

Physical Realization of Lunar Time Using a Surface Atomic Clock and Earth-Moon Time Transfer

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As international efforts towards sustained lunar exploration expand, the need for shared lunar infrastructure and standards is becoming increasingly important. In particular, precise and consistent timekeeping will be necessary to support navigation, scientific measurements, interoperability between independently operated systems, and coordination between lunar and Earth-based assets. In response to this need, the White House directed NASA to establish a time standard for the Moon (Dunbar, 2024). In the same month, the International Astronomical Union (IAU) adopted a resolution establishing standard definitions for the Lunar Celestial Reference System (LCRS) and its corresponding Lunar Coordinate Time (TCL) (IAU, 2024).

However, establishing such a lunar time standard requires more than defining a coordinate time mathematically. Recent works have developed relativistic transformations relating TCL to previously defined coordinate times such as Barycentric Coordinate Time (TCB) and Geocentric Coordinate Time (TCG) (Kopeikin and Kaplan, 2024; Lu et al., 2025; Turyshev, 2026). With these coordinate-time relationships established, an important remaining challenge is the physical realization of a common lunar reference timescale using stochastic clocks that measure proper time, analogous to local realizations of Coordinated Universal Time (UTC).

Since TCL is a coordinate time and cannot be directly realized by a physical clock, Bourgoin et al. (2026) distinguish TCL from Lunar Time (TL), which they define as a linear function of TCL. In this work, we adopt TL as the reference timescale to be physically realized from lunar clock measurements and set TL equal to TCL throughout our analysis. This choice is consistent with the recommendation of Bourgoin et al. (2026) and avoids introducing assumptions about non-standardized lunar scaling constants. In addition to accurately realizing TL, a practical lunar timekeeping architecture must maintain traceability to an Earth-based reference timescale, or in this case, a real-time realization of UTC.

RELATED WORK

Bourgoin et al. (2026) investigate possible definitions and physical realizations of a lunar reference timescale and its traceability to UTC. Their work establishes a framework for defining and realizing a lunar reference timescale and relating that realization to terrestrial time standards. However, they do not quantify how realization accuracy depends on physical clock stability and the availability of Earth-Moon time-transfer measurements, and leave that to future work.

The need to characterize this relationship was also highlighted at the 2026 Joint ICG-IOAG Multilateral Cislunar PNT Workshop. NASA identified the need to understand how the cadence and precision of Earth-Moon time-transfer measurements affect timing performance during intervals without Earth contact. The workshop further identified traceability to UTC as a key requirement for a practical lunar timekeeping architecture (Gramling and Crenshaw, 2026).

Recent work has also begun to investigate the relationship between a physical clock's proper time and candidate lunar reference timescales. Yang et al. (2026) consider an ideal clock in lunar orbit and investigate how its accumulated proper time can be related to TCL and a reference timescale aligned with the lunar geoid, or selenoid (which is still to be defined). Their analysis quantifies the resulting desynchronization under modeled lunar dynamics, but does not consider stochastic clock behavior or intermittent time transfer with Earth. In contrast, the present work considers the realization of TL from a stochastic clock located on the lunar surface and evaluates its performance between Earth-Moon time-transfer measurements.

Realizing lunar time using a surface clock is motivated by the proposed NovaMoon reference station, which is planned to launch in 2030 (Molli et al., 2026). NovaMoon is a lunar surface geodetic and timing station proposed for the south polar region. Its payload includes high-stability atomic clocks as well as a receiver capable of direct-to-Earth radio links. The station will have a dedicated Time Laboratory to support a physical realization of a lunar time reference. The NovaMoon concept therefore provides a representative architecture in which to evaluate the clock stability, Earth-Moon time-transfer cadence, and holdover duration required to maintain an accurate realization of TL.

PROPOSED WORK

We consider the proposed NovaMoon surface station as the lunar timing architecture for this study. Since the final NovaMoon landing site and onboard atomic clock specifications have not yet been determined, we evaluate candidate lunar surface locations and atomic clocks with varying stability. For the Earth segment, we consider the three deep-space stations in the European Space Tracking (ESTRACK) network: Cebreros, Malargüe, and New Norcia (Sesta et al., 2025). For each candidate NovaMoon location, we determine visibility to these ground stations and characterize the resulting Earth-Moon contact schedule. Intervals without visibility to any ground station define the holdover durations over which the NovaMoon clock must maintain the realization of TL without an external timing update. Ground-station scheduling constraints are outside the scope of this study, so we assume that a time-transfer measurement is available whenever geometric visibility exists.

To construct the simulation truth, we use ephemeris data with TCB as the independent time argument. The LTE440 lunar time ephemeris (Lu et al., 2025), which provides transformations between TCB and TCL to sub-nanosecond precision, is used to generate the ground-truth TCL. Because we set TL equal to TCL, this also defines the ground-truth lunar reference timescale. We then compute the proper time accumulated by a clock at the lunar surface and apply a three-state stochastic clock model that propagates clock phase, fractional frequency, and frequency drift rate. The model is parameterized by the diffusion coefficients of a given atomic clock, producing a simulated lunar clock reading that includes both relativistic effects and stochastic clock noise.

During periods of Earth contact, we model asynchronous two-way time-transfer measurements between the lunar station and an Earth ground station referenced to $UTC(k)$, following a measurement architecture similar to Iess et al. (2026). We use $UTC(k)$, where k denotes the timing laboratory, because UTC is computed retrospectively by the International Bureau of Weights and Measures (BIPM), whereas $UTC(k)$ provides an operational real-time realization of UTC. Propagation delays and relativistic corrections are modeled to reduce the time-transfer observable to a measurement of the lunar clock error state. An Extended Kalman Filter (EKF) then estimates the lunar clock phase, fractional frequency, and frequency drift rate. Combining the estimated clock bias with the modeled proper-time-to-TL transformation yields an estimate of the realized lunar timescale. The realization error is evaluated directly against the ground-truth TL. The complete simulation architecture is shown in Figure 1.

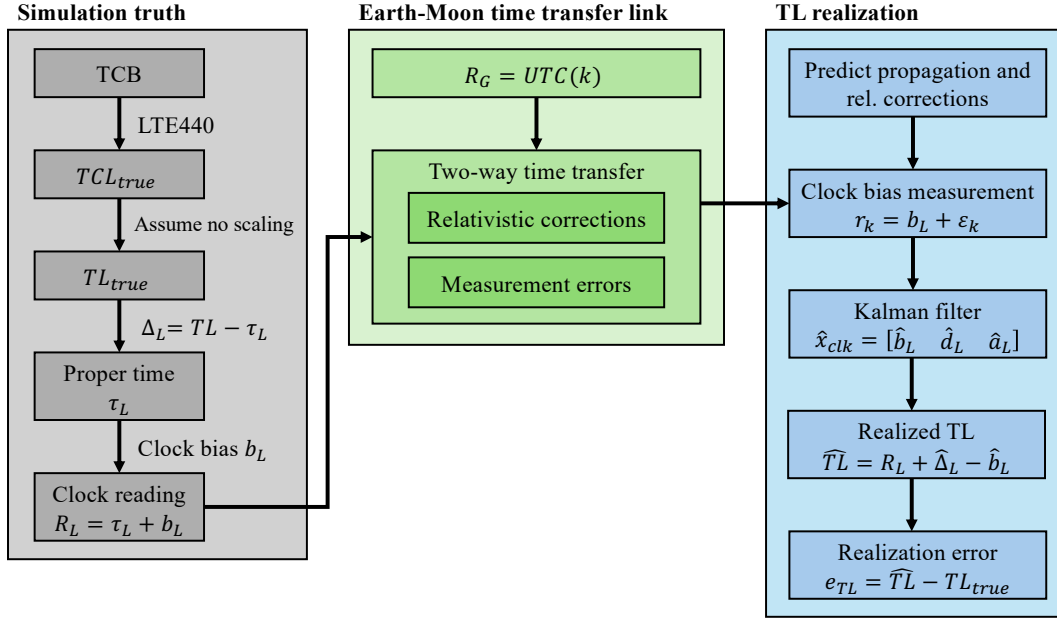


Figure 1: Architecture flow chart for TL realization and traceability to $UTC(k)$

INITIAL RESULTS

We evaluate two candidate lunar surface locations: the Apollo 15 (A15) lunar laser ranging reflector site at 26.2° N, 3.6° E (Zhang et al., 2025) and a representative Artemis Basecamp location in the lunar south polar region at 87° S, 50.5° E (Keane et al., 2022). Over a 60-day simulation, no ESTRACK ground station is visible for 8.9% of the interval at the A15 site and 55.9% at the south polar site. The maximum continuous outage across all three ground stations is approximately 6 hours at A15, whereas the south polar site experiences outages exceeding 10 days as the Earth moves below the local horizon due to lunar libration. These results demonstrate that Earth-contact availability, and consequently the required holdover duration, can

vary substantially with lunar surface location. Although landing-site selection is driven by many considerations beyond timing, these visibility results suggest that a lower latitude NovaMoon site could reduce extended losses of direct Earth contact.

As an initial assessment of whether candidate atomic clocks can maintain TL over these outage durations, we consider an optimistic scenario in which the clock state is known perfectly at the beginning of an outage. Propagating only the stochastic clock model provides a lower bound on the TL realization error that can be achieved by a given clock during holdover. We conduct this analysis for atomic clocks spanning a range of stabilities to determine how long each clock class can maintain a 1-ns TL realization accuracy. Using a three-state clock model parametrized by the diffusion coefficients reported by Long and Stacey (2025), a free-running Deep Space Atomic Clock (DSAC) remains below 1 ns of realization error due to stochastic clock noise for approximately 40 days, whereas a free-running Rubidium Atomic Frequency Standard (RAFS) reaches the same threshold after approximately 1.2 days. Thus, even before accounting for time-transfer measurement error or estimation uncertainty, a RAFS-class clock cannot maintain a 1-ns realization throughout the longest outages observed for the south polar site. In contrast, the same clock provides substantial margin relative to the maximum outage observed at the A15 site. This initial study provides a preliminary indication of the clock stability required to maintain a given TL realization accuracy over the expected periods without Earth contact. The full analysis will incorporate time-transfer measurement errors, relativistic corrections, imperfect clock-state estimation, and filtering to quantify the end-to-end TL realization error during both Earth contact and holdover.

DESCRIPTION OF NEW AND INNOVATIVE ASPECTS

The new and innovative aspects of this work are as follows:

- We develop an end-to-end framework for physically realizing TL from a non-ideal lunar surface clock while maintaining traceability to UTC(k). The framework combines relativistic coordinate-to-proper-time transformations, stochastic clock modeling, asynchronous Earth-Moon time transfer, and clock-state estimation.
- We quantify how Earth-Moon time-transfer contact intervals, time-transfer measurement accuracy, and lunar clock stability jointly determine the TL realization accuracy.
- Using the proposed NovaMoon station as the mission architecture, we translate lunar timekeeping requirements into design trades on candidate clock classes and station location. These results will determine which configurations can maintain a specified TL realization accuracy during periods without Earth contact.

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