Removing the Discontinuity in UTC caused by Leap Seconds

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Outline

- Atomic time scale: TAI
- Astronomical time scale: UT1, GMT, …
- UTC as a combination of UT1 and TAI
- Leap seconds in UTC and problems
- Non-sanctioned solutions
- Summary and a possible way forward

Time Scales - 1

- International Atomic Time (TAI)
  - Continuous time scale based on seconds derived from cesium hyperfine frequency
    - 1 s = 9 192 631 770 cycles
  - Computed by the BIPM (www.bipm.org) based on data from many laboratories
  - No physical realization
  - No time signal
  - TAI is an *integrated* time scale

Time Scales - 2

- Astronomical Time scales
  - Position of Earth relative to distant stars
    - Observed with Very Long Baseline Interferometry
  - UT1, GMT, …
    - Data converted to observations at Greenwich
  - These are *dynamical* time scales
    - The length of the second is a *derived quantity*
  - Length of UT1 second > Length of TAI second
    - Clocks in TAI run fast relative to UT1 and GMT
    - Difference is generally increasing with **irregular variations** that cannot be accurately predicted, **but increase stopped since ~ 2016 (*not predicted*)**

Time Scales - 3

- Coordinated Universal Time (UTC)
  - Length of second derived from TAI
- "Leap Seconds" added to UTC as needed to compensate for the difference in the length of the second in the two scales
  - Maintain |UT1-UTC| < 0.9 s
  - ***Allows UTC to be used as a proxy for UT1 in many applications***
  - 37 positive leap seconds from 1972 to date
  - Negative leap seconds defined but never needed
  - Last leap second 31 December 2016
    - 6+ year interval since then was not predicted

Uses of UTC

- Provides reference time stamps
  - Time scale must be monotonic and single valued
- Provides reference frequency
  - time interval realizes cesium frequency
- Provides reference time for ephemerides, astronomical calculations
  - UT1-UTC can be ignored
  - UT1-UTC must be known and bounded

Leap seconds and problems

- Extra second added after 23:59:59 UTC
- Announced by the IERS (www.iers.org)
  - International Earth Rotation and Reference Service
- Official name is 23:59:60, 23:59 has 61 seconds
- Most clocks cannot display this time
- Particularly difficult for digital systems that measure time as number of seconds since some epoch
  - NTP, GPS and other global navigation satellites
  - Need for future leap seconds cannot be predicted
  - Previous leap second list not generally available

Leap Second problems

- Discontinuity in time interval and frequency across a leap second
  - Navigation, frequency calibrations, real-time processes affected
- Leap second occurs at UTC midnight, but occurs in working day in California, Asia and Australia
- Time formats of digital systems (NTP, GPS, …) cannot represent leap second
  - No Unambiguous time stamp

Multiple unsanctioned solutions

- Ignore leap seconds
  - Many versions of PC operating systems
  - GPS, Galileo, BeiDou System Times after initial epoch
- Stop clock for 2 s at 23:59:59 (NTP)
  - Two seconds have same name
  - Time ordering, causality problems
    - 23:59:59.5, …, 23:59:59.9, 23:59:59.0, 23:59:59:1, …
- Stop clock for 2 s at 00:00:00 of next day (POSIX)
  - Same problems as previous
  - Extra second added at 00:00:00 is in the wrong day
- Add leap second as frequency smear
  - Many different methods: before, after, before and after …
  - Not compatible with each other
- All methods not compatible with UTC as presently defined
  - Offset with respect to UTC ≈ 0.5 s
    - Very large relative to many legal and regulatory requirements
- Client does not know which method is used by server

Summary, possible way forward

- Make no change
  - Multiple, incompatible solutions will continue and usage will increase
  - Users will be faced with a multiplicity of time scales that are not compatible with UTC and which disagree with each other in the vicinity of a leap second with differences ~ 0.5 s.
  - Users will use their "favorite" time scale
    - Usefulness of UTC as a universal time scale will decreased

Summary, 2

- Increase maximum difference allowed for UT1-UTC with advance notice (in 2035?)
  - Link between astronomical and atomic times is maintained
  - UTC is still a low-accuracy proxy for UT1
- Leap events become much less frequent
  - If maximum difference <= 30 s, about 1 leap event or less per century
    - Will not break GPS, BeiDou formats of UT1-UTC
    - Will not break ephemeris tables
- A leap event becomes a bigger deal
  - Define a universal, internationally sanctioned smear method to be used by all services
    - Time stamps deterministic, unique and single-valued
    - Can be removed deterministically to recover SI frequency
    - Leap event defined deterministically: 12 UTC on 29 Feburary?

Summary, 3

- Stop leap events permanently (in 2035?)
- UTC no longer linked to UT1 at all
  - Divergence ~ 1 minute/century
    - Not detectable in civilian timekeeping
- UTC now monotonic and deterministic
- ***Many*** astronomical applications, data tables, transmission formats affected
  - Ephemeris tables will break at 31 s
  - GPS, BeiDou formats will break at 64 s
  - These applications are ***not*** going away

Summary, 4

- A binary decision has been sought for 20+ years
- Both sides minimize the arguments of the other side
  - Arguments are simply repeated at a higher volume
- Result has been a repeated stalemate

Summary, 5

- Question is considered as a "hot topic" by the BIPM
  - Current discussions within the Consultative Committee for Time and Frequency
- Question will be considered at the World Radio Conference of the ITU in 2023
  - Current discussions within Study Group 7 and Working Party 7A

Thank you

- Questions or comments now or later to judah.levine@nist.gov

As US Secretary of State Blinken has said, the United States and its allies and partners are united in the face of Russian aggression and will continue to stand with Ukraine as it fights for its future