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Discussion of Lunar Time Standards

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Abstract

To meet the future requirements of lunar users for unified time and spatial systems, the construction of a lunar time metrology system is proposed, focusing on three key aspects: time units, the time epoch, and the lunar calendar. This paper discusses a method for realizing independent lunar timekeeping, elucidates the relationship between lunar and terrestrial time metrology, and proposes a fundamental concept for a lunar calendar. It is argued that the syzygy of the Earth, Moon, and Sun, as a simultaneous phenomenon, acting as a bridge between Earth-based and lunar calendars. Finally, specific requirements for timekeeping, time dissemination, and time information regulations are outlined.

1. Introduction

The Moon currently lacks a unified timekeeping framework, making the establishment of a lunar time metrology system a pressing topic of contemporary discussion. One perspective advocates transmitting Earth's standard time to the Moon, enabling users on the lunar surface and in its vicinity to directly receive navigation signals from Earth satellites, thereby synchronizing with Terrestrial Time. Since 2021, the establishment of timekeeping systems out of the Earth has emerged as a major scientific issue[1]. A growing number of researchers are shifting away from the traditional viewpoint of absolute time, recognizing that a relativistic time viewpoint based on General Relativity provides the solution for establishing a unified time rule on independent celestial bodies. An alternative view holds that the Moon should adopt its own intrinsic time scale. Using the 2000 resolution of the International Astronomical Union (IAU), Kopeikin and Kaplan[2] derived a conversion formula between lunar coordinate time (TCL) and geocentric coordinate time (TCG). Similarly, Ashby and Patla[3], employing Einstein's field equations and the Schwarzschild metric, derived a transformation formula from proper time on the lunar surface (LT) to terrestrial time (TT) on Earth's geoid. Despite differences in their methodologies, both studies arrived at the approximate conclusion that clocks on the Moon, when using International System of Units (SI) seconds, run faster than their terrestrial counterparts. The principle of general relativity thus suggests that the Moon requires its own time unit as well as unique rules for timekeeping and dissemination. This paper aligns with the latter perspective, proposing an independent lunar time metrology framework grounded in general relativity. The proposed methodology is also extendable to other celestial bodies, such as Mars, Jupiter's satellites, and Saturnian satellites.

2. Study on the rule of time

Under the relativistic viewpoint of time, each independent celestial body's center-of-mass coordinate system should possess its own local rule of time. The lunar surface and its vicinity represent such a coordinate system, necessitating the creation of distinct lunar time rules. These rules encompass three fundamental elements: time units, a time epoch, and a calendar. The time unit for the Moon should conform to the SI second as defined by the General Conference on Weights and Measures (CGPM), while the lunar calendar should be derived from observable celestial phenomena on the lunar surface, distinct from the "year-month-day" system used on Earth[4].

3. Regarding the Lunar Local Time

A "time keeping – time dissemination" approach is proposed to standardize time across the lunar surface and its adjacent orbits. The generation of a local standard time is referred to as timekeeping, with multiple options available for establishing Lunar Standard Time:

1) Lunar Equipotential Surface Time (LT)
Analogous to Terrestrial Time (TT) on the Earth's geoid, this approach requires the definition of a reference gravitational equipotential surface on the Moon. Proper time would be reproduced using SI seconds, with multiple atomic clocks positioned at various locations on the lunar surface. Similar to the weighted average used to derive International Atomic Time (TAI) on Earth, these measurements would be combined to derive a unified time standard, such as UTC. However, this method faces significant challenges. First, the Moon does not exhibit a diurnal rotation relative to Earth. The existence of a well-defined equipotential surface similar to the geoid remains uncertain. Second, the deployment of multiple timekeeping atomic clocks and their intercommunication for comparison poses considerable engineering difficulties.

2) Lunar Coordinate Time (TCL) as Standard Time
Alternatively, selecting the coordinate time within the lunar barycentric coordinate system as the Lunar Standard Time (Lunar Coordinate Time, TCL) is another option. Coordinate time can not be directly measured, it must be derived from proper time through relativistic

transformations. This process effectively shrinks the equipotential surface to a single point, specifically the origin of the coordinate system. An observer initially measures local proper time according to the SI second definition. If the observer is orbiting in a near-lunar trajectory, the transformation formula includes a transformation coefficient that exhibits long-term drift and is dependent on orbital parameters. Similarly, if the observer is stationary on the lunar surface, due to the Moon's tide locked by the Earth, the transformation formula also includes a transformation coefficient that exhibits periodic variations and is dependent on the observer's altitude. This method presents relatively low engineering complexity. As the Lunar Standard Time is established in a progressive manner, beginning with a small number of observers, the standard will become increasingly stable with the inclusion of more timekeeping observers on the lunar surface or in lunar orbit. The initial position of the lunar barycenter is uncertain, but as the ephemerides of the timekeeping observers are refined, the location of the lunar barycenter will converge toward the agreed-upon origin of the coordinate system.

Here we briefly describe the process of unifying coordinate time among multiple timekeeping observers, which requires a decentralized comparison and adjustment protocol. If multiple observers, located in different orbits or at different positions on the lunar surface, each reproduce the SI second and measure their respective local proper times, these proper times cannot be directly compared. Instead, each observer must apply their specific transformation coefficients within the transformation formula to convert their proper time measurements into their respective coordinate time values. Only these coordinate time values can be intercompared. Prior to comparison, a path delay offset, corresponding to the time delay due to the distance between each observer and the coordinate system origin, must be incorporated. Then the timekeeping observers can disseminate their coordinate time data. We recommend a decentralized comparison and adjustment principle: each timekeeping observer communicates with all other timekeeping observers, bi-directionally broadcasting their respective measured coordinate time data, analogous to traditional two-way time transfer. After subtracting the path delay, clock deviations are obtained, and each observer broadcasts their clock deviation relative to all other timekeeping observers. Each observer maintains a record of these clock offsets, compiling a two-dimensional table containing the pairwise clock deviation data for all timekeeping observers. The observer with the largest deviation from the mean should then refine their transformation coefficient by adjusting either their orbital ephemerides or the gravitational potential model, while other observers make no adjustment. Through iterative application of this process, with an increasing number of participating timekeeping observers, the orbital parameters or gravitational potentials will converge more rapidly, ultimately converging to a relatively stable coordinate time. The permissible clock deviations should be on the level of tens of nanoseconds per 30 days, constrained by the short-term stability of the timekeeping atomic clocks. Consequently, each observer can trace their measured proper time back to the coordinate time of the lunar barycentric coordinate system, which constitutes the Lunar Standard Time.

Timekeeping observers, whether situated in lunar orbit or on the lunar surface, can disseminate the Lunar Standard Time. Time service can be achieved through various technological means including, but not limited to, optical fiber networks, radio frequency (RF) transmissions, and laser communication. When using wireless communication channels for time dissemination, the spatial coordinates of the transmitting antenna must be provided. Time users can then utilize the positional coordinates and standard time data from multiple distinct time disseminators to determine their own time and position, analogous to terrestrial radio navigation systems..

4. Lunar and Terrestrial Time Metrology

The relationship between Lunar Standard Time (TCL) and Universal Time Coordinated (UTC), the Earth's standard time, are equal rights. Due to relativistic effects, the local time (LT) on the lunar surface advances by approximately 56 μs/d relative to Terrestrial Time (TT). This offset is persistent; even if identical atomic clocks at both locations reproduce local proper time according to the SI second definition, the differing spacetime curvature at each location results in disparate rates of time dilation. Continuously transmitting terrestrial standard time to the Moon for lunar users to synchronize their clocks would introduce non-uniformities and instabilities in the received time service signal. This is further exacerbated by the periodic variation in the Earth-Moon distance, from approximately 363 300 km at perigee to 405 500 km at apogee, which induces a Doppler effect causing periodic variations in the time service signal with peak values of approximately ±2.39 ms/d. Furthermore, the cumulative relativistic effects lead to long-term clock drift. Remote time dissemination methods are inconsistent with the principles of general relativity. Therefore, lunar time metrology must be independent of terrestrial metrology. Time at these two locations can only be compared, with the comparison facilitated through a time-comparison table. Time synchronization is not feasible, and one standard time should not be used as the local standard time of the other.

Through derivation (supported by separate paper), the relationship between TCL and TCG is relatively straightforward:

$$\Delta TCL = (1 + L_{\mathrm{GL}})\ \Delta TCG \qquad (1).$$

$$\text{或} \quad \Delta TCG = (1 - L_{\mathrm{GL}})\ \Delta TCL$$

where: L_{GL} is the coordinate time transformation coefficient between Earth and Moon.

The transformation coefficient L_{GL} is also subject to long-term variation. The appropriate approach to establishing a relationship between Earth and Moon time requires periodic transmission of time-stamp signals between the two locations, which allows for the creation of a time-comparison table. This table can be used, along with actual measured data, to predict future variations.

Analogous to the terrestrial calendar, lunar calendar units also have long-period, medium-period, and short-period categories, with defined conversion ratios between them. The long-period units in the lunar calendar correspond to the orbital period of the Earth-Moon barycenter around the Sun. The medium-period units correspond to the synodic period of the Earth-Moon system. The short-period units correspond to the period of the recurring appearance of Earth-based fiducial markers. And even shorter timekeeping units are also available. The second is the fundamental unit of Lunar Standard Time, defined by timekeeping/time dissemination rules. Sixty seconds constitute one minute, sixty minutes constitute one hour, and subsequently non-integer ratios are employed: approximately 24.82 hours constitute one period of Earth-based fiducial marker reappearance, approximately 28.6 periods of Earth-based fiducial marker reappearance constitute one synodic period of the Earth-Moon system, and approximately 11.7 synodic periods constitute one orbital period of the Earth-Moon barycenter around the Sun.

5. On the Lunar Calendar

The terrestrial calendar system based on "year-month-day" cannot be directly adopted for the Moon. The Moon requires its own distinct calendrical rules, typically employing its rotational period, revolution period, and arbitrarily defined time intervals as fundamental units of timekeeping. An observer on the lunar surface perceives periodic celestial motions, the periodicity of which stems from the intrinsic rotation and revolution of celestial bodies. The reference frame for these rotations and revolutions can be chosen within a multi-tiered coordinate system. The Principle of General Relativity dictates that stable rotational and revolution periods are measurable only when the reference frame is selected within the local or a immediate upper-level coordinate system. For a lunar surface observer, there are three categories of apparent celestial motion cycles suitable as timekeeping units: those of the Earth, the Sun, and the Stars. The Earth belongs to a immediate upper-level coordinate tier relative to the Moon, making the Earth-referenced lunar calendrical cycles exhibit more stable periodicity. It is crucial to emphasize that the apparent celestial motion is non-uniform. According to Kepler's Second Law, which uniform angular velocity in the true anomaly along an elliptical orbit is not simultaneously compatible with uniform time flow. In other words, when considering one of the foci of the ellipse as a reference point—such as the Earth at the focal point of the lunar orbit—the Earth appears to oscillate back and forth near its position during equal time intervals. This, combined with the lunar libration, causes highly non-uniform apparent motion of the Earth. However, when using the Earth as the reference point for observing the Sun's and the fixed Star's apparent motion, cycles analogous to the synodic month on Earth are obtainable. Furthermore, using the Sun as a reference point to observe the apparent motion of the fixed Star relative to the Sun yields cycles analogous to the Earth's tropical year. All of these apparent celestial motion cycles can be adopted as calendrical units for the Moon.

When the Earth, Moon, and Sun are approximately aligned, the phenomenon is simultaneously observable from both the Earth and the Moon; specifically, lunar syzygy cycle and terrestrial syzygy cycle, which act as a bridge linking the Earth and lunar calendar systems.

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6. Conclusion

Lunar time metrology regulations should be uniformly implemented among lunar inhabitants through formal agreements or statutory frameworks. Two categories of time users exist on the lunar surface and in nearby space orbits: Firstly, time users possessing both timekeeping and time dissemination capabilities. These users should be subject to metrological regulations and protections, with only a select few authorized timekeeping stations and time dissemination facilities possessing such qualifications. Secondly, regular time users who do not possess timekeeping capabilities or time dissemination functionality, but can receive disseminated time signals. A fundamental principle of lunar time is the indivisibility of space and time. Lunar time metrology regulations encompass, but are not limited to, the following aspects:

1)Timekeeping Aspects: Define the Lunar Standard Time; prescribe synchronization and coordination protocols among timekeeping observers; establish the essential qualifications and authorization procedures for timekeeping observers.

2)Time Dissemination Aspects: Specify that the Lunar Standard Time should be disseminated via wireless channels, such as radio frequency (RF) or laser, with accompanying coordinate information; define dissemination frequencies and bandwidths; stipulate message content and formats. The One pulse per second (1 PPS) signals are to be confined to localized areas or wired networks. Different nations, organizations, systems, or missions can define their own time epochs, adhering to a first-come, first-served principle. Later time disseminators, if implementing a new time origin, must include in their message the relationship to previously established time origins and avoid interfering with existing channels.

3)Time Information Content: Time information should cater to the needs of diverse time users, and can be either comprehensive or simplified, such as: lunar calendar unit + Lunar Coordinate Time (in seconds) + position coordinates + time difference relative to the earlier time epoch + the corresponding terrestrial time. The corresponding terrestrial time is supplementary information appended by the timekeeping system, and is neither essential for the standard time nor does it exhibit a linear relationship.

The above constitutes the recommendations of the URSI China Committee Commission A "Lunar Time Standard" Working Group, submitted for discussion at the URSI Commission A meeting.

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