2 Basics of Time and Frequency Standard

2-1 Definitions of Time and Frequency Standard

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The definition of most basic concepts in the time and frequency standards field, time and timescale, depends on the science and technology level of the times and is never immutable. In this paper, the historical change in the definitions of time and timescales such as International Atomic Time and Coordinated Universal Time are reviewed.

Keywords
Time and frequency standard, Standard time, International atomic Time, Coordinated universal time, International system of units

1 History of time and frequency standards

Time—together with its inverse quantity, frequency—stands as one of the most basic physical quantities of daily life, included among quantities such as length and mass. Since ancient times, humans have attempted to measure time more and more precisely, relying on a variety of physical phenomena observed in nature. It is well known that the calendar was developed in ancient Egypt through celestial observations, a result of the need for precise time in agriculture, the basic industry of the time. As overseas trade developed in Europe in the 17th and 18th centuries, the establishment of a technology to determine longitude precisely, needed for safe and efficient navigation, became one of the greatest challenges for sea-fairing nations. Major European countries set up astronomical observatories, including the Greenwich Observatory and the Paris Observatory, and encouraged the development of accurate clocks, in part by offering generous rewards for success. The marine chronometer was one of the products of such policies[1]. In today's advanced scientific world, the atomic clock plays a crucial role in many high-technologies, such as satellite positioning technology (exemplified by the GPS), synchronization in high-data-rate digital communication networks, and precision measurement applications.

2 Establishment of standard time systems

Humans have developed precise time-measurement technologies by applying the best scientific knowledge available in each era. Meanwhile, the definition of time itself has grown in importance since the 19th century, with improvements in measurement accuracy and the evolution of economic activities. In Europe in the 18th century, particularly in Britain, mechanical clocks became popular among the middle class. At that time, there was no such thing as standard time; as a reference, noon was determined as the moment the sun crosses the meridian in a given local area. This method posed no real problems, as human activities were generally limited to individual local areas. However, in the 19th century, as railways developed and people and goods moved more quickly over long distances, time differences among local areas became a problem. In response, the London and Northwestern Railway determined a standard time in 1848, based on the time in Greenwich, England. As this standard railway time gained acceptance, Greenwich Time became adopted by law in 1880 as British standard time[2]. At the same time, discussions were taking place regarding an international standard time, and in October 1884, the International Meridian Conference was held in Washington D.C. in the United States to discuss world standard time. The following points were agreed upon[3][4].

① A single prime meridian for all nations would be adopted in place of multiplicity of initial meridians.

② The adoption of the meridian passing through the center of the transit instrument at the Observatory of Greenwich would be proposed to member countries as the initial meridian for longitude.

③ From this meridian longitude shall be counted in two directions up to 180 degrees, east longitude being plus and west longitude minus.

④ A universal day would be adopted. This would not interfere with the use of local times.

⑤ The universal day would be a mean solar day, begin for all the world at the moment of mean midnight of the initial meridian, and be counted from zero up to twenty-four hours.

⑥ The astronomical and nautical days should start at midnight.

⑦ Angular space and time should be expressed by the decimal system.

Based on these resolutions, Japan issued Imperial Edict No.51, entitled "Initial Meridian Longitude Calculation Method and Standard Time" on July 13, 1886[4], the first establishment of a standard time in Japan. At this time, the second was defined as 1/86,400 of a mean solar day.

3 The Convention of the Metre and definition of the second

In the late 19th century, an important event took place with respect to the measurement of length, a physical quantity as basic as time: the Convention of the Metre (Convention du Métre) of 1875. The Comité International des Poids et Mesures (International Committee of Weights and Measures, or CIPM) was formed below the governing organization Conférence Générale des Poids et Mesures (the General Conference on Weights and Measures, or CGPM, which met every four years). The Bureau International des Poids et Mesures (International Bureau of Weights and Measures, or BIPM) was then established to conduct various metrological activities under the control of the CIPM. After 1875, a number of metrological units, including time, were defined internationally within the framework of the Convention of the Metre. In Resolution 12 of the 11th CGPM, 1960, the International System of Units (SI unit) was established, and remains in use to this day[5]. SI units can be classified into basic units and derivative units, combinations of basic units. This method of dividing units into two classes is not uniquely determined by physics but is in fact somewhat subjective. Nevertheless, from viewpoints of international exchange, education, and research, there were many advantages to the establishment of a single, practical, international unit system. Considering these advantages, the CGPM has adopted seven clearly defined units (the meter, the kilogram, the second, the ampere, the Kelvin degree, the candela, and the mol, the last of which was added to the original basic units in 1971) and 27 derivative units (including frequency). However, although the official definitions of SI units are authorized by the CGPM, these definitions are not immutable. They reflect the progress of science and technology in each era and are subject to corresponding revision. In this context, in 1927 the CIPM established a committee to discuss a number of issues, including revisions to the definition of the various units. In particular, the group thus formed—the Consultative Committee for Time and Frequency (CCTF)—convened to discuss the definition of the second. As mentioned earlier, the second was initially defined as 1/86,400 of a mean solar day. However, astronomical measurements had indicated that the irregularity of the Earth's rotation affected the accuracy of time measured in this manner. Thus the 11th CGPM, 1960 adopted the following definition of the second[5], based on the solar year as defined by the International Astronomical Union.

"The second is the fraction 1/31,556,925. 9747 of the tropical year for 1900 January 0 at 12 hours ephemeris time."

This definition, however, posed a problem in that long-term astronomical observations would be required to provide accurate measurements of the second. Meanwhile, the Cs atomic frequency standard, developed in the rapidly evolving field of microwave spectroscopy, was found to be able to determine the length of a second with a much higher degree of accuracy. From 1955 to 1958, the British NPL and the American USNO jointly measured the frequency of a Cs frequency standard based on ephemeris time[6]. Using the results of this measurement, the definition of the second was revised as follows by the 13th CGPM in 1967-1968[5].

"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 cesium 133 atom"

The above definition assumes that all the Cs atoms are in the ideal state, free of any physical disturbance. This definition was epoch-making in the sense that for the first time in the history humans adopted the atomic time in stead of astronomical time, the latter having served as the reference for time since pre-Egyptian eras. In practice, however, many national time and frequency standard authorities had adopted atomic time scale prior to the 13th CGPM. To bestow official authorization on the use of atomic time, it was requested in Resolution 1 adopted at the 14th CGPM 1971 that the CIPM define International Atomic Time (TAI) and that it take the necessary steps to effect the worldwide adoption of TAI, in cooperation with associated international organizations. Based on this request, the CIPM defined TAI as follows.

"International atomic time (TAI) is the time reference coordinate established by the Bureau International de l'Heure on the basis of the readings of atomic clocks operating in various establishments in accordance with the definition of the second, the time unit of time of the International System of Units."

The definition of TAI was revised as follows in 1980 based on the theory of relativity [5].

"TAI is a coordinate time scale defined in a geocentric reference frame with the SI second as realized on the rotating geoid as the scale unit."

We cannot ignore the effects of relativity when considering precise time in the context of modern science and technology. The effects of relativity on space-time have been discussed in detail elsewhere[7]. Note that TAI is designated as starting at 0 sec 0 min 0 hr on January 1, 1958 of UT1. Until 1969, TAI was provided by averaging the times of the atomic clocks in what was then the Bureau International de l'Heure. Since 1969, TAI has been provided by averaging the atomic clocks of research institutes in many countries, in order to improve the reliability and short-term stability of TAI[8]. Most of the clocks used to determine TAI are commercial Cs atomic clocks with accuracies of approximately 10^{-12}. Thus to increase the accuracy of TAI, frequency calibration using a primary frequency standard becomes very important. As a case in point, in 1976, all the primary Cs frequency standards of the U.S. NBS (now NIST), the Canadian NRC, and the German PTB indicated that the determined TAI frequency was higher than the defined value by a margin of approximately 10^{-12}. A frequency correction of -1×10^{-12} was therefore made to TAI on January 1, 1977.

Currently time is no longer based on astronomical time but rather is described in terms of atomic time. However, since we continue to live on Earth, universal time based on the Earth's rotation is still widely used. This universal time, however, is irregular and tends to result in delay in the long term, as it is based on the Earth's rotation. As a result, UT will gradually fall behind TAI if left uncorrected. Coordinated Universal Time (UTC) is a time scale generated by applying TAI the so called "leap second adjustment," which adds or removes one second to TAI as necessary in order to reduce the discrepancy between TAI and UT within 0.9 sec. Individual national time and frequency standard authorities provide UTC or the standard time offset from UTC by an integral number of hours through standard frequency and time signals emissions. UTC is therefore defined as follows, not by the CGPM but rather in accordance with Recommendation ITU-R TF460 of the International Telecommunication Union (ITU) in charge of general telecommunications, including standard radio.

"UTC is the time scale maintained by the BIPM, with assistance from the IERS, which forms the basis of a coordinated dissemination of standard frequencies and time-signals. It corresponds exactly in rate with TAI but differs from it by an integral number of seconds. The UTC scale is adjusted by the insertion or deletion of seconds (positive or negative leap seconds) to ensure approximate agreement with UT1."

As UTC prevailed in terms of international use, the 15th CGPM, 1975, Resolution 5 recommended the use of UTC as follows[5].

"The 15th Conférence Générale des Poids et Mesures, considering that the system called "Coordinated Universal Time" (UTC) is widely used, that it is broadcast in most radio transmissions of time signals, that this wide diffusion makes available to the users not only frequency standards but also International Atomic Time and an approximation to Universal Time (or, if one prefers, mean solar time), note that this Coordinated Universal Time provides the basis of civil time, the use of which is legal in most countries, judges that this usage can be strongly endorsed."

Today the UTC has gained wide acceptance as a reference for time in a range of societal applications; Germany, for example, adopts middle European time as "legal" time, determined as one hour ahead of UTC, and has appointed the PTB as the organization in charge of realization of this time scale. Reference[9] describes the details of the ways in which UTC and TAI are internationally determined and the history of leap seconds.

In addition to TAI and UTC, the GPS time has emerged as an important element in the time and frequency standard field. GPS time commenced at a UTC time of 0 hr, January 5, 1980 (USNO). This time is regulated to synchronize UTC (USNO) within a margin of error of 1 μsec, although the leap seconds used in UTC are not employed[10].

4 New trends in unit definitions

The definition of a physical quantity gains the practical meaning for the first time when it is physically realized. Such definitions thus depend significantly on the level of available science and technology, and must be revised as necessary. As is well known, the definition of length, previously based on the wavelength of radiant light from Kr atoms, was modified in the 17th CGPM, 1983, at which point a meter came to be defined as "the length of the path traveled by light in vacuum during a time interval of 1/299,792,458 of a second." This modification was a result of improved accuracy in the measurement of standard time; the new definition thus offered greater accuracy than available under the Kr standard.

Currently, the accuracy attained by the Cs atomic clock is 10^{-14} to 10^{-15}, the highest level of accuracy in the measurement of any physical quantity. However, the current definition of time is already about 40 years old, and with the remarkable recent progress in laser technology, it appears possible that the degree of uncertainty in the standard frequency for light will be reduced to the order of 10^{-18} or so[11]. Accordingly, the present time and frequency definition, relying on the Cs atom, may in the future be redefined in terms of the frequency of light. Any research on time and frequency standards must be pursued in view of this and other trends.

References

1 Dava Sobel, "Longitude: The True Story of a Lone Genius Who Solved the Greatest Scientific Problem of His Time", Penguin USA (Paper); Reprint edition, 1996.

2 S. Tsunoyama, "Tokei no Syakaishi", Chuokoron-Sha, 1984. (in Japanese)

3 http://millennium-dome.com/info/conference-finalact.htm

4 S. Aoki, "Toki to Koyomi", University of Tokyo Press, 1982. (in Japanese)

5 Bureau International des Poids et Mesures, "The International System of Units (SI)", 6^{th} edition, 1991.

6 W. Markowitz, et al., "Frequency of cesium in terms of ephemeris time", Phys. Rev. Lett., 1, 3, p.105, Aug. 1958.

7 M. Hosokawa, "Four Dimensional Space-Time and Reference Frame", Review of the Communications Research Laboratory, Time scales and Frequency Standards Special issue, pp.3-18, Vol.45, No.1/2, March/June 1999. (in Japanese)

8 B. Guinot, P.K.Seidelmann, "Time scales: their history, definition and interpretation", Astron. Astrophys., 194, pp.304-308, 1988.

9 M. Imae, "Atomic Time Scale and Frequency Standards", Review of the Communications Research Laboratory, Time scales and Frequency Standards Special issue, pp.19-26, Vol.45, No.1/2, March/June 1999. (in Japanese)

10 W. Lewandowski, C. Thomas, "GPS Time Transfer", Proc. IEEE Vol.79, No.7, Jul. 1991.

11 Th. Udem, R. Holzwarth & T. W. Hänsch, "Optical frequency metrology", Nature, Vol.416, 14, Mar. 2002.

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