EVOLUTION OF TIME SCALES

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ABSTRACT. Time scales evolve to meet user needs consistent with our understanding of the underlying physics. The measurement of time strives to take advantage of the most accurate measurement techniques available. As a result of improvements in both science and in measurement technology, the past fifty years has witnessed a growing number of time scales as well as the virtual extinction of some. The most significant development in timing has been the switch to frequencies of atomic transitions and away from the Earth's rotation angle as the fundamental physical phenomenon providing precise time.

1. INTRODUCTION

Time scales have continued to evolve to meet the developing needs of users in modern times. Fifty years ago time based on astronomical observations of the Earth's rotation was sufficient to meet the needs for time, both civil and technical. During that fifty-year interval, however, not only have these scales been expanded, but the advent of practical atomic clocks has led to the development of time scales based on atomic frequency transitions. In addition, the development of modern space techniques and the improvement in observational accuracy by orders of magnitude have led to the improvement of the theoretical concepts of time and the resulting relativistic definitions of time scales. The following sections provide a brief description of the chronological development of time scales since the middle of the twentieth century. A comprehensive description of time scales is presented by Nelson *et al.*, (2001).

2. MEAN SOLAR TIME

Mean solar time as derived from astronomical observations was the basis for time in the mid 1900s. It is based on the concept of a fictitious mean Sun as defined by Simon Newcomb. The mathematical expression for the right ascension of the fictitious mean Sun provides the direction to a conventional point on the equator that completes one revolution in the celestial reference frame in the same time interval as the actual Sun completes its annual path on the ecliptic. The mean solar day is the time interval between successive transits of this fiducial point, and the mean solar second, is 1/86 400 of a mean solar day (Kovalevsky, 1965; McCarthy, 1991). Apparent solar time, the time determined by using a sundial or by measuring the altitude of the Sun is defined by the motion of the observed Sun. The difference between apparent and mean solar time is called the equation of time. The maximum amount by which apparent noon precedes mean noon is about 16.5 min around 3 November, while the maximum amount by which mean noon precedes apparent noon is about 14.5 min around 12 February (Nelson *et al.*, 2001).

3. UNIVERSAL TIME (UT)

Universal Time as designated by "UT1" is considered to be equivalent to mean solar time referred to the meridian of Greenwich and reckoned from midnight. As defined today, UT1 is a measure of the Earth's rotation angle that is used as a time scale. In practice, it is determined not by solar observations but by astronomical observations of objects in the celestial reference system with instruments fixed in a terrestrial reference system. In the middle of the twentieth century the observing instruments were optical meridian telescopes and the objects observed were stars in a galactic reference system. Very long baseline interferometry is used today to observe extragalactic radio sources to determine the Earth's rotation angle.

Observations used to determine UT1 can be made in two ways. Determinations of UT1-UTC can be determined from observed corrections to an assumed sidereal time based on a conventional expression for sidereal time. In 2000 the IAU adopted an expression for the Earth rotation angle $\theta = f(UT1)$. Observations of this angle can be used to provide corrections to an *a priori* estimate of UT1. UT0, a designation no longer in common use, is UT1 corrupted by the motion of the Earth's axis of rotation with respect to the Earth's surface, called polar motion. When observations were made using meridian instruments, UT0 was the observed quantity. However meridian instruments are no longer used for practical determination of Universal Time, and corrections to *a priori* estimates of UT1 can be observed directly. The time scale UT2 is another scale no longer in common use that attempted to provide a more uniform time scale by correcting UT1 for the known seasonal variation in the Earth's rotational speed.

Astronomical observations show that time scales based on the Earth's rotation are not uniform because of variations in the Earth's rotational speed. A wide spectrum of quasi-random and periodic fluctuations has been well documented (Lambeck, 1980). These include the secular variation due chiefly to tidal friction slowing the Earth's rotational speed and lengthening of the day by about 0.0005 to 0.0035 s per century, irregular changes apparently correlated with physical processes occurring within the Earth, and higher-frequency variations known to be largely related to the changes in the total angular momentum of the atmosphere and oceans. Periodic variations associated with tides are also present.

4. EPHEMERIS TIME (ET)

Ephemeris Time, originally suggested by G. M. Clemence (1948) is a time scale based on the period of the revolution of the Earth around the Sun, as represented by Newcomb's *Tables of the Sun*. The definition is based on Newcomb's formula for the geometric mean longitude of the Sun (Newcomb, 1895):

$$L = 279°41'48.04'' + 129602768.13''T + 1.089''T^2, \tag{1}$$

where T is the time reckoned in Julian centuries of 36 525 days since January 0, 1900, 12h UT. The IAU adopted this definition in 1952 at its 8th General Assembly in Rome (*Trans. Int. Astron. Union*, 1954).

Newcomb's formula indicates that the tropical year of 1900 contains 31 556 925.9747 s. The International Committee for Weights and Measures (CIPM) in 1956, therefore, defined the second of ET to be "the fraction 1/31 556 925.9747 of the tropical year for 1900 January 0 at 12 hours ephemeris time." This definition was ratified by the General Conference on Weights and Measures (CGPM) in 1960 (*BIPM Proc.-Verb. Com. Int. Poids et Mesures*, 1956; *The*

International System of Units (SI), 1998). In 1958, the International Astronomical Union (IAU) General Assembly defined the epoch of ET by (*Trans. Int. Astron. Union*, 1960): "Ephemeris Time (ET), or Temps des Ephémérides (TE), is reckoned from the instant, near the beginning of the calendar year A.D. 1900, when the geometric mean longitude of the Sun was $279°41'48.04''$, at which instant the measure of Ephemeris Time was 1900 January 0d 12h precisely."

Although defined using Newcomb's expression, ET was realized using observations of the direction of the Moon in the celestial reference frame. These observations were used together with conventional lunar ephemerides to derive estimates of ET. This led to a set of realizations of ET based on the actual ephemeris used that were denoted ET0, ET1 and ET2 (Guinot, 1989). Although astronomical ephemerides adopted ET as the independent variable, it was inconvenient to obtain accurate, real-time estimates of ET, and it did not include relativistic effects.

5. ATOMIC TIME

Following the appearance of the first operational Caesium beam frequency standard in 1955 at the National Physical Laboratory (NPL) in the U. K. (Essen and Parry, 1957), the Royal Greenwich Observatory (RGO), U.S. Naval Observatory (USNO), and U. S. National Bureau of Standards (NBS) began to produce atomic time scales. The details of the development of these scales into the current standard TAI (International Atomic Time) is contained in Nelson *et al.*, (2001).

L. Essen and J. V. L. Parry of the NPL, in cooperation with Wm Markowitz and R. G. Hall at the USNO, determined the frequency of the NPL Caesium standard with respect to the second of ET. Photographs of the Moon and surrounding stars were taken using the USNO dual-rate Moon camera from 1955.50 to 1958.25 to determine ET from the direction of the Moon at a known UT2 determined from optical observations made at the USNO. This information was used to calibrate the Caesium beam atomic clock at NPL. The measured Caesium frequency was 9 192 631 770 Hz with a probable error of ± 20 Hz (Markowitz *et al.*, 1958). In October 1967 the atomic second was adopted as the fundamental unit of time in the International System of Units. It was defined as (*Metrologia*, 1968) "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," thus making the second of atomic time equivalent to the second of ET in principle.

The Comité Consultatif pour la Définition de la Seconde (CCDS) of the CIPM recommended guidelines for the establishment of International Atomic Time (TAI) in 1970. It stated that "International Atomic Time (TAI) is the time reference coordinate established by the Bureau International de l'Heure [BIH] on the basis of readings of atomic clocks operating in various establishments in accordance with the definition of the second, the unit of time of the International System of Units" (*Metrologia*, 1971). The CCDS (*BIPM Com. Cons. Déf. Seconde*, 1970) defined the origin so that TAI would be in approximate agreement with UT2 on 1 January 1958, 0h UT2. This definition was refined in 1980 to account for relativistic concerns with the statement, "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" (*Metrologia*, 1981). TAI, when formally adopted in 1971, was an extension of the BIH atomic time scale that had been continuous back to 1955. In 1988, the Bureau International des Poids et Mesures (BIPM) assumed responsibility for maintaining TAI. Today approximately two hundred clocks maintained in fifty laboratories contribute to the formation of TAI.

6. COORDINATED UNIVERSAL TIME (UTC)

The term "Coordinated Universal Time" was introduced in the 1950s to designate a time scale in which the adjustments to quartz crystal clocks were coordinated among participating laboratories in the U. S. and U. K. The scale evolved over the years to the state where the BIH coordinated adjustments to an internationally accepted standard Coordinated Universal Time, designated UTC, that involved adjustments in both rate and epoch to stay in step with astronomical time.

The concept of the leap second was proposed independently by G. M. R. Winkler (1968) and L. Essen (1968) at a meeting of the CIPM in 1968 (Commission Préparatoire pour la Coordination Internationale des Échelles de Temps, 1968). Steps of integer seconds were proposed to replace the steps of 100 ms or 200 ms then being used. To meet the needs of navigators, it was suggested that coded information might be incorporated in the emission of radio time signals to provide the difference between UTC and UT2.

The current UTC system is defined by ITU-R (International Telecommunications Union Ũ Radiocommunications Section, formerly International Radio Consultative Committee (CCIR)) Recommendation ITU-R TF.460-5 (*ITU-R Recommendations: Time Signals and Frequency Standards Emissions*, 1998): "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." The interval between time signals of UTC is thus exactly equal to the SI second. A history of rate offsets and step adjustments in UTC is given at `http://www.iers.org`. In practice leap seconds are inserted to keep $|\text{UT1-UTC}| \leq 0.9\text{s}$. Recently the requirement for leap seconds has been questioned. Working groups of various international scientific organizations are now investigating the need to continue the practice.

7. DYNAMICAL TIME SCALES

The concept of time scales based on the dynamics of the solar system was refined in 1976 when the International Astronomical Union (IAU) defined time-like arguments consistent with the general theory of relativity (*Trans. Int. Astron. Union*, Vol. XVI B, 1977). This led to the development of Terrestrial Dynamical Time (TDT) and Barycentric Dynamical Time (TDB) (*Trans. Int. Astron. Union*, Vol. XVII B, 1980) that distinguish coordinate systems with origins at the center of the Earth and the center of the solar system, respectively. In 1984 TDT replaced ET as the tabular argument of the fundamental geocentric ephemerides. It has an origin of 1 January 1977 0h TAI, with a unit interval equal to the SI second, and maintains continuity with ET. In 1991 the IAU renamed TDT simply Terrestrial Time (TT). A practical realization of TT in terms of the atomic time scale, TAI, is (*Explanatory Supplement to the Astronomical Almanac*, rev. ed., 1992) $TT = TAI + 32.184s$.

The constant offset represents the difference between ET and UT1 at the defining epoch of TAI on 1 January 1958. In practice any difference between TAI and TT is a consequence of the physical defects of atomic time standards. In most cases, and particularly for the publication of ephemerides, this deviation is negligible.

TDB was defined to be used as the time-like argument for ephemerides referred to the barycenter of the solar system. By adopting an appropriately chosen scaling factor, TDB varies from TT or TDT by only periodic variations, with amplitudes less than 0.002 s.

In 1991 the IAU General Assembly introduced the general theory of relativity explicitly as the theoretical basis for the celestial reference frame and the form of the space-time metric was specified (*Trans. Int. Astron. Union*, Vol. XXI B, 1992). At that time it also clarified the definition of Terrestrial Time and defined two new time scales, Geocentric Coordinate Time (TCG) and Barycentric Coordinate Time (TCB) (Seidelmann and Fukushima 1992). The "coordinate" time scales TCG and TCB are complementary to the "dynamical" time scales TT (or TDT) and TDB. They differ in rate from TT and are related by four-dimensional space-time coordinate transformations (*IERS Conventions (1996)*). These definitions were further clarified by resolutions adopted at the IAU General Assembly in 2000 (*Trans. Int. Astron. Union*, 2001). The dynamical time scales are now used only for specialized studies and to develop astronomical ephemerides. TCG is defined by the expression

$$TCG - TT = L_G(Julian\ Date - 2443144.5) \times 86400s, \tag{2}$$

where the defining value of L_G, chosen to provide continuity with TT so that its measurement unit agrees with the SI second on the geoid is $6.969290134 \times 10^{-10}$(*IERS Conventions (2003)*).

An approximation to TCB-TCG in seconds is

$$TCB - TCG = [L_C \times (TT - TT_0) + P(TT) - P(TT_0)]/(1 - L_B) + \frac{1}{c^2}[\mathbf{v_e} \cdot (\mathbf{x} - \mathbf{x_e})] + P, \tag{3}$$

where $\mathbf{x_e}$ and $\mathbf{v_e}$ are the barycentric position and velocity of the Earth's center of mass, $\mathbf{x}$ is the barycentric position of the observer, $L_C = 1.4808268671x10^{-8}(\pm 2 \times 10^{-17})$, TT_0 is JD 2443144.5 TAI (1977 January 1, 0h) and the periodic terms, $P(TT)$, have a maximum amplitude ~ 1.6 ms. The current estimate of L_B is $1.55051976772 \times 10^{-8} (\pm 2 \times 10^{-17})$ *IERS Conventions (2003)*. However, since no precise definition of TDB exists, there is no definitive value of L_B, and such an expression should be used with caution. The periodic terms can be evaluated by the "FB" analytical model (Fairhead and Bretagnon, 1990; Bretagnon, 2001), or $P(TT) - P(TT_0)$ may be provided by a numerical time ephemeris such as TE405 (Irwin and Fukushima, 1999). A series, HF2002, providing the value of $L_C \times (TT - TT_0) + P(TT) - P(TT_0)$ as a function of TT over the years 1600-2200 has been fit (Harada and Fukushima, 2002) to TE405.

8. FUTURE

Time scales will continue to evolve to meet user needs. It is likely that the definition of UTC will continue to be discussed in the next few years and that new navigational time scales will be developed. We may also expect the development of time scales to meet developments in space exploration and to take advantage of improvements in timekeeping precision. We may see the definition of a Galactic Coordinate Time.

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