A Brief History of UTC Leap Second

Włodzimierz Lewandowski and Michał Marszalec

National Institute of Telecommunications, Warsaw, Poland

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Abstract — Approximately once a year, since 1972, a leap second is introduced into UTC, the world's atomic time scale for civil time, 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. The question of leap second is being debated since 2000 in different working groups of various international organizations, especially in the ITU-R WP 7A, is whether there still a need for the leap second, with its many technical inconveniences. In these groups overwhelmingly prevails an opinion that 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. The National Institute of Telecommunications in recent years became one of the leaders of this process. This article gives brief history of the current practice of UTC and outlines various solutions.

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

1. Introduction

The International Bureau of Weights and Measures (BIPM), 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 (positive or negative) is added to UTC to keep it in step with the slightly irregular rotation of the Earth [1], [2]. UTC is based on the uniform atomic time scale – International Atomic Time (TAI) to which leap seconds are not applied. TAI and UTC are paper time scales, but UTC, unlike TAI, has real-time approximations maintained at the national laboratories and astronomical observatories that supply the data for its calculation.

The 15th General Conference on Weights and Measures (CGPM) in 1975, noting that UTC provides the basis of civil time, the use of which is legal in most countries, judged 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) and 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 particularly the ITU-R is responsible of dissemination of [UT1–UTC] by radio broadcasting.

The ongoing and increasing, difficulties created by the periodic insertion of leap second into UTC, in particular to GNSS systems and possible solution of this problem are addressed in this paper. The paper also describes mutual roles of the CGPM and the ITU-R in defining and disseminating, international time scale UTC. An important step ahead was accomplished in December 2023, during World Radiocommunication Conference (WRC-23) in Dubai, UAE, in which the National Institute of Telecommunications played a major role. Taken decisions by member countries will greatly improve safety of critical infrastructure, particularly of telecommunication networks.

2. Measurement of Time – Historical Note

"Since antiquity, the celestial bodies, the Sun, Moon, and stars, have been the fundamental markers 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" [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. While the notion of 24 equal hours was applied in theoretical works of Hellenistic astronomy. It was not until the fourteenth 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 longitude determination on sea vessels. Then in the middle of eighteen centaury a spiral balance spring clock was invented, which resolved accurate determination of longitude for sea navigation. These clocks where primary standards for sea navigation until the introduction of modern electronics. Quartz-crystal clocks were developed as an outgrowth of radio technology in the 1920s and 1930s. The National Bureau of Standards in Washington, USA (now the National Institute of Standards and Technology) constructed the first atomic clock in 1948 using the microwave absorption line of ammonia to stabilize a quartz oscillator. Essen and Parry at the British National Physical Laboratory in Teddington, designed a practical cesium beam atomic clock in 1955 [6]. Commercial caesium frequency standards appeared a year later. Norman Ramsey developed the hydrogen maser at Harvard University in 1960.

Once practical atomic clocks became operational, the 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 given to the 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 in October 1967 adopted the atomic second as the fundamental unit of time 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". The following gives brief descriptions of some timescales in use currently.

Universal Time UT1. UT1 is computed from the raw observed universal time UT0 by correcting it for the effect of polar motion on the longitude of the observing site. UT1 is commonly understood as a time based on Earth 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 served as the basis for the definition of the second until 1956, when International Committee for Weights and Measures (CIPM) adopted a new definition based on ephemeris time which refers 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 at the same time as it adopted 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 with 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 the formal definition of International Atomic Time (TAI). TAI is an international time standard. The origin of TAI was set such that UT1-TAI was approximately 0 on 1 January 1958. 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. It is established at the BIPM on the basis of the readings of about 400 atomic clocks operating in various establishments around the world in accordance with the definition of the second, and using an optimized weighting algorithm.

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 [7]. A distribution of approximately four hundred clocks maintained in about seventy laboratories contribute 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 sometimes used for scientific studies.

Coordinated Universal Time UTC. UTC is currently defined as an atomic time scale adjusted to be close to UT1. Before 1972, this was done by introducing changes in the length of the UTC second as well as by step adjustments, principally to facilitate navigation by celestial observations. The UTC system as defined today is a stepped atomic time scale (i.e., a scale that includes leap seconds) and was adopted in 1972 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 application of the leap seconds is irregular, depending on the unpredictable long-term irregularities of the Earth's rotation. In 2011, the difference between the continuous TAI and UTC amounts to 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 applying a correction of 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 in national metrology laboratories and observatories that contribute to the formation of the international time scales at the BIPM.

The dissemination of UTC is provided by the publication in the monthly BIPM Circular T, that gives traceability to UTC via the approximations UTC(k), see some examples in Fig. 1 and [1]. The broad dissemination of UTC through broadcast and satellite time signals is the responsibility of the national metrology laboratories and some observatories, following the recommendations of the ITU-R [4]. In many countries UTC is used as the basis for the definition of legal times. Also, predictions of some UTC(k) times are 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, between the CGPM and the ITU-R, defines mutual responsibilities of two organizations ITU-R and BIPM: the BIPM is on charge of the definition, computing and disseminating UTC, ITU-R is on charge of settling the regulations and formats for radio broadcasting of UTC, and [UT1-UTC]. The rational reason for the leap second, is because the second as

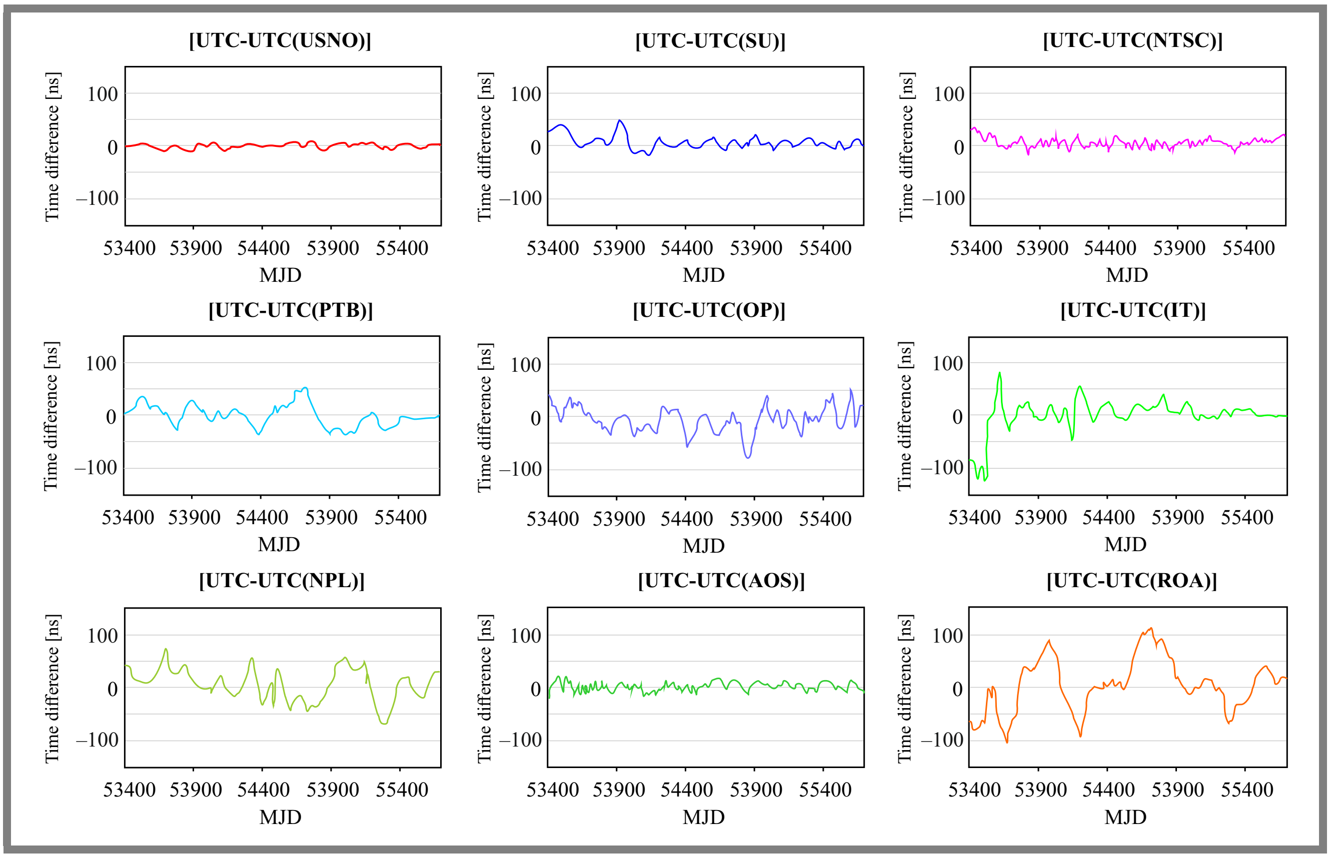


Fig. 1. [UTC-UTC(lab)] since year 2005, for USNO, SU, NTSC, PTB, OP, IT, NPL, AOS and ROA.

presently defined is "too short" to keep in step with the Earth. Subsequently, the 27th CGPM in 2022, adopted the 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, which provides the UTC reference to all modern critical infrastructures, such as distributed smart grids, telecom 5G, financial markets and broadcasting. Moreover, the observed strong migration of smaller IT and Industry 4.0 (OT) systems to "cloud" makes it a fifth critical infrastructure. The following problem affects all countries and all segments of each individual economy. It is complicated by the lack of leap-second servicing standard, the poor dialogue between the IT and time metrology community, the diversity of implementation of GNSS receivers, as well as different approach of serving UTC between 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 method of synchronization. This will demand systems to be 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" [16]. 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.

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.

Further continuation of handling UTC leap second introduces a high risk of failure for IT and OT. Although the leap-second problem has always existed, currently with exponentially growing automation and the close interdependence of entire Industry 4.0 systems, there is a need for urgent suspension of the UTC leap-second [17], [18]. Currently considered the first in history negative leap-second makes users especially worry.

The UTC leap second can trigger a large-scale domino effect, leading to a blackout: in telecommunication, power systems and Industry 4.0 automation. Sooner or later, such failures must begin to occur, unless a leap-second being abolished. Considering very likely the upcoming of a negative leap second, which has never been put into practice before, it will be particularly very dangerous experiment on a working active production environment [16].

5. Problem of GNSS System Times

Ideally, GNSS system times should follow the recommendations of the ITU-R and the CGPM, and conform as closely as possible to UTC, including its leap seconds. However, it is difficult for a GNSS to deal with the discontinuities that arise when a leap second occurs because it would usually be done by stopping the clocks for 1 s. This is difficult for a system that is measuring physical observables (positions of moving objects) that do not stop for 1 second. In practice, only 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 zero second difference with UTC. GPS time is 19 seconds behind TAI, and in 2023, 18 seconds ahead of UTC – see Fig. 4.

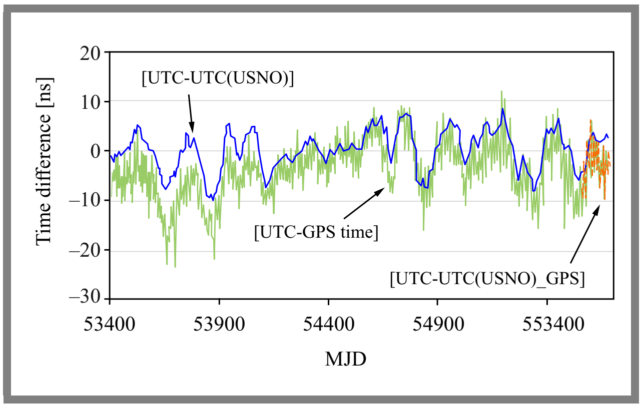


Fig. 2. [UTC-UTC(USNO)], [UTC-GPS time] modulo 1 s, and [UTC-UTC(USNO)_GPS], where UTC(USNO)_GPS is a prediction of UTC(USNO) broadcast by GPS [1].

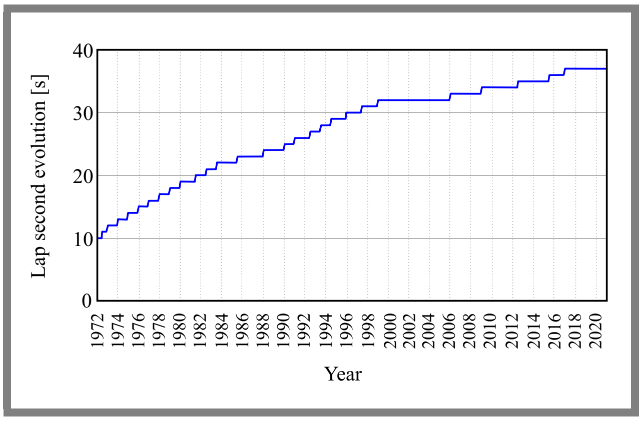


Fig. 3. Difference between TAI and UTC due to leap seconds since 1972.

In the early stages of the definition 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 the GST. However, the final decision has been to set up GST with zero second difference with GPS time, and steered to UTC, modulo 1s. This is shown on Fig. 4, where GST with seconds equal to TAI seconds, is crossed out. This solution should enhance the interoperability between the two systems. The Chinese system BeiDou has chosen another reference epoch for its continuous internal system time BeiDou System Time (BST), which is 1 January 2006, 0 h 00 UTC [13] (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, that each system broadcasts a prediction of UTC, such 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 inconsistencies in the dating.

For the values listed in Fig. 5 the standard deviation is characterizing the dispersion of individual measurements, which is for GPS about 2 ns, and for GLONASS 7 ns. As the GPS Master Control Station and the GPS time receivers were absolutely calibrated, Type B uncertainty for the values from GPS is estimated at about 10 ns. GLONASS Master Control Station and GLONASS time receivers were not absolutely calibrated, this why 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 values, depending on the equipment used.

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 objectives, see Fig. 4. If that happens, UTC will receive less acceptance as an international standard.

6. The ITU-R and the CGPM Works

In 2000, a question was raised in the ITU-R WP 7A in Geneva, whether the insertion of leap second into UTC should continue to apply. This was motivated by rising number of

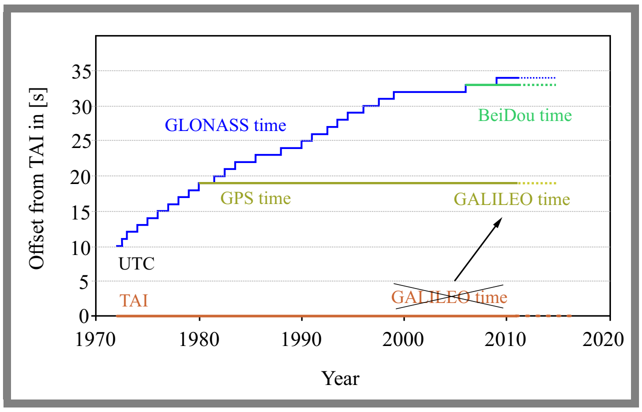
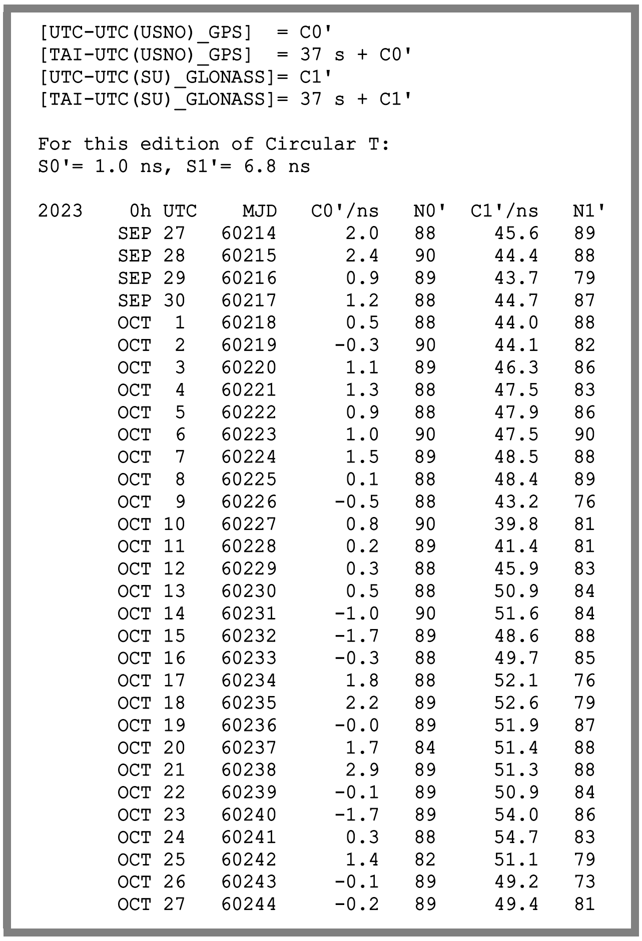


Fig. 4. Offset from TAI in integral number of seconds: [TAI- Time scale (i)] for UTC, GPS time, GLONASS time, Galileo System Time and BeiDou System Time.



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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 nr 430 of November 2023) – unit is 1 ns.

incidents during application of 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] to modify the update six of Recommendation ITU-R TF.460, of 1970, defining the UTC. Between 2000 and 2015, there was not all progress on this subject in the ITU-R. This was mainly due to lack of competence of ITU-R in time metrology. Definition of UTC Recommendation ITU-R TF.460, was adopted by ITU-R for some historical reasons: BIH, then on charge of computing UTC, was not a formally recognized intergovernmental organization. This is why, ITU-R, ad-hoc in 1970, adopted a recommendation defining UTC. However, since then, in 1985 the BIH service moved to the BIPM, a formal intergovernmental body.

This led to Resolution 2 (2018) of the 26th CGPM providing the definition of UTC and confirming that UTC, produced by the BIPM is the only recommended time scale for international reference and the basis of civil time in most countries. Next, in 2020 was signed a Memorandum of Understanding, between the CGPM and the ITU-R, defining mutual responsibilities of two organizations: the BIPM is on charge of the definition, computing and disseminating UTC, ITU-R is on charge of defining the regulations and formats for radio broadcasting of UTC, and [UT1-UTC].

Following this, the 27th CGPM in 2022, adopted the 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 application of leap second and increasing the tolerance for [UT1-UTC] will be taken during the 28th CGPM in 2026.

As a result of above works [17], [18] and decisions, a draft revision of Resolution 655 leading to updating Recommendation ITU-R TF.460-6, considering CGPM decision of the abolition of leap seconds in UTC was submitted in July 2023, to the ITU-R Study Group 7 for adoption by ITU-R Member States during the WRC-23 in November-December 2023 in Dubai. 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, accordingly to the decisions which are planned to be taken at the 28th CGPM in 2026.

7. Conclusion

The main reason for introducing the leap second was at the end of 1960s to meet the requirement of celestial navigation to keep the difference between solar time and atomic time to within 1 s. However, the motivation for celestial navigation has diminished because of the availability of satellite navigation systems, such as GPS and others, while the operational complexities of maintaining precise timekeeping systems have made the insertion of leap second adjustments increasingly difficult, costly, and 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 to the international standard UTC, there is an obvious need for international coordination to simplify the operation of GNSSs 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 improvements in this synchronization. Recommendations of the United Nations International Committee for GNSS (ICG) show that interoperability is one of the main objectives of the ICG. In 2010 the ICG strongly recommended that the BIPM should provide a rapid (weekly) solution of UTC to enhance synchronization and interoperability of various GNSS; this “rapid UTC” would serve as the reference for broadcasting GNSS time offsets. This new BIPM service is functioning already for a decade. GNSS navigation messages broadcast system times and should consequently follow the recommendations of being as close as possible to UTC. However, for the sake of Safety of Life services and other relevant reasons, most GNSS service providers adopt alternative continuous time scales. These uniform system times are becoming, for similar reason, alternative time scales for some civil applications. This is leading to a major confusion, a number of possible examples are given that apply not only when users do not have any metrological background, but also in the case of some system operations.

Because of the difficulties caused by the leap seconds to modern infrastructures, in particular to GNSS, and because the main original reason for keeping leap seconds, celestial maritime navigation, is no longer used, the definition of UTC is now under revision. ITU-R and CGPM by their works are approaching common decision on stopping in near future the application of leap second to UTC and adopting new increased tolerance for [UT1–UTC]. This was confirmed in December 2023, by WRC-23 decisions.

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Włodzimierz Lewandowski, Ph.D.
Electrical, Electronic, and Optoelectronic Metrology Laboratory
https://orcid.org/0009-0003-4385-3628
E-mail: w.lewandowski@il-pib.pl
National Institute of Telecommunications, Warsaw, Poland
https://www.gov.pl/web/instytut-lacznosci

Michał Marszalec, M.Sc.
Electrical, Electronic, and Optoelectronic Metrology Laboratory
https://orcid.org/0000-0002-4711-1870
E-mail: m.marszalec@il-pib.pl
National Institute of Telecommunications, Warsaw, Poland
https://www.gov.pl/web/instytut-lacznosci