A Brief History of UTC Leap Second

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https://doi.org/10.26636/jtit.2023.4.1486

Abstract — Since 1972, a leap second has been added, approximately once a year, into UTC, the world's atomic time scale used for civilian purposes, to keep it in phase with the Earth's rotation. Leap seconds ensure that the Sun remains over the Greenwich meridian at noon, with the accuracy of approximately 1 s. The issue of adding the leap second has been debated since 2000 by different working groups of various international organizations, especially ITU-R WP 7A. The main question remains whether the need for the leap second still exists, as its introduction is associated with numerous technical inconveniences. An overwhelming opinion that prevails in those groups is that it would be more beneficial to let the atomic time run its course and accept that the world's civilian time scale is bound to slowly diverge from the rotation of the Earth. The National Institute of Telecommunications has become, in recent years, one of the leaders of this process. This article provides a brief history of the current UTC-related practices and outlines various potential solutions to the problem.

Keywords — atomic time, GNSS time scales, leap second, time in digital systems, UTC

1. Introduction

The International Bureau of Weights and Measures (BIPM) located in Sèvres near Paris is responsible for the monthly computation and publication of the international reference time scale – Coordinated Universal Time (UTC) [1]. From time to time, a leap second (a positive or negative value) is added to UTC to keep it in pace with the slightly irregular rotation of the Earth [1], [2]. UTC is based on a uniform atomic time scale – the International Atomic Time (TAI), with leap seconds not applying thereto. TAI and UTC are paper time scales, but UTC, unlike TAI, is characterized by real-time approximations offered by national laboratories and astronomical observatories supplying data for its calculation.

The 15th General Conference on Weights and Measures (CGPM) held in 1975 noted that UTC provides a basic civilian time scale the use of which is legally certified in most countries. It was also stressed that its usage should be strongly endorsed [3]. On the other hand, the ITU Radiocommunication Sector (ITU-R) is responsible for setting standards for the content and structure of time signals to be disseminated via radiocommunication systems, including the standard frequency and time signal service (SFTS) as well as the standard frequency and time signal-satellite service (SFTSS), and recommends that all standard-frequency and time signal emissions should conform as closely as possible to UTC [4]. In particular, ITU-R is responsible for the dissemination of [UT1-UTC] by means of radio broadcasting.

The ongoing and increasing difficulties created by the periodic insertion of the leap second into UTC, affecting in particular GNSS systems, and the potential solution of this problem are addressed in this paper. The paper also describes mutual roles of CGPM and ITU-R in defining and disseminating the UTC international time scale. An important step forward was made in December 2023, during the World Radiocommunication Conference (WRC-23) in Dubai, UAE, in which the National Institute of Telecommunications played a major role. Decisions taken by the member countries are intended to greatly improve the safety of critical infrastructures, with a particular emphasis placed on telecommunication networks.

2. Measurement of Time – Historical Note

"Since ancient times, celestial bodies – the Sun, the Moon and the stars – have served as the fundamental markers of time. Rising and setting Sun, along with the stars, determines the day and night cycle. Different phases of the Moon determine the month and positions of the Sun and stars along the horizon determine the seasons" [5]. Sundials were among the first instruments used to measure the time of day. The Egyptians divided the day and night into 12 hours each, which varied with the seasons. The notion of 24 equal hours, meanwhile, was first introduced in the theoretical works of Hellenistic astronomy. It was not until the 14th century that an hour of uniform length became customary due to the invention of mechanical clocks [5].

In the era of telescopic observations, pendulum clocks served as the standard means of keeping time. Unfortunately, they were useless for determining geographic longitude on seagoing vessels. Then, in the middle of the 18th century, a spiral balance spring clock was invented, resolving the problem of accurate determination of longitude in sea navigation. These served as a primary piece of sea navigation equipment until the introduction of modern electronics. Quartz-crystal clocks were developed as radio technology advanced in the 1920s and 1930s. The National Bureau of Standards in Washington, D.C. (currently the National Institute of Standards and Technology) designed the first atomic clock in 1948, using the microwave absorption line of ammonia to stabilize a quartz oscillator. Essen and Parry developed, at the British National Physical Laboratory in Teddington, a practical cesium beam atomic clock in 1955 [6]. Commercial cesium frequency standards were introduced a year later. Norman Ramsey developed the hydrogen maser at Harvard University in 1960. Once practical atomic clocks became operational, Bureau International de l'Heure (BIH) and several national laboratories began to establish atomic time scales. The responsibility for the maintenance of the international standard is now with Bureau International des Poids et Mesures (BIPM). An atomic time scale has been maintained continuously since 1955 [7].

3. Modern Time Scales

The 13th CGPM held in October 1967 adopted the atomic second as a fundamental unit of time used in the International System of Units. The second was defined as [8] "the duration of 9192631770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium 133 atom". Below, brief descriptions of some timescales in use at present are given.

Universal Time (UT1). UT1 is computed from the raw, observed universal time UT0 by correcting it for the effect of polar motion at the longitude of the observing site. UT1 is commonly understood as a time based on the Earth's rotation and is close to what used to be known as GMT. It is loosely related to the apparent diurnal motion of the Sun and used to serve as a basis for the definition of the second until 1956, when the International Committee for Weights and Measures (CIPM) adopted a new definition based on ephemeris time, referring to the period of the orbit of the Earth around the Sun [7]. This decision was ratified by the 11th General Conference on Weights and Measures (CGPM) in 1960, simultaneously adopting the International System of Units, SI.

International Atomic Time (TAI). TAI is an atomic time scale with its second equivalent to the second of ephemeris time, as adopted in 1956. The first-time measurements relying on atomic standards became possible in 1955, with the first operational cesium-beam standard, at the National Physical Laboratory (NPL) in the United Kingdom [6]. The 13th CGPM (1967/1968) adopted a definition of the SI second (based on a cesium transition) and opened the way towards formal definition of the International Atomic Time (TAI). TAI is an international time standard based on the assumption that UT1-TAI was approximately 0 on 1 January 1958. TAI is a coordinate time scale defined with the use of a geocentric reference frame, with the SI second as realized on the rotating geoid as the scale unit. It is established at the BIPM on the basis of the readings of approximately 400 atomic clocks operating in various establishments around the world, in accordance with the definition of the second and using an optimized weighting algorithm.

When formally adopted in 1971, TAI was an extension of the BIH atomic time scale dating back to 1955. In 1988, the responsibility for maintaining TAI was transferred from BIH to BIPM [7]. An array of approximately four hundred clocks maintained at about seventy laboratories contributes to TAI, using an optimized weighting algorithm.

TAI is a paper time scale not physically represented by clocks. Consequently, it is not used for time dissemination. It is only a step in producing UTC and is sometimes used for scientific purposes.

Coordinated Universal Time (UTC). UTC is currently defined as an atomic time scale adjusted to be close to UT1. Before 1972, such corrections were performed by introducing changes in the length of the UTC second, as well as by step adjustments, principally to facilitate navigation based on celestial observations. As defined today, the UTC system is a stepped atomic time scale (i.e., a scale that includes leap seconds) and was adopted in 1972, based on the recommendation of the Radiocommunication Sector of the ITU (ITU-R) [4]. It has been defined so that the difference between UTC and UT1 remains less than 0.9 s in absolute value and is adjusted by integer (leap) seconds. The leap second, either positive or negative, is introduced into UTC whenever the International Earth Rotation and Reference Systems Service (IERS) recommends that an adjustment is necessary based on astronomical observations of the Earth's rotation [2]. The periodicity of introduction of the leap second is irregular, depending on the unpredictable long-term irregularities of the Earth's rotation. In 2011, the difference between continuous TAI and UTC equaled 34 s [1], [2].

UTC has been adopted by the ITU-R as the international time scale for time dissemination. It is derived from TAI by correcting an integral number of seconds. Like TAI, UTC is a "paper" time scale, but it is approximated by local physical representations UTC(k) through clocks located at national metrology laboratories and observatories that contribute to the establishment of international time scales at BIPM.

UTC is disseminated by its publication in the monthly BIPM Circular T, providing traceability to UTC via the UTC(k) approximations – see some examples in Fig. 1 and [1]. The broad dissemination of UTC through terrestrial and satellite time signal broadcasts is the responsibility of specific national metrology laboratories and some observatories, following the recommendations of ITU-R [4]. In many countries, UTC is used as the basis for the definition of legal times. Predictions of some UTC(k) times are also broadcast by GNSSs, see Fig. 2.

The name "Coordinated Universal Time (UTC)" was approved by a resolution of IAU Commissions 4 and 31 at the 13th General Assembly in 1967 [9]. The present UTC system is described by ITU-R (formerly CCIR) Recommendation ITU-R TF.460-6 [4]: "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" and defined by Resolution 2 On the definition of time scales of the 26th CGPM in 2018 [10] – see Fig. 3.

Furthermore, a Memorandum of Understanding of 2020, concluded between CGPM and ITU-R, defines mutual responsibilities of two organizations (ITU-R and BIPM). BIPM is in charge of defining, computing and disseminating UTC, while ITU-R is in charge of defining regulations and formats for radio broadcasting of UTC and [UT1–UTC].

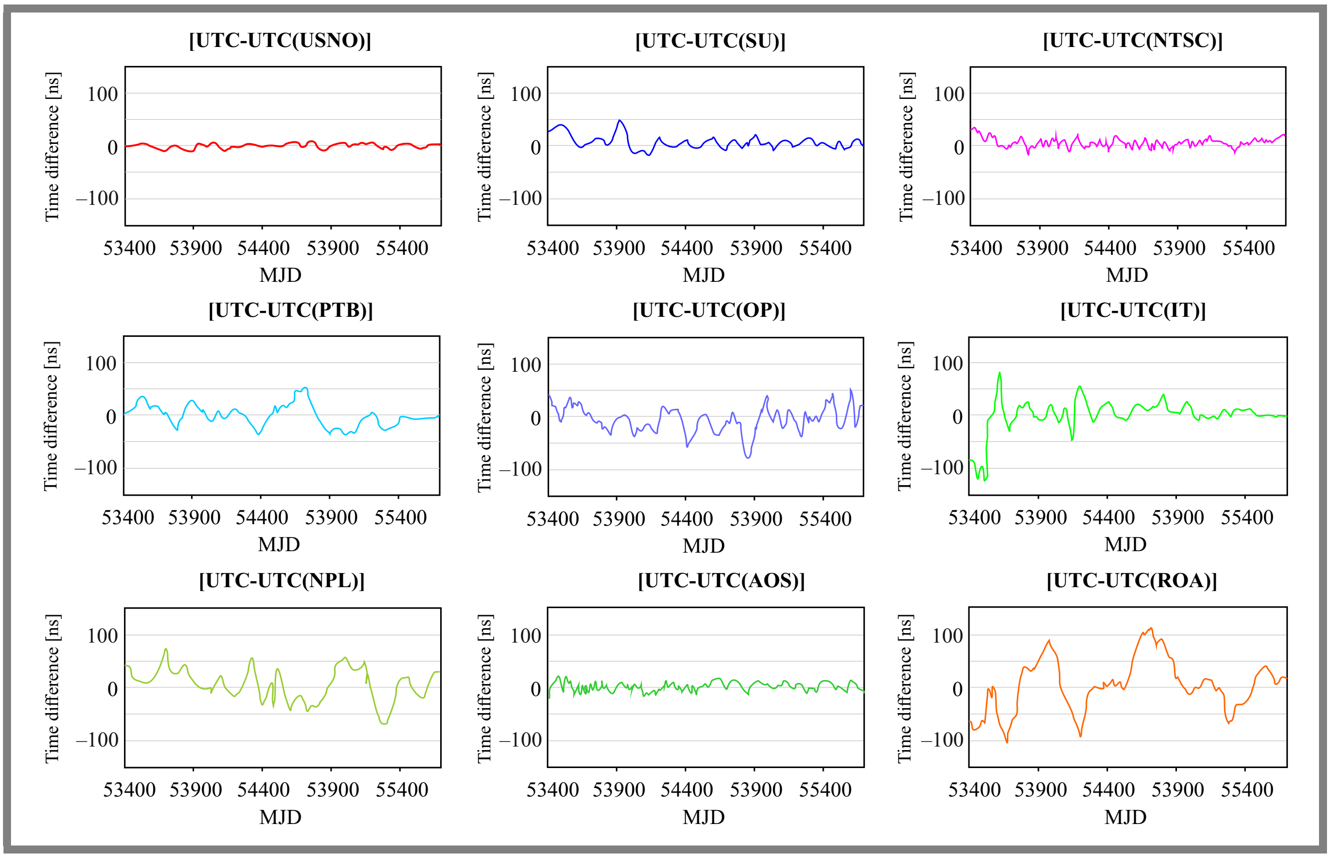


Fig. 1. [UTC-UTC(lab)] since 2005, for USNO, SU, NTSC, PTB, OP, IT, NPL, AOS, and ROA.

The rationale behind the introduction of the leap second is that the second, with its present definition, is “too short” to keep up with the Earth’s rotation. Subsequently, the 27th CGPM in 2022 adopted Resolution 4 **deciding** that the maximum value for the difference (UT1-UTC) will be increased in, or before, 2035 [19]. This was confirmed by WRC-23 in December 2023 in Dubai.

4. Leap Second is Creating Problems for Modern Infrastructure

The global economy is strongly dependent on GNSS, providing a UTC reference to all modern critical infrastructures, such as distributed smart grids, 5G telecommunication systems, financial markets and broadcasting networks. Moreover, the observed strong migration of smaller IT and Industry 4.0 (OT) systems to cloud makes the latter a fifth critical infrastructure category. The ensuing problem affects all countries and all segments of each individual economy. It is exacerbated by the lack of a leap-second servicing standard, poor quality of dialogue between IT and time metrology communities, great variety of GNSS receivers in use, as well as different approaches to serving UTC adopted by GLONASS vs. GPS/GALILEO/BEIDOU/IRNSS [11]–[15].

Upcoming improvements in navigation accuracy, reliability, integrity, and availability will rely on further improvements of clocks and synchronization methods. This will require the specific systems to be free of any unpredictable epoch changes.

Many telecommunications systems rely on precise time synchronization. Spread-spectrum communications, for instance, 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 display little or no sensitivity to epoch.

The growing use of computers is another important consideration. In today’s world of high-speed computer-based communications with time stamp messages at the sub-second level, one second can be a significantly long period of time. In addition, clocks normally move from 59 s to 0 s of the following minute. Leap seconds require a count sequence of 59 s, 60 s, and then 0 s of the following minute. Many computer systems face a problem when introducing the “60th” second [16]. A similar concern is that when dating events using the Julian Day (JD) or Modified Julian Day (MJD), including fractions of days, a positive leap second would create a situation where two events occurring 1 s apart can receive identical dates when those dates are expressed with a numerical precision of 1 s.

Stand-alone data-gathering systems, isolated by specialized technical applications, are now extremely rare. Modern data systems rely on continuous, highly accurate time. A potential disruption of the continuity of service would have a major im-

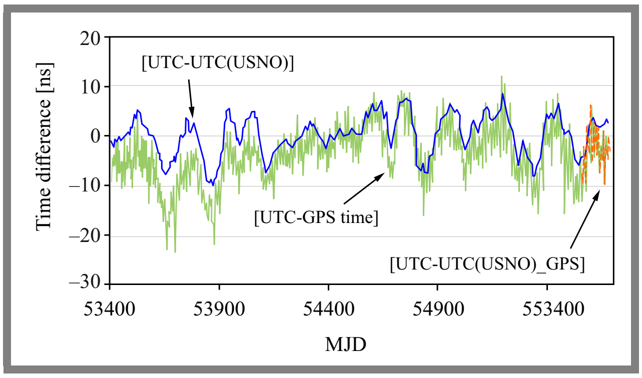


Fig. 2. [UTC-UTC(USNO)], [UTC-GPS time] modulo 1 s, and [UTC–UTC(USNO)_GPS], where UTC(USNO)_GPS is a prediction of UTC(USNO) broadcast by GPS (see [1]).

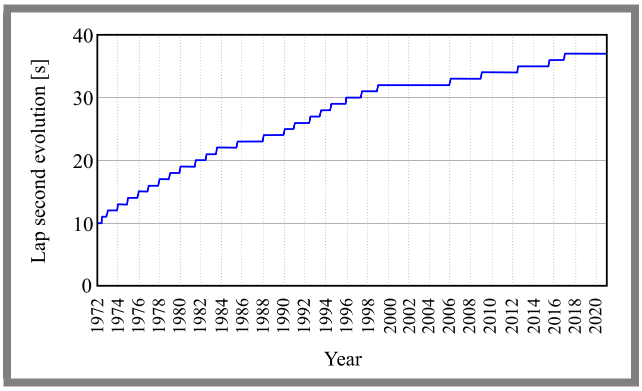


Fig. 3. Difference between TAI and UTC due to leap seconds since 1972.

pact on their interactive operation. In some cases, the need to avoid disruptions has led to the introduction of non-traditional timekeeping systems, such as GPS Time or a time scale maintained by an individual government contractor.

Continued introduction of UTC leap second poses a high risk of failure for IT and OT. Although the leap-second problem has always existed, the exponential growth of automation and the close interdependence of the entire Industry 4.0 systems creates a need for urgent suspension of the UTC leap second [17], [18]. The first ever introduction of a negative leap second that is planned currently is a great concern for the users.

The UTC leap second can trigger a large-scale domino effect, leading to a blackout in telecommunication, power, as well as and Industry 4.0 automation systems. Sooner or later, such failures must begin to occur, unless the introduction of leap seconds is abolished. The very likely, upcoming introduction of a negative leap second – a step that has never been tested in practice before, will be highly hazardous experiment conducted in an active production environment [16].

5. Problem of GNSS System Times

Ideally, GNSS system times should follow the recommendations of ITU-R and CGPM, and should conform, as closely as possible, to UTC, including its leap seconds. However, it is difficult for GNSS to deal with the discontinuities that arise when a leap second is introduced, as it would usually require that the clocks be stopped for 1 second. Such a remedy is difficult for a system that is measuring physical observables (positions of moving objects) that fail to stop for 1 s. In practice, only the GLONASS system time follows strictly UTC, with its leap seconds [12]. Other GNSS have chosen to use uniform time scales that do not include leap seconds. For example, GPS uses GPS time, which is a continuous time scale without leap seconds. It was set in 1980 to have a zero second difference with UTC – see Fig. 4. GPS time is 19 seconds behind TAI and, in 2023, 18 seconds ahead of UTC.

In the early stages of working on the assumptions of the Galileo system, it was decided that Galileo System Time (GST) would be a continuous time scale, without leap seconds, and that TAI would be used as reference for numbering seconds and steering GST. However, the final decision has been to set up GST with a zero second difference to GPS time, and steer to UTC, modulo 1s. This is shown in Fig. 4, where GST with the number of seconds equal to TAI seconds, is crossed out. This solution should enhance interoperability between the two systems. The Chinese BeiDou system relies on another reference epoch for its continuous internal time (BeiDou System Time – BST), namely 1 January 2006, 0 h 00 UTC [13], see Fig. 4.

Each of these systems is programmed to broadcast a prediction of UTC, including the leap seconds. But at the same time, they also broadcast their respective GNSS times which are more convenient for some applications, since they are uniform time scales. Despite this positive aspect (i.e. the fact that each system broadcasts a prediction of UTC), such a proliferation of various time scales is likely to lead to confusion. In particular, ambiguities will arise when a GNSS system time is used in an application that also uses UTC, thus provoking dating inconsistencies.

For the values listed in Fig. 5, the standard deviation is the frequency of individual measurements, equaling approx. 2 ns for GPS and 7 ns for GLONASS. As the GPS Master Control Station and the GPS time receivers were subjected to absolute calibration, the Type B uncertainty for the values from GPS is estimated at be approx. 10 ns. As GLONASS Master Control Station and GLONASS time receivers were not absolutely calibrated, the Type B uncertainty for the values from GLONASS is estimated to be of the order of hundreds of nanoseconds. The actual uncertainty of users' access to time values broadcast by GPS and GLONASS may differ from these figures, depending on the equipment used.

Continued use of a non-uniform time scale, including leap seconds, could lead – in the face of the problems described above – to the proliferation of independent uniform times, adopted with their suitability for specific objectives taken into consideration – see Fig. 4. If that is the case, UTC will see diminishing acceptance as an international standard.

6. The ITU-R and the CGPM Works

In 2000, a question was raised at the ITU-R WP 7A in Geneva, whether the leap seconds should continue to be inserted

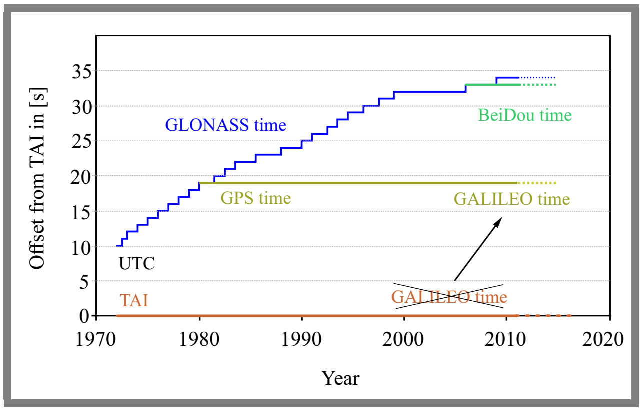
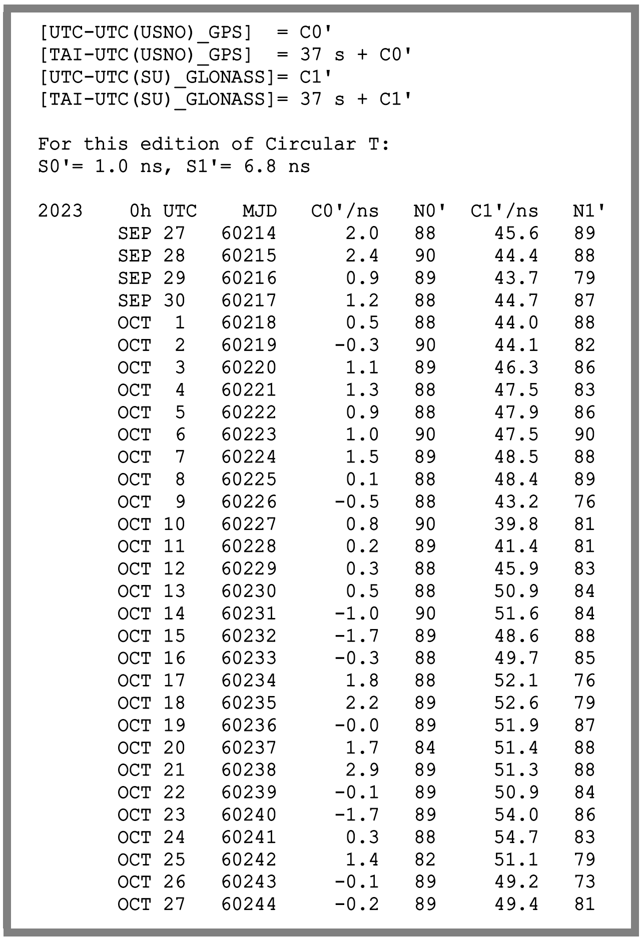


Fig. 4. Offset from TAI in integral number of seconds: [TAI–Time scale (i)] for UTC, GPS time, GLONASS time, Galileo System Time and BeiDou System Time.



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[UTC-UTC(USNO)_GPS]   = C0'
[TAI-UTC(USNO)_GPS]   = 37 s + C0'
[UTC-UTC(SU)_GLONASS]= C1'
[TAI-UTC(SU)_GLONASS]= 37 s + C1'

For this edition of Circular T:
S0'= 1.0 ns, S1'= 6.8 ns

2023       0h UTC     MJD    C0'/ns    N0'   C1'/ns    N1'
           SEP 27    60214      2.0    88      45.6    89
           SEP 28    60215      2.4    90      44.4    88
           SEP 29    60216      0.9    89      43.7    79
           SEP 30    60217      1.2    88      44.7    87
           OCT  1    60218      0.5    88      44.0    88
           OCT  2    60219     -0.3    90      44.1    82
           OCT  3    60220      1.1    89      46.3    86
           OCT  4    60221      1.3    88      47.5    83
           OCT  5    60222      0.9    88      47.9    86
           OCT  6    60223      1.0    90      47.5    90
           OCT  7    60224      1.5    89      48.5    88
           OCT  8    60225      0.1    88      48.4    89
           OCT  9    60226     -0.5    88      43.2    76
           OCT 10    60227      0.8    90      39.8    81
           OCT 11    60228      0.2    89      41.4    81
           OCT 12    60229      0.3    88      45.9    83
           OCT 13    60230      0.5    88      50.9    84
           OCT 14    60231     -1.0    90      51.6    84
           OCT 15    60232     -1.7    89      48.6    88
           OCT 16    60233     -0.3    88      49.7    85
           OCT 17    60234      1.8    88      52.1    76
           OCT 18    60235      2.2    89      52.6    79
           OCT 19    60236     -0.0    89      51.9    87
           OCT 20    60237      1.7    84      51.4    88
           OCT 21    60238      2.9    89      51.3    88
           OCT 22    60239     -0.1    89      50.9    84
           OCT 23    60240     -1.7    89      54.0    86
           OCT 24    60241      0.3    88      54.7    83
           OCT 25    60242      1.4    82      51.1    79
           OCT 26    60243     -0.1    89      49.2    73
           OCT 27    60244     -0.2    89      49.4    81
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Fig. 5. Relations between UTC, TAI and predictions of UTC(k) disseminated by GNSS: UTC(USNO)_GPS and UTC(SU)_GLONASS (an excerpt from Section 4 of BIPM Circular T No. 430 of November 2023) – 1 ns units.

into UTC. This was motivated by a rising number of incidents occurring while applying the leap second, especially within GNSS.

Since then, because of these and many other considerations described above in this paper, the utility of leap seconds was under discussion within the ITU-R [8], with the intention to modify update six of Recommendation ITU-R TF.460 of 1970, defining the UTC. Not much progress in this area was made by ITU-R between 2000 and 2015. This was mainly due to the lack of time metrology-related competence of ITU-R. UTC Recommendation ITU-R TF.460 was adopted by ITU-R for some historical reasons: BIH – an authority that was then in charge of computing UTC – was not a formally recognized intergovernmental organization. Therefore, ITU-R adopted, in 1970, an ad-hoc recommendation defining UTC. However, in 1985, BIH was integrated with BIPM, a formal intergovernmental body.

This has led to Resolution 2 (2018) of the 26th CGPM providing for the definition of UTC and confirming that UTC, defined by BIPM, is the only time scale recommended for international reference as the basis of civilian time in most countries.

Then, in 2020, a Memorandum of Understanding was signed between CGPM and ITU-R, defining mutual responsibilities of the two organizations: BIPM is in charge of defining, computing and disseminating UTC, while ITU-R is in charge of defining the regulations and formats for radio broadcasting of UTC and [UT1–UTC].

Following this, the 27th CGPM adopted, in 2022, Resolution 4 deciding that the maximum value for the difference (UT1-UTC) will be increased in, or before, 2035 [19]. A decision fixing the date of stopping the introduction of leap seconds and increasing the tolerance for [UT1–UTC] will be taken at the 28th CGPM in 2026.

As a result of the above activities [17], [18] and decisions, a draft revision of Resolution 655 leading to updating Recommendation ITU-R TF.460-6, considering CGPM decision to abolish leap seconds in UTC, was submitted – in July 2023 – to ITU-R Study Group 7 for adoption by ITU-R Member States at WRC-23 in November/December 2023 in Dubai, UAE. On 11 December 2023, ITU-R member states adopted revised Resolution 655, as described above [20]. This clears the way for the World Radiocommunication Conference WRC-27 in 2027 to modify Recommendation ITU-R TF.460-6 in line with the decisions which are planned to be taken at the 28th CGPM in 2026.

7. Conclusion

At the end of the 1960s, the main reason for introducing the leap second was to meet the celestial navigation-related requirement to maintain the difference between solar time and atomic time within 1 s. However, the importance of celestial navigation-related motivations has diminished due to the 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, costly, and have contributed to creating great risks [17], [18].

Although for the purposes of navigation, internal time scales of Global Navigation Satellite Systems do not need to be synchronized with the international standard UTC, there is an obvious need for international coordination to simplify the operation of GNSS and enhance their interoperability. This concern is reflected in the recommendations of the Consultative Committee for Time and Frequency (CCTF) and of the International Committee of Weights and Measures [13].

There is a need for further synchronization-related improvements. Recommendations of the United Nations International Committee for GNSS (ICG) show that interoperability is one of the main objectives of ICG. In 2010, ICG strongly recommended that BIPM should provide rapid (weekly) UTC updates to enhance synchronization and interoperability of various GNSS. This "rapid UTC" would serve as a reference point for broadcasting GNSS time offsets. This new BIPM service has already been functioning for a decade now.

GNSS navigation messages broadcast system times and should consequently follow the recommendations of remaining as close as possible to UTC. However, for the sake of life safety-related services and other relevant reasons, most GNSS service providers adopt alternative continuous time scales. These uniform system times are becoming, for similar reasons, alternative time scales for some civilian applications. This is leading to major confusion, with numerous potential problems encountered not only when specific users do not have any metrological background, but also when operating some specific systems.

Because of the difficulties experienced by modern infrastructures (in particular by GNSS) in connection with the introduction of leap seconds, and since the original reason for introducing leap seconds (i.e. celestial maritime navigation) is no longer valid, the definition of UTC is now under revision. ITU-R and CGPM are approaching, in the course of their work, a common decision on abandoning, in the near future, the introduction of leap seconds to UTC and adopting a new, increased tolerance value for [UT1–UTC]. This was confirmed in December 2023 by WRC-23 decisions.

Acknowledgments

Authors would like thank Mr. Tomasz Pińciurek from the Ministry of Digitalization, Jerzy Nawrocki, PhD from the Space Research Center (PAS) and Mr. Tomasz Widomski of Elproma for their continuing and lasting support and advice.

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