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Time scales, their users, and leap seconds

P Kenneth Seidelmann[1] **and John H Seago**[2]

[1] University of Virginia, Department of Astronomy, PO Box 400325, Charlottesville, VA 22904-4325, USA
[2] Analytical Graphics, Inc., 220 Valley Creek Blvd, Exton, PA 19341-2380, USA

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Abstract
Numerous time scales exist to address specific user requirements. Accurate dynamical time scales (barycentric, geocentric and terrestrial) have been developed based on the theory of relativity. A family of time scales has been developed based on the rotation of the Earth that includes Universal Time (specifically UT1), which serves as the traditional astronomical basis of civil time. International Atomic Time (TAI) is also maintained as a fundamental time scale based on the output of atomic frequency standards. Coordinated Universal Time (UTC) is an atomic scale for worldwide civil timekeeping, referenced to TAI, but with epoch adjustments via so-called leap seconds to remain within one second of UT1. A review of the development of the time scales, the status of the leap-second issue, and user considerations and perspectives are discussed. A description of some more recent applications for time usage is included.

1. Introduction

Time is so much a part of daily experience that no thought is ordinarily given to its meaning; nevertheless, the scientific measurement of time interval requires the definition of a standard unit of measurement that is reasonably invariant to human experience [1]. Apparent celestial motions have been exalted through history as a preferred mode of reckoning time, evidenced by calendars based on recurring celestial phenomena and the fact that civil time of day has been based on solar time in one form or another since antiquity. The so-called *leap second* is the means by which invariant frequency standards are reconciled with the astronomical conventions that serve as the basis of civil timekeeping. But this could soon change as the necessity of reconciliation has come under question in recent years [2].

2. Time scales from 2000 BC to AD 2000

Two general approaches to time reckoning have been used since antiquity. Communities often divided the day into hours of seasonally varying duration as indicated by sundials. This variation is a consequence of the duration of the apparent solar day changing over the course of the year, due to the eccentricity of the Earth's orbit and the inclination of the Earth's rotational axis relative to its orbital plane. While the dials of hydraulic (water) clocks were adaptable to indicating variable hours also, the mechanical arrangement itself commonly measured uniform intervals. Hence, astronomers and some other scientists began to reckon time in equal hours at an early date, taking hours at the equinox as standard [3]. The quarter-hour departures between mean and apparent solar time of day over the course of the year—now known as the *equation of time*—were empirically determined at least as far back as the second century AD by Ptolemy [4].

The rotation of the Earth relative to the distant stars is almost uniform in the near term, having unpredictable high-frequency variations on the order of milliseconds per day. By precisely measuring the duration of the year in terms of sidereal days (i.e. 366.242 transits of the vernal equinox), and by recognizing that there is one less solar day per annum than sidereal days, the concept of *mean solar time* is realized by a clock with a diurnal rate of operation that exceeds the sidereal day by approximately $3^{m}56^{s}$ (1/366.242 of a sidereal day). Mean solar time and mean sidereal time are thereby proportional to Earth rotation, which is measured by observing cataloged celestial objects beyond the solar system from fixed observatories. Apparent solar time was still maintained by astronomical almanacs until the early 19th century out of concern to navigators; however, mean solar time is especially useful for civil timekeeping purposes, being the form of sidereal time that keeps pace with the synodic day on average. As a uniform time scale, mean solar time remained basic to both civil and scientific timekeeping into the 20th century.

For centuries some astronomers continued to investigate the conjecture that the rate of Earth rotation was practically

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invariant. In 1675 Flamsteed tested the hypothesis using the best chronometers of the time and concluded that Earth's rotation was 'isochronical' (of constant rate) [5]. By 1906, Newcomb still suggested that 'we are obliged, in all ordinary cases, to treat [Earth-rotation rate] as invariable, for the reason that its change, if any, is so minute that no means are available for determining it with precision and certainty' despite having 'theoretical reasons for believing that the speed of rotation is slowly diminishing from age to age' [6]. Published analyses of systemic variations in the longitudes of solar-system objects, as well as the eventual introduction of quartz-crystal oscillators for observatory clocks, finally affirmed that Earth rotation was less than perfectly uniform by the 1930s.

For the purposes of developing a more absolute uniform time scale, 20th-century astronomers moved to the dynamical time-like argument of Newcomb's solar-system theory [7]. This led to an unprecedented separation of two timekeeping concepts by the 1950s. Mean solar time at Greenwich eventually became known as *Universal Time* (UT) and was synonymous with the (slightly varying) rotation of the Earth, while the Newtonian-time argument of solar-system theory eventually became known as *Ephemeris Time* (ET) and was synonymous with a theoretically uniform time scale for scientific applications. When Ephemeris Time was proposed by Clemence in 1948, it 'seemed logical to continue the use of mean solar time [. . .] for civil purposes' with Ephemeris Time 'for the convenience of astronomers and other scientists only' [8]. By so doing, horologists made a distinction between precise *time* as the dating of physical phenomena, and precise *time interval* as the accumulation of uniformly increasing duration [9].

As the independent variable of solar-system ephemerides, Ephemeris Time was realized by comparing astronomical observations with a pre-relativistic solar-system theory based on observations from the 18th and 19th centuries. The duration of the *ephemeris second* in terms of the tropical year 1900 was adopted by the International Astronomical Union (IAU) in 1952, with the ephemeris second adopted as metric system's unit of duration in 1960 [10]. However, the practice of determining Ephemeris Time, primarily through observed lunar motion, was untimely and inconvenient. By 1956 atomic resonators provided an ultra-stable source of frequency independent of astronomical phenomena, and a campaign resulted to calibrate the duration of the ephemeris second against cycles of radiation emitted from hyperfine transitions of cæsium-133 [11]. The practicality and accuracy of laboratory time scales based on ensembles of atomic frequency standards led to the abrogation of the ephemeris second within the *Système International d'Unités* (SI) in favour of an equivalent duration in terms of atomic frequency in 1968 [12]. Consequently, the sequence of atomic seconds maintained and coordinated by the International Bureau of Weights and Measures (BIPM) became its own laboratory time scale known as the *Temps Atomique International* (TAI) [13].

The definition of an SI second in terms of atomic frequency is intrinsically local, or, relativistically *proper* [14]. By the 1970s, the improving accuracies of clocks, astronomical measurements and time-transfer methods required the introduction of general relativity theory into the modelling of the solar system, the reduction of astronomical observations, and the maintenance of time scales over large distances. Theoretical coordinate time scales were necessitated based on the hypothetical duration of SI seconds at the surface geoid of the rotating Earth (*Terrestrial Time*, TT), the geocentre of the Earth (*Geocentric Coordinate Time*, TCG) and the barycentre of the solar system (*Barycentric Coordinate Time*, TCB), along with the relativistic Lorentz transformations between them [15]. Descriptions were improved to clarify that TAI was a practical realization of TT, the rate of which was offset from TCG [16, 17]. Ephemeris Time would be replaced by TT, TCG and TCB, depending on the application, although solar-system ephemerides such as those developed by the Jet Propulsion Laboratory (JPL) use a form of barycentric coordinate time that is rescaled and adjusted to closely match TT (figure 1) [18].

Universal Time also continued to be more accurately defined as the science of Earth orientation advanced [19]. Since 1956 Universal Time has been classified three ways: UT0 (as observed), UT1 (UT0 corrected for polar motion) and UT2 (UT1 corrected for seasonal fluctuation). UT1, being the variant that most precisely represents the instantaneous orientation of the Earth's surface about its rotational axis, is currently defined as being linearly proportional to the so-called *Earth rotation angle* [20]. The constant of proportionality between UT1 and Earth angle has traceability back to Newcomb's determination of the mean motion of the Sun, thereby making UT1 a very close approximation to the mean diurnal motion of the Sun and the best indicator of astronomical time of day currently maintained.

3. Coordinated Universal Time (UTC)

From the beginning of World War II until the advent of atomic frequency standards, quartz-controlled vacuum-tube oscillators were commonly used to maintain radio transmission frequencies. Prior to 1956, broadcasts of mean solar time were maintained in the USA within several hundredths of a second of US Naval Observatory clocks by tuning NIST radio station WWV's control oscillator frequency higher or lower to gradually advance or retard the broadcast time. Soon after atomic frequency standards replaced the use of quartz for time broadcasts, incremental stepping was also used in conjunction with oscillator rate offsets to track Universal Time. The *Bureau international de l'Heure* (BIH) in Paris provided a more definitive version of Universal Time by referring global time-service emissions and astronomical observations to the BIH master clock, with corrections published a month or more after the fact via *Bulletin Horaire* [21]. Beginning in 1960, US and UK broadcast time services started closely coordinating their broadcast time signals, as the observation of artificial satellites made it necessary to have a single worldwide system of timing signals that avoided months of waiting for coordinated corrections [22]. Increasing numbers of time services participated directly within the framework of the IAU and *Comité Consultatif International pour la Radio* (CCIR), and by 1964 the transmission of time and frequency by radio

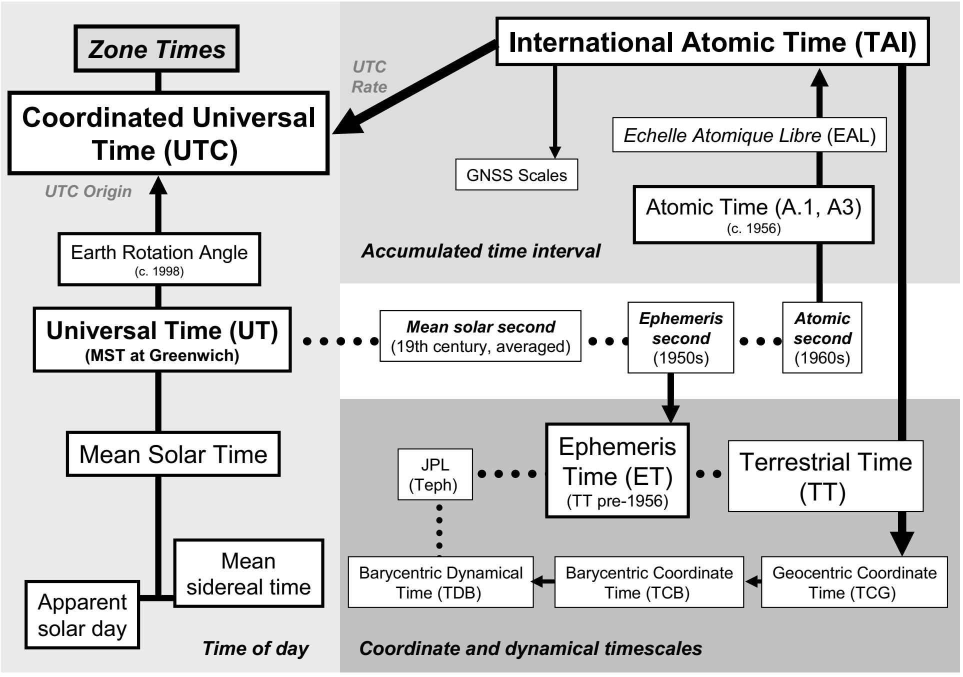

Figure 1. Time scale classifications and their relationships.

was mostly on atomic time. The system of time broadcasts soon became known as 'Coordinated' Universal Time, with the BIH designating annual rate offsets and announcing when time steps should be added into these broadcasts [23]. Its conventional acronym 'UTC' eventually supplemented the existing family of Universal Time acronyms UT0, UT1 and UT2.

By 1968 timing signals via radio were also becoming increasingly used for economically important applications such as equipment automation, thus moving the emphasis of timekeeping towards the uniformity of the scale and the constancy of the unit [24]. The changing offsets in frequency from the cæsium resonance became a nuisance as precise calibration of television and radio transmitters was necessary to maintain the congested frequency spectrum. Precise calibration was also required for the operation of radio-navigation systems; with the proposed introduction of an air collision-avoidance system in the early 1970s based on precise frequency, the use of varying frequency offsets was deemed intolerable [25].

It was nonetheless understood that 'time scales have traditionally provided the time of day and the season of the year, as well as time interval, and, if it is to be of universal use, the atomic scale must be coordinated with astronomical scales' [24]. At a 1968 meeting of the CIPM, the concept of the *leap second* was proposed by Winkler and Essen as a more convenient method for synchronizing atomic frequency standards with astronomical time of day. As time signals eventually deviated from Universal Time by approximately ± 0.5 s, the encoded date within the signals would permanently shift by one second to maintain proximity to Universal Time without disrupting frequency.

Celestial navigation is sometimes cited as the primary reason for introducing the concept of leap seconds, but leap seconds alone did not meet the needs of navigation, surveying and related applications. Uncertainty in UT1 greater than 0.2 s was already considered too imprecise for navigation purposes [26, 27]. Supplementary information was therefore coded to radio timing signals for recovery of UT1 to a precision of 0.1 s, which was considered to be the practical limit for unaided human time-discrimination. Beyond the technical requirements of navigation, national statutes and regulations also obliged the maintenance and distribution of mean solar time at Greenwich as a basis for timekeeping globally, with national time zones correlated to the mean solar time of standard meridians. The *Conférence Générale des Poids et Mesures* (CGPM) endorsed the usefulness of adopting UTC as a basis of civil timekeeping only after 'considering that [. . .] UTC is [. . .] an approximation to Universal time, (or, if one prefers, mean solar time)' [28]. Leap seconds thereby allowed regulatory authorities to substitute legally prescribed Universal Time with its atomic approximation, Coordinated Universal Time.

3.1. Definitions and descriptions of atomic timekeeping

In the 20th century, wireless radio signals became the primary means for transferring time and frequency. As an organization involved with the regulation of radio emissions, The Radiocommunications Sector of the International Telecommunication Union (ITU-R) became responsible for maintaining UTC's transmission guidelines. ITU-R Recommendation TF.460 defines UTC as a *time scale* in the sense that 'a time scale is a system of assigning dates to events' [29]. Such ITU-R recommendations prescribe operational, technical, procedural and regulatory information to which participating administrations have agreed, but the ITU-R is not ordinarily responsible for the development and maintenance of time scales and as an administrative regulatory union it cannot ensure that UTC is produced, disseminated or utilized correctly. Rather, the maintenance of TAI is the responsibility of the BIPM, which is chartered through the Treaty of the Metre. As a successor to the BIH since 1988, the International Earth Rotation and Reference Systems Service (IERS) determines the timing of leap seconds via its monitoring of Earth rotation as a joint service of the IAU and International Union of Geodesy and Geophysics (IUGG) [30].

Officially, UTC is evaluated in arrears by the BIPM through published corrections to the emissions of primary frequency standards via *Circular T* [31]. However, the multitudes of ordinary users (e.g. beyond metrologists and timing centres) simply require an instantaneous realization. While ITU-R Recommendation TF.536-2 recommended the nomenclature 'UTC(k)' for realizations from contributing timing centres (where k symbolizes an acronym identifying a particular time service), the distinction between real-time UTC(k) and latent UTC(TAI) is not obvious from the context of Recommendation TF.460 [32]. TF.460 has always been foremost a transmission specification for real-time time-signal emissions, i.e. UTC(k); however, Annex I of TF.460-6 describes UTC as being 'maintained by the BIPM' although that realization is never emitted [33]. Mention of 'UTC' by non-experts could therefore refer to UTC(TAI), UTC(k), or some less accurate yet convenient realization that meets the users' immediate requirements. Analogously, discussion of 'TAI' could refer to TAI(k), which equals UTC(k) + DTAI per Recommendation ITU-R TF.536-2, with DTAI equaling TAI – UTC per Recommendation ITU-R TF.460-6. Non-experts might also refer to 'TAI' as a method of internal dating equal to some convenient realization of UTC plus DTAI.

The suggested use of 'TAI' as a real-time internal reference scale for systems has been recommended in the past by the Director of the BIPM, the Consultative Committee on Time and Frequency (CCTF) and the ITU-R via Recommendations TF.485-2, TF.536-2 and TF.1552 [34–36]. The recommendation to broadcast DTAI for this purpose continues to be prescribed by Recommendation TF.460-6. The ITU-R study group responsible for these Recommendations simultaneously acknowledged that UTC study documents contributed by expert and non-expert users 'demonstrate a clear misunderstanding of the definitions and applications of time scales and system times for internal synchronization,' also noting that 'TAI is not an option for applications needing a continuous reference' as it has no means of dissemination and is not physically represented [37]. It was also noted that 'GPS time is not a reference time scale but is instead an internal time for GPS system synchronization'; nevertheless, many operational systems rely on high-precision GPS signals to establish internal reference time scales, such as CDMA mobile-communications networks. The recent suppression of Recommendations TF.536-2 and TF.1552 may serve to increase user uncertainty regarding the recommended descriptors for real-time realizations of timing signals.

In addition to user confusion over time scale nomenclature, widespread suggestions that UTC is not 'continuous' may also lead to potential misunderstandings over its definition. Within the prescriptions of Recommendation TF.460, UTC as a *time scale* (system of labelling dates) is a completely sequential and coherent atomic scale, having the same rate as TAI by definition. The interval of a positive leap second is to be precisely labelled as 23h 59m 60s; conventionally every second of UTC is thereby uniquely described. Calendars are not described as 'discontinuous' because of an unambiguous insertion such as February 29; therefore, the coercion of clock hardware incompatible with the display of a 61st second likely contributes to the mischaracterization of UTC as 'discontinuous' or of leap seconds creating 'ambiguity in dating events.' UTC's progression of TAI seconds arguably qualifies it as a uniform time scale for very many applications, although leap seconds affect the length of day such that some UTC days have lasted one second longer than other UTC days.

The degree to which a user's frequency standard provides accurate time intervals depends on the method of synchronization and the stability of the oscillator being synchronized. Today, UTC may be realized through many different means to various levels of fidelity, including shortwave and very-long-wave (VLF) radio signals, satellite broadcasts, electronic navigation services, telephone time codes, microwave links, cable and various other modes of telecommunication. Hence, while the distribution of precision timing signals remains a telecommunication matter in general, the definition of UTC is no longer an issue specific to the radiocommunications sector. Because UTC serves as the global basis of all precision timekeeping, and because its user population is so vast, this raises a question as to what degree other international organizations should be involved with the definition of UTC.

3.2. Study efforts for revising UTC

A proposal to redefine UTC by halting leap seconds after 2017 has been advanced from ITU-R Study Groups for consideration by the Radiocommuncations Assembly in January 2012. The proposal originated within ITU-R Working Party 7A, which appointed a Special Rapporteur Group (SRG) on the future of UTC in October 2000 to address Study Question ITU-R 236/7:

(1) What are the requirements for globally-accepted time scales for use both in navigation and telecommunications systems, and for civil timekeeping?
(2) What are the present and future requirements for the tolerance limit between UTC and UT1?
(3) Does the current leap-second procedure satisfy user needs, or should an alternative procedure be developed?

The Study Question originally decided that the results 'should be completed by 2002 at the latest' but the completion date has been extended up to the present (2011).

Following the activity of several coordination and technical exchange meetings, the rapporteur group presented a consensual opinion—the so-called *leap hour*—at a Special Colloquium in 2003 [38]. Because this proposal did not allow UTC to remain a viable realization of UT1, and because the label 'Universal Time' has always been reserved for time linked to Earth rotation, continued use of the labels 'Coordinated Universal Time' and 'UTC' would no longer be appropriate

[39]. Colloquium attendees drafted a summary of finding recommending a change of name if leap seconds were ever discontinued to avoid technical confusion. The establishment of a new name for UTC without leap seconds—suggested to be 'International Time' (TI)—would also be technically advantageous by allowing for retroactive conversion of historic data onto a newly named scale [40]. But the recommendation for a new name was dismissed to avoid 'great confusion and complications in the ITU-R process' [41].

The proposal to redefine Coordinated Universal Time has since become 'the most intensely discussed and controversial issue in timekeeping' [42]. Many of the perceived issues surrounding leap seconds have been spawned by newer technologies, particularly those related to Information Technology. Not surprisingly then, records of electronic discussions over the past decade abound within the realm of cyberspace on the advantages, disadvantages, issues and concerns over the definition of UTC, although expert participation from ITU-R study-groups and other organizations traditionally involved with timekeeping is not prominent within these fora.

Discussions between the members of organizations traditionally involved with timekeeping issues have not led to a recognizable consensus either. There remains a shortage of unified responses by many major stakeholder organizations, a situation which has 'been interpreted as [these organizations] having no concern' by relevant ITU-R study groups, or, that these organizations are 'completely or more or less neutral' on the subject of UTC redefinition [37, 43]. However, abstentions in many cases reflect ambivalence or a lack of consensus amongst memberships, rather than official neutrality or indifference. Ordinarily, abstention might be regarded as contentment with the *status quo*, but abstentions may also reflect ignorance of the technical issues and their impact. Because consensus could not be reached within ITU-R Study Group 7 and Working Party 7A, a questionnaire was circulated among the almost 200 member-state administrations of the ITU-R in 2010 [44]. Approximately 5% responded to the questionnaire before the Study Group 7 chairman elected to advance the proposed Recommendation to the 2012 Radiocommunications Assembly. The handful of responsive administrations (both for and against) were mostly represented within Study Group 7 and Working Party 7A already, and thereby had keen familiarity with the issues and concerns of the questionnaire.

The points of debate are quite numerous [45]. Those who favour the cessation of leap seconds note that their introduction has caused operational disruptions in the past, such that they might cause disruptions in the future. The number of leap seconds per decade is also expected to increase into the future due to angular deceleration of the Earth. Currently, leap seconds are perceived as an anomaly within increasingly complex telecommunication, navigation and networked-computing systems because of their relative rarity, raising questions about the safety of future real-time systems. Concerns have also been expressed over a potential increase of 'pseudo-' time scales that do not keep pace with UTC. Philosophically, it is argued that the general public should remain insensitive to the secular separation of clock time from Earth orientation because the seasonal differences between apparent solar time and wall-clock time already suggest that astronomical time has limited impact on modern culture. Applications requiring Universal Time should also benefit from a realization more precise than UTC, published by the IERS as a predicted correction to UTC without leap seconds.

Those who favour the *status quo* note that the assumption of a small difference between UT1 and UTC is already hardwired into deployed systems, and the costs to modify and test such systems (including the ability to receive Universal Time from sources other than time signals) appear to be unstudied on a large scale. There are alternative time scales (systems of labelling dates) already available for applications that are inconvenienced by leap seconds, such as TAI(k) and global navigation satellite system (GNSS)-based scales. Some less-precise applications, such as date-stamping by personal computer operating systems, have the option to speed up their oscillators in the vicinity of a leap second. Reported problems with leap seconds often seem isolated, anecdotal or lacking in detailed consequences (for example, one high-profile 'failure' repeatedly attributed to leap seconds—a 20 hour outage of the GLONASS navigation system—was actually scheduled maintenance announced in advance) [46, 47]. Changing UTC will not eliminate the need to manage leap seconds that have already happened, and preserving the name 'Coordinated Universal Time' and acronym 'UTC' for a fundamentally new system could invite confusion. Because the issue of decoupling civil time and Earth rotation has never been seriously considered before now, long-term philosophical and sociological concerns have yet to be carefully explored.

4. Users and their applications

The myriad of modern time scales have been developed to satisfy or anticipate user requirements, whether they are very accurate relativistic time scales, accurate Earth rotation, precision frequency and duration, or some combination thereof. Except for Universal Time, all these time scales practically originate from TAI. Because UTC serves as the basis of all precision timekeeping, and because UTC also maintains the dual purpose of providing both precision time interval and astronomical time of day, the user population of UTC is exceedingly immense relative to other time scales. Computing scientists suggest that the present definition of UTC poses 'no significant problem for distributed computer systems' [48]. Programmers suggest that leap seconds cause complications as new applications are not being designed to correctly deal with UTC as historically defined.

4.1. Issues introducing and communicating leap seconds

Precise network-time synchronization is essential for modern network performance analysis, and significant expense may be incurred characterizing, analysing and managing networked systems. The IEEE P1003.1 (POSIX) standard is an example of how device operating systems use a formula to convert 'seconds since epoch' into calendar date and time of day [49]. However, such a formula does not account for leap seconds (partly because the standard does not require system clocks to be accurate). System calls exist to support adjustment of the POSIX system clock times when a leap second occurs, but its execution requires a widely implemented kernel modification that receives a leap-second announcement and automatically performs leap-second correction. This is usually by way of the Network Time Protocol (NTP), a commonly used distributed service that synchronizes a computer clock to an ensemble of sources. NTP response packets include a leap indicator field that notifies networking elements that a leap second should be inserted at the end of the current UTC day. The insertion of leap seconds in UTC and NTP does not affect their oscillation, but only the conversion between UTC and NTP network time (which also represents timestamps in units of seconds since epoch) [50]. NTP can be made leap-second aware via the *ntp leap* command which inserts a leap second within the month the leap is to occur, and via the operating system's leap-second file from the US National Institute of Standards and Technology (NIST) which is available months in advance [51].

While support exists for leap seconds within NTP services, temporary loss of synchronization still is sometimes reported after leap seconds occur. It is often unclear whether such incidents result from outdated server software, inadequate network-device notifications or something else. It is also unclear how much economic or technical adversity results from synchronization losses in general. Oscillators steered by GNSS receivers can now provide precise timing signals more directly.

4.2. Issues displaying and handling leap seconds

Operating system kernels tend to present UTC or zone time during a leap second in ways that contradict with Recommendation TF.460. Some system clocks are programmed to step backward by one second, which possibly misrepresents the ordering of sequentially timed events. A system clock holding the same time stamp throughout the leap second avoids this apparent time reversal but potentially creates duplicate time stamps. A more recent practice is for operating systems to temporarily slew the system clock frequency by a small percentage, which preserves monotonicity but results in less-accurate time stamping in proximity of a leap second [52]. Because computer oscillators are not accurate clocks and must be reset to the time of an accurate time source anyway, yet another approach is to simply reset the clock against a timing service soon after a leap-second, but this practice can cause a surge of network traffic for network-based time services [53]. Programmed date arithmetic that ignores the possibility of a leap second will also convert UTC time stamps into inaccurate time intervals. Oftentimes such neglect is intentional as only specialized applications require time precise to better than one second. But inconsistent treatments between shared data may affect interoperability in potentially unpleasant ways.

At the same time, software is inherently upgradable and extensible, and computing equipment is now relatively low cost and often rapidly replaced. One might suppose that the future of all civil timekeeping should not hinge on the limitations of certain transient technologies. It also seems reasonable to expect that hardware and software will continue to improve their support for proper leap second handling and UTC display should the definition of UTC remain unmodified.

4.3. Issues for systems reliant on UT1

Proposed changes to UTC should impact technologies related to astronomy, astrodynamics and celestial mechanics, ground-to-space satellite communications, navigation, remote sensing, space surveillance and similar fields [40]. The accuracy of transformations between the terrestrial reference frame and the celestial reference frame could be adversely affected should UTC no longer represent Universal Time. Some UTC-compliant systems might need to be modified to distinguish between UTC without leap seconds and UT1, thus requiring careful software reviews and hardware testing. Even systems requiring no change would need to be methodically assessed at significant expense to determine this for a fact.

In some segments an execution error might occur as soon as the difference exceeded ± 0.9 s because of operational features designed around the bounded nature of UT1 − UTC. For example, Earth-orientation parameters are entered by a human operator for operational systems firewalled from network connectivity, such that the ± 0.9 s limitation serves as a check against gross data-entry errors. Knowledge that UT1 − UTC can never be very large also allows engineers to design systems to function even when the actual difference is unknown or invalid, although perhaps at a slightly degraded level of performance. Because systems can maintain Universal Time simply by referring to a time signal without operator involvement, large-scale evaluations might be required to determine how to get UT1 − UTC corrections into component applications where they may have never existed before. This makes reliable cost-estimates difficult.

A general concern with draft Recommendation TF.460-7 is that its details are not directly available to the multitude of UTC users outside the delegations of the ITU-R. Presumably the IERS will continue with the determination of UT1 regardless; however, the IERS is not a telecommunications service and distributing UT1 beyond the existing practice of issuing of bulletins and tables would extend its current purview. If the *status quo* is altered, this would be a notable change from current operating paradigms, especially if electronic transmission of requests is required. Active transmission is generally harder and more expensive than passive reception, and it is also unknown how many operational systems might be isolated from transmission networks for reasons of cost, convenience or security. There are, however, promising suggestions that GNSS services may broadcast UT1 − UTC in the future, such as the navigation messages of GLONASS-M navigation satellites including UT1 offsets from UTC(SU).

4.4. Societal issues

History suggests that timekeeping based on heavenly motions will continue to be specially regarded far into the future. Future dates are expected to be maintained according to astronomical calendars, and astronomical imperfections in calendars have been historically corrected once noticed, rather than ignored. Today's system of leap seconds makes calendrical adjustments almost inconspicuous, but should we choose to formally sever global clock readings from the motion of the sky, it is unclear how the two systems could ever be realigned [54]. The suggestion that futuristic systems will be well positioned to 'simply add' large increments to atomic time after many decades or centuries appears incompatible with the tandem conjecture that current systems may already be too complex to accommodate one-second adjustments of much greater regularity [55]. The abandonment of leap seconds would also purge expectations that timekeeping and telecommunications equipment accept and display intercalary adjustments, whether they be a 61st second, 61st minute or 25th hour, thereby creating technical hindrances to re-correlating global timekeeping practices back to celestial time of day. The opinion that future societies will amicably tolerate large changes because of daylight-saving time is also fragile: summer-time changes are a means to maximize the availability of sunlight during waking hours that is not practiced globally and is relatively new (historically speaking), yet large adjustments to the underlying global *basis* of uniform time of day (e.g. either atomic time or mean solar time) are without modern precedent.

Researchers have suggested that as the number of leap seconds per decade gradually increases due to tidal deceleration of the Earth by the Moon, the number of communications and software problems could increase correspondingly. Such could lead to a growth of alternative time scale representations [56]. However, it seems just as reasonable to hypothesize that any immediate problems associated with leap seconds are a consequence of their unusual rarity; increasing regularity should also cause increasing awareness and lead to improved support, communication and automation [54]. The rate of two leap seconds per calendar year is often cited as a potentially troublesome benchmark, although this already occurred in 1972.

The repercussions for some non-technological yet socially significant applications also appear uncertain, as position statements are lacking from elements of society that might have vested reliance or very strong philosophical preferences regarding the representation and global distribution of astronomical time of day. For example, expectations of religious concerns have been discussed, but not pursued, within the precision timekeeping community [57]. Certain religious customs depend on actual near-term sightings of the Sun or the Moon, but when these events are obscured due to, say, local weather or topography, or when it is otherwise impractical for individuals to accomplish accurate astronomical sightings, clocks and almanacs (or equivalent software) serve as intermediates. Some estimates have suggested that civil clocks may diverge from the heavens by 2.5 min by the end of the century if UTC is redefined [58]. Yet many ritual activities regulated by Earth rotation are predictable to accuracies of minutes to seconds, limited in part by the precise knowledge of one's location and the local meteorological conditions affecting atmospheric refraction.

5. Conclusion

Once it became necessary to distinguish between Earth-rotation time and more-uniform realizations of time interval, it was deemed undesirable 'to transmit two kinds of time because of the confusion that would result' [59]. Rather, it was held that a single transmission should serve as many users as possible, which led to time broadcasts providing both standard time interval and astronomical time of day. As a leading developer of atomic resonators and one of the original proposers of the leap second, Essen argued that the original UTC transmissions of the 1960s based on 'rubber' or 'elastic' broadcast seconds presented certain disadvantages, namely, that timing corrections had to be occasionally applied, that equipment sometimes had to be modified when offsets periodically changed, and that automatic equipment might be upset by adjustments [24].

It is therefore ironic, but not unexpected, that comparable arguments have been revived against the leap second as 'continuing pressure for the adoption of atomic time without steps' in time-signal emissions was forewarned at the onset of leap seconds four decades ago [60]. Predictably then, today there is still no strong consensus on what to do next regarding UTC. Conflicting opinions and concerns exist within various communities over the problems that leap seconds cause and the scale of their injury. Most, if not all, of today's concerns about UTC are far beyond the scope of radiocommunications, where the responsibility for UTC historically landed. There appears to be a dearth of published investigations, both by potentially disenfranchised stakeholders and by authorities currently entrusted to explore this topic, that sufficiently survey the advantages and disadvantages of changing UTC now. The paradigm for having a singly transmitted time scale has been fractured by the worldwide exposure, easy access and high accuracy of GNSS signals now used for internal timekeeping of systems and networks.

The halt of future leap seconds from UTC would not necessarily diminish the use of, or need for, existing time scales already addressing specific user requirements and their cessation does not ensure against the creation of new proprietary scales. Reinstating intercalary adjustments will be difficult if they are retired for any length of time, and there are long-term consequences of breaking civil timekeeping from the heavens that have not been satisfactorily assayed. Yet *status-quo* UTC requires no changes to most operations and would provide a minimum of concerns to those relying on it as a realization of UT1 [56]. Because UTC without leap seconds is no more precise than UTC with leap seconds, it seems that there is still a strong case to prefer leap seconds.

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