The leap second: its history and possible future

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Abstract. This paper reviews the theoretical motivation for the leap second in the context of the historical evolution of time measurement. The periodic insertion of a leap second step into the scale of Coordinated Universal Time (UTC) necessitates frequent changes in complex timekeeping systems and is currently the subject of discussion in working groups of various international scientific organizations. UTC is an atomic time scale that agrees in rate with International Atomic Time (TAI), but differs by an integral number of seconds, and is the basis of civil time. In contrast, Universal Time (UT1) is an astronomical time scale defined by the Earth's rotation and is used in celestial navigation. UTC is presently maintained to within 0.9 s of UT1. As the needs of celestial navigation that depend on UT1 can now be met by satellite systems, such as the Global Positioning System (GPS), options for revising the definition of UTC and the possible role of leap seconds in the future are considered.

1. Introduction: why we have leap seconds

Approximately once a year, a leap second is introduced into UTC, the world's atomic time scale for civil time, in order to keep it in phase with the rotation of the Earth. Leap seconds ensure that, on average, the Sun continues to be overhead on the Greenwich meridian at noon to within about 1 s. When the atomic definition of the International System of Units (SI) second was introduced in 1967, it was effectively made equivalent to an astronomical second based on a mean solar day of 86 400 s in about 1820. However, over approximately the past 1000 years, the Earth's rotation has been slowing at an average rate of 1.4 ms per century, so that the day is now about 2.5 ms longer than it was in 1820. A difference of 2.5 ms per day amounts to about 1 s per year and this is the reason for the more or less regular insertion of leap seconds. Superimposed on this very slowly increasing difference are shorter-term variations in the length of the day. Periods between leap seconds are not, therefore, constant and, in fact, over the past thirty years there have been several years in which leap seconds have been omitted.

The primary reason for introducing the concept of the leap second was to meet the requirement of celestial navigation to keep the difference between solar time and atomic time small. However, the motivation for the leap second has diminished because of the wide availability of satellite navigation systems, such as GPS, while the operational complexities of maintaining precise timekeeping systems have made the insertion of leap second adjustments increasingly difficult and costly.

The question currently being debated in recently created working groups of various international scientific organizations is whether there continues to be a need for the leap second, with its many technical inconveniences, or whether it would be better simply to let atomic time run freely and accept that the world's civil time scale will slowly diverge from the rotation of the Earth? This article gives the history and detailed technical background to the current practice and outlines various solutions.

2. Measurement of time

2.1 Clocks

Two elements are needed to measure the passage of time: (a) a time "reckoner", which is a repeatable

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phenomenon whose motion or change of state is observable and obeys a definite law, and (b) a time reference, with respect to which the position or state of the time reckoner can be determined. These elements correspond to the two properties of time measurement: interval and epoch. Together, the time reckoner and the time reference constitute a clock.

From remote antiquity, the celestial bodies – the Sun, Moon and stars – have been the fundamental reckoners of time. The rising and setting of the Sun and the stars determine the day and night; the phases of the Moon determine the month; and the positions of the Sun and stars along the horizon determine the seasons.

Sundials were among the first instruments used to measure the time of day. The Egyptians divided the day and night into 12 h each, which varied with the seasons. While the notion of 24 equal hours was applied in theoretical works of Hellenistic astronomy, the unequal "seasonal hour" was used by the general public [1]. When the first reliable water clocks were constructed, great care was taken to reflect the behaviour of a sundial instead of the apparent motion of the heavens [2]. It was not until the fourteenth century that an hour of uniform length became customary due to the invention of mechanical clocks. These clocks were significant, not only because they were masterpieces of mechanical ingenuity, but also because they altered the public's perception of time [3, 4].

In the era of telescopic observations, pendulum clocks served as the standard means of keeping time until the introduction of modern electronics. Quartz-crystal clocks were developed as an outgrowth of radio technology in the 1920s and 1930s [5]. Harold Lyons [6] at the National Bureau of Standards in Washington, D.C. (now the National Institute of Standards and Technology, Gaithersburg, Md.) constructed the first atomic clock in 1948 using the microwave absorption line of ammonia to stabilize a quartz oscillator. Louis Essen and J. V. L. Parry [7] at the National Physical Laboratory in Teddington, UK, constructed a practical caesium beam atomic clock in 1955. Commercial caesium frequency standards appeared a year later. Norman Ramsey developed the hydrogen maser at Harvard University in 1960 [8].

Once practical atomic clocks became operational, the Bureau International de l'Heure (BIH) and several national laboratories began to establish atomic time scales [9]. The responsibility for the maintenance of the international standard is now given to the Bureau International des Poids et Mesures (BIPM). Some form of atomic time has been maintained continuously since 1955 [10].

2.2 Time scales

Three primary methods of measuring time have been in common use for modern applications in astronomy, physics and engineering. These methods have evolved as the design and construction of clocks have advanced in precision and sophistication. The first is Universal Time (UT), the time scale based on the rotation of the Earth on its axis. The second is Ephemeris Time (ET), the time scale based on the revolution of the Earth in its orbit around the Sun. The third is Atomic Time (AT), the time scale based on the quantum mechanics of the atom. Each of these measures of time has had a variety of refinements and modifications for particular applications.

The true measure of the Earth's rotation is UT1, which is the form of Universal Time corrected for polar motion and used in celestial navigation. However, owing to irregularities in the Earth's rotation, UT1 is not uniform. UT2 is UT1 corrected for the seasonal variation.

Ephemeris Time (ET) is a theoretically uniform time scale defined by the Newtonian dynamical laws of motion of the Earth, Moon, and planets. This measure of time has been succeeded by several new time scales that are consistent with the general theory of relativity.

The scale of International Atomic Time (TAI) is maintained by the BIPM with contributions from national timekeeping institutions. TAI is a practical realization of a uniform time scale.

The basis of civil time is Coordinated Universal Time (UTC), an atomic time scale that corresponds exactly in rate with TAI but is kept within 0.9 s of UT1 by the occasional insertion or deletion of a 1 s step. The decision to insert this leap second is made by the International Earth Rotation Service (IERS). Since 1972, when UTC was introduced, there have been twenty-two leap seconds, all of which have been positive.

3. Time measured by the rotation of the Earth

3.1 Universal Time

Universal Time (UT1) is the measure of astronomical time defined by the rotation of the Earth on its axis with respect to the Sun. It is nominally equivalent to mean solar time referred to the meridian of Greenwich and reckoned from midnight. The mean solar day is traditionally described as the time interval between successive transits of the fictitious mean Sun over a given meridian. Historically, the unit of time, the mean solar second, was defined as 1/86 400 of a mean solar day [11, 12].

The ecliptic is the apparent annual path of the Sun against the background of stars. The intersection of the ecliptic with the celestial equator provides a fundamental reference point called the vernal equinox. In practice, Universal Time is determined, not by the meridian transit of the mean Sun, but by the diurnal motion of the vernal equinox in accordance with a conventional formula specifying UT1 in terms of Greenwich Mean Sidereal Time (GMST). The current defining relation for UT1 with respect to the astronomical reference system of the Fifth Fundamental Katalog (FK5) [13] is given in [14].

UT0, a designation no longer in common use, is UT1 corrupted by the torque-free precessional motion of the Earth's axis of rotation with respect to the Earth's surface [15]. This effect, called variation of latitude, was predicted by Leonhard Euler [16] in 1765 as a property of rigid body motion and was identified observationally by Seth Chandler [17] in 1891. The difference [*UT0 – UT1*] has a maximum value of about 20 ms at mean latitude [18].

Apparent solar time, as read directly by a sundial or more precisely determined by the altitude of the Sun, is the local time defined by the actual diurnal motion of the Sun. However, because of the tilt of the Earth's axis and the elliptical shape of the Earth's orbit, the time interval between successive passages of the Sun over a given meridian is not constant. The difference between mean and apparent 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. Until the early nineteenth century, apparent solar time was used as the argument for astronomical ephemerides. However, as clocks improved and their use by ships at sea and by railroads grew, apparent solar time was gradually replaced by mean solar time.

3.2 Sidereal Time

Local Sidereal Time (LST) is the measure of astronomical time defined by the rotation of the Earth with respect to the stars. LST may be defined as the right ascension of the local meridian, which is the angle between the vernal equinox and the local meridian measured along the celestial equator. In particular, Greenwich sidereal time is the right ascension of the Greenwich meridian.

The sidereal day is the time interval between successive transits of the vernal equinox. It represents the Earth's period of rotation relative to the stars and is approximately 86 164.0905 mean solar seconds. Owing to precession of the Earth's axis with respect to the celestial reference system, the sidereal day is about 0.0084 s shorter than the actual period of rotation in inertial space. Thus the true rotational period of the Earth is approximately 86 164.0989 mean solar seconds. However, the mean solar day presently exceeds a day of exactly 8 400 SI seconds by about 2.5 ms. Therefore, the Earth's period of rotation is currently about 86 164.1014 SI seconds.

Even LST is not a uniform measure of astronomical time. In the early twentieth century, the inherent accuracy of the Shortt free-pendulum clocks first revealed the periodic effects of nutation. The principal term consists of an eighteen-year oscillation with an amplitude of about 1 s. These effects cannot be neglected and it became necessary to introduce the concept of mean sidereal time, which is affected only by precession.

Greenwich Mean Sidereal Time (GMST) is mean sidereal time with respect to the Greenwich meridian, from which Universal Time (UT1) is derived. In the past, UT1 was determined using a worldwide network of visual transit telescopes, photographic zenith tubes and impersonal (prismatic) astrolabes. Three basic techniques are now used to estimate UT1: (a) Very Long Baseline Interferometry (VLBI) measurements of selected radio point sources, mostly quasars; (b) satellite laser ranging; and (c) tracking of GPS satellites. Strictly speaking, because of the motion of satellite orbital nodes in space, VLBI provides the only rigorous determination of UT1. A revised conventional celestial reference frame based on the observed positions of extragalactic objects is being developed that changes the basis for UT1, removes the need for the equinox, and changes the use of precession and nutation.

3.3 Variations in the Earth's rotation

Three types of variation in the Earth's rotation have been identified: a steady deceleration, random fluctuations, and periodic changes [19].

As early as 1695, Sir Edmond Halley [20] was led to suspect an acceleration in the mean motion of the Moon from a study of ancient eclipses of the Sun recorded by Claudius Ptolemy and the medieval Arabian astronomer, Muhammed al-Battānī. By the mid-eighteenth century, the lunar acceleration was fully established. In 1754, Immanuel Kant [21] suggested that this acceleration might be an apparent phenomenon caused by a steady deceleration in the Earth's rotation due to tidal friction. Part of the effect was later attributed to the variation in the solar perturbation on the Moon's orbit. As shown by Pierre-Simon Laplace and John Couch Adams, the planetary perturbations cause the Earth's orbital eccentricity to diminish and, as a consequence, the Sun's mean action on the Moon also diminishes. In addition, the observed lunar acceleration is affected by the recession of the Moon from the Earth in order to compensate the decrease in the Earth's rate of spin by conservation of angular momentum. It was not until the twentieth century that an apparent acceleration of the Sun was also identified [22-24].

Recent studies of eclipses by F. R. Stephenson and L. V. Morrison [25, 26] suggest that the long-term average rate of increase in the length of the day is about 1.7 ms per century (-4.5×10^{-22} rad/s^2). Although the increase in the length of day seems miniscule, it has a cumulative effect on a time scale based on the Earth's rotation. In the past 2000 years the Earth acting as a clock has lost over 3 h. For example, the calculated path of the total eclipse of the Sun witnessed in Babylon in 136 B.C. would be in error by 48.8°, corresponding to a time difference of 11 700 s, assuming a uniform rate of rotation [27].

Sir Harold Jeffreys made the first quantitative estimate of global tidal friction in 1920 [28, 29]. He found that the energy dissipation in the shallow seas appeared to be of the correct order of magnitude to account for the apparent lunar and solar accelerations. The rate of energy dissipation by tidal friction is now considered to correspond to a rate of increase in the length of day of 2.3 ms per century (-6.1×10^{-22} rad/s^2). To account for the observed deceleration, there must also be a component in the opposite direction of about 0.6 ms per century ($+1.6 \times 10^{-22}$ rad/s^2), which is possibly associated with changes in the Earth oblateness parameter J_2 caused by post-glacial rebound [30] or with deep ocean dissipation [31].

Evidence for a long-term deceleration in the Earth's rotation, extending over millions of years, also exists in coral fossils that exhibit both daily and annual growth rings [32]. For example, several corals dating from the middle of the Devonian Period, some 370 million years ago, indicate that the number of days in the year was between 385 and 410. The evidence suggests that the rate of deceleration was substantially the same then as it is now [33].

Besides a steady decrease, the Earth's rotation is subject to frequent small changes that are random and cumulative [34, 35]. This variation was inferred from studies of statistical irregularities in the displacements of the Moon, Sun, Mercury and Venus in proportion to their mean motions. Random fluctuations were first observed directly by atomic clocks in the mid-1950s [36].

There is also a periodic seasonal variation caused principally by meteorological effects. The seasonal variation was first reported in 1936 by A. Scheibe and U. Adelsberger [37], who performed measurements of the Earth's rotation with excellent quartz-crystal clocks at the Physikalische-Technische Bundesanstalt (Germany). N. Stoyko [38] at the BIH in 1937 found that the length of the day in January exceeded that in July by 2 ms, based on the performance of Shortt pendulum clocks and by comparison of the rates of quartz-crystal clocks at the national time services. The seasonal variation in the length of the day is now known to be of the order of 0.5 ms about the mean [39]. The rotation of the Earth runs slow by about 30 ms in May and runs fast by a similar amount in November. By international agreement, an empirical correction for the seasonal variation has been applied since 1 January 1956, resulting in the time scale UT2. The difference between UT2 and UT1, as currently applied, is given in [40]. UT2 has a peak-to-peak amplitude of about 60 ms.

4. Time measured by the orbital motions of the celestial bodies

The need for more uniform measures of astronomical time resulted in the definition of time scales determined from the motions of the celestial bodies in the solar system. Originally based on Newtonian mechanics, they have been refined to take into account the effects of general relativity.

In addition, the unit of time, previously within the exclusive domain of astronomy, was incorporated into the creation of the SI. In 1948, at the request of the International Union of Pure and Applied Physics (IUPAP), the 9th General Conference on Weights and Measures (CGPM) resolved to adopt for international use a practical system of units covering all branches of metrology. A limited set of base units, including the second, was selected by the 10th CGPM in 1954 and a representative list of derived units was compiled by the International Committee for Weights and Measures (CIPM) in 1956. The SI was officially established by the 11th CGPM in 1960 [41].

4.1 Ephemeris Time

Because the variations in the Earth's rotation are complex, the CIPM referred the study of a new definition of the second to the International Astronomical Union (IAU) in 1948. At the suggestion of G. M. Clemence [42], the Conference on the Fundamental Constants of Astronomy held in Paris in 1950 recommended to the IAU that, instead of the period of rotation of the Earth on its axis, the new standard of time ought to be based on the period of revolution of the Earth around the Sun, as represented by Newcomb's *Tables of the Sun* published in 1895. The measure of astronomical time defined in this way was given the name Ephemeris Time (ET).

The working definition of Ephemeris Time was through Newcomb's formula for the geometric mean longitude of the Sun for an epoch of January 0, 1900, 12^{h} UT [43],

$$L = 279^\circ\ 41'\ 48''.04 + 129\,602\,768''.13\ T + 1''.089\ T^2,$$

where T is the time reckoned in Julian centuries of 36 525 days. The linear coefficient determines the unit of time, while the constant determines the epoch. The IAU adopted this proposal in 1952 at its 8th General Assembly in Rome [44].

Initially, the period of revolution of the Earth was understood to be the sidereal year. However, it was subsequently pointed out by André Danjon that the tropical year is more fundamental than the sidereal year, as the length of the tropical year (equinox to equinox) is derived directly from Newcomb's formula, whereas the length of the sidereal year (fixed star to fixed star) depends on the adopted value of the precession [45].

From the value of the linear coefficient in Newcomb's formula, the tropical year of 1900 contains

$[(360 \times 60 \times 60)/129\,602\,768.13] \times 36\,525 \times 86\,400 = 31\,556\,925.9747$ s. Therefore, at the recommendation of the CIPM, the 10th CGPM in 1954 proposed the following definition of the second:

"The second is the fraction 1/31 556 925.975 of the length of the tropical year for 1900.0."

But although the IAU approved this definition at its General Assembly in 1955, Danjon commented that the fraction ought to have a slightly more precise value to bring about exact numerical agreement with Newcomb's formula [46]. Consequently, the CIPM in 1956, under the authority given by the 10th CGPM in 1954, 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 [47]. Reference to the year 1900 does not imply that this is the epoch of a mean solar day of 86 400 s. Rather, it is the epoch of the tropical year of 31 556 925.9747 s.

Although ET was defined in terms of the longitude of the Sun, in practice it was realized indirectly by comparison of observations of lunar positions with lunar ephemerides. Thus, a set of secondary time scales (denoted by ET0, ET1 and ET2) were defined that differed because of subsequent improvements to the conventional ephemerides [48].

In 1958, the IAU General Assembly adopted a resolution that defined the epoch of Ephemeris Time to coincide with Newcomb's formula as follows [49]:

"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 0^{d} 12^{h} precisely."

The resolution also included the definition of the second given by the CIPM in 1956. In a separate resolution, the epoch for Universal Time was chosen as 1900 January 0^{d} 12^{h} UT based on the Fourth Fundamental Katalog (FK4) [50]. However, the equinox of Newcomb's Sun, the lunar theory, and the FK4 did not agree precisely and they were moving with respect to one another. Thus the actual instant in time corresponding to the epoch of ET was approximately 4 s later than the epoch of UT [51].

Ephemeris Time (ET) is a dynamical time determined by the theory of celestial mechanics and is theoretically uniform [52]. ET may be characterized as the independent variable that brings the observed positions of the celestial bodies into accord with their calculated positions constructed from the Newtonian laws of motion. Therefore, in effect, it is defined by these laws [53].

4.2 Relativistic time scales

In 1960, ET replaced UT1 as the independent variable of astronomical ephemerides. However, ET did not include relativistic effects and did not distinguish between proper time and coordinate time. Accordingly, at the 16th General Assembly in Grenoble in 1976, the IAU defined time-like arguments that distinguish coordinate systems with origins at the centre of the Earth and the centre of the solar system, respectively, and are consistent with the general theory of relativity [54]. In 1979, these time scales received the names Terrestrial Dynamical Time (TDT) and Barycentric Dynamical Time (TDB) [55].

TDT replaced ET in 1984 as the tabular argument of the fundamental geocentric ephemerides. TDT has an origin of 1 January 1977 0 h TAI, with a unit interval equal to the SI second, and maintains continuity with ET. At this epoch, 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 [56]. In 1991 the IAU renamed TDT simply Terrestrial Time (TT). A practical realization of TT is [57]

$$[TT] = [TAI] + 32.184 \text{ s.}$$

The constant offset represents the difference between ET and UT1 at the defining epoch of TAI on 1 January 1958.

The relationship between TT and TAI is not strictly rigorous for two fundamental reasons [58]. First, TAI is a statistically formed time scale based on contributions from the major timing centres, whereas TT is theoretically uniform. Second, a scale of time based on the laws of gravitation may not be philosophically equivalent to one based on the quantum mechanics of the atom.

For ephemerides referred to the barycentre of the solar system, the argument is TDB. Through an appropriately chosen scaling factor, TDB varies from TT or TDT by only periodic variations, with amplitudes less than 0.002 s.

From the deliberations of the IAU Working Group on Reference Systems formed in 1988, there arose nine recommendations that were contained in Resolution A4 adopted by the 21st IAU General Assembly in 1991 [59]. The general theory of relativity was explicitly introduced as the theoretical basis for the celestial reference frame and the form of the space-time metric to post-Newtonian order was specified. The IAU also clarified the definition of Terrestrial Time (TT) and adopted two additional time scales, Geocentric Coordinate Time (TCG) and Barycentric Coordinate Time (TCB) [60]. 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 [61]. These definitions were further clarified by resolutions adopted at the 24th IAU General Assembly held in Manchester in 2000 [62].

5. International Atomic Time

Although ET was a uniform time scale, it was not easily realized or disseminated. The rapid development of atomic clocks permitted yet another definition of time [63].

5.1 Experimental atomic time scales

The first operational caesium beam frequency standard appeared in 1955 at the National Physical Laboratory (NPL, UK) [64]. The Royal Greenwich Observatory (RGO) established a time scale, known as Greenwich Atomic (GA), using free-running quartz-crystal clocks periodically calibrated in terms of this standard.

A commercial caesium frequency standard, the "Atomichron", was developed in 1956 [65]. The US Naval Observatory (USNO) inaugurated its A.1 atomic time scale on 13 September 1956, initially based on a caesium clock at the Naval Research Laboratory (NRL) consisting of an Atomichron caesium standard and a quartz-crystal clock. The frequency of the crystal was matched daily to the caesium standard, which was not operated continuously [66]. The National Bureau of Standards (NBS) in Boulder, Colo., also maintained an atomic time scale, NBS-A, starting 9 October 1957. The epochs of A.1 and NBS-A were made coincident and set equal to UT2 on 1 January 1958 [67].

The A.1 time scale was introduced for world use on 1 January 1959. By 1961, A.1 was based on atomic oscillators at the USNO, NRL, NBS, USNO Time Service Sub-Station (Richmond, Florida), Harvard University, National Research Council (Ottawa), NPL, Centre National d'Études des Télécommunications (Bagneux), and Observatoire de Neuchâtel (Switzerland) [68, 69].

Once continuous atomic time became established at various laboratories, the BIH began a mean atomic time scale based on frequency comparisons by means of VLF carriers at 3 kHz to 30 kHz used for long-distance communications and radio navigation [70]. Initially it was designated AM, and then A3, representing an average of the three best scales. In 1960, the BIH began publication of the differences between UT2 and various individual atomic times obtained by integration of accurate frequency comparisons. By 1969 the BIH had redefined A3 to be an averaged atomic time scale (TA) based on several primary laboratory standards. In 1971, this scale became the scale of International Atomic Time (TAI) [71].

5.2 Atomic definition of the second

In June 1955, Louis Essen and J. V. L. Parry of the NPL measured the operational resonance frequency of the laboratory's caesium standard with respect to the second of UT2 as (9 192 631 830 ± 10) Hz by comparison with the adopted frequency of a quartz standard, which was calibrated from astronomical measurements performed at the RGO [72]. Over the following three years, in cooperation with William Markowitz and R. G. Hall at the USNO, they determined its value in terms of the second of Ephemeris Time. Photographs of the Moon and surrounding stars were taken by the USNO dual-rate Moon camera over the period 1955.50 to 1958.25 to determine the Ephemeris Time from the position of the Moon at a known UT2. The UT2 scale, based on observations made with photographic zenith tubes (PZTs) at the USNO, was calibrated with the caesium-beam atomic clock in Teddington via simultaneous observations of the intervals between time pulses broadcast by radio stations WWV (then in Greenbelt, Md.) and GBR (Rugby, UK). The measured caesium frequency was 9 192 631 770 Hz with a probable error of ±20 Hz [73]. The principal uncertainty arose from the astronomical measurements themselves.

Only seven years after the definition of the ephemeris second as an SI unit in 1960, the 13th CGPM in October 1967 adopted the atomic second as the fundamental unit of time in the International System of Units. The second was defined as [74]

"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".

The second of atomic time is in principle equivalent to the second of Ephemeris Time. However, this decision did not consider a recommendation of Commissions 4 (Ephemerides) and 31 (Time) of the IAU in 1967 in Prague, which requested the CGPM to recognize the ephemeris second as a part of the IAU system of astronomical constants, thus causing objections from some astronomers [75].

5.3 Establishment of TAI

A prevalent opinion among astronomers in the mid-1960s had been that the atomic standards could provide the unit of time, but not the continuous scale of time that they needed [76]. But, on the contrary, the BIH was convinced that an atomic standard was the best reference for time and devoted its resources to the establishment of a practical international scale of atomic time [77].

In 1967, IAU Commissions 4 and 31 [78] recommended that the BIH compute an international scale of atomic time, comprising independent time scales of the major national time services based on experience gained from the experimental scale A3. It also suggested that this scale be published in the form of corrections to the contributing time scales with respect to the international scale. Similar recommendations followed from the International Union of Radio Science

(URSI) in 1969 and the International Radio Consultative Committee (CCIR) in 1970.

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. The CCDS stated [79]:

"International Atomic Time (TAI) is the time reference coordinate established by the Bureau International de l'Heure 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."

In conformity with the recommendations of IAU Commissions 4 and 31 in 1967, the CCDS [80] defined the origin so that TAI would be in approximate agreement with UT2 on 1 January 1958, 0 h UT2. The 14th CGPM approved the establishment of TAI in 1971.

Yet an important task remained. To define the scale of atomic time completely, one must define where in the universe the SI second is to be realized. In recognition of the framework of general relativity, the definition was completed in 1980 by the statement [81]:

"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."

Thus relativistic corrections are required 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.

TAI, when formally adopted in 1971, was an extension of the BIH atomic time scale that had been continuous back to 1955. In 1988, responsibility for maintaining TAI was transferred from the BIH to the BIPM. A distribution of approximately two hundred clocks maintained in fifty laboratories contribute to TAI using an optimized weighting algorithm.

6. Coordinated Universal Time

There were two communities of users. Some, such as astronomers, geodesists and navigators, wanted a broadcast time connected with the angle of the Earth's rotation in space. Others, such as physicists and engineers at time and frequency laboratories, wanted it to be perfectly uniform to agree with the best clocks. Attempts to meet the needs of both communities led to the creation of Coordinated Universal Time (UTC).

6.1 Original UTC system

Originally, radio time signals controlled from the Royal Greenwich Observatory were kept closely in phase with the Earth's rotation using direct astronomical observations, resulting in a nominal time interval of a second that could vary slightly from day to day. Beginning in 1944, the time signals were generated by quartz-crystal clocks at a uniform rate, with step corrections introduced when necessary to maintain agreement with astronomical time. When an atomic standard became available at the NPL in 1955, the MSF time and frequency broadcast service of the UK based its signal on the provisional frequency of 9 192 631 830 Hz for caesium. In 1958, the NPL adopted the frequency 9 192 631 770 Hz, but announced that the MSF service would have an annual rate offset of a stated amount, in addition to step corrections, to keep the disseminated time signals close to the scale of UT2 [82].

Following the creation of their atomic time scales in the period 1956-57, the USNO and the NBS each maintained two systems of atomic clock time. The USNO system of uniform time, A.1, was related to Ephemeris Time, while the USNO Master Clock was adjusted daily to UT2 from PZT observations. Similarly, the NBS time scale NBS-A had a uniform rate synchronized with A.1, while NBS-UA was derived by applying rate offsets and small steps to follow UT2 and was disseminated by radio station WWV. A summary of the corrections utilized by WWV is given in [83].

At first, time signals broadcast from various countries were so loosely controlled that a listener monitoring several stations could hear the pulses arriving at different times. To reduce the disparities, the World Administrative Radio Conference (Geneva) in 1959 requested the CCIR to study the question of establishing and operating a worldwide standard frequency and time signal service.

The nautical almanacs of the UK and the USA were combined in 1957, beginning with the editions for 1960. In August 1959 it was also agreed to coordinate their time and frequency transmissions. Coordination began 1 January 1960. The participating observatories and laboratories were the USNO, RGO, NBS, NRL and NPL. Gradually other countries joined the system, which was entrusted to the BIH in 1961. In January 1965, the BIH decided to attach UTC to its atomic time A3 (which became TAI) by a mathematical relationship [84]. This was the origin of the link between TAI and UTC. The name "Coordinated Universal Time (UTC)" was approved by a resolution of IAU Commissions 4 and 31 at the 13th General Assembly in 1967 [85].

6.2 Revised UTC system

Details of the UTC system were formalized by CCIR Study Group 7 in Geneva in 1962 and were adopted by the CCIR in its Recommendation 374 [86] of 1963. The frequency offset was announced by the BIH, after consultation with the observatories concerned, to match as nearly as practical the rotational speed of the Earth and remained constant for each year, while steps of 100 ms were inserted periodically at the beginning of the month, on dates determined by the BIH, to maintain the time signals to within about 0.1 s of UT2.

As UTC included rate offsets to reduce the need for step adjustments, the broadcast time signals indicated neither the SI second nor the mean solar second, but rather variable intervals to stay in step with UT2, from which the SI second could be obtained by applying a known correction. Attempts to follow these fluctuations necessitated revisions in complex equipment on a frequent basis and risked temporary interruptions of service. At an interim session in Monte Carlo during March 1965, Study Group 7 suggested that experimental broadcasts and studies should be made to investigate how to provide both the epoch of Universal Time and the international unit of time interval in the same emission [87].

The revised CCIR Recommendation 374-1 [88] of 1966 allowed for the limited and provisional use of an experimental "Stepped Atomic Time (SAT)", in which the broadcast time rate was the atomic time rate, with no carrier deviation, but in which frequent step adjustments of 200 ms were applied to match UT2 to within 0.1 s. The existence of two parallel systems, UTC and SAT, was regarded as a phase in the evolution and adoption of a single, practical and internationally acceptable system [89].

6.3 Present UTC system

At the 15th General Assembly of the URSI in Munich in 1966, Commission 1 expressed the opinion that all proposed methods of operating standard time and frequency services contained defects and that these services must inevitably develop towards a system of uniform atomic time and constant frequency. For those requiring astronomical time, some form of correction would be necessary [90, 91]. In 1967, at a meeting held in Brussels under the auspices of the URSI to consider frequency coordination in Europe, it was unanimously agreed that both rate offsets and step adjustments should be discontinued. It was suggested that the deviations of UTC from UT2 would have no significance for civil purposes, but could be disseminated to navigators in tables or in the transmissions themselves [92].

Dissatisfaction with the existing form of UTC and the need to study the implications of the new definition of the second adopted in 1967 prompted discussions by the CIPM and the CCIR. Following a recommendation of the CCDS, the CIPM formed a preparatory commission for the international coordination of time scales. The concept of the leap second, analogous to the leap day in the calendar, was proposed independently by G. M. R. Winkler [93] and Louis Essen [94] at a meeting of the commission held at the BIPM in May 1968 [95, 96]. It was proposed that integer steps of seconds replace the steps of 100 ms or 200 ms then being used because they were too frequent and too small. Consideration of possible modifications to UTC was also given by CCIR Study Group 7 in Boulder in August 1968 [97]. The view was expressed that the best system would be one with 1 s steps without rate offsets, so that equipment generating a pulse train would not require a change in frequency. To meet the needs of navigators, it was suggested that coded information might be incorporated in the emission to indicate the difference between UTC and UT2 to higher resolution. An Interim Working Party, IWP 7/1, was formed to investigate requirements, submit proposals, and fix a date for the introduction of the new system. The options under consideration at this time were summarized as follows [98]:

"Discarding the suggestion (for practical reasons and to avoid confusions) of two time scales, one approaching UT (the present UTC) and the other without offsets and adjustments, only three alternatives remain: (a) step adjustment of 0.1 s or 0.2 s to maintain the UTC sufficiently near to UT2 to permit to ignore the difference in most of the applications; (b) complete disuse of UTC system, replacing it with a coordinated uniform time scale without offsets and steps and therefore not approaching UT; (c) step adjustment of 1 s exactly."

Specific proposals were made by Study Group 7 in Geneva in October 1969, which were approved by the CCIR XIIth Plenary Assembly in New Delhi in January 1970. In its Recommendation 460 [99], the CCIR stated that (a) carrier frequencies and time intervals should be maintained constant and should correspond to the definition of the SI second; (b) step adjustments, when necessary, should be exactly 1 s to maintain approximate agreement with Universal Time (UT); and (c) standard signals should contain information on the difference between UTC and UT. The CCIR also decided to begin the new UTC system on 1 January 1972.

At the IAU's 14th General Assembly in Brighton, UK, in August 1970, the chairman of CCIR IWP 7/1, H. M. Smith, sought the views of Commissions 4 (Ephemerides) and 31 (Time). The appropriate method of providing both precise Earth orientation to navigators and uniform time to time and frequency laboratories was discussed. As the navigator requires knowledge of UT1 rather than UT2, it was recommended that radio time signals should disseminate differences in the form of [*UT1 – UTC*]. Several astronomers emphasized that visual observers in astronomical and related fields require UT1 to a precision of 0.1 s, as this is about the limit of human time discrimination. In addition, the almanacs were designed to permit a determination of position to 0.1 minute of arc, and for this a comparable precision in time of 0.25 s was required. At Brighton, Commission 31 adopted recommendations similar to those of the CCIR. Also, the IAU General Assembly resolved that adequate means should be provided to ensure that the difference [*UT1 – UTC*] would be available before permitting UTC to depart from UT1 by more than about 0.1 s [100].

Detailed instructions for the implementation of CCIR Recommendation 460 were drafted at a further meeting of Study Group 7 that was held in February 1971 [101]. The defining epoch of 1 January 1972, 0 h 0 m 0 s UTC was set 10 s behind TAI, which was the approximate accumulated difference between TAI and UT1 since the inception of TAI in 1958, and a unique fraction of a second adjustment was applied so that UTC would differ from TAI by an integral number of seconds. The recommended maximum departure of UTC from UT1 was 0.7 s. The term "leap second" was introduced for the stepped second. An additional correction DUT1 was introduced, having integral multiples of 0.1 s, to be embodied in the time signals such that, when added to UTC, they would yield a better approximation to UT1. For example, this second level of correction was achieved by NBS radio stations WWV and WWVH by using double ticks or pulses after the start of each minute in its UTC broadcasts [102].

The recommendations of the IAU were formalized by resolutions of Commissions 4 and 31 at the 15th General Assembly in Sydney in 1973 and, after further discussion, the name UTC was retained [103]. UTC was recommended as the basis of standard time in all countries, the time in common (civil) use as disseminated by radio signals. The limit of [*UT1* – *UTC*] was set at ±0.950 s, as this is the maximum difference that can be accommodated by the code format. The maximum deviation of UT1 from [*UTC* + *DUT1*] was set at ±0.100 s. In 1974, the CCIR increased the tolerance for [*UT1* – *UTC*] from 0.7 s to 0.9 s.

The present UTC system is defined by ITU-R (formerly CCIR) Recommendation ITU-R TF.460-5 [104]:

"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 in [105].

7. The leap second

7.1 Rate of increase in length of day

Because the Earth's rotation is gradually slowing down, and in addition has both random and periodic fluctuations, it is not a uniform measure of time. The time difference $\Delta T = [ET - UT1] = [TT - UT1]$ represents the difference between the uniform scale of Ephemeris Time or Terrestrial Time and the variable scale of Universal Time. Values of ΔT are summarized in [106]. Before 1955, the values are given by $\Delta T = [ET - UT1]$ based on observations of the Moon. After 1955, values are given by $\Delta T = [TT - UT1] = [TAI + 32.184\ \text{s} - UT1]$ from measurements by atomic clocks as published by the BIH and the BIPM.

According to Stephenson and Morrison [107], over the past 2700 years ΔT can be represented by a parabola of approximately the form

$$\Delta T = (31\ \text{s/cy}^2)\ (T - 1820)^2/(100)^2 - 20\ \text{s},$$

where ΔT is expressed in seconds and T is the year. Figure 1 plots this equation together with observations since 1620. The curve has a minimum at the year 1820 and passes through 0 at the year 1900. Actual values of ΔT based on astronomical data may differ somewhat from this smoothed fit. For example, the value of ΔT is 32.184 s at 1958.0, the origin of TAI. However, no single parabola can satisfactorily represent all modern and historical data.

The derivative of ΔT is

$$\Delta L_{\text{day}} = (0.0017\ \text{s/d/cy})\ (T - 1820)/100,$$

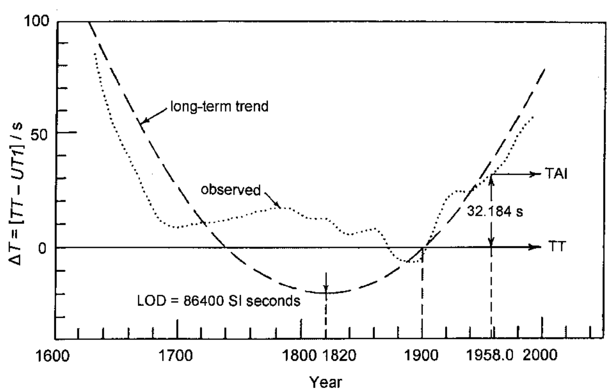

Figure 1. Observations and parabolic fit of ΔT versus time since 1620 (after Stephenson and Morrison [26]).

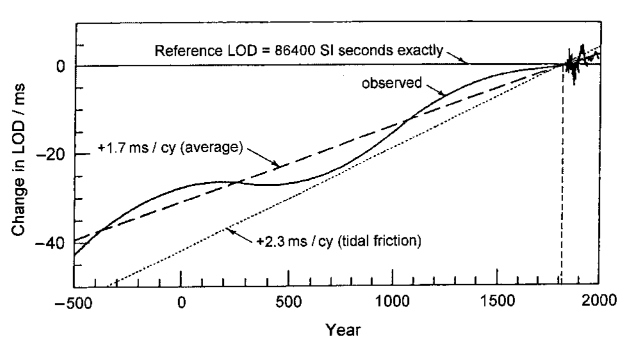

Figure 2. Change in the length of day with respect to a reference day of 86 400 s versus time (after Stephenson and Morrison [26]).

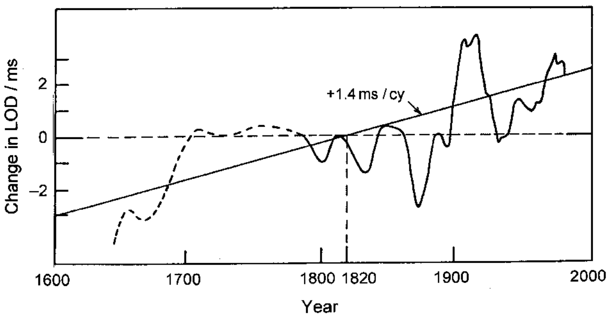

Figure 3. Change in the length of day since 1620 (after Stephenson and Morrison [25]).

which represents the change in the length of day (LOD) in SI seconds relative to the standard reference day of exactly 86 400 SI seconds. This equation is plotted in Figure 2. According to this long-term trend, the rate of increase in the length of the day is about 1.7 ms per century.

Figure 3 illustrates observations of changes in the length of day during the era of telescopic observations, from 1620 onwards. Over this modern period, the LOD has been increasing at about 1.4 ms per century [108]. That is, today is approximately 1.4 ms longer than a day a century ago. Other studies imply slightly different values [109, 110]. The actual value of the LOD will depart from any long-term trend due to short-term fluctuations of between –3 ms and +4 ms on a time scale of decades. The epoch at which the mean solar day was exactly 86400 SI seconds was approximately 1820. This is also the approximate mean epoch of the observations analysed by Newcomb, ranging in date from 1750 to 1892, that resulted in the definition of the second of Ephemeris Time from which the SI second was derived [111].

7.2 Motivation for the leap second

UTC is kept within 0.9 s of UT1 by the occasional insertion of a leap second adjustment. When the present UTC system was established in 1972, the time difference $\Delta T = [TT - UT1] = [TAI + 32.184 \text{ s} - UT1]$ was equal to 42.23 s. Thus the difference between TAI and UT1 in 1972 was approximately 10 s. To maintain continuity with UT1, UTC was initially set behind TAI by this amount. As of 1 January 2001, 22 positive leap seconds have been added. Thus UTC is presently behind TAI by 32 s. Figure 4 illustrates the relationships between TAI, UTC and UT1.

The 1 s increments are indications of the accumulated difference in time between a uniform time and a time measured by the Earth's rotation. By analogy, if a watch that loses 2 s per day were synchronized with a perfect clock at the beginning of a certain day, then after one day the watch would be in error by 2 s. At the end of a month, the watch would be in error by roughly 1 min. It would then be convenient to reset the watch by inserting 1 min of time.

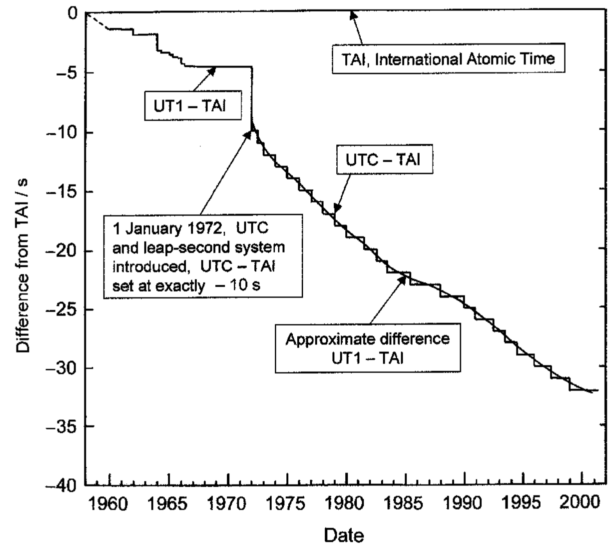

Figure 4. Difference between TAI and UT1 since 1955 (from Quinn [70]).

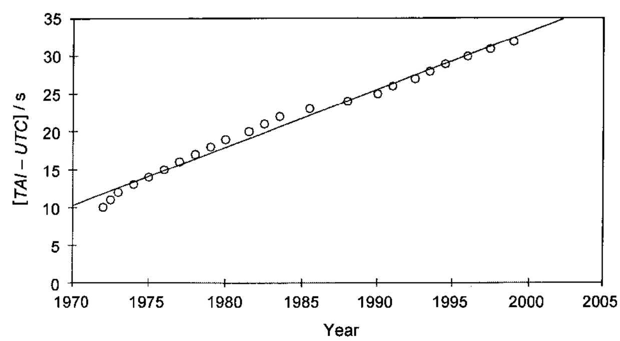

Figure 5. Difference between TAI and UTC due to leap seconds since 1972.

Similarly, the insertion of leap seconds is due to the fact that the present length of the mean solar day is about 2.5 ms longer than a day of precisely 86400 SI seconds, as a consequence of the long-term trend, so that the Earth's rotation runs slow with respect to atomic time. The SI second is equivalent to the second of Ephemeris Time, which in turn is equal to the mean solar second of the early nineteenth century. The length of the day was exactly 86400 SI seconds in about 1820. Before then, the mean solar day was less than 86400 s and since then it has been greater than 86400 s. At the rate of about 1.4 ms per century over the past 180 years, the length of the day has increased by roughly 2.5 ms, so that today the length of the day is about 86400.0025 SI seconds. The difference of 2.5 ms per day accumulates to nearly 1 s over an entire year. It is this accumulated difference that is compensated by the occasional insertion of a leap second to make the length of the year 1 s longer. A change in the frequency of occurrence of leap seconds is an indication of the slowing down or acceleration of the Earth's rotation.

A least-squares fit of the difference [*TAI* – *UTC*] since 1972, shown in Figure 5, implies a nearly linear increase with a slope of (2.10 ± 0.05) ms per day. This value represents the average excess in the length of day during the past three decades and is in approximate agreement with the value computed on the basis of the long-term trend. Recent global weather conditions have contributed to a short-term change in the length of day. Decade fluctuations due to the interaction between the Earth's core and mantle and global ocean circulation may also contribute. Thus at present, the day is actually closer to 86 400 SI seconds and leap seconds have not been required. However, this condition cannot persist and the long-term trend will be eventually restored.

The motivation for the leap second, therefore, is due to the fact that the second as presently defined is "too short" to keep in step with the Earth. However, had the second been defined to be exactly equal to a mean solar second at the origin of TAI in 1958, the discrepancy would not have been removed; the agreement between the SI second and the mean solar second would have only been temporary and their difference would simply have become gradually more apparent over the next century.

7.3 Operational difficulties of preserving the leap second

Modern commercial transport systems depend almost entirely on satellite navigation systems. Future systems are likely to rely on these systems and their augmentation systems to improve navigation accuracy, reliability, integrity and availability beyond current capabilities. Increasing worldwide reliance on satellite navigation for air transport is likely to demand systems free of any unpredictable changes in epoch.

Many telecommunications systems rely on precise time synchronization. For example, spread-spectrum communications are not possible without a coherent time reference. Thus, during the introduction of a leap second, communications can be lost until synchronization is re-established. However, only systems that depend specifically on time are affected by the introduction of leap seconds; systems depending on frequency have little or no sensitivity to epoch.

Another important consideration is the growing use of computers. In today's world of high-speed intercomputer communications that time stamp messages at the sub-second level, 1 s can be a significant length of time. In addition, clocks normally count from 59 s to 0 s of the next minute. Leap seconds require a count sequence of 59 s, 60 s, and then 0 s of the next minute. Many computer systems have a problem introducing the second labelled "60". A similar concern is that when dating events using the Julian Day (JD) or Modified Julian Day (MJD) including fractions of a day, a positive leap second would create a situation where two events 1 s apart can receive identical dates when those dates are expressed with a numerical precision equivalent to 1 s.

In global synchronization operations involving multiple locations, one frequently deals with differing hardware and software systems based on different standards and operating practices. The possible introduction of one or two 61 s minutes per year into continuous site processes would directly affect synchronization if the leap seconds were not treated identically at the same instant at all cooperating sites.

The real-world operation of timing systems is confronted by equipment upgrades and personnel changes. The possible effects of maintenance procedures and human factors in accommodating leap second steps should be given consideration in assessing the reliability of such systems.

Stand-alone data-gathering systems, isolated by specific specialized technical applications, are now extremely rare. Modern data systems rely on continuous, highly accurate time. The possibility of disruptions to continuous service would have a major impact on their interactive operation. In some cases, the need to avoid disruptions has led to considerations of using non-traditional timekeeping systems, such as GPS Time or a time scale maintained by an individual government contractor, as a means of serving this purpose.

Continuing use of a non-uniform time scale including leap seconds in the face of these considerations could lead to the proliferation of independent uniform times adopted to be convenient for particular objectives. If that happens, UTC would receive less acceptance as an international standard.

7.4 Operational difficulties of eliminating the leap second

Many astronomers and satellite ground-station operators would prefer that leap seconds should not be eliminated. There is a significant amount of operational software at astronomical observatories and satellite ground stations that assumes implicitly that DUT1 will always be a small number less than 1 s. This assumption would no longer be true if leap seconds were eliminated. Fixing, testing and documenting all the computer codes could be an enormous task.

The current transmission formats for radio and telephone broadcasts of time signals depend on the fact that DUT1 is less than 1 s. It may be difficult to change these formats due to the prevalence of legacy hardware.

In commercial industry, there are certain clocks that receive radio broadcast time signals to automatically display accurate time. These and similar devices might be affected adversely by a change in the broadcast format.

8. Satellite navigation systems

Historically, the rationale behind the definition of UTC was for its application to celestial navigation while providing a precise standard for time and frequency.

Celestial navigation using stellar observations requires knowledge of UT1 at the time of the observations. When it was introduced, UTC was still the most readily available worldwide system for independent determination of position. But as the formation of UTC progressed, the ability to track satellites on a worldwide basis and the growing global communication and positioning capabilities they could provide became major considerations.

Today, with GPS [112] and GLONASS [113], complemented by LORAN and other radionavigation systems, celestial position determination is not as common. These systems and the augmentation systems they have fostered have been incorporated into virtually every facet of international, telecommunication, military and commercial technology. With extremely high accuracy and global coverage, satellite navigation systems have collectively become a new public utility known by the general designation of Global Navigation Satellite System (GNSS).

8.1 GPS

The Global Positioning System (GPS) is a satellite navigation system developed by the US Department of Defense. The programme evolved from earlier systems and was formally chartered in 1973 [114]. The GPS comprises a nominal constellation of twenty-four satellites with an orbital radius of 26 560 km, corresponding to a period of revolution of 12 sidereal hours (11 h 58 min). There are six orbital planes inclined at 55° with four satellites per plane. The constellation geometry ensures that between four and eleven satellites are simultaneously visible at all times from any point on the Earth. Block I developmental prototype satellites were launched between 1978 and 1985, while Block II production satellites were launched beginning in 1989. The system was declared fully operational in 1995. The current GPS constellation consists of twenty-eight Block II/IIA/IIR satellites.

Each satellite carries multiple caesium and rubidium atomic clocks. The fundamental clock frequency is 10.23 MHz. The satellite and global tracking network atomic clocks are used to generate the continuous system time known as GPS Time, which is specified to be within 1 μs of UTC as maintained by USNO, except leap seconds are not inserted. The algorithm defining the relationship between GPS Time and UTC thus includes a correction for leap seconds. The origin of GPS Time is midnight of 5/6 January 1980, with the consequence that TAI is ahead of GPS Time by 19 s, a constant value. As of 1 January 2001, GPS Time is ahead of UTC by 13 s. With appropriate corrections for signal propagation, relativity, and other effects, GPS provides a reference for time with a precision of 10 ns or better.

The GPS satellites transmit signals at two carrier frequencies in L-band: the L1 component with a centre frequency of 1575.42 MHz and the L2 component with a centre frequency of 1227.60 MHz. The precision P code (or the encrypted Y code used in place of the P code) is a spread-spectrum, pseudo-random noise (PRN) code with a bit rate ("chip rate") of 10.23 MHz. The P(Y) code has a period of 38.058 weeks, but it is truncated into one-week segments to distinguish individual satellites. The coarse/acquisition C/A code is a PRN code with a bit rate of 1.023 MHz that repeats itself every 1 ms [115, 116].

GPS provides two levels of service. The Precise Positioning Service, intended for authorized users, employs the P(Y) code, which is transmitted on both the L1 and L2 frequencies. The Standard Positioning Service, intended for civil users, employs the C/A code, which is transmitted on only the L1 frequency. The C/A code is also used for satellite acquisition by all users.

The determination of position may be characterized as the process of triangulation using pseudo-range measurements from four or more satellites. The military P(Y) code receiver has a 95 % horizontal position accuracy of about 5 m. Until recently, the civil C/A code was intentionally degraded by a technique called Selective Availability (SA), which introduced position errors of 50 m to 100 m by dithering the satellite clock data. This technique also restricted time transfer to about 300 ns in real time. However, on 2 May 2000, under a US presidential directive, the SA feature of the C/A code was set to zero. Consequently, the civil GPS accuracy is now about 10 m to 30 m in position and 10 ns to 30 ns in time. Differential correction systems, where they are available, can permit position determination to an accuracy of less than a metre.

A variety of GPS modernization initiatives are under way. With the addition of a new L2 civil (L2C) signal on GPS Block IIR-M satellites in 2003, the civil 95 % horizontal position accuracy will become about 5 m to 10 m. Also, in 2000 the World Radiocommunication Conference (Istanbul) approved a third civil frequency, known as L5, to be centred at 1176.45 MHz in the Aeronautical Radio Navigation Services (ARNS) band. This third frequency, to be available on GPS Block IIF satellites in 2005, would permit the creation of two beat frequencies that would yield sub-metre positioning accuracy in real time [117]. A new generation of GPS with enhanced capabilities, GPS III, is to be implemented beginning in 2010.

The orbit determination process for GPS, like virtually all other Earth-orbiting satellites, requires precise knowledge of [*UT1* – *UTC*]. The common procedure involves integration of the equations of motion in an Earth-Centred Inertial (ECI) reference frame. The tracking stations, however, are located in the Earth-Centred Earth-Fixed (ECEF) reference frame of the rotating Earth. The usual choice of the inertial coordinate system is the J2000.0 reference frame based on the FK5 star catalogue, while the physical model of the Earth is the World Geodetic System 1984 (WGS 84)

[118, 119]. The data from the tracking stations are typically time-tagged with a particular realization of UTC. Moreover, the Earth's gravitational field is also rotating with the Earth and the perturbing gravitational forces must be transformed, via four rotation matrices, from the ECEF frame into the ECI frame as part of the orbit determination process. The matrices account for the Earth's polar motion, variable rotation, nutation and precession. Near real-time orbit determination must use predictions of [*UT1* – *UTC*]. Today, these predictions are expressed in the form of a polynomial model that is updated weekly [120].

As GPS Time does not include leap seconds, the introduction of a leap second into UTC does not affect GPS users. The GPS operational control segment, however, must carefully account for the leap second step in [*UT1* – *UTC*]. Prior to a leap second event, two sets of "Earth Orientation Parameters" are provided to the GPS control segment. One set is used up to the time a leap second is inserted and a second set, which contains the new 1 s step in [*UT1* – *UTC*], is used after the leap second is inserted.

8.2 GLONASS

The Russian Global Navigation Satellite System (GLONASS) has many features in common with GPS [121, 122]. The nominal constellation consists of twenty-four satellites in three planes inclined at 64.8°. The orbital radius is 25 510 km and the period is 8/17 sidereal day (11 h 15 min). The first satellite was launched in 1982. The system was fully deployed in early 1996 but currently there are only nine operational satellites. However, there is a commitment to restore the complete twenty-four satellite constellation by 2004.

In contrast to GPS, the GLONASS satellites all transmit the same codes and are distinguished by individual L-band carrier frequencies. Thus, while GPS uses the spread-spectrum technique of Code Division Multiple Access (CDMA), GLONASS uses Frequency Division Multiple Access (FDMA). The GLONASS design uses Moscow Time, [*UTC* + 3 h], as its time reference instead of its own internal time. Thus, users of this system are directly affected by leap seconds. During the process of resetting the time to account for a leap second, the system is unavailable for navigation service because the clocks are not synchronized.

8.3 Utilization of satellite systems

Current CGPM, ITU-R and IAU recommendations address the use of satellites for space services, frequencies, and time transfer. The growing utilization of satellite systems and their internal time scales may gradually become the primary source of time for many practical applications. Laboratories separated by several thousand kilometres can routinely perform time comparisons using GPS common-view techniques with a precision of a few nanoseconds. GLONASS can provide continental time transfer with somewhat less precision. Another technique coming into wider use is Two-Way Satellite Time Transfer (TWSTT) using geostationary communications satellites. This technique utilizes the wideband communications capability to transmit bidirectional, spread-spectrum ranging codes that permit time comparisons at the sub-nanosecond level.

In comparison, the DUT1 code available in terrestrial radio signals that disseminate UTC has a resolution of 0.1 s. The corresponding position error on the equator is about 50 m. A 1 s resolution between UT1 and UTC corresponds to a position error using celestial measurements of 0.5 km. As a result, satellite systems are superseding UTC radio signals as a means of time determination for navigation.

9. International agreements on time

No single international agency by itself could assume complete responsibility for the definition and rules for the dissemination of time. Many international scientific organizations, listed below, have combined their efforts in the development, realization and dissemination of International Atomic Time (TAI) and Coordinated Universal Time (UTC). Their work has established the link between the traditional astronomical determination of time and that based on fundamental atomic phenomena. This essential cooperation was required to support the necessary scientific foundation.

(1) The General Conference on Weights and Measures (Conférence Générale des Poids et Mesures, CGPM), which has responsibility for the International System of Units (Système International d'Unités, SI), was established by the Convention of the Metre (Convention du Mètre), signed in Paris by representatives of seventeen countries in 1875 and amended in 1921. The Convention now has fifty-one signatories. Under the terms of the Convention, the Bureau International des Poids et Mesures (BIPM) operates under the supervision of the International Committee for Weights and Measures (Comité International des Poids et Mesures, CIPM), which itself comes under the authority of the CGPM [123, 124]. During the period when TAI and UTC were developed, the CIPM received guidance from the Comité Consultatif pour la Définition de la Seconde (CCDS), set up in 1956. This committee was renamed the Consultative Committee for Time and Frequency (Comité Consultatif du Temps et des Fréquences, CCTF) in 1997. The BIPM organizes the time links used for computing and disseminating TAI and UTC. It issues a monthly *Circular T* that contains the information needed to obtain these time scales at the best level of accuracy.

(2) The International Radio Consultative Committee (CCIR) of the International Telecommunication Union (ITU) was established in 1927 to coordinate technical studies, tests and measurements in the various fields of telecommunications and to establish international standards. Recommendations for standardization of international broadcast time were drafted at the CCIR Xth Plenary Assembly in Geneva in 1963 and XIth Plenary Assembly in Oslo in 1966. Study Group 7 was formed in 1959 to include space radiocommunication and frequencies and was responsible for the definition of UTC as the standard for frequency and time dissemination. The ITU Plenipotentiary Conference of 1992 reorganized the CCIR into the ITU-R (Radiocommunication Sector). Working Party 7A continues as the responsible body for Standard Frequency and Time Signals.

(3) The International Astronomical Union (IAU) was established during the Constitutive Assembly of the International Research Council (IRC) held in Brussels in 1919. The IRC was succeeded by the International Council of Scientific Unions (ICSU) in 1931 (renamed the International Council for Science in 1998) [125, 126]. Through its Commissions 4 (Ephemerides), 19 (Rotation of the Earth), and 31 (Time), the IAU standardized the definitions of Universal Time, Ephemeris Time, and the various relativistic time scales and determined their relationships to International Atomic Time.

(4) The International Union of Geodesy and Geophysics (IUGG) is a member of the ICSU and was established by the IRC in 1919. The IUGG is dedicated to the scientific study of the Earth and its environment in space and includes the International Association of Geodesy (IAG).

(5) The International Union of Radio Science (URSI) is a member of the ICSU and was established by the IRC in 1919 to encourage scientific studies of radiotelegraphy and promote international cooperation. Its present charter includes intercomparison and standardization of the measuring instruments used in scientific work and scientific aspects of telecommunications. URSI made the original recommendation for the worldwide broadcast of offset atomic time.

(6) The Bureau International de l'Heure (BIH) was established at the Paris Observatory in 1919 by the IRC Constitutive Assembly to coordinate international radio time signals. Originally, the BIH was under the direction of IAU Commission 31, but in 1956 it became a service of the Federation of Astronomical and Geophysical Data Analysis Services (FAGS) with the IAU, IUGG and URSI as parent unions. The BIH was requested by the CCIR in 1963 to determine the proper offsets between UT2 and broadcast atomic time and to coordinate the worldwide standard frequency and time signal service prescribed by the CCIR. The BIH transferred this function, as well as the establishment of International Atomic Time, to the BIPM on 1 January 1988, while its activities on the rotation of the Earth were taken over by a new service, the International Earth Rotation Service.

(7) The International Earth Rotation Service (IERS) was established in 1987 by the IAU and the IUGG and began operation on 1 January 1988. Its structure was reorganized commencing in 2001. The IERS is an international consortium of national laboratories and observatories that provides operational data related to the orientation of the Earth in space. It has the responsibility for decisions regarding changes to UTC based on observations of the Earth's rotation and determines when leap seconds should be applied. The IERS publishes four bulletins. *Bulletin A* (daily and semiweekly) is issued by the Sub-Bureau for Rapid Service and Predictions at USNO and contains rapid determinations for Earth Orientation Parameters; *Bulletin B* contains monthly Earth Orientation Parameters. *Bulletin C*, containing announcements of the leap seconds in UTC, and *Bulletin D*, containing announcements of the value of DUT1, are distributed as required.

Merely to enumerate these agencies and their commissions, study groups and sub-committees is to realize the complexity of the international establishment in charge of time, and the difficulty of making fundamental changes. The present definition of UTC is the result of far-reaching compromises among the communities that these agencies represent.

Today's user communities have changed significantly in the few ensuing decades, just as the uses of time have changed. The traditional radio broadcast of time signals is being overtaken by satellite signals linked directly to atomic standards. Ensembles of atomic standards in individual laboratories and high-speed computer networks are synchronized to these same standards. The many and diverse purposes that an international time scale must serve are now part of an international telecommunication and commercial infrastructure involving significant economic interests in which changes represent a major financial investment. This new relationship could make change more difficult. If a new or revised international standard is to represent all the legitimate interests, coordination with non-traditional agencies and groups may be necessary.

10. Legal time

An important consideration with the current definition of UTC is the legal definition of time implied within the domestic laws of individual countries [127]. The purpose of statutes governing legal time is to promote commerce and the public interest.

10.1 Standard Time

The advent of the railroads in the second quarter of the nineteenth century introduced an era of high-speed transport and mobility. Efforts to coordinate schedules culminated in the adoption of regional zones of Standard Time and the choice of Greenwich as the international reference for the prime meridian.

Greenwich Mean Time (GMT) has been the legal time in the UK since 1880. In the USA, the Standard Time Act of 19 March 1918, as amended by the Uniform Time Act of 1966, established eight time zones that are based on mean solar time and are nominally separated in longitude by intervals of 15° (1 h) with respect to the Greenwich meridian [128, 129]. It also authorized the Interstate Commerce Commission to modify the time zone boundaries. In 1983 this responsibility was transferred to the Department of Transportation.

The publication of the British *Nautical Almanac* beginning with the year 1767 by the Astronomer Royal Nevil Maskelyne, which enabled the determination of longitude at sea using observations of the Moon's position with respect to the stars, and the contemporaneous development of the marine chronometer by John Harrison, had established Greenwich as the de facto fundamental reference for longitude and time for over a century [130, 131]. The Greenwich meridian was formally recommended as a worldwide standard reference for longitude and time at the International Meridian Conference, held in Washington, D.C., in October 1884 at the invitation of the United States Government, as a result of discussions that had taken place at several scientific conferences over the previous decade. By then nearly three-quarters of the world's commercial ships used charts based on the Greenwich meridian. The Conference also recommended the adoption of a Universal Day, defined as a mean solar day counted from 0 up to 24 hours, that would begin at midnight at the prime meridian [132, 133].

The idea of time zones was first proposed in 1870 by Charles F. Dowd [134], an American college professor, as a method of regulating time for the railroads. In Dowd's plan, standard time would be used by the railroads, while each city and town would preserve its own local time. A similar proposal, but one that recommended adjusting local time to railroad time, was later successfully promoted by William F. Allen [135], editor of a prominent railroad periodical and Secretary of the American Railway Association. Important contributions were also made by Cleveland Abbe [136] of the US Signal Service and Sandford Fleming [137] of the Canadian Pacific Railway. To permit a more convenient location of time zone boundaries, the Greenwich meridian was chosen as the primary reference rather than Washington, D.C. "Standard Railway Time" was adopted throughout North America at noon on Sunday, 18 November 1883, reducing the number of railroad times from forty-nine to five, and was soon extended to civil time [138].

The rapid growth of the railroads created a demand for time synchronization across large distances and the continuing expansion of the network of telegraph wires along their rights of way provided the means for achieving it. Towards the end of the nineteenth century, the US Naval Observatory was disseminating a daily time signal via the Western Union Telegraph Company to cities throughout the East, South and Midwest of the USA [139].

Daylight Saving Time was conceived by William Willett, a successful London builder, in 1907 [140]; it was first introduced in Europe and North America during the First World War as a means of conserving energy [141]. In the USA, the Standard Time Act of 1918 required the observance of Daylight Saving Time, which is advanced 1 h ahead of Standard Time over seven months of the year, in addition to providing a legal basis for five time zones (extended to eight in 1966 to cover all US territories).

10.2 Greenwich Mean Time

Originally, Greenwich Mean Time (GMT) was defined as mean solar time on the meridian of Greenwich reckoned from mean noon. In 1919, the BIH undertook to coordinate the emission of radio time signals on the basis of Greenwich Civil Time (i.e. GMT plus 12 h), as recommended by the International Meridian Conference.

The astronomical almanacs kept GMT as the time argument until 1925. Beginning in 1925, the British *Nautical Almanac* and many other national ephemerides reckoned GMT from midnight to coincide with the civil day, rather than noon as had been the traditional astronomical practice. The redefined GMT was designated Universal Time (UT) by the IAU in 1928 [142]. However, the term GMT persisted in almanacs and navigation publications and the ambiguity in its intended meaning was the cause of some confusion [143].

10.3 Coordinated Universal Time

The terms "mean solar time" and "GMT" have come to be recognized as being synonymous with UTC in ordinary language. In 1970, Commission 31 of the IAU recommended that clocks in common use would indicate minutes, seconds and fractions of UTC and that the term "GMT" would be accepted as the general equivalent of UTC in navigation and communications [144]. The 15th CGPM in 1975 adopted the following resolution [145]:

"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 is strongly endorsed."

The international diplomatic authority for the decisions of the CGPM and its organs is conveyed through the Convention of the Metre of 1875. The CCIR in 1978 and the World Administrative Radio Conference (Geneva) in 1979 recommended that UTC should be used to designate the time in all international telecommunication activities [146].

The ITU *Radio Regulations* define UTC as the time scale, based on the SI second, as specified in Recommendation ITU-R TF.460-5. The definition is accompanied by the following Note [147]:

"For most practical purposes associated with the Radio Regulations, UTC is equivalent to mean solar time at the prime meridian (0° longitude), formerly expressed in GMT."

This definition is cited in the *Code of Federal Regulations*, Title 47, that specifies the rules of the US Federal Communications Commission (FCC) [148].

The role that UTC plays in national and international monetary exchange, telecommunications and related forms of commerce is not clear. Should the definition of UTC be revised, the effect on legal codes may need to be investigated.

11. Future developments

11.1 Options for UTC

There exist a variety of options for the future of UTC. Some of these options are identified and discussed below.

(1) *Maintain the status quo.* The advantage of maintaining the present form of UTC is that established timekeeping practices will not require modification. On the other hand, if leap seconds were continued, the required number and frequency can only increase, as shown in Figure 6. By 2100 there would be a need for nearly *two* leap seconds per year. The current emerging problems and the resulting dissatisfaction with leap seconds will only continue to grow. The operational impact and associated cost of maintaining leap seconds in complex timekeeping systems must be considered in evaluating their continued use in the future.

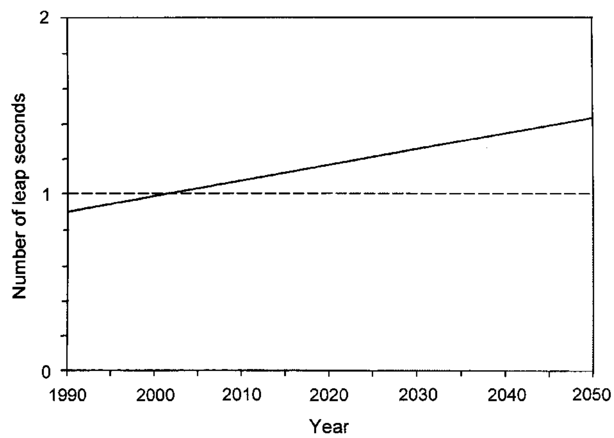

Figure 6. Projected increase in leap seconds versus time (after McCarthy and Klepczynski [149]).

(2) *Increase the tolerance between UT1 and UTC.* A small increment of several leap seconds could be inserted into UTC every few years or, alternatively, a "leap minute" in about fifty years. The advantage of this approach is that it would be relatively easy to adopt. However, due to the parabolic rate of departure between solar time and atomic time, the tolerance would have to be continually increased and eventually larger time steps would be required.

(3) *Periodic insertion of leap seconds.* A time step could be inserted into UTC at a well-defined interval, such as on 29 February every four years. The advantage is that the date would be predictable. However, the number of leap seconds would not be predictable and large time steps would still be required.

(4) *Variable adjustments in frequency.* This alternative is similar to the original form of UTC that was abandoned. Introducing a variable atomic scale in step with solar time would cause significant disruptions to equipment and would not disseminate the unit of time, the SI second.

(5) *Redefine the second.* This option would appear to be the most fundamental solution. However, it would be inconsistent with the usual practice in metrology, which is to adopt a new definition of a unit only when its realization under the old definition becomes the limiting source of experimental uncertainty and to maintain continuity between the old and new realizations. Changing the definition of the second to be closer to the current rotational second would alter the value of every physical measurement and render obsolete every instrument related to time. Moreover, the solution would be only temporary as the Earth continues to decelerate.

(6) *Substitute TAI for UTC.* TAI is the fundamental atomic time scale "in the background" from which other scales of uniform time are derived. TAI is related to UTC by the relation $[TAI] = [UTC + \Delta AT]$, where ΔAT is the increment to be applied to UTC to give TAI and is equal to the total number of leap seconds plus 10 s. In 2001, the value of ΔAT was +32 s. The advantage of TAI is that it is a continuous, atomic time scale without steps. However, TAI is currently not easily available to the precise time user and, as TAI is currently ahead of UTC by an offset of 32 s, a worldwide adjustment of clocks would be required if it were adopted as the scale of civil time. Promotion of two parallel time scales for civil timekeeping, one with leap seconds and one without, would be potentially confusing. In addition, as UTC is recognized as the primary basis of civil time in resolutions of various international treaty and scientific organizations and by many conforming national legal codes, a worldwide change in the legal definition of time would be required if UTC were replaced by TAI.

(7) *Discontinue leap seconds in UTC.* This option would permit continuity with the existing UTC time scale and would eliminate the need for future adjustments to complex timekeeping systems. Figure 7 shows the projected difference between UTC without leap seconds and UT1. If the current rate of deceleration of the Earth's rotation were to persist and no leap seconds were added, by 2050 the difference between UTC and UT1 would be about 1 min. By the end of the twenty-first century, the expected difference would be about 2.5 min [149]. However, these differences are minor compared with the difference between apparent solar time and mean solar time (up to 16.5 min), mean solar time and clock time within a given time zone (nominally up to 30 min), or Daylight Saving Time and Standard Time (1 h). It is thus unlikely that the growing difference between clock time and levels of daylight would be noticeable for the foreseeable future. Also, certain religious customs depend on the actual observation of the Sun or the Moon and do not depend on clock time. Therefore, the elimination of leap seconds would have no practical effect on the correspondence between civil time and solar time or on contemporary social conventions. The use of UTC without leap seconds would retain all the advantages of TAI. The transition to a continuous UTC system might be planned for a future date sufficiently far in advance that changes to existing hardware and software, where necessary, could be accommodated within the normal maintenance and replacement schedules.

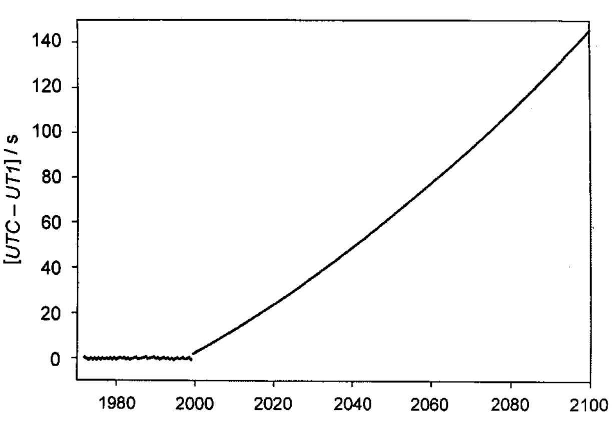

Figure 7. Projected difference between UTC and UT1 if leap seconds were discontinued (after McCarthy and Klepczynski [149]).

11.2 Requirements of celestial navigation

There remains the need to meet the requirements of celestial navigation. Three possible options for addressing this need if the current UTC system were revised are considered. Additional alternatives may be identified as the issue is debated.

(1) *Alternative time scale for navigation.* A new broadcast scale of time, possibly designated "UT1C", might be disseminated by supplementary coded signals that provide the approximate difference between the newly defined UTC and UT1, just as DUT1 codes currently give the difference between the presently defined UTC and UT1 to the nearest 0.1 s. However, most time code formats would have to be modified to accommodate a difference in time greater than 1 s. As a beneficial trade-off, the resolution might be increased in the process, for example to 0.001 s. The time difference $[UTC - UT1C]$ might also be conveniently disseminated in satellite navigation messages, possibly as a commercial service.

(2) *Greater emphasis on UT1 predictions.* These requirements might also be met by published predictions of $[UT1 - UTC]$. The IERS/USNO provides daily and semiweekly predictions in *Bulletin A*, available on the Internet at http://www.iers.org. The estimated accuracies are 0.0017 s at 10 days and 0.0039 s at 30 days. For example, the National Imagery and Mapping Agency (NIMA) provides Earth Orientation Parameter Prediction coefficients based on IERS/USNO weekly post-fit values that are used to generate $[UT1 - UTC]$ predictions for GPS orbit determination. In addition, long-term projections might be included in the nautical ephemerides with less precision. With the usual yearly schedule of publication, the extrapolation should not bring errors exceeding 1 s (leading to a position error of 0.5 km at most). Through both short-term and long-term UT1 predictions, it

would be possible to complement the information to navigators by disseminating a correction to the argument of the ephemerides, as is done currently with DUT1.

(3) *Greater emphasis on satellite navigation systems.* Due to the availability of the GPS and GLONASS satellite navigation systems and the possibility of similar future systems, such as Galileo, the need for coded terrestrial radio time signals is less than it once was. Existing international agreements might be recast to redirect the focus of those agreements towards increased use of modern satellite navigational aids.

12. Conclusions

The transition from solar time to atomic time, made possible by the development of atomic clocks, represents a paradigm shift in the way time itself is perceived that is not unlike the transition from the unequal hour to the equal hour five hundred years ago, brought about by the invention of mechanical clocks, or the transition from apparent time to mean solar time some two hundred years ago that was made possible by improvements to pendulum clocks. The most basic issue in the future of UTC is the nature of the social requirement to adjust an extremely precise, uniform time scale to the time determined using the variable rotation of the Earth. Common practice today has already compromised this requirement to the point that we are content with conventional constructions such as mean solar time, zone time and Daylight Saving Time. We should realize that, as a result of the change from apparent to mean time, the local mean noon of our clocks can sometimes be about 15 min before or after the apparent noon of the Sun; thus the afternoons in November are half an hour shorter than the mornings, while in February the mornings are half an hour shorter than the afternoons. This change was even more fundamental than that from local mean time to zone time [150].

All these conventions introduce substantial differences between the commonly accepted time and solar time that are orders of magnitude larger than the difference between a uniform time scale and a solar time scale. We anticipate that this difference will grow by an additional 2 min over the next century. Will we be willing to neglect this difference in civil time scales? The astronomically determined rotation angle will be measured with improving accuracy during that period and will be made available to users sooner. Will this be able to satisfy user needs?

In each stage of the evolution of timekeeping, there has been an incremental step away from the Sun as the measure of time in favour of a more uniform, accessible, or convenient standard. The next stage in the evolution of UTC may be a definition of civil time in terms of a continuous scale of atomic time and a disassociation of civil time from solar time altogether, accompanied by the adoption of a representation of UT1 for those users who need it.

Throughout the history of time measurement, from sundials to atomic clocks, time scales have always been established by taking into account prevailing technology and needs. Since the UTC system of leap seconds was introduced thirty years ago, both of these factors have changed. Therefore, we should perhaps not be too hesitant in adapting to modern technology and modern needs.

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