Conceptual Framework for Lunar Time

尹东山
Yin Dongshan
National Time Service Center, CAS
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Topics to be covered

1. Reference system and coordinate time for Moon
2. Difference between lunar time and terrestial time
3. Different requirements for lunar time
4. Strategy for generation of UTC
5. Definition of lunar time
6. Relationship between lunar time and UTC
7. Envisioned realization of lunar time
8. Topics proposed to be pursued

Reference system and coordinate time

- **For definition of local lunar inertial reference system, Lunar Celestial Reference system(LCRS) and Lunar Coordinate Time(TCL), are adopted in IAU2024-Resolution2;**
- $$TCB - TCG = L_c(JD - 2443144.5) \times 86400 + \frac{1}{c^2}\vec{V}_E \cdot \left(\vec{X} - \vec{X}_E\right) + P$$
- **Transformation between TCB and TCL be given as above formula, with substitution of quantities related to Moon for those related to Earth;**
- **For any transformation between lunar fixed reference system and International Celestial Reference System, such as lunar orientation determination w.r.t. celestial background, LCRS and TCL are needed.**

	BCRS	GCRS	LCRS
origin	SSB	geocentric	selenocentric
pole,axis	north celestial pole as Z-axis, points to vernal equinox as X-axis, right-handed	parallel to BCRS's	parallel to BCRS's
plane	mean celestial equatorial plane	parallel to BCRS's	parallel to BCRS's
realization	ICRF3,Hipparcos, gaiaDR3,etc	plus parallax and aberration	plus parallax and aberration
time	TCB	TCG	TCL

Difference between lunar time and terrestial time

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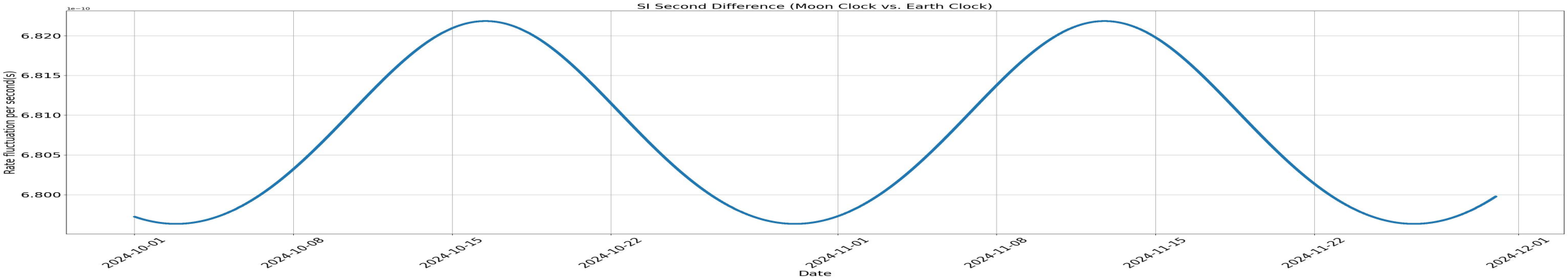
- Einstein’s theory of relativity couples space and time together;
- Certain reference frame comes with a certain set of constants, including gravitational potential, radius, rotation angular velocity, etc;
- Lunar astronomical constants system differs significantly from Earth’s, which leads to difference in gravitational field and velocity(including orbital motion and rotation);
- Einstein equation tells us gravitational field and coordinate velocity both pose influence on time scale;
- Our calculations show that:

  (1)clock rate differs between Earth’s clock and Moon’s clock, which will introduce clock difference between two systems at about $58.8\mu s/day.$

  (2)plus periodic fluctuation caused by eccentricity of Moon’s orbit(27.3 days period).



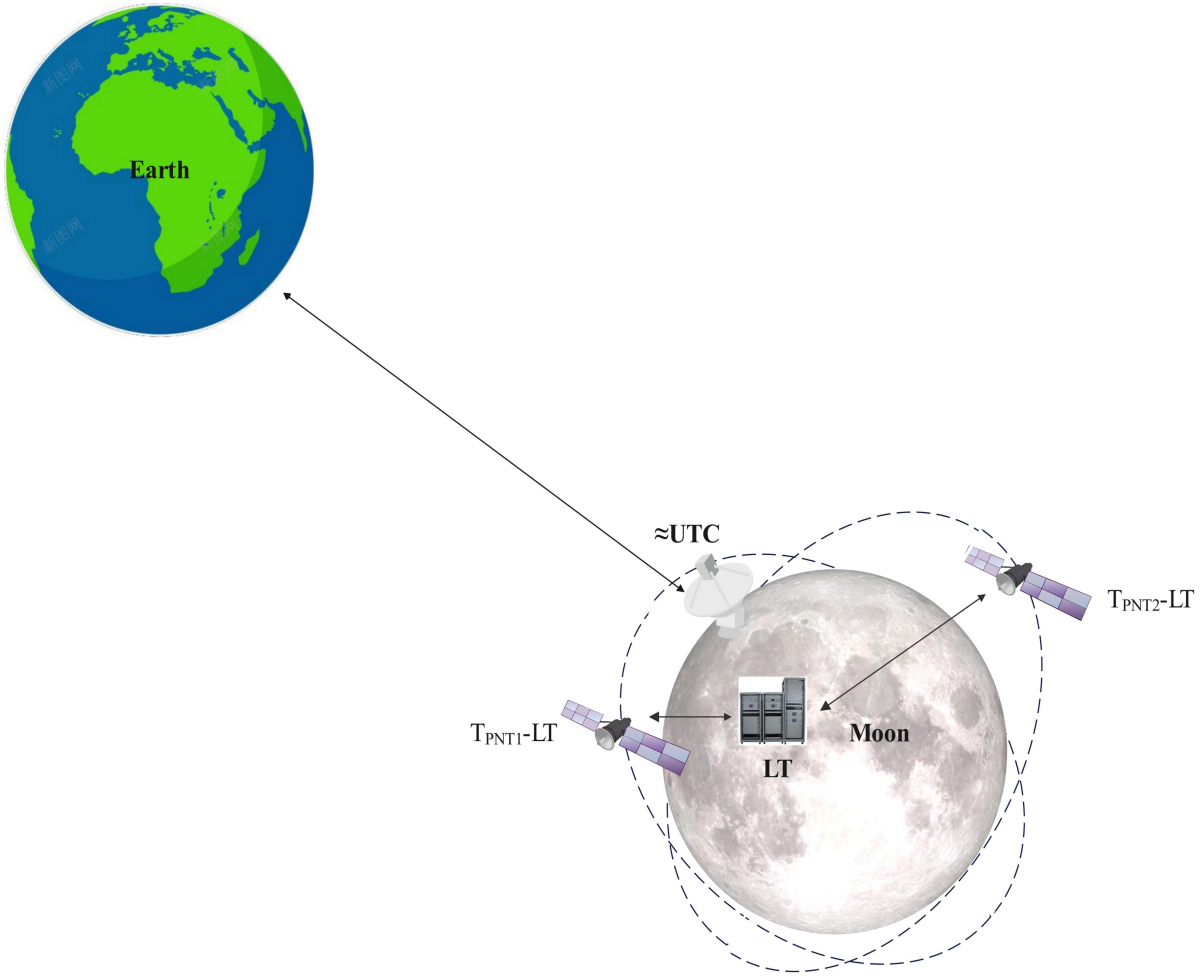
Different requirements for lunar time standard

- For activity conducted in accordance with Earth, such as communication between them, requires critical sync. between lunar time and UTC/TAI, the higher bandwidth is, the more stringent time sync. is required;
- $$\text{steered LT} = \text{UTC}$$
- For activity conducted independently under lunar gravitational field, such as lunar PNT, requires time standard in local inertial system.

$$L = \tau \cdot c + \sigma$$

distance measured under lunar gravitational field

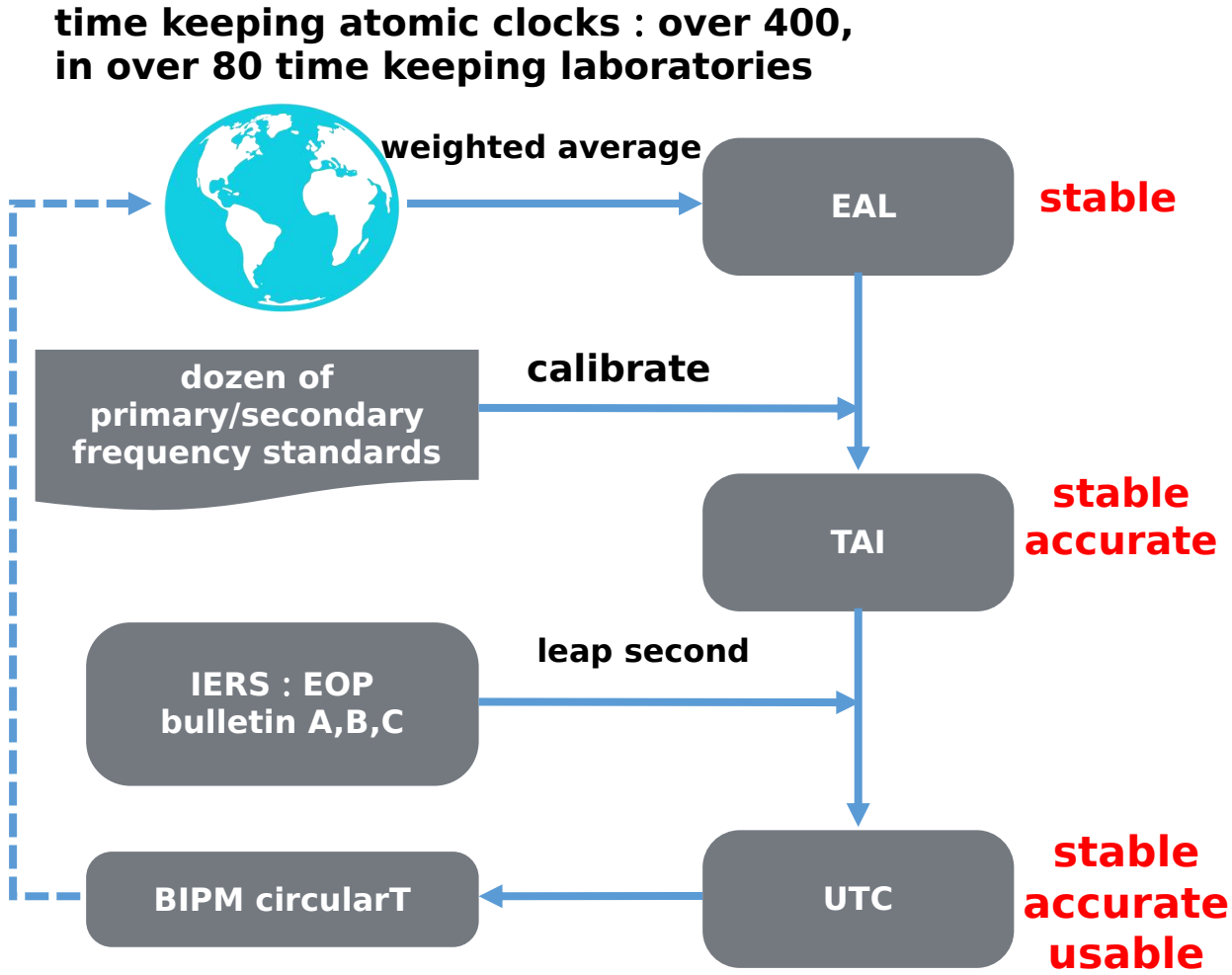
time interval measured under lunar gravitational field



communication with Earth and lunar PNT

Realization of UTC

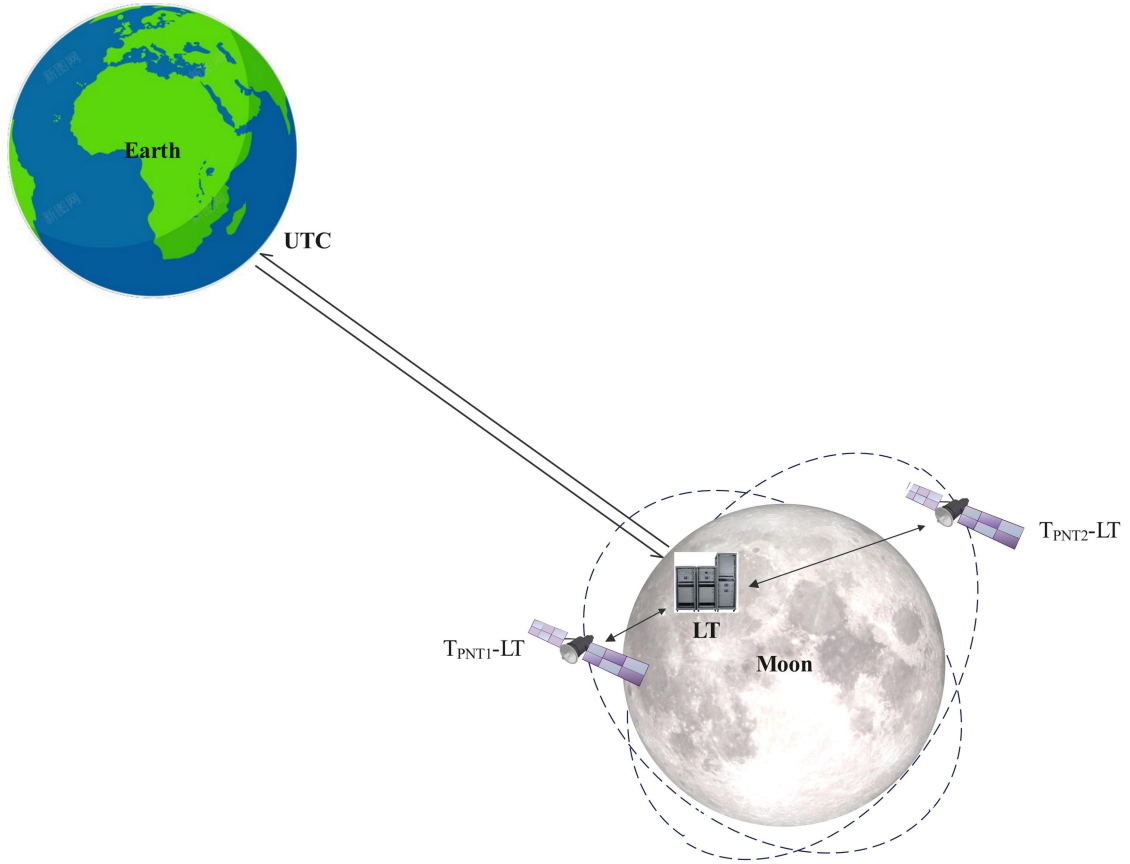
- On Earth, UTC is universal time standard worldwide, which provides an uniform and unique time reference for all activities on Earth;
- UTC/TAI is based on the SI second, and leap seconds are introduced to maintain approximate alignment with UT1, which is derived from earth rotation;
- UTC/TAI is defined exactly at geoid and realized from an ensemble of atomic clocks around the globe, and gravitational potential differences are accounted for during time comparison and calibration;



generation of UTC

Definition of lunar time

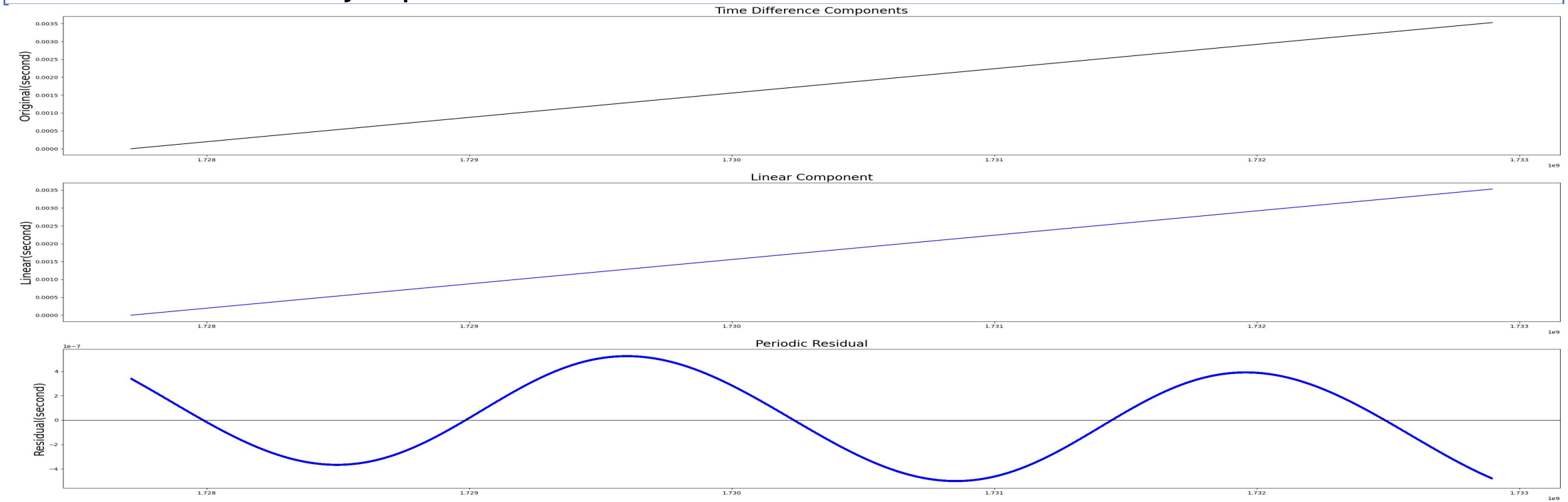
- Lunar standard time should be defined at specific lunar ellipsoid, with certain gravitational potential on it;
- Atomic clock ensemble is physical basis for lunar time realization, and its elevation from reference ellipsoid is clearly determined;
- Lunar time should be accurately traceable to UTC;
- Lunar time could be kept independently;
- Serve as pivot among lunar PNTs system time.



tracibility established between lunar time and UTC

Lunar time difference from UTC/TAI

- Lunar time exhibits two primary patterns of variation w.r.t. UTC/TAI :
  1. Linear drift resulting from differences in length of second ;
  2. Periodic variations resulting from the eccentricity of Moon’s orbit around the Earth。
- Both regular and irregular variations induced by gravitational perturbations from the Sun and major planets.



Time Difference Moon clock vs. Earth clock and its main components(10.1.2024~11.30.2024)

Lunar time difference from UTC/TAI

- $\Delta T_{LT-TT} = \boldsymbol{initial}\ \Delta T + \boldsymbol{linear} + \boldsymbol{periodic} + \boldsymbol{\sigma}$
- $\boldsymbol{initial}\ \Delta T$: clock offset between the lunar time and UTC/TAI at the initial epoch;
- $\boldsymbol{linear}$:average deviation between lunar time second and UTC second accumulates over time, which could be expressed as $a_1(t-t_0)$, calculation shows $a_1 = 6.808E-10$;
- $\boldsymbol{periodic}$:derived from periodic component remaining after subtracting the average circular orbit from Moon's orbital motion around the Earth , which is two orders of magnitude smaller than linear component , second-order series expansion could be performed on this component ;
- $\boldsymbol{\sigma}$: clock offset caused by the differential gravitational perturbations from the Sun and major planets on the Earth-Moon system , atomic clock operates with irregularity, etc.
- $\Delta T_{LT-TT} = \Delta T_0 + a_1(t-t_0) + a_{p1}(t-t_0) + a_{p2}(t-t_0)^2 + \sigma$
- $\Delta T_{LT-TT} = \Delta T_0 + a_1^{'}(t-t_0) + a_{p2}(t-t_0)^2 + \sigma$

Envisioned realization of lunar time

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➢ Implementing lunar time for clocks deployed on the Moon :

1. Approach 1:
   - adjusting the length of the second for a relative change of 1×10^{-10} only requires modifying the ones digit of 9,192,631,770 ;
   - its output is close to UTC, exhibiting only periodic variations on the order of microseconds ;
   - lunar atomic clock is frequently and routinely steered so that its time closely aligns with UTC ;
   - facilitating communication between Earth and Moon, high dependence on comparison link。
2. Approach 2:
   - adjusting the length of the second ;
   - its output is close to UTC, exhibiting only periodic variations on the order of microseconds ;
   - no frequent steering on the clock, whch is more conducive to lunar PNT

Envisioned realization of lunar time

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- Both approaches are based on physical signal from lunar atomic clock, and directly tracable to UTC ;

1. for approach 1:
   - lunar time is directly derived from lunar clock, which is also UTC after frequent and routinely steering ;
   - broadcast the model of the clock offset of lunar time relative to UTC.
2. for approach 2:
   - lunar time is directly derived from lunar clock, without frequent steering;
   - broadcast clock offset model of lunar time relative to UTC, with the periodic component as dominant term.

- Based on comparison results, either the lunar clock is adjusted or the coefficients of the clock offset model are revised ;
- The system times of lunar PNT systems can be referenced to lunar time, thereby establishing mutual clock offset relationships.

Topics proposed to be pursued

- Which approach is more advantageous—adjusting the output second length of the lunar clock or leaving it unadjusted? This needs to be determined after a detailed discussion. ;
- Earth's mass is 80 times that of the Moon and it is very close to the Moon. When considering atomic clocks on the lunar surface, can the Earth be simply treated as a gravitational perturbation source ?
- To accurately model the atomic clock behavior on Moon’s surface and at the Lagrange points, it is necessary to compute the differential gravitational perturbations from the Sun and major planets within the Earth–Moon system. Can the existing DE series or INPOP series ephemerides meet these requirements ?