Leap-second adjustments to Coordinated Universal Time (UTC)

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Outline

- The astronomical time scales: UT0, UT1, and UT2
- The atomic time scales: TAI and UTC
- Leap seconds and the UTC adjustment process
- Possible changes to the adjustment process
- Advantages and problems
  - A negative leap second
- The schedule and the players
- Summary and conclusion
- References

Astronomical time scales - 1

- UT0 is measured by observing the times at which the images of distant stars are directly North or South of the observer
  - This is the “meridian transit” of the star
- UT0 is affected by “polar motion” -- the irregular motion in the axis of rotation of Earth with respect to the stellar coordinate system
  - Historically observed by the irregular motion of the image of the North Star
  - Polar motion is a combination of precession, nutation, and an additional irregular and unpredictable contribution

Astronomical Time scales - 2

- UT1 was originally computed by combining the UT0 data from many observatories at different latitudes
  - This separates the angular position of Earth with respect to the distant stars from the effects of polar motion
- UT1 is now measured by Very Long Baseline Interferometry that uses data from distant radio sources received at widely-separated antenn
  - VLBI provides information on the rotation an polar motion
  - VLBI measures UT1 directly and replaces U

Astronomical Time scales - 3

- UT2 is computed from UT1 by an algebraic equation that corrects UT1 for the small annual variation due to the orbital motion of Earth.
- The UT2 adjustment to UT1 is documented in Bulletin A of the International Earth Rotation and Reference Service (www.iers.org)

Greenwich Mean Time (GMT)

- GMT is computed from UT1 by transforming the angular position in stellar coordinates to the angular position with respect to the Sun as would have been observed on the Greenwich meridian.
  - 00:00:00 UT1 is approximately solar midnight at Greenwich
- GMT includes an average of the annual variation in UT1 resulting from the orbital motion of Earth
  - The “Equation of Time” is the difference between t
    apparent solar time at Greenwich on any day an
    annual-average value given by GMT. The maxim
    of the differences is of order 16 minutes.

Atomic Time -1

- International Atomic Time (TAI) is computed by counting SI seconds from an origin time defined by astronomy
  - SI second is 9 192 631 770 cycles of the hyperfine transition in the ground state of cesium-133, (including some additional footnotes)
- TAI is computed by the International Bureau of Weight and Measures (BIPM, www.bipm.org) from data supplied by a world-wide network of timing laboratories and National Metrology Institutes
  - The data are derived from about 400+ commercial c clocks and hydrogen masers at the remote sites
  - Data from primary frequency standards (cesium and a few optical clocks) are used the adjust th frequency of TAI as needed.

Atomic Time - 2

- Since 1972, Coordinated Universal time (UTC) is computed by the BIPM from TAI by adding integer seconds to TAI so that the magnitude of UTC-UT1 does not exceed 0.9 s (A different adjustment process was used before 1972.)
- TAI and UTC have the same frequency and differ in time only by these integer “leap seconds”

Adjustment process

- A leap second is scheduled when the magnitude of UTC-UT1 is predicted to approach the maximum tolerance (0.9 s)
- The leap second is normally scheduled for the last second of 30 June or 31 December
- The initial length of the UTC day was shorter than the length of the UT1 day so that positive leap seconds were added to UTC to allow UT1 to catch up
- Positive leap seconds are named 23:59:60 and are inserted between 23:59:59 UTC and 00:00:00 UTC of the next day.
- The length of the astronomical day has been decreasing so that the interval between leap seconds has increased fr about 1 per year in 1972 to no leap seconds since 201
  - A negative leap second might be needed if this trend co
    - 23:59:58 UTC would be followed by 00:00:00 UTC of the nex case. The time 23:59:59 would be skipped.

The Problems -1

- Clocks generally cannot display 23:59:60, so that various ad hoc methods are used to indicate the leap second
  - The clock is stopped and 23:59:59 is repeated
  - The clock is stopped and 00:00:00 of the next day is repeated
    - These methods assign the same name to two consecutive seconds
  - The leap second is “smeared” by a frequency adjustment before the leap event, after the leap event or both before and after
    - The time is monotonic in these adjustments, but the frequency of UTC is wrong for a considerable period near the event
- Adjustment methods are not compatible with UTC or with each other and time sources often do not indi which method is used
  - Data from different sources cannot be compared or

The Problems - 2

- Applications that depend on time interval or frequency have problems with UTC
  - Navigation, communications, power distribution
  - UTC no longer used by these applications
    - Time from GNSS becoming *de-facto* standard
- Supporting these applications is more important than maintaining a tight link between UTC and UT1

Possible Solutions

- Increase the maximum tolerance between UT1 and UTC so that leap events much less frequent
  - New tolerance of a few minutes
    - Leap events about once per century
    - Difference of GMT from UTC not generally observable
  - New tolerance of about one hour
    - Leap events about once every 3 or 4 centuries
    - Adjustment method too far in the future to specify now
  - No maximum tolerance
    - No leap events, no further adjustments
    - UTC and GMT would slowly diverge without limit
      - Current rate or order one minute per century
- One hour tolerance and no maximum tolera
  effectively the same for a very long time

Current Schedule

- International Telecommunications Union (ITU) and BIPM agree that:
  - Adjustment process changed in or before 2035
    - Possibly delayed until 2040 for hardware upgrades
    - No change before then
  - New tolerance should be not less than 100 s
  - The BIPM will define the adjustments to UTC
  - The ITU will define the formats and methods for transmitting UTC and UT1-UTC
    - Increasing the tolerance will break transmission fo
  - Details of the adjustment will be discussed BIPM governing committee in 2026

Advantages and Problems

- All solutions improve UTC for applications that depend on frequency or time interval
- Leap events will be less frequent but will still be irregular and unpredictable
  - Rare events make implementation errors more likely
  - Define an algorithmic adjustment process
    - J. Levine, Metrologia
- Any adjustment process is more complicated than no adjustment process
  - Why use UTC when GNSS time is continuous?
- No limit on maximum tolerance will have o
  in principle even if difference is small

A Negative Leap Second

- Probability of a negative leap in the next 10 years is unknown but not negligible
- Negative leap events have never happened
  - Implementation never tested
  - Implementation of positive leap seconds still have problems after 50+ years
- What happens if a negative leap second is needed before the current transition date of 2035?
  - Should the decision be accelerated?

Summary and Conclusions

- Most clocks cannot represent the leap second and use some ad-hoc, non-standard and poorly-defined method
- The current method of linking UTC to UT1 has problems for applications that use UTC as a reference for time interval or frequency
- Increasing the maximum tolerance between UTC and UT1 reduces the impact of these problems
- Removing the link between UTC and UT1 would solve these problems but UTC would diverge from UT1 and GMT
- The new method would not be implemented befo
  - The need for a negative leap second might accelerat change
- A decision is likely at the BIPM meeting in 2026

References

- Judah Levine, Patrizia Tavella, and Martin Milton, “Towards a consensus on a continuous UTC”, Metrologia, doi: 10.1088/1681-7575/ac98cb
- Judah Levine, “A proposal to change the leap-second adjustments to UTC”, Metrologia, doi:10.1088/1681-7575/ad6266