Evolution of timescales from astronomy to physical metrology

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Evolution of timescales from astronomy to physical metrology

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Abstract
Astronomy has provided a means to mark the passage of time throughout history. One of the repeating phenomena that makes this possible is the Earth's rotation. The basic variability in its rotational speed, however, makes astronomical techniques unsuitable for timekeeping with the precision required for modern applications. Physical metrology from the first mechanical clocks to the most sophisticated atomic standards of today has assumed a growing role in timekeeping. Along with this progress in technology, more sophisticated concepts of timescales have appeared to take advantage of those improvements.

1. Introduction

The diurnal changes in the appearance of the sky made it natural that astronomy would play an important part in timekeeping throughout history. As the need for precision developed, so too did the requirement for more precise timekeeping devices as well as increased formalism in the definitions of timescales. The development of clocks, both mechanical and electronic, however, drove the need for timescales more appropriate for timekeeping with devices rather than with the sky. When it became apparent that the Earth's rotational speed was variable, astronomers and physicists further developed the concepts and means of measuring the passage of time. We have now reached the situation where the duration of a second is defined not by astronomy but by an energy level transition in the caesium atom. The designation of seconds for the timescale in common everyday use still is connected to the Earth's rotation, but many technical applications are looking to timescales that are disconnected from astronomy so as not to be affected by the variations in the Earth's rotational speed. These developments have caused timescales to evolve in order to take advantage of more precise timekeeping devices and to meet society's need for precision.

2. Developments in devices

Progress in timekeeping devices has proceeded from observing the shadow of a rod in the sand to modern standards that use a single atom to provide the means to measure time intervals. Along the way we have made use of sundials, water clocks, candles, mechanical clocks and various kinds of electronic standards. These advances have been documented in a number of references [1–3]. Figure 1 shows a comparison of the stability of time provided by astronomical observations and that of physical timekeeping devices. Also shown there is the stability of the time provided by the Earth, which is limited by its variability in rotational speed.

It is clear that the stability of physical metrological devices has surpassed astronomical observations and, as a result, our definitions of timescales have evolved to take advantage of that situation.

3. Timescales defined

The definition of the word 'timescale' may not be completely obvious. Generally we think of a timescale as a system that is accepted to relate a succession of events. Guinot [4] writes that 'A timescale is a system which makes it possible to assign without ambiguity a temporal coordinate to any event. ... A timescale is thus one of the coordinate axes of a space-time reference frame.' He goes on to write 'It would be useful to distinguish by appropriate designations an ideal timescale ... from its realizations, as is done for space references: reference system for the definition, reference frame for the realizations, but there is no agreed convention for such a distinction' [5].

For the purposes of this review the nomenclature 'timescale' refers to the concept (and the means to achieve that concept) of a set of numerical values that relate changes in a designated four-dimensional reference system. The changes may be in location or any other relevant physical property. As an example, within a space-time reference system under consideration, we can relate the location of objects with respect

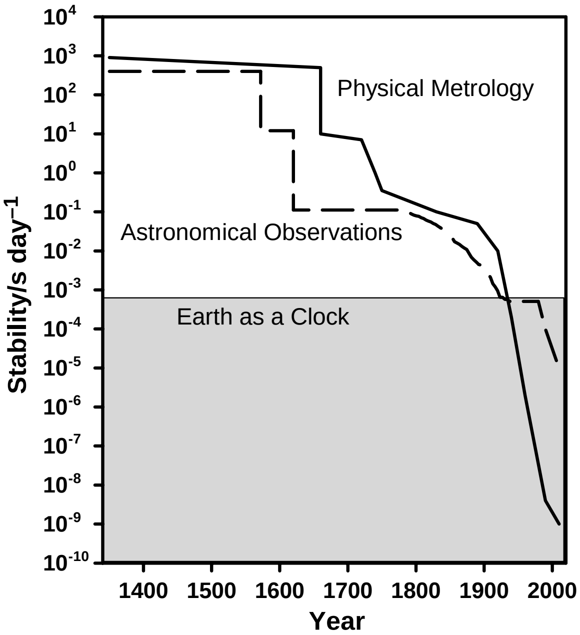

Figure 1. Comparison of the stability of time provided by astronomical observations and physical timekeeping devices.

to one another using a three-dimensional set of coordinates that are consistent with a conventional distance scale. We can relate changes in the relationships using a timescale to characterize the fourth dimension. The events, however, are not limited to changes in location. The events in question could just as well be changes in physical characteristics, for example, that do not involve change in spatial coordinates.

4. Development of timescales

Diurnal changes in the environment are obvious, and so they provided our earliest timescale. The fundamental problem with any time based on the Earth's rotation, however, is that the Earth does not rotate with a constant speed. Nevertheless time based on the Earth's rotation with respect to the Sun has been formalized by astronomers in a number of ways over the years, resulting in a series of timescales based on evolving astronomical observational capabilities. The following eleven subsections address each of the timescales in this evolution separately from time based on the rotation of the Earth with respect to the Sun up to the timescales that will be required for applications in space.

4.1. Apparent solar time

Apparent solar time is measured by the Sun's hour angle, and depends on the location of the observer on the Earth. Accordingly we have local apparent solar time that refers to the time measured at any longitude and we have Greenwich apparent solar time referring to the local apparent solar time measured on the meridian where the longitude is assumed to be zero. The difference between the two is merely the astronomical longitude of the observer expressed in hours, minutes and seconds. Mathematically, then,

$$\text{Local Apparent Solar Time} = \text{Hour Angle of the Sun} + 12\,\text{h}, \quad (1)$$

and

$$\text{Greenwich Apparent Solar Time} = \text{Hour Angle of the Sun} + \text{Observer's Longitude (positive west)} + 12\,\text{h}. \quad (2)$$

A complication with apparent solar time is that the duration of each apparent solar day varies depending on the day of the year because the Earth's orbit is not circular and is inclined with respect to the plane of the Earth's equator. Hence, although each local apparent solar day contains 86 400 s, the duration of those seconds varies during the year.

In addition to the fact that apparent solar time has variable units of measurement, it may also be inconvenient to relate apparent solar times at widely spaced locations. Until the latter part of the eighteenth century, though, apparent solar time was generally used as the basis for civil time, and it was used as the time argument in astronomical almanacs and ephemerides until the early nineteenth century. Mechanical clocks, which had been introduced towards the end of the thirteenth century, were regulated using this brand of solar time. Clocks were allowed to operate independently, and astronomical determinations of apparent solar time were made. The two were then compared and the clock adjusted to match the astronomical data.

A more practical procedure is to measure the times when stars transit the local meridian and then relate the Sun's position with respect to those stars by means of a published solar ephemeris. Knowing the position of a particular star from a published catalogue of star positions, the expected clock time when it will transit the meridian can be derived. Observing the actual clock time of the star's transit and comparing that time with the time it was supposed to be there provides a clock correction. Knowing the Sun's right ascension from an ephemeris in the same reference system then, we know

$$\text{Local Apparent Solar Time} = \text{Right Ascension of the Star} - \text{Right Ascension of the Sun} + 12\,\text{h}. \quad (3)$$

4.2. Mean solar time

To address the problems associated with apparent solar time mean solar time substitutes for the actual Sun an artificial point defined to move uniformly along the plane of the Earth's equator with a rate equivalent to the average rate of the actual Sun in the ecliptic. This fiducial point is sometimes called the 'fictitious mean sun' or just the 'mean sun.' As with apparent solar time, mean solar time depends on the longitude of the observer so that we have Greenwich mean solar time as well as local mean solar time. Mathematically,

$$\text{Local Mean Solar Time} = \text{Hour Angle of the Fictitious Mean Sun} + 12\,\text{h}, \quad (4)$$

and

$$\text{Greenwich Mean Solar Time} = \text{Hour Angle of the Fictitious Mean Sun} + \text{Observer's Longitude (positive west)} + 12\,\text{h}. \quad (5)$$

The concept of mean solar time goes back at least as far in the past as the astronomer Ptolemy (*c* 90–*c* 168 CE). The variable length of the apparent solar day was recognized at that time, and astronomers realized then the value of a more uniform timescale in describing the apparent motion of the Sun in the sky. Mean solar time can be determined by observing the apparent solar time and applying corrections to account for the difference in hour angle between the 'mean' and apparent Sun.

The difference between the mean and apparent time, called the equation of time (figure 2), was tabulated by medieval Islamic scholars, and Christiaan Huygens is credited with being the first European to provide accurate tables of the equation of time in 1660. Huygens' development of an accurate pendulum clock in 1656 made tables such as these necessary in order to take advantage of the more uniform time that was produced by a mechanical clock.

As the use of mechanical clocks developed, mean solar time gradually replaced the use of apparent solar time during the latter part of the eighteenth and early nineteenth centuries. The tabular arguments of the British *Nautical Almanac* were changed to mean solar time in 1834 and the equation of time began to be published in the sense of apparent minus mean instead of mean minus apparent at that time. This was done to facilitate the calculation of apparent time from mean time in contrast with earlier practice.

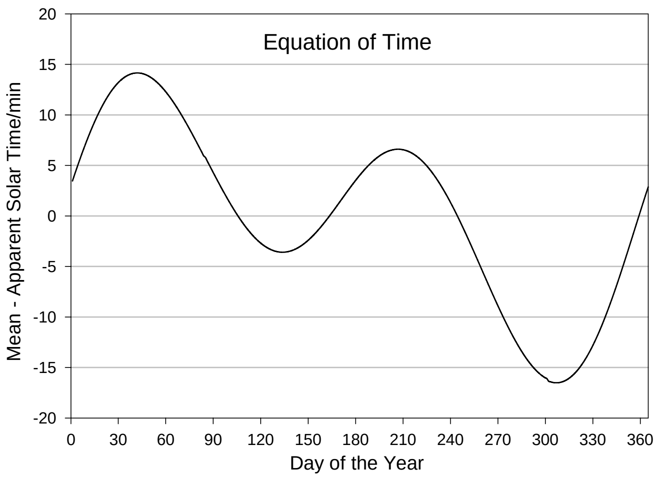

Figure 2. Equation of time.

4.3. Sidereal time

In actual practice mean solar time was determined mainly by its relation to sidereal time. The difference between solar and sidereal time is that, while solar time is defined by the Earth's rotation with respect to the Sun, sidereal time is defined by the Earth's rotation with respect to the adopted directions to stars that realize the celestial reference system. During one sidereal day the Earth moves in its orbit so that it must turn through an additional angle before it completes one rotation with respect to the Sun. The actual determination of mean solar time, then, generally required observation of the directions to stars and relied on a conventionally adopted relationship between sidereal and solar time. That relationship is based on a mathematical expression for the right ascension of that fictitious point as well as the adopted representation of the Earth's precessional motion.

4.4. Greenwich Mean Time

After the first issue of the *Nautical Almanac and Astronomical Ephemeris* appeared in 1766, the Greenwich meridian gradually began to be used as the prime meridian for navigation. However, it was not officially accepted as the international reference meridian until a series of international conferences was held from 1881 to 1884. The International Meridian Conference in Washington in October, 1884, finally recommended [6] 'the meridian passing through the center of the transit instrument at the Observatory of Greenwich as the initial meridian for longitude.' In that conference participants also proposed '... the adoption of a universal day for all purposes for which it may be found convenient, and which shall not interfere with the use of local or other standard time where desirable. ... this universal day is to be a mean solar day; is to begin at the moment of mean midnight of the international meridian, coinciding with the beginning of the civil day and date of that meridian; and is to be counted from zero up to twenty-four hours.'

Astronomers, nevertheless, continued measuring days from noon to noon. The mean solar time measured from mean noon at Greenwich was designated as 'Greenwich Mean Time' (GMT). In 1919 the Bureau International de l'Heure (BIH), the international service for time, began to coordinate the emission of time signals by radio stations based on Greenwich Civil Time (GCT), which is GMT plus 12 h. In 1925 astronomers adopted a day measured from midnight to midnight when the astronomical almanacs introduced a 12 h discontinuity so that the date previously referred to as 31.5 December 1924 was now to be known as 1.0 January 1925. The British *Nautical Almanac* continued to call this time Greenwich Mean Time, but *The American Ephemeris* referred to this new timescale as Greenwich Civil Time. To avoid confusion, the name 'Greenwich Mean Astronomical Time' (GMAT) was used to designate the time measured from noon to noon.

The nomenclature 'GMT' continues to cause confusion to this day because of its use in the United Kingdom as the name attached to the civil time and its common navigational usage to mean UT1, discussed below. With all of these identities it is not advisable to use the term GMT as a timescale for precise purposes without carefully defining its meaning.

4.5. Universal Time

In 1928, The IAU recommended [7] using the name 'Universal Time' to replace GMT or GCT in astronomical almanacs. Although there had been previous references to a 'universal time' in the sense of a conceptual conventional time to be used to avoid confusion among times in various time zones, this was the first 'official' designation of the term 'Universal Time.' In 1935 IAU Commissions 3 (Notations) and 4 (Ephemerides) recommended [8], 'Que l'on adopte pour l'usage international Universal Time (UT), Temps Universel (TU) ou Weltzeit (WZ) pour le Temps Moyen de Greenwich

(GMT) compté a partir de minuit. Que à l'avenir Greenwich Civil Time (GCT) ne soit plus employé.' In 1948 the IAU General Assembly attempted to clarify the usage of Universal Time by accepting the recommendation of IAU Commission 4: 'La Commission recommande que la désignation 'Temps Universel' (Universal Time; Weltzeit) soit seule utilisée par les astronomes pour designer le temps solaire moyen, compte a partir de minuit du méridien de Greenwich. Elle exprime le voue que cette désignation remplace aussitôt que possible les autre expressions encore employées.'

The International Research Council had already established the BIH at the Paris Observatory in 1919 [9] to coordinate transmissions of radio time signals by routinely publishing the difference between various broadcast radio signals and the astronomically determined time. The actual determination of this time continued to rely on astronomical observations of star transits that were used to set mechanical, and later, electronic clocks. Beginning in 1956 the IAU recognized three versions of Universal Time. The Greenwich mean solar time as observed at any location on the Earth was designated 'UT0.' 'UT1' was UT0 corrected for the motion of the rotational pole with respect to the Earth's surface. The third form, 'UT2', was obtained by applying a conventionally adopted expression to UT1 to account for the observed seasonal variation in the Earth's rotational speed in the form of

$$a \sin 2\pi F + b \cos 2\pi F + c \sin 4\pi F + d \cos 4\pi F, \quad (6)$$

where F is the fraction of the year. This time was generally regarded in the early 1950s as being the best representation of a uniform timescale, and radio time signals of that time were based on UT2. Originally the concept was to adopt values annually for the coefficients in (6) that were consistent with recent observations. Eventually, however, a conventional formula was used in which the coefficients never changed. It was accepted that the difference between UT2 and UT1 would be the conventional expression given by [10]

$$\begin{aligned}\mathrm{UT2} = \mathrm{UT1} &+ 0.022\,\mathrm{s} \sin 2\pi t_{\mathrm{B}} - 0.012\,\mathrm{s} \cos 2\pi t_{\mathrm{B}} \\ &- 0.006\,\mathrm{s} \sin 4\pi t_{\mathrm{B}} + 0.007\,\mathrm{s} \cos 4\pi t_{\mathrm{B}},\end{aligned} \quad (7)$$

where t_{B} is the fraction of the Besselian year and given by

$$t_{\mathrm{B}} = \mathrm{mod}\left[2000 + \frac{(\text{Julian Date} - 2\,451\,544.533)}{365.2422}, 1\right]. \quad (8)$$

UT1 is a measure of the Earth's rotation angle expressed in time units and treated conventionally as an astronomical timescale defined by the rotation of the Earth with respect to the Sun. In practice, Universal Time was defined until 1 January 2003 by means of conventional formulae defining Sidereal Time [11]. Resolution B1.8 adopted by the 24th General Assembly of the International Astronomical Union in 2000 [7] recommended the use of the 'non-rotating origin' both in the Geocentric Celestial Reference System (GCRS) and the International Terrestrial Reference System (ITRS). These origins are now designated as the Celestial Intermediate Origin (CIO) and the Terrestrial Intermediate Origin (TIO) in the respective reference systems. The 'Earth Rotation Angle' (ERA) is defined as the angle measured along the equator of the Celestial Intermediate Pole between the CIO and the TIO. This resolution also recommended that UT1 be linearly proportional to the ERA, and that the transformation between the ITRS and GCRS be specified using the ERA.

$$\begin{aligned}\mathrm{ERA} = 2\pi(&0.779\,057\,273\,264\,0 \\ &+ 1.002\,737\,811\,911\,354\,48 t_u),\end{aligned} \quad (9)$$

where

$$t_u = \text{Julian UT1 date} - 2\,451\,545.0.$$

The Julian UT1 date is calculated using the value of UT1−UTC published routinely by the International Earth Rotation and Reference Systems Service (IERS). For example

$$\begin{aligned}\text{Julian UT1 date} = {} & \text{Julian UTC Day Number} \\ & + \text{UTC time interval since 0 h UTC} \\ & + (\text{UT1} - \text{UTC}) \text{ from IERS}.\end{aligned} \quad (10)$$

These expressions effectively define UT1 today through the use of observations of extragalactic quasars with respect to a conventionally defined terrestrial reference frame to determine the ERA, and from this, deduce the corresponding value of UT1. This definition of UT1 is insensitive at the microarcsecond level to the precession–nutation model. UT1 is considered to be nominally equivalent to mean solar time reckoned from midnight on the meridian of Greenwich. There is no foreseeable reason to change the numerical values in the expression unless systematic rotations were somehow introduced directly into the reference frames as realized by the quasar directions.

4.6. Ephemeris Time

A timescale based on the dynamics of the motions of solar system bodies was originally conceived as an answer to the need for a more uniform, astronomically based timescale unrelated to the Earth's rotation. Ephemeris Time, which came into use in the 1950s, was based on ephemerides that assumed Newtonian mechanics. Since that time, a series of dynamical timescales have been developed to account for evolving developments in modelling the effects of general relativity. In current practice, dynamical timescales are used to provide the independent variable of the equations of motion of the bodies in the solar system.

Ephemeris Time (ET) refers to the timescale suggested by Clemence [12]. He proposed a timescale based on the period of the revolution of the Earth around the Sun, as represented by Newcomb's *Tables of the Sun* published in 1895 [13]. It is defined practically through the use of Newcomb's formula for the geometric mean longitude of the Sun,

$$L = 279^\circ 41' 48.04'' + 129\,602\,768.13'' T + 1.089'' T^2, \quad (11)$$

where T is the time reckoned in Julian centuries of 36 525 days since January 0, 1900, 12 h UT. The IAU adopted this proposal in 1952 at its 8th General Assembly in Rome [14].

Newcomb's formula implies that, if we use the motion of the Sun at $T = 0$, that is $\mathrm{d}L/\mathrm{d}T = 1\,296\,027.6813''$ per year, we would expect the year to contain $365.25\,\text{days} \times 86\,400\,\text{s/day} \times (360 \times 60 \times 60''/\text{rev.})/(\mathrm{d}L/\mathrm{d}T) = 31\,556\,925.9747\,\text{s}$. The 10th General

Conference on Weights and Measures (CGPM) in 1954, therefore, proposed the definition of the second, 'The second is the fraction 1/31 556 925.975 of the length of the tropical year for 1900.0.' Consequently the International Committee for Weights and Measures (CIPM) in 1956 defined the second of ephemeris time 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 11th CGPM in 1960. In 1958, the IAU General Assembly defined the epoch of ET by [15]: '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 $279^\circ\ 41'48.04''$, at which instant the measure of Ephemeris Time was 1900 January 0d 12 h precisely.'

Although ET was defined following Newcomb's expression, it was realized in practice using observations of the position of the Moon with respect to the celestial reference frame. These observed lunar positions together with conventional lunar ephemerides provided 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 [5]. ET was determined in practice using the expression

$$\mathrm{ET} = \mathrm{UT1} + \Delta T, \qquad (12)$$

where ΔT was determined from astronomical observations and made available in *The Astronomical Almanac*. Although astronomical ephemerides adopted ET as the independent variable, it was inconvenient to obtain in real-time, and it did not include relativistic effects.

4.7. Atomic time

At about the same time that astronomers were developing the concept of Ephemeris Time physicists were pursuing molecular and atomic clocks to provide a more uniform timescale. Rather than rely on astronomical phenomena to provide the repeatable events that mark the passage of time, physicists began to investigate the use of energy level transitions in the alkali elements to produce a stable frequency that could be used to drive clocks. To realize the benefits of this effort, a new timescale was required.

4.7.1. Atomic clocks. In 1955, Essen and Parry of the National Physical Laboratory in the United Kingdom calibrated the resonance frequency of the laboratory's caesium standard with respect to the UT2 second of that epoch [16]. Together with Markowitz and Hall at the US Naval Observatory (USNO), they later calibrated the frequency in terms of the ET second using observations made with the USNO dual-rate Moon camera over the period 1955.50 to 1958.25. The measured caesium frequency was 9 192 631 770 Hz with an uncertainty of ±20 Hz mostly due to the measurement of ET [17].

Despite initial reluctance to accept time determined by means other than from astronomical observations of the Earth's rotation, atomic time began to be accepted gradually. Essen describes the gradual acceptance in the following remarks [18]:

> 'A sub-committee of the International Committee of (*sic.*) Weights and Measures was set up to discuss atomic time and it is interesting to follow its gradual and reluctant acceptance by astronomers. The meeting in 1957 refused to accept the term atomic clock insisting that it was simply a frequency standard for the second: the second meeting in 1961 accepted that it was a standard of time interval but continued to stall by recommending that further work should be done: the third meeting in 1963 recommended the adoption of an atomic unit of time the value being that obtained at the NPL. No formal steps were taken to implement this recommendation and the International Scientific Radio Union, in which I was the chairman of the relevant section, had to stress the urgency of putting the resolution into effect. It was formally adopted as the unit of time in 1968 with only one abstention, the representative of the Greenwich Observatory, I regret to say.'

4.7.2. Early atomic timescales. The earliest atomic timescales were designed to employ a single atomic frequency standard to steer quartz crystal clocks. In 1955, the Royal Greenwich Observatory (RGO) established its timescale, called 'Greenwich Atomic' (GA). It used the NPL caesium frequency standard to calibrate periodically the frequencies of quartz crystal clocks. On 13 September 1956 the US Naval Observatory began its atomic timescale, called 'A.1,' again using a quartz crystal clock calibrated daily with a caesium beam standard located at the US Naval Research Laboratory (NRL) in Washington (Time Service Notice No 6). In both cases the atomic frequency standards were switched on only for short durations to calibrate the frequency of the quartz devices.

The Bureau International de l'Heure (BIH) began an atomic timescale in July, 1955, that has been continuous since that time. Until 1969 they used comparisons of local caesium standards and comparisons of phases of very low frequency radio signals reported by cooperating institutions with atomic clocks to produce a timescale, called T_m or AM. As was the case with A.1 this timescale was set equal to UT2 at 0 h, 1 January 1958. Beginning in 1960, the BIH routinely published the difference between AM and astronomically observed UT2 in periodic bulletins.

Other laboratories and institutions followed quickly in constructing atomic timescales, including the US National Bureau of Standards (NBS) in Boulder, Colorado, which began an atomic timescale, NBS-A, on 9 October 1957. Like A.1, its origin was set equal to UT2 on 1 January 1958 [19].

In 1963 the BIH changed its procedure to use only the three standards located at the US National Bureau of Standards, the Swiss Laboratoire Suisse de Recherches Horlogères, and the National Physical Laboratory in the UK rather than all of the clocks that were contributing data at that time to produce its atomic timescale. The timescale was renamed A3 in recognition of the exclusive use of the data from the three institutions. It was expanded in 1966 to use the contributions from other laboratories, but the name A3 was retained [20, 21].

In 1967 the 13th CGPM adopted the atomic second as the unit of time in the International System of Units. It was defined as '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' [22–24]. The second of atomic time, therefore, is in principle equivalent to the second of Ephemeris Time, which is approximately equivalent to the mean value of what would have been a second of UT1 in the 19th century because Newcomb used observations of that time to formulate his expression for the longitude of the Sun.

Technological advances in time transfer along with portable caesium clocks to improve calibrations allowed the BIH to improve its timescale significantly. Beginning in 1969 the timescale constrained to be continuous with A3 was designated TA(BIH). The initial timescales, designated TA(k) with k representing a laboratory identifier, included in TA(BIH) were those of the Physikalische Technische Bundesanstalt (PTB) of Germany, the Commission Nationale de l'Heure of France (F), and the US Naval Observatory (USNO). During 1969 the Royal Greenwich Observatory (RGO), the National Research Laboratory of Canada (NRC), the National Bureau of Standards (NBS), and the Observatoire de Neuchâtel (ON) in Switzerland were added to the list of contributors.

The timekeeping community was able to use the BIH timescale by means of the published values of TA(BIH) − TA(k) that were available in monthly BIH circulars. Institution k could then determine the time-varying relation of its timescale TA(k) with respect to the standard TA(BIH) and make any appropriate changes in its scale to comply more closely with that of the BIH. The TA(BIH) − TA(k) data were available with a delay of one to two months and with uncertainties of 1 µs to 10 µs [20].

The International Astronomical Union (IAU) recommended the unification of time through an atomic timescale in 1967. This was followed by similar recommendations of the International Union of Radio Sciences in 1969 and the International Radio Consultative Committee, now the International Telecommunication Union, in 1970. In June, 1970, the Comité Consultatif pour la Définition de la Seconde (CCDS) discussed the need for an atomic scale and that the International Bureau of Weights and Measures (BIPM) should deal not only with the definition of the timescale interval (the duration of the second), but also with timescales. Consequently they submitted two resolutions to the Comité International des Poids et Mesures (CIPM) on the subject of timescales. The first one pointed out the need for an international atomic timescale to coordinate time signals, serve as a uniform time reference especially for the dynamics of natural or artificial celestial objects, and to compare frequency standards operating in different places or times. The second suggested a definition of international atomic time [25]. They also endorsed the definition of International Atomic Time as 'The International Atomic Time is the time reference coordinate established by the Bureau International de 1'Heure on the basis of the results given by the atomic clocks working in various establishments in accordance with the definition of the second, the time unit of the International System of Units' [26, 27]. Also in 1970 the CCDS recognized that TAI would be in approximate agreement with UT2 on 1 January 1958, 0 h UT2. The 14th CGPM officially approved the establishment of TAI in 1971. The abbreviation 'TAI' first appears in a recommendation of the CGPM the following year [28, 29]).

In 1980 the definition of TAI was refined by the statement, 'TAI is a coordinate timescale defined in a geocentric reference frame with the SI second as realized on the rotating geoid as the scale unit' [30, 31]. This meant that it was now necessary to make relativistic corrections for the primary laboratory realizations of the SI second used in the calibration of TAI to compensate the frequency shifts between their individual locations and a point fixed on the surface of the rotating geoid. In 1988 the BIPM assumed responsibility for maintaining TAI.

To take advantage of the increasing availability of potential contributing atomic clocks, possible modifications of the timescale algorithm were considered. Important timescale characteristics include reliability, frequency stability, frequency accuracy and accessibility [20]. A large number of clocks helps to ensure reliability by reducing the dependence on a few contributors. To be stable in frequency the scale need not necessarily be accurate, but it must have a ratio of its scale interval to the standard second that is as constant as possible. Frequency accuracy, on the other hand, requires that the scale interval be as close as possible to the standard second. Accessibility is provided by the clocks whose data are used in the formation of the timescale. In the process of computing the timescale, the arithmetic differences between the contributed clock time and the timescale can be provided to the contributors, who, in turn, can provide them to their client users of precise time. Thought also must be given to the desired period over which the frequency of the resultant timescale is to be stabilized, as well as the period of time between the contributed comparisons of the clock data. Still other considerations include how often the timescale is to be computed and the time between the last contributed data and the time when the product is made available [2].

Although TAI has been acknowledged as an atomic timescale, it has never been disseminated directly nor has it been recognized as the international standard for timekeeping. That distinction is retained for Coordinated Universal Time (UTC). Since 1972 TAI and UTC differ by an integral number of seconds, but UTC is the timescale recognized as the international standard. See [32] for details on the formation and dissemination of TAI.

4.8. TDT/TDB/T_{eph}

When the usage of precise time and frequency reached the point that the general theory of relativity needed to be accounted for in practical applications, it was realized that Ephemeris Time would not be adequate. Consequently the 16th IAU General Assembly in 1976 defined time-like arguments, consistent with the general theory of relativity, that distinguish coordinate systems with origins at the centre of the Earth and the centre of the solar system [33]. The recommendations for the definition of dynamical time adopted at the IAU General Assembly of 1976 were

(a) At the instant 1977 January 01 d 00h 00m 00s TAI, the value of the new timescale for apparent geocentric ephemerides, will be 1977 January 1d.0003725 (1d 00h 00m 32.184s) exactly.
(b) The unit of this timescale will be a day of 86400 SI seconds at mean sea level.
(c) The timescales for equations of motion referred to the barycentre of the solar system will be such that there will be only periodic variations between these timescales and those of the apparent geocentric ephemerides.

These were given the names Terrestrial Dynamical Time (TDT) and Barycentric Dynamical Time (TDB), respectively, in 1979 [34].

The epoch of TDT is referred to International Atomic Time (TAI) on 1 January 1977 0 h. Its basic unit is the SI second, and it maintains continuity with ET. The reason for the selection of the epoch in January 1977 is that, at this time, a rate correction of -10×10^{-13} was applied to TAI to bring the unit of TAI more closely into accord with the SI second [33, 35]. For years prior to 1955, when atomic time was not available, TDT must be extrapolated backwards, using dynamical theory fitted to observations made since 1955.

The definition of TDB was found to be ambiguous during the 1980s. In particular, the form of the relativistic metric was not made explicit. This led to improvements in the definition of relativistic timescales in 1991 and 2000. Recommendation 5 (1976) of IAU Commissions 4, 8 and 31, completed by Recommendation 5 (1979) of IAU Commissions 4, 19 and 31, stated that Terrestrial Dynamical Time and Barycentric Dynamical Time should differ only by periodic variations [36]. Therefore TDB would differ in rate with Barycentric Coordinate Time (TCB) which was introduced in 1991 (see section 4.11). The relationship between these timescales in seconds is now defined by an IAU recommendation (2006) to be

$$\mathrm{TDB} = \mathrm{TCB} - L_\mathrm{B} \times (\mathrm{JD}_\mathrm{TCB} - 2\,443\,144.500\,372\,5) \times 86\,400\,\mathrm{s} + \mathrm{TDB}_0, \tag{13}$$

where $\mathrm{TDB}_0 = -6.55 \times 10^{-5}$ s and the value of L_B is defined to be $1.550\,519\,768 \times 10^{-8}$.

Barycentric Ephemeris Time (T_eph) is a coordinate time related to TCB by an offset and a scale factor. Ephemerides based upon the coordinate time T_eph are automatically adjusted in the creation process so that the rate of T_eph has no overall difference from the rate of Terrestrial Time (TT) (see section 4.9) [37], therefore also no overall difference from the rate of TDB. For this reason space coordinates obtained from the ephemerides are consistent with TDB.

4.9. Terrestrial Time

In 1991 the IAU renamed TDT as Terrestrial Time (TT). IAU Resolution B1.9 (2000) redefined Terrestrial Time [7, 38]. A practical realization of TT [4, 33, 35, 39] is

$$\mathrm{TT} = \mathrm{TAI} + 32.184\,\mathrm{s}. \tag{14}$$

The constant offset represents the difference between ET and UT1 at the defining epoch of TAI on 1 January 1958. TT is intended to be used as the time reference for apparent geocentric ephemerides. Any difference between TAI and TT is a consequence of the physical defects of atomic time standards, and has probably remained within the approximate limits of $\pm 20\,\mu$s. It will increase at a slower rate in the future as time standards improve. In most cases, and particularly for the publication of ephemerides, this deviation is negligible.

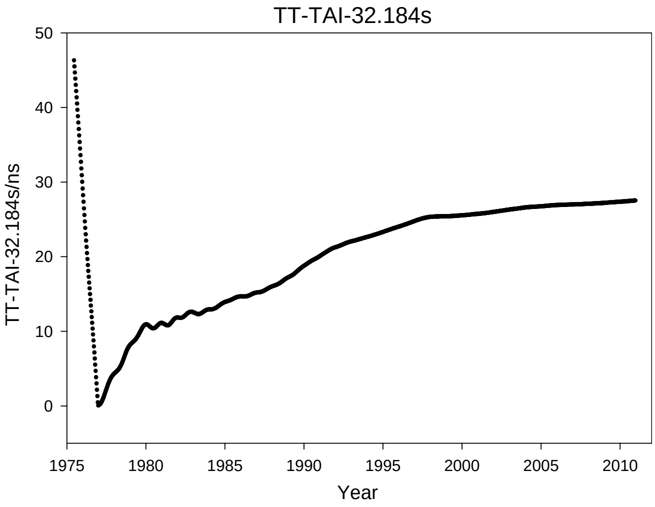

Figure 3. Difference between TT(BIPM10) and TAI.

The unit of measurement of TT was initially defined as the SI second on the geoid, but in 2000 the IAU redefined the unit of TT by adopting a conventional relationship with Geocentric Coordinate Time (TCG). (See section 4.11 and [7].) Corresponding time intervals of TAI are in agreement with the TT intervals within uncertainties of the primary atomic standards. Realizations of TT are designated TT(xxx), where xxx is an identifier. One is TT(TAI) = TAI + 32.184 s and is suitable for near real-time applications.

TT is also made available annually after a reanalysis of the data used to produce TAI. These versions of TT are designated TT(BIPM*yy*) where the *yy* stands for the last two digits of the last year of data used in the reanalysis. Thus TT(BIPM06), for example, was computed in January, 2007, using all of the data contributed through 2006. TT(BIPM10) is the most recent version available from the BIPM at ftp://ftp2.bipm.org/pub/tai/scale/TTBIPM/ttbipm.10. It is identical to all past realizations since TT(BIPM99) for all dates before 2 January 1993 and is within 4 ns of the previous realization TT(BIPM09). Figure 3 shows a plot of the difference between TT(BIPM10) and TAI.

4.10. Coordinated Universal Time

In 1944 quartz crystal clocks began to be used to broadcast time signals. These devices kept time with a uniform rate and were adjusted as needed to keep pace with time determined astronomically. Atomic clocks based on the frequency of an atomic transition in the caesium atom became available operationally in 1955, and radio time signals determined using an atomic clock were begun in the UK. In the United States, the US Naval Observatory and the National Bureau

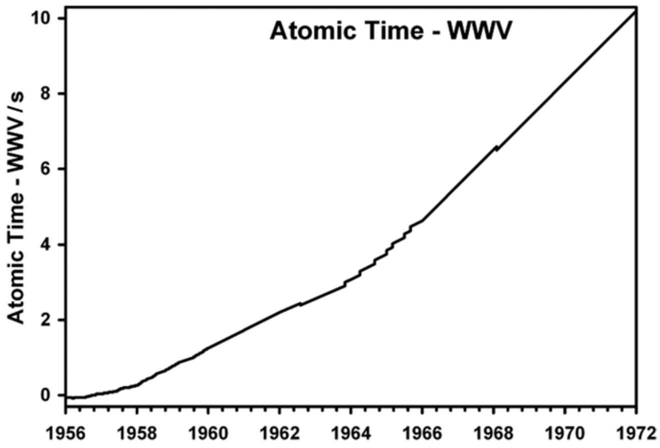

Figure 4. Atomic Time − WWV.

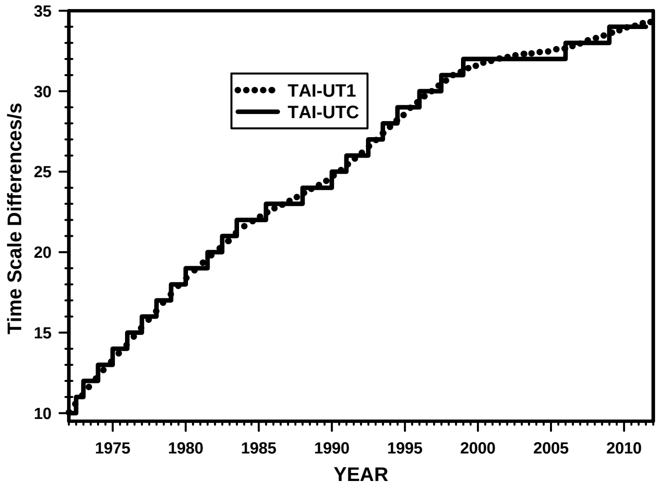

Figure 5. TAI − UTC.

of Standards (NBS) (now the National Institute of Standards and Technology) also developed timescales based on caesium atomic clocks. This work was done from 1956 to 1957 and, as a result, the NBS radio station WWV began broadcasting time signals based on atomic clocks that were adjusted in rate and offsets to match the UT2 that was determined from star transits. Figure 4 shows the difference between a uniform atomic time and the time broadcast by WWV from 1956 until 1972 when the current definition of UTC was implemented. The time broadcast by WWV was being adjusted according to the recommendations in place at the time of the broadcast.

The World Administrative Radio Congress of 1959 recognized that not all time signals being broadcast by radio stations established to provide precise time were consistent, and they asked the International Radio Consultative Committee, abbreviated 'CCIR' to study the problem. The UK and the US had already decided in 1957 to combine Nautical Almanacs beginning with the 1960 edition, and in 1959, they also agreed to coordinate their time and frequency transmissions by making the same adjustments, at the same time, to their caesium-based timescales to stay close to UT2. This coordination began officially on 1 January 1960 and the resulting timescale began to be called 'Coordinated Universal Time'. Timing laboratories from other countries also began to participate over time, and in 1961 the BIH began to coordinate the process internationally.

Details of the UTC system were formalized by the International Radio Consultative Committee (CCIR) Study Group 7 in 1962 and were formally adopted by the CCIR in Recommendation 374 of 1963 [40]. Offsets in the atomic frequency to match the rotational speed of the Earth were announced each year by the BIH, and steps of 100 ms were inserted as needed on dates determined by the BIH, to maintain time signals to within less than 0.1 s of UT2. Because UTC included rate offsets, the broadcast time signals indicated neither the SI second nor the mean solar second. Instead they provided variable intervals designed to stay in step with UT2, from which the SI second could be obtained by applying known corrections. This process required frequent adjustments to complex electronic instrumentation, eventually resulting in a revised definition of UTC.

In 1965, the BIH related UTC to its internally derived atomic timescale A3 by a mathematical relationship [41]. This led to the link between TAI and UTC [21]. The name 'Coordinated Universal Time (UTC)' was approved by a resolution of IAU Commissions 4 and 31 at the 13th General Assembly in 1967 [42].

The current system of Coordinated Universal Time began with a meeting of the International Union of Radio Science (URSI) in 1966 when participants noted the need for a uniform timescale where the units did not change from year to year. At the 1967 meeting of URSI, participants agreed that all adjustments to atomic time should be eliminated, and that UT2 information could be distributed in tables or in radio transmissions. In May, 1968, the idea of introducing only one-second adjustments in the UTC timescale was introduced independently by Louis Essen and Gernot Winkler at a meeting of a commission organized by the International Committee for Weights and Measures (CIPM) to discuss the issue. In that same year, CCIR Study Group 7, meeting in Boulder, Colorado, discussed possible changes in the definition of UTC. They formed an 'Interim Working Party' to provide proposals for a possible new definition of UTC. The options considered were (1) steps in UTC of 0.1 or 0.2 s to keep UTC close to UT2, (2) replacing UTC with a timescale with no adjustments, and (3) one-second adjustments.

Study Group 7 then formulated specific proposals that were approved in January 1970 at the CCIR 12th Plenary Assembly in New Delhi. The recommendation adopted then provides the basis for the current definition of the world's civil timescale. It specified that (a) radio carrier frequencies and time intervals should correspond to the atomic second based on the caesium atom; (b) step adjustments should be exactly one second to maintain approximate agreement with UT; and (c) standard time signals should contain information on the difference between UTC and UT. The new system was to begin on 1 January 1972. In February 1971 Study Group 7 specified more details regarding the implementation of the 1970 recommendation. As a result of these recommendations UTC became a timescale in which the basic unit of measurement is the SI second. However, the accounting of those seconds must

Table 1. TAI − UTC.

From			To			TAI − UTC
1961	Jan.	1	1961	Aug.	1	1.422 818 s + (MJD − 37 300) × 0.001 296 s
	Aug.	1	1962	Jan.	1	1.372 818 s + (MJD − 37 300) × 0.001 296 s
1962	Jan.	1	1963	Nov.	1	1.845 858 s + (MJD − 37 665) × 0.001 1232 s
1963	Nov.	1	1964	Jan.	1	1.945 858 s + (MJD − 37 665) × 0.001 1232 s
1964	Jan.	1		April	1	3.240 130 s + (MJD − 38 761) × 0.001 296 s
	April	1		Sept.	1	3.340 130 s + (MJD − 38 761) × 0.001 296 s
	Sept.	1	1965	Jan.	1	3.440 130 s + (MJD − 38 761) × 0.001 296 s
1965	Jan.	1		Mar.	1	3.540 130 s + (MJD − 38 761) × 0.001 296 s
	Mar.	1		Jul.	1	3.640 130 s + (MJD − 38 761) × 0.001 296 s
	Jul.	1		Sept.	1	3.740 130 s + (MJD − 38 761) × 0.001 296 s
	Sept.	1	1966	Jan.	1	3.840 130 s + (MJD − 38 761) × 0.001 296 s
1966	Jan.	1	1968	Feb.	1	4.313 170 s + (MJD − 39 126) × 0.002 592 s
1968	Feb.	1	1972	Jan.	1	4.213 170 s + (MJD − 39 126) × 0.002 592 s
1972	Jan.	1		Jul.	1	10 s
	Jul.	1	1973	Jan.	1	11 s
1973	Jan.	1	1974	Jan.	1	12 s
1974	Jan.	1	1975	Jan.	1	13 s
1975	Jan.	1	1976	Jan.	1	14 s
1976	Jan.	1	1977	Jan.	1	15 s
1977	Jan.	1	1978	Jan.	1	16 s
1978	Jan.	1	1979	Jan.	1	17 s
1979	Jan.	1	1980	Jan.	1	18 s
1980	Jan.	1	1981	Jul.	1	19 s
1981	Jul.	1	1982	Jul.	1	20 s
1982	Jul.	1	1983	Jul.	1	21 s
1983	Jul.	1	1985	Jul.	1	22 s
1985	Jul.	1	1988	Jan.	1	23 s
1988	Jan.	1	1990	Jan.	1	24 s
1990	Jan.	1	1991	Jan.	1	25 s
1991	Jan.	1	1992	Jul.	1	26 s
1992	Jul.	1	1993	Jul.	1	27 s
1993	Jul.	1	1994	Jul.	1	28 s
1994	Jul.	1	1996	Jan.	1	29 s
1996	Jan.	1	1997	Jul.	1	30 s
1997	Jul.	1	1999	Jan.	1	31 s
1999	Jan.	1	2006	Jan.	1	32 s
2006	Jan.	1	2009	Jan.	1	33 s
2009	Jan.	1				34 s

be adjusted occasionally to keep UTC close to UT. This is in order to comply with a conventionally adopted relationship between time based on the Earth's rotation with respect to the stars and time defined by the direction to a fiducial point loosely related to the Sun's motion in the sky.

The current UTC system is defined by the Radiocommunications Section of the International Telecommunications Union (ITU-R) (formerly CCIR) Recommendation ITU-R TF.460-6: 'UTC is the timescale 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.' [7]. Seconds of UTC are thus exactly equal to the SI second. Step adjustments are now made in order to ensure that $|\mathrm{UT1} - \mathrm{UTC}| < 0.9\,\mathrm{s}$. The preferred times to make the adjustment are at the end of the last minute of 30 June or 31 December. Leap second adjustments may also be made in the last minute of 31 March or 30 September as a secondary choice, and, if necessary, adjustments can be made during the last minute of the last day of any month in the year. A history of rate offsets and step adjustments in UTC is given in table 1.

For users of time scales that do not require precision better than a second the terms 'mean solar time,' 'Greenwich Mean Time' or 'GMT' are now generally considered as being equivalent to UTC, although, as pointed out in section 4.4, there is ambiguity in the use of GMT. The 15th CGPM in 1975 adopted the following resolution [24, 29].

'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),
>
> **notes** 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.'

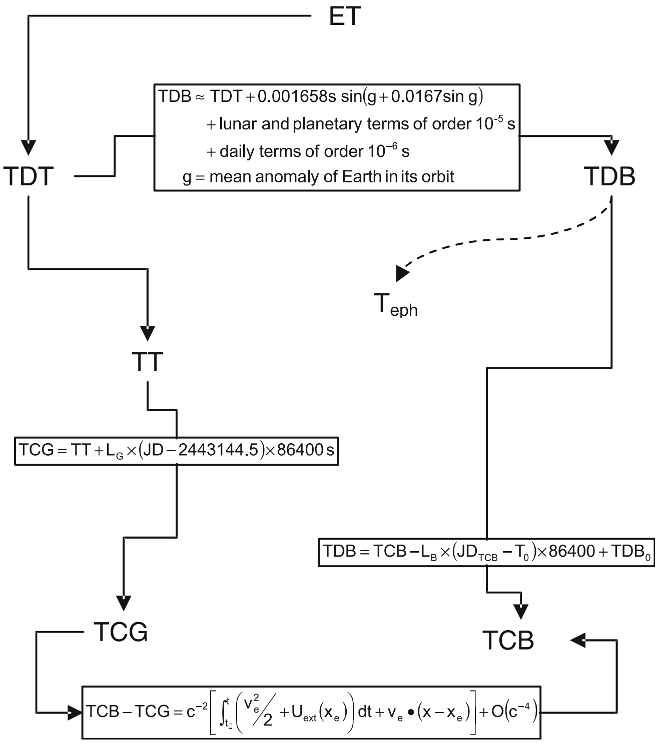

Figure 6. Relationships among timescales.

The continued use of leap second adjustments is under discussion. However, there is no agreement on an alternative means to maintain a relationship between UT1 and atomic time. Figure 5 and table 1 shows the difference between UTC and TAI since 1972 when leap seconds began to be implemented in UTC to keep it within 0.9 s of UT1.

4.11. Barycentric and Geocentric Coordinate Times

In the 1980s the concepts of general relativity came to be more important in practical realizations of timescales. The 21st IAU General Assembly in 1991 adopted nine recommendations in resolution A4 dealing with the celestial and terrestrial reference systems and the space-time metrics [4, 43]. The simplest form of these metrics, which does not introduce scaling factors, defines Barycentric Coordinate Time (TCB) and Geocentric Coordinate Time (TCG) [44]. These coordinate times differ in mean rate between themselves and also with TDB and TT (or TDT). They are related by four-dimensional space-time coordinate transformations [4, 43, 45]. These definitions were further made more precise by resolutions adopted at the 24th IAU General Assembly in Manchester in 2000 [46, 47]. At the same General Assembly, TT was redefined by a linear conventional relation with TCG, its unit being very close to the proper second on the rotating geoid.

The origins of coordinate times have been arbitrarily set so that these times all coincide with the Terrestrial Time (TT) at the geocentre of 1977 January 1 0h 0m 0s TAI. When realizations of TCB and TCG are needed, they are designated by expressions such as TCB(xxx) where xxx indicates the source of the realized timescale (e.g. TAI) and the theory used for transformation into TCB or TCG. The relation TCB − TCG involves a full four-dimensional transformation

$$\mathrm{TCB} - \mathrm{TCG} = c^{-2}\left[\int_{t_0}^{t} (v_e^2/2 + U_{\mathrm{ext}}(\boldsymbol{x}_e))\,\mathrm{d}t + \boldsymbol{v}_e \cdot (\boldsymbol{x} - \boldsymbol{x}_e)\right] + O(c^{-4}), \qquad (15)$$

where $\boldsymbol{x}_e$ and $\boldsymbol{v}_e$ denote the barycentric position and velocity of the Earth's centre of mass, and $\boldsymbol{x}$ is the barycentric position of the observer. The external potential U_{ext} is the Newtonian potential of all solar system bodies apart from the Earth and is evaluated at the geocentre. In the integral, t = TCB and t_0 is chosen to agree with the epoch of Terrestrial Time (TT). As an approximation to TCB − TCG in seconds one might use

$$\mathrm{TCB} - \mathrm{TCG} = \frac{L_{\mathrm{C}} \times (\mathrm{TT} - \mathrm{TT}_0) + P(\mathrm{TT}) - P(\mathrm{TT}_0)}{1 - L_{\mathrm{B}}} + c^{-2}\boldsymbol{v}_e \cdot (\boldsymbol{x} - \boldsymbol{x}_e). \qquad (16)$$

The current estimate of the value of L_{C} is $1.480\,826\,867\,41 \times 10^{-8} (\pm 2 \times 10^{-17})$ [47]. TT_0 corresponds to JD 2443144.5 TAI (1977 January 1, 0 h). Periodic terms denoted by $P(\mathrm{TT})$ have a maximum amplitude of around 1.6 ms and can be evaluated by the 'FB' analytical model [48]. Alternatively, $P(\mathrm{TT}) - P(\mathrm{TT}_0)$

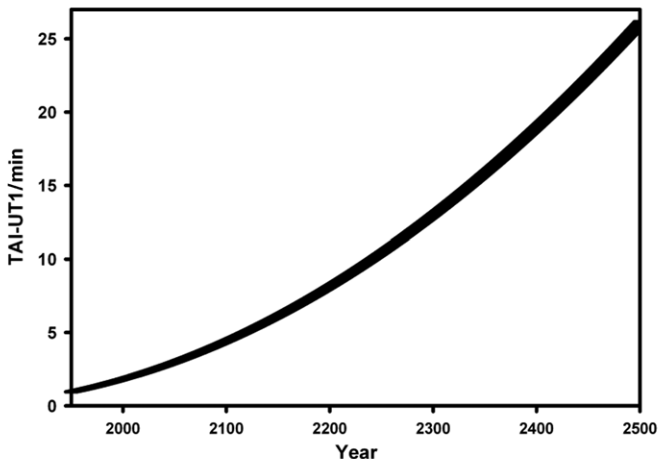

Figure 7. Predicted difference between a uniform time and time based on observations of the Earth's rotation since 700 BCE [53–56].

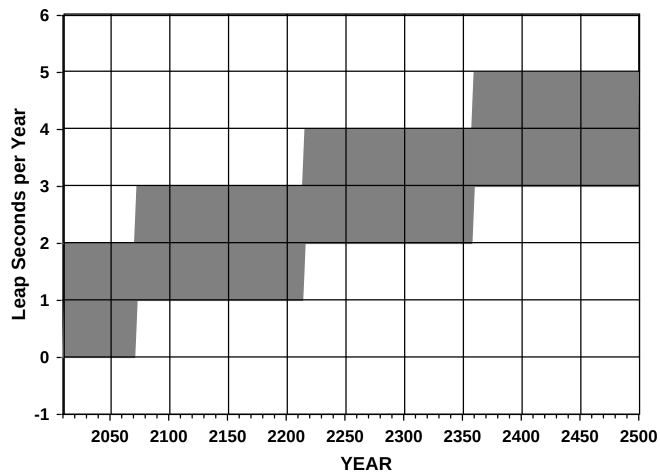

Figure 8. Expected number of leap seconds per year based on observations of the Earth's rotation since 700 BCE [53–56].

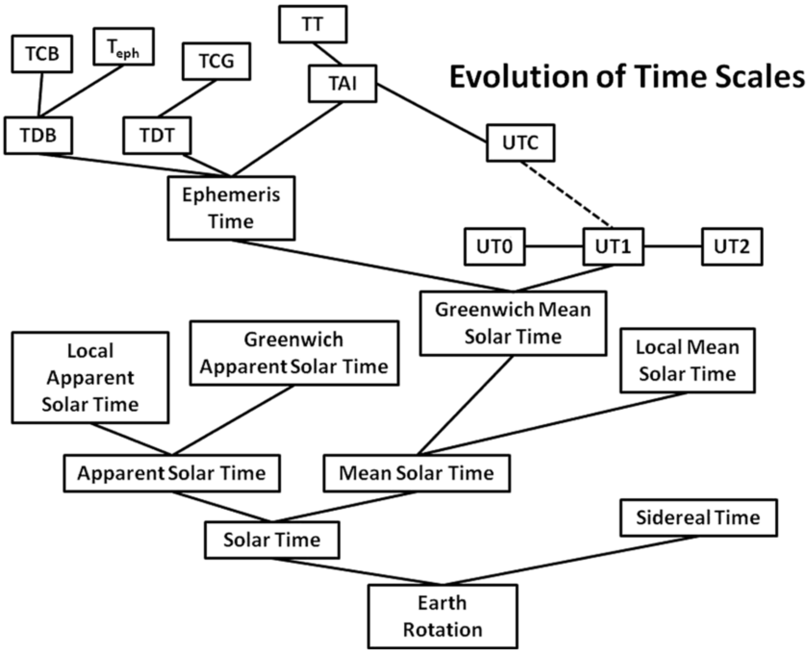

Figure 9. Evolution of timescales, showing the development of the relationships among timescale concepts leading to the suite of modern time scales.

may be provided by a numerical time ephemeris such as TE405 [49], which provides values with an accuracy of ± 0.1 ns from 1600 to 2200. A series, HF2002, providing the value of $L_C \times (\mathrm{TT} - \mathrm{TT}_0) + P(\mathrm{TT}) - P(\mathrm{TT}_0)$ as a function of TT over the years 1600–2200 has been fitted [50] to TE405. This fit differs from TE405 by less than 3 ns over the years 1600–2200 with an rms error of ± 0.5 ns. The last term is diurnal at the surface of the Earth, with an amplitude smaller than 2.1 µs.

Terrestrial Time differs from TCG in seconds by a scaling factor and can be approximated by

$$\mathrm{TCG} - \mathrm{TT} = L_G \times (\mathrm{JD(TAI)} - 2\,443\,144.5) \times 86\,400. \tag{17}$$

The defining value of L_G, chosen to provide continuity with the definition of TT in which its measurement unit agrees with the SI second on the geoid, is $6.969\,290\,134 \times 10^{-10}$ [47, 51]. Figure 6 shows the relationship among these timescales.

5. The future

With the exception of the specialized scientific and engineering communities dealing with the specification of the orientation of the Earth in inertial space for astronomical research and space applications, there is no longer much practical application of the traditional concepts of apparent and mean solar times. Knowledge of the Earth's rotation angle is required for observers on the Earth who want to know their orientation in an inertial reference frame. This includes navigators, astronomers and geodesists. The Earth's rotational speed remains essentially unpredictable with high precision due to the incompletely understood irregular variations. Because of this, astronomical observations continue to be made regularly with improving accuracy, and the resulting data are the subject of continuing research in the field.

The Earth's rotation, however, still remains an integral part of current timekeeping procedures because of its role in the realization of UTC. Observations of the deceleration of the Earth's rotation due chiefly to tidal friction tell us that we can expect to see the difference between UT1 and a uniform time to grow as shown in figure 7. From that plot it appears likely that we will see a 10 min difference by around the year 2300, and by 2500 we can expect an accumulation of over 25 min.

In order to compensate for the Earth's rotation then, assuming that the current definition of UTC is continued, we can expect to see an increase in the number of leap seconds required. Figure 8 shows the number of leap seconds per year that would be expected accounting for the fact that the Earth's rotation is difficult to predict. From that figure we see that in the year 2300 we should expect to see two to four leap seconds per year and that in 2500 we could expect as many as five.

The development of increasingly sophisticated frequency standards in the future is obviously likely to affect the future evolution of time scales. Still another development on the horizon for timescales is the possible practical application of pulsars as a means to provide time. The periodicity of pulsar pulses is very stable and we might expect that, with appropriate modelling, the long term stability of existing atomic time scales could be improved by making use of stable millisecond pulsars. Time determined from binary pulsars might also be a practical contributor to future timescales [52].

6. Conclusion

Figure 9 shows schematically the evolution of timescales as discussed above. The concept of precision timescales has continued to evolve in a direction away from a direct connection to astronomical observations. The process began, after the introduction of mechanical clocks, in the latter part of the thirteenth century. That direction was followed in order to take advantage of the increasing availability of mechanical clocks in everyday life. For this it was necessary to accommodate the fact that time between successive transits of the Sun on the observer's meridian varied during the year due to the inclination of the Earth's equator with respect to the plane of its orbit and to the fact that the Earth's orbit is not circular. Although this effect could be described by the equation of time, it needlessly complicated the development of mechanical clocks and so the first steps were taken to move away from the use of observations of the Sun as a means to keep track of time for everyday purposes

In more recent times we have come to realize that another complication exists in the variability of the Earth's rotation. This causes the duration of the second to vary from day to day if we rely on the Earth's rotation for our definition of a second and led to the adoption of a definition of a second that is no longer related to the Earth's rotation.

We are now left with a set of timescales in which the duration of a second is defined by an atomic energy level transition in the caesium atom. The definition of UTC still requires a connection to astronomy. However, this connection continues to be discussed, and it is possible that the next step in the evolution of timescales may be a total separation of astronomy from precision timekeeping or even a return to astronomy through the use of pulsar data.

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