Towards Continuous Universal Time and the Future of the Leap Second

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Acknowledgement

This work is a summary of the Leap second presented on behalf of the BIPM’s Task Group on Continuous UTC.

- TaskGroup is co-chaired by:
  - Judah Levine (NIST Boulder)
  - Patrizia Tavella (BIPM Time Department Head).
- Instantiated in 2023 following the General Conference on Weights and Measures (GCPM) Meeting in 2022.
- Main goal is to recommend a new tolerance for the offset of UT1 – UTC (dUT1)

History of UTC and the Leap Second

- Since 1972, UTC has been defined such that UTC – TAI = *n*. This puts TAI and UTC at the same rate.
- Leap seconds keep UTC aligned to the timescale UT1 determined by Earth's rotation.
- The International Earth Rotation Service (IERS) monitors |UT1 – UTC| and directs the insertion of a leap second when this difference gets close to one second.

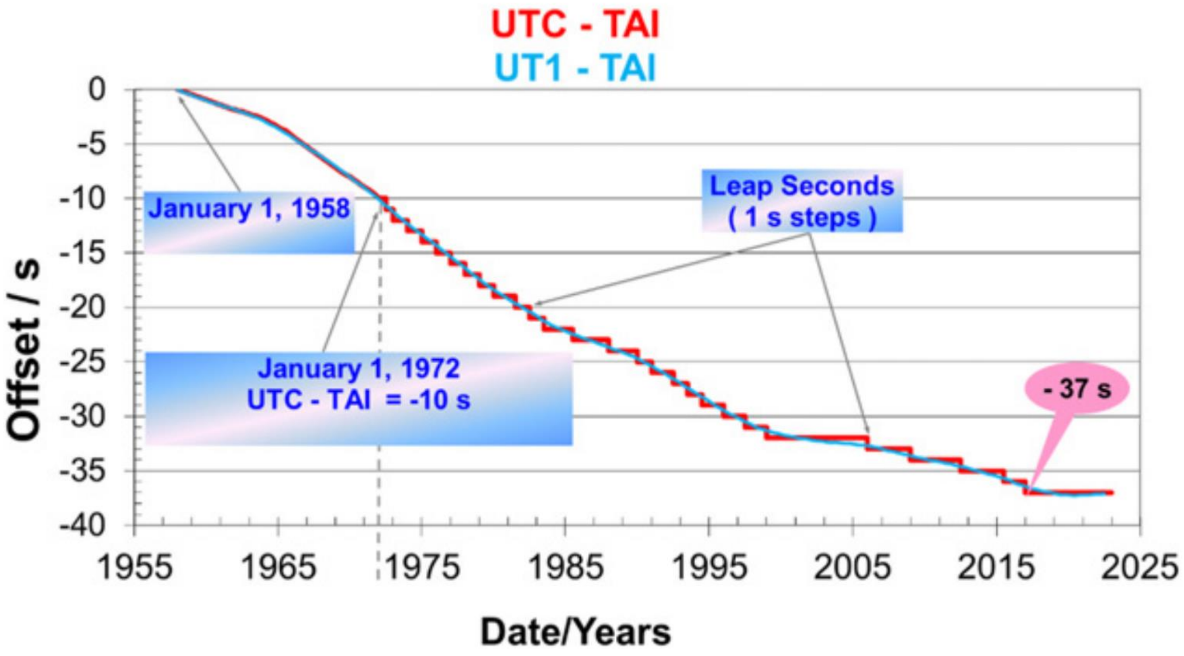
Why eliminate leap seconds ?

They risk malfunctions in critical infrastructure including GNSS, telecommunications and energy transmission.

Network and GNSS operators apply different methods to handle leap seconds that do not follow any agreed standards.

Implementation of differing and uncoordinated methods threatens resilience of synchronization capabilities world wide.

Recent rotation rate observations indicate the possible need for a negative leap second whose insertion has been neither foreseen nor tested.



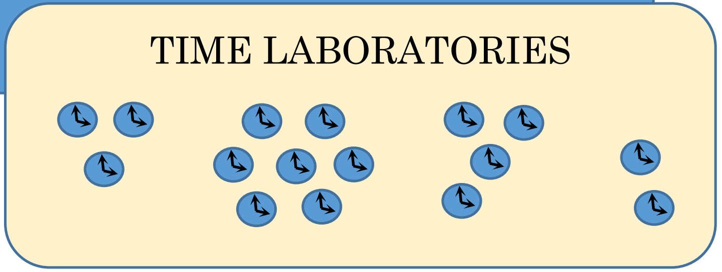
How is a leap second implemented?

IERS
Determines the offset of UT1 – UTC routinely.

Publishes a notification that a leap second must be added to UTC when reaching the maximum tolerance is predicted in the next few months.

BIPM
Maintains UTC with contributions from National Metrological Institutes and other participating Timing Laboratories.

Coordinates additional second with Time labs at the time directed by the IERS.



Current Implementation Methods

Official UTC Labs

- TAI (Temp Atomique International) is unaffected.
- UTC timestamps are shifted at the event of the leap second

UTC Before	After
23:59:57	23:59:57
23:59:58	23:59:58
23:59:59	23:59:59
00:00:00	23:59:60
00:00:01	00:00:00
00:00:02	00:00:01

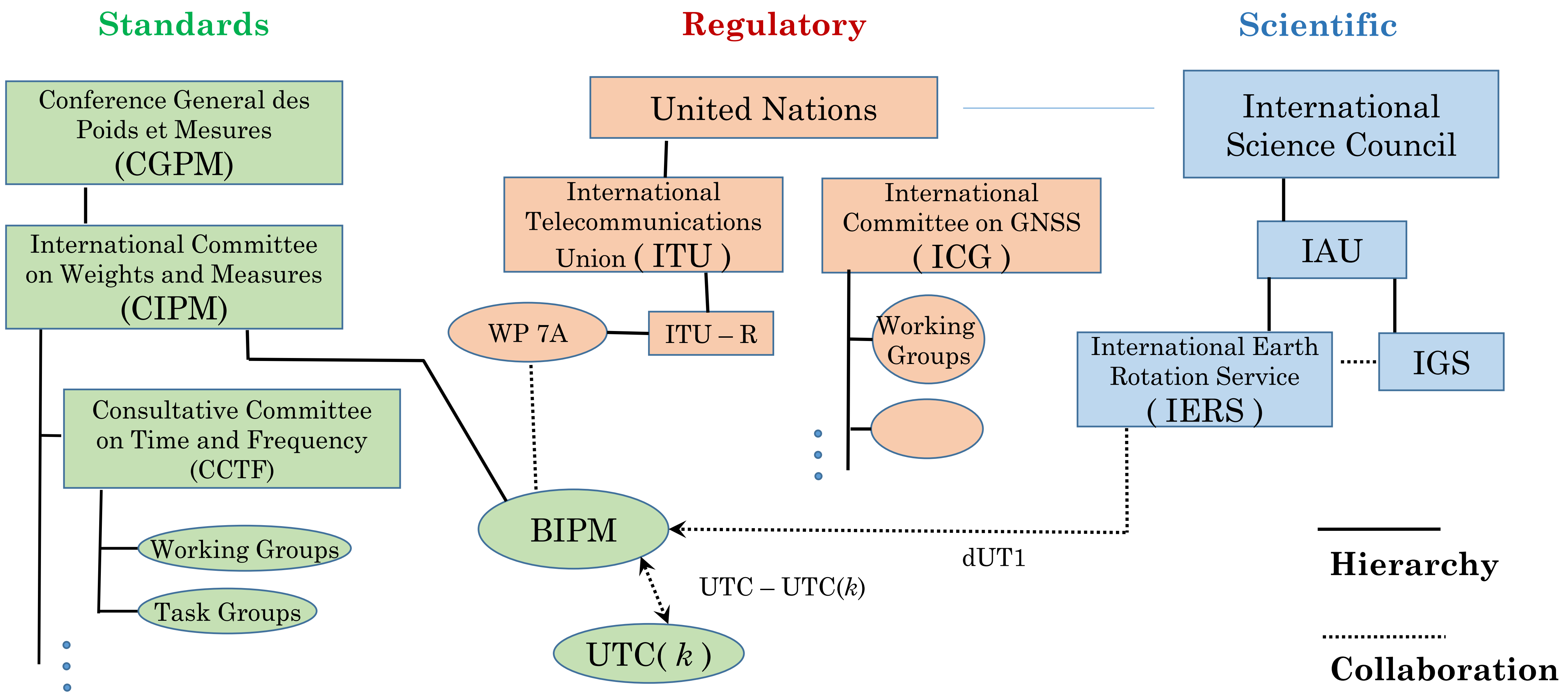
Clock Smears

- A variety of approaches smear the timestamps rate of UTC over a prescribed time around the leap event.
- The current implementations are not good since:
  - There is inconsistency between smearing approaches.
  - The realized time broadcast has a rate differing from UTC during that time.
- Google has information published on its approach to smearing its public NTP during a leap second event.

Efforts to Eliminate the Leap Second

- Because leap second pose a number of problems, efforts arose to eliminate them over the past two decades.
- Strides made in ITU–R Working Party 7A (WP7A), but no concensus was found over the last two decades.
- Recently, at the WRC 23, a number of agreements were made including:
  - ITU–R resolved to work further with the BIPM, CIPM and CGPM to propose a new maximum tolerance for dUT1 and on the implementation of continuous UTC.
  - ITU – R and BIPM agreed on the different responsibilities: BIPM define and realize UTC, while ITU disseminate it (and DUT1) through radio signals.
- The CGPM had a reciprocating resolution at its 27th meeting in regards to finding a new maximum tolerance of dUT1.

Stake holder organizations



CGPM 2022 Resolution 4 (Paraphrase)

The General Conference on Weights and Measures (CGPM)

- **welcomed** the signature of a Memorandum of Understanding between the BIPM and the International Telecommunication Union (ITU), which ensures that they continue their joint work to improve global access to UTC,
- **noted that:**
  - the accepted maximum value of the difference (UT1 – UTC) has been under discussion for many years because the consequent introduction of leap seconds creates discontinuities that risk causing serious malfunctions in critical digital infrastructure,
  - operators of digital networks and GNSSs have developed and applied different methods to introduce the leap second, which do not follow any agreed standards,
  - the implementation of these different uncoordinated methods threatens the resilience of the synchronization capabilities that underpin critical national infrastructures,
  - the use of these different methods leads to confusion that puts at risk the recognition of UTC as the unique reference time scale and also the role of National Metrology Institutes (and Designated Institutes) as sources of metrological standards,
  - recent observations on the rotation rate of the Earth indicate the possible need for the first negative leap second whose insertion has never been foreseen or tested,
  - the Consultative Committee for Time and Frequency (CCTF) has conducted an extensive survey amongst metrological, scientific and technology institutions, and other stakeholders.

CGPM 2022 Resolution 4 (Paraphrase)

The General Conference on Weights and Measures

- **recognizes** that the use of UTC as the unique reference time scale for all applications, including advanced digital networks and satellite systems, calls for its clear and unambiguous specification as a continuous time scale, with a well-understood traceability chain,
- **decides** that the maximum value for the difference (UT1 – UTC) will be increased in, or before, 2035,
- **requests** that the CIPM consult with the ITU, and other organizations that may be impacted by this decision in order to
    - propose a new maximum value for the difference (UT1 – UTC) that will ensure the continuity of UTC for at least a century,
    - prepare a plan to implement by, or before, 2035 the proposed new maximum value for the difference (UT1 – UTC),
    - propose a time period for the review by the CGPM of the new maximum value following its implementation, so that it can maintain control on the applicability and acceptability of the value implemented,
    - draft a resolution including these proposals for agreement at the 28th meeting of the CGPM (2026),

Task Force on Continuous UTC

- Work with the CCTF, all UTC laboratories, GNSS providers, stakeholders, and liaison organizations to prepare a draft resolution for the CGPM 2026 containing:
    - The extended tolerance value of UT1 – UTC.
    - A procedure to align UTC and UT1 when this limit is reach.
    - The periodicity to revise this decision at the CGPM.
    - Exact date of implementation.
- Contribute to the broad communications and education, participation to the user forum.
- The group started with the following important notes:
    - Not everyone will get what exactly what is desired in their respective sectors.
    - UTC should have a known and well disseminated relationship with UT1.

Candidate Tolerance Values

- The TG established some candidates for a dUT1 maximum tolerance.

Tolerance Value	Motivation	Frequency of Adjustment	Initial Thoughts on Impact
1 Sec	Existing	~ 18 Months	Changes nothing.
60 Sec	Something larger, but not too large.	~ 100 Years	Adjustment will come in foreseeable future, but we won't pass experience down to next generations.
256 Sec	Maximize use of bytes in computing.	~ 500 Years	Perhaps a good choice for IT equipment
3600 Sec	Equal 1 hour – similar to Daylight Saving jump	~ 4000 Years	Impossible to assess true impact on a society that far into the future.
Infinite	Eliminates Leap Second	Never	Unlikely to be accepted.

- We need to better understand which among these minimizes both the problems caused by a large dUT1 and the risk of installing discontinuities in UTC.
- A set of questions was prepared to disseminated from the TG to collect opinions from various sectors reliant on UTC and/or UT1.

Use and Impact in GNSS

- GNSS have mostly fixed their system times to avoid the complexity of new leap seconds. But, leap seconds still have impact.
- The number of leap seconds included in each system time differs.

GNSS	Sys Time / Sys	Start / Ref Epoch	Alignment	Broadcast
BDS	BDST / Beidou	01 Jan 2006 00:00:00 UTC	TAI – 33 sec	UTC_BDS
GAL	GALT / Galileo	21 Aug 1999 23:59:47 UTC	TAI – 19 sec	UTC_GAL
GLO	GLOT / GLONASS		UTC	UTC(SU)
GPS	GPST / GPS	06 Jan 1980 00:00:00 UTC	TAI – 19 sec	UTC(USNO)
NavIC	IRNSST	21 Aug 1999 23:59:47 UTC	TAI – 19 sec	UTC(NPLI)
QZS	QZST / QZSS	06 Jan 1980 00:00:00 UTC	TAI – 19 sec	UTC(NICT)

- Receiver firmware is generally impacted as leap seconds need to be tracked to resolve UTC. Some programmers wrote firmware with the assumption that leap seconds would arrive at a certain frequency. Recently… they have not!

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Questionnaire to GNSS Community

The task group prepared and disseminated a questionnaire to GNSS and RNSS representatives summarizing the task force goals and asking questions regarding:

- The (current and future) broadcast of UT1 – UTC in the navigation message.
- Possible impact of changing the tolerance of DUT1 on:
  - Broadcast message format, orbit models, ground control algorithms, receiver engine firmware, reference frame, inter-component communications, etc…
- The preferred new value of the tolerance for DUT1.
- If UTC were to become continuous, would the GNSS system re-align its timescale to UTC, rather than TAI – 19, etc?

Answers from GNSS Providers

Impacts of a new tolerance

GALILEO

- Verification that the format and processing of the DUT1 parameter with a higher value is properly handled.
- ICD: current algorithm and associated parameters format (type, number of bits…) for the new leap period adjustment will have to be checked, tested and verified, even if it is executed only once per century
- Strongly recommended that any change in tolerance is timely and clearly communicated to us so that it can be properly implemented.

GPS

- Necessitate an engineering assessment of all GPS ground and on-orbit software models that presently assume that UT1 – UTC < 1.0 second.
- Necessitate more "unconventional" time stamps to be documented during the leap interval (for example, currently using 23:59:60.xxx) in ICD.
- A large discontinuity in UTC occurring approximately once per century is likely to cause a host of problems, there will be no real (i.e., non-simulated) experience to handle it.

QZSS

- broadcast message format and ground control algorithms.

NavIC

- Change in the broadcast parameters, corresponding section in SIS ICD, and receiver firmware.

Answers from GNSS Providers

Recommended Leap Interval:

Galileo: Preferred tolerance would be the one that minimizes the occurrences of new leap period adjustments, **therefore no limit**.

GPS: Answers vary depending on agency. Some thoughts heard:

- choose a limit that minimizes operational costs across among world-wide users;
- leave the leap second alone since procedures exist and have worked for 40+ years;
- avoid a new (different) value since countless pieces of software/firmware need re-programming.

QZSS: No direct recommendation, but noted that DUT1 needs to be within 64 seconds to avoid broadcast message format and ground control algorithm changes (a value of 1 minute or less might be preferred).

No direct recommendation from other systems.

On GNSS Time Alignment to UTC:

ALL: No.

General comments suggest that risk and cost of modifying the system time outweigh benefits of alignment to UTC.

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Specific Questions to GNSS Receiver Manufacturers

GNSS user equipment experiences and handles leap seconds in different ways from the space and control segment. For this reason, a separate set of questions was disseminated to a large group of manufacturers.

1. Are you using, or do you plan to use a broadcast difference between UTC and UT1?
2. What affect would *any* change to the current leap second procedure have on your GNSS products? What components would be affected? Here is a list of items we have in mind that might be impacted.

   Please elaborate on the way the component(s) would be affected.
3. Assuming the tolerance does expand, which would be an acceptable or preferred tolerance for your GNSS products? Can you elaborate on the technical reasons for your answer?

Answers from Manufacturers

Responses obtained from six different manufacturers in both the North America and Europe. Several noted that their products would likely be able to adapt to any change in the dUT1 tolerance. Other notable comments are below.

General Comment
Need for predictable leap second, well in advance (~25 years), so that there is no unforeseen change over the lifetime of our products.

Are you using, or do you plan to use a broadcast difference between UTC and UT1?
Yes, this is used, as described above, related the output of positions that are related to UTC time. The offset used is typically that between GPS Time and the current UTC, based upon the leap seconds that have been inserted since the start of GPS Time (midnight between January 5-6, 1980), which is itself a continuous timebase.

What affect would any change to the current leap second procedure have on your GNSS products?
Components affected would be related to the GNSS position output, but not related to the GNSS position calculation itself.

Assuming the tolerance does expand, which would be an acceptable or preferred tolerance for your GNSS products? Can you elaborate on the technical reasons for your answer?
If the only change is in the UT1-UTC (or in this case, the UTC to GPS Time) offset in terms of number of leap seconds, then potentially any value could be used – subject to this not impacting any form of GNSS reference time assistance solution and alteration of software and interfaces using such data.

As it would be required to not diverge too much from UT1 (which might then require a third time base to be re-introduced, to match the true rotation UT1)**, then it may be a limits of 1 minute may suffice (or even shorter, such as 32 seconds)**.

Feedback from Astronomical Union (IAU)

Telescope Pointing

- Instrument point applications can now generally use estimates of UT1 – UTC from networks or GNSS to satisfy needs.
- Safe to assume that accuracy requirement would be satisfied with max 1 second error.
- Software adjustments might then be minimal with adequate lead time.

Astronomical Software Applications

- Applications that assume UTC is a reasonable proxy for UT1 may need modification.
- Current and predicted estimates of UT1 – UTC from on-line or GNSS are expected to satisfy needs.
- Software adjustments might then be minimal with adequate lead time.

Proposed changes to the tolerance would increase the importance of reporting from the IERS.

Perhaps a more-real time basis would be needed?

New tolerance for UT1 – UTC	Strengths	Weaknesses	Opportunities	Threats
No Limit	Eliminates need for future adjustments	Backward-incompatibility, engineering effort to assess re-designing system aspects, and thus cost/schedule/priorities impacts.	Some user equipment attached to receivers is sensitive to leap second insertions. Testing, integration and operations of such equipment would be easier if UTC were to be continuous.	
1 Minute		Backward-incompatibility, engineering effort to assess re-designing system aspects, and thus cost/schedule/priorities impacts.		Likely to need implementation within the lifetime of current GNSS systems and it is hard to pass experience in handling such a unit from one generation to the next. Requires unconventional timestamps not presently in use, for example 23:60:24, etc. Without common ground established, there could be widespread incompatibility issues amongst GNSS hardware.
1 Hour		Implementation too far into the future to be practical for operational documents on current systems. Backward-incompatibility, engineering effort to assess re-designing system aspects, and thus cost/schedule/priorities impacts.		Requires unconventional timestamps not presently in use, for example 23:60:24, etc. Without common conventions well established, there could be widespread incompatibility issues amongst GNSS hardware. An interval of one hour would occur once per ~4000 years, so it would be hard to socialize this.

Considerations

The following considerations have been suggested. These can be used as important arguments in favor or against any recommendation proposed. *None is an absolute rule that restricts our options.*

IMPACT

Explicit link between UTC and UT1 (civil time) should be maintained.

Minimize disruption to services resulting from any change.

IMPLEMENTATION

Any new process should not use signed time steps.

Process should be standard, well-defined and internationally accepted.

Process should be algorithmic and digitally defined so TAI could be recovered by reversing the implementation.

OCCURENCE

Algorithm should be unchanging for many decades.

If UTC adjustments remain part of the solution, they should occur frequently enough that the knowledge base to implement it can be passed to the next generation.

Should be done outside business hours (to the maximum extent possible).

WE MIGHT WANT TO AVOID …

Leaving any known problem for the future… increases the chance that it will get solved in a "crisis" mode.

Complexity… a simpler solution is more likely to be accepted and implemented well once established.

Some Proposed Procedures

These ideas have been proposed among from various group members. None are official or even yet favored as the preferred recommendation.

	Present	Some Proposed Ideas 1	Some Proposed Ideas 2
Correction Type	Discontinuity. • Algorithmically simple. Push timestamps down one second. • Causes processing problems for computing infrastructure.		Controlled slew of UTC over prescribed time. Double the rate of UTC for a positive leap second, half the rate for a negative. • UTC and TAI maintain the same rate outside this period. • Should be well-defined and published so entities running time servers enact a common and standardized approach.
Time of the Discontinuity	Extra second, designated 23:59:60, put between 23:59:59 and 00:00:00 UTC on either 31 Dec - 1 Jan or 30 June - 1 July. • Bad time for East Asian and Western US as the leap second could well occur during business hours.	• Maintain the status quo of inserting in either January or June at 00:00 UTC.	Install correction event around 12:00:00 UTC on 01 January. • Closest date we have to "International Holiday" • Puts the correction at a time when the entire globe is within the date of 01 January.
Regularity of Discontinuity Events	Leap Second added when IERS determines that |dUT1| will exceed 0.9 sec. • The step interval and action is the same every time, • Occurance is not periodic and only known for sure once an announcement from the IERS is made.	Leap Second added when IERS determines that |dUT1| will exceed 1 hour. • No adjustment for at least 100 years. • Establish regular reviews (20–25 years) to assess the Earth rotation and impact of taking this approach.	Adjust UTC by 10% of predicted century long evolution once every 10 years (2040, 2050, 2060, etc). • Occurance of the discontinuity event would be well established and known in advance. • Jump amount might not be the same in the next century, but the period and approach would remain unchanged.

Additional Inputs

- Additional input or comments from the GNSS community (especially those in the provider segment) are valuable.
- Consider any components that might be affected:
  - Critical hardware issues
  - Software modifications
  - Data format limitations
  - Broadcast message limitations
- Please contact us if you can provide further detail from any particular GNSS, especially if you work closely with administrative agencies.
  - Mike Coleman michael.j.coleman134.civ@us.navy.mil

References

- J. Levine et al. *Towards a Consensus on a Continuous Coordinated Universal Time*. Metrologia 60(1), November 2022.
- ITU News Magazine. *The Future of Coordinated Universal Time*, Number 2, 2023.
- Hubert, B. *Leap Seconds: Causing Bugs Even When They Don't Happen*. August 2021.
- Beard, R. *The Role of the ITU – R in Time Scale Definition and Dissemination*. Metrologia 48(4), 2011.