Considerations for Lunar Time Scale

Developed by:

Cheryl Gramling
NASA HQ
Space Communications and Navigation

23 June, 2025 v2

Submitted to NIST and USNO for BIPM Task Group on Moon Time

NASA Perspective on Reference Lunar Time System

Maintaining the SI second (hence meter) is of primary importance for in-situ real time operations for navigation and timing.

Philosophies employed in developing LunaNet Interoperability Specification:

1. Keep the system as easy as possible for the users, and mitigate the user burden in terms of size, mass, power, and applicability.
2. Reuse as many of the GNSS techniques and principles as possible.

- The majority of the users will be on the surface, others will be in low lunar orbit (50-200 km above the surface) or landing/ascending from the surface.
- Part of lowering the barrier to entry and making it easier for the user community to explore, habitate, and perform science on the Moon, is to not require each mission, each robotic asset, each science investigation, each drilling/mining operation, each lander, and each human to pre-tune their watch to a time scale.
- The preference is to have the clocks on these assets be as representative as possible to their environment -- the lunar surface.
- Following philosophy #2, above, GNSS employ a time scale based on the Earth's geopotential surface.

- ❑ Having a lunar time scale referenced to the equipotential surface allows us to leverage Concepts for Operations from Earth/GNSS, and not burden the user with having to pre-tune all of the oscillators in their equipment to a scale that is 1783 km away, at the center of Mass of the Moon and introduces a 2us per day drift wrt the surface user.
- ❑ Time scale referenced to the lunar equipotential surface maintains the SI second consistent with the SI meter in that frame applicable to the surface users.
- ❑ IAG WG is working to define the lunar geoid.

NASA Perspective on Reference Lunar Time System

Discussion on TCL :

- One of the reasons TCL may be attractive is because the IAU has accepted the resolution for IAU to define TCL along with the Lunar Celestial Reference System, and that such definition can be done in short order/the near term. [NOTE: the IAU has not made progress on that resolution since it was accepted in August 2024.]
- TCL perhaps more readily scalable to other bodies .

<u>User impact</u>:

However, if employed and disseminated through PNT systems, users on the surface will have to adjust their clocks by a minimum of 2 microseconds per day every day.

In order to maintain time and perform accurate navigation, users either have to have persistent PNT services delivering that time scale, and/or an excellent [read that as high size, mass, power] oscillator to carry them through periods of outages and/or to meet the NASA requirement for Time To First Fix for a 4D solution within 600 seconds. During IOC, we will only have radionavigation satellite services over the service volume of interest (lunar South Pole) for 40% of an Earth day. Thus, a user's time knowledge will drift considerably between updates from the PNT service provider. Or a user must carry a stable oscillator with the associated burden.

When the LNSP PNT service returns to the service volume, the user will then have to adjust their clock to accommodate the update from the drift. 2us * 60% = 1.5 us of adjustment. This significant time knowledge change will have to be implemented so as not to impact ongoing user operations. A typical way to handle an update is through an orchestrated time-slicing update of a low offset that will not impact the operations; e.g. 0.005 us in the 8^{th} 0.100 CPU interval every 1 second, which would take 300 seconds to adjust time.

This approach is antithesis to terrestrial operations.

<u>Validation:</u>
How we can validate a model of TCL (coordinate time) if we cannot appropriately realize time at the center of the Moon?
However, if we define a lunar geoid, we can place clocks at a location representative of the geoid (or as close as practical) and realize a lunar time scale on the equipotential surface.

NASA Perspective on Reference Lunar Time System

- **NASA favors a practical approach that can fully realize a lunar time scale that represents the primary operating environment (the surface), maintains the SI second in a relevant frame, and enables reuse of techniques and principles of GNSS. This is time on the lunar [equipotential] surface.**

- Propose **use of time on the lunar geoid** (whatever BIPM names it TL, LT, LTC) for all* Lunar Comm & PNT systems:
  - Aligns with philosophies employed by LunaNet;
  - Analogous to GNSS implementations at Earth;
  - Supports differential corrections from the surface;
  - Enables a consistent reference frame/reference system with the gravitational potential and derived geoid;
  - Maintains the SI second (and meter) in the relevant frame;
  - Can be derived from WN/ITOW/TOI already part of LunaNet Augmented Forward Signal message.
    - Possibly can use a combination of "convention" for the secular drift, and polynomial for periodic terms;
  - Can readily BE INFORMED by in-situ realization to fully validate the model.
  - Lowers the barrier to entry for users outside traditional space agencies.

- Will need to identify how best to represent lunar time as well as its relationship to UTC, and to what accuracy the two scales must be correlated/traced.

- Immediate need is to have the international time standards community, through BIPM, agree on the math model for the lunar time scale(s) and relationship to UTC (and TCB).

* "all" is listed to ensure safety of navigation across all systems.

Requests from Timing & Ref Systems Standards Community

From Timing:

1. Establish, sanction, and document a mathematical representation of LT(scale) from UTC. Sept 2025.
2. Define an epoch for LT(scale) (wrt UTC/TAI). Ensure time wrt selected epoch can readily be represented in a rational number of bits. Perhaps a convention can aid this repsect by noting an epoch, then a standard offset to apply to “delay the epoch” to a more current date/time, e.g. Jan 1, 2020. Sept 2025.
3. Identify the Δt offsets across the maximum/minimum gravitational potential at the Moon, as well as distinct geographic locations on Moon wrt Earth. Sept 2025.
4. For a set of Use Cases, identify the time scale(s) to apply. Sept 2025.

Given that the Moon will not have a means for precise metrology for a long period, we have to focus on what is acceptable in the nearer term:

5. What holdover is needed/can be achieved? Commensurately, how often does a TWTT with Earth need to be performed; and to what accuracy/resolution/precision is the TWTT? Sept 2025.
6. Current thinking is that <u>no Time Zones</u> will be needed at the Moon; confirm if this is the correct operational approach. Sept 2025.
    i. What about at Mars, will Time Zones be needed?
7. Work with IAG to define a surface of equipotential.

----- END -----