the Ph.D. degree in astrometry, celestial mechanics and geodesy from Observatoire de Paris, Paris, France, in 1990.

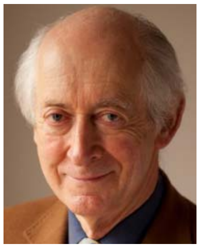
She was the Director of the BIPM Time Department, Sèvres, France, from 1999 to 2017. She was a Professor at the University of La Plata, and the Director of the Buenos Aires Naval Observatory, Buenos Aires, from 1991 to 1999. She continues to cooperate with IERS and the Observatoire de Paris, Paris, France. Since 2018, she has been a long-term-visitor with Paris Observatory, with activities at the Systèmes de reference temps-espace (SYRTE) Department. She has published about 110 scientific papers on time metrology and astrometry, and is frequently solicited for reviewing articles in specialized journals.

Dr. Arias is a Corresponding Member of the French Bureau des longitudes.

Demetrios Matsakis received the bachelor's degree in physics from MIT, Cambridge, MA, USA, and the Ph.D. degree from the University of California, Berkeley, CA, USA. His Ph.D. dissertation, under C. Townes, focused on building masers and using them for molecular radio astronomy and interferometry.

In 1979, he joined the U.S. Naval Observatory (USNO), where he measured variations in the earth's rotation and orientation using connected element interferometry and very long baseline interferometry. Beginning in the early 1990s he started working on atomic clocks, and in 1997 was appointed Head of the USNO's Time Service Department, where he is currently Chief Scientist. He has worked on most aspects of timekeeping, published over 150 articles, and secured one patent.

Dr. Matsakis has served on many international commissions and is past President of the International Astronomical Union's Commission on Time.



Terry J. Quinn was educated at the Universities of Southampton and Oxford, England.

He worked in thermometry and radiometry at the National Physical Laboratory, Teddington, from 1962 to 1977. In 1997, he joined the International Bureau of Weights and Measures (BIPM), Sèvres, France, and was Director from 1988 to 2003. He is currently Emeritus Director of BIPM. While at the BIPM, he carried out experiments on balances and gravitation as well as being very involved in international metrology.

Dr. Quinn was elected a fellow of the Royal Society of London in 2002.

Patrizia Tavella (M'07–SM'09) received the degree in physics and the Ph.D. degree in metrology.

She was with the Italian Metrology Institute for 30 years. She is currently Director of the Time Department, Bureau International des Poids et Mesures, Sèvres, France. She has been deeply involved in the development of the European Navigation System Galileo, being responsible of more than 15 European projects. Her main interests include mathematical and statistical models mostly applied to atomic time scale algorithms.