# Looking for a Lunar Reference Timescale

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# Numerous upcoming/recent projects for Moon exploration…

中国探月
CLEP




РОСКОСМОС

NASA

ARTEMIS


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# Need to adopt common reference frames


**LunaNet Interoperability Specification (LNIS V4)**

(NASA proposal for interoperability framework)

Space agencies and interested parties are seeking inter-operable data transfer and navigation system

-> Need for a « Lunar GNSS », and therefore a better definition of a common lunar time scale

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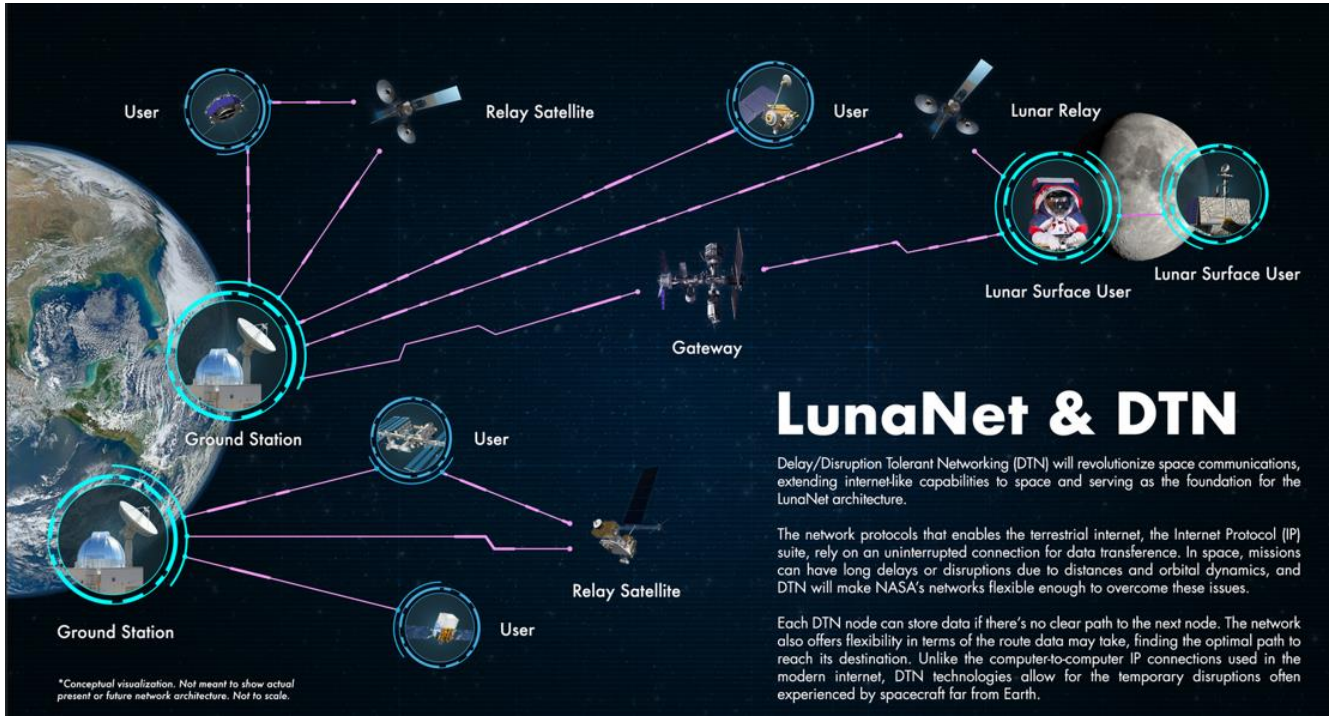
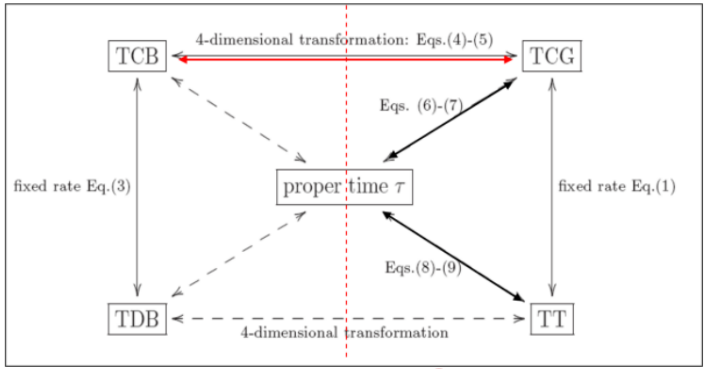
# An example of global network scheme



# IAU Resolutions

- Resolution A4 of the XXI-st General Assembly (1991) sets the basis for relativistic celestial reference frames
- Resolution B1.5 of the XXIV-th General Assembly (2000) covers "*Extended relativistic framework for time transformations and realization of coordinate times in the solar system*" (with B1.3 defining **BCRS** and **GCRS**)
- Following these resolutions leads to a well-defined LCRS
- Next General Assembly in Aug 2024, recommendation on Lunar reference frame is expected

# Currently defined relativistic reference frames




Barycentric sys.: time coordinate TCB

TDB may be used $\frac{\mathrm{d}TDB}{\mathrm{d}TCB} = 1 - L_B$

$L_B \overset{\text{def}}{=} 1.550519768 \times 10^{-8}$

Geocentric sys.: time coordinate TCG

TT is used in practice $\frac{\mathrm{d}TT}{\mathrm{d}TCG} = 1 - L_G$

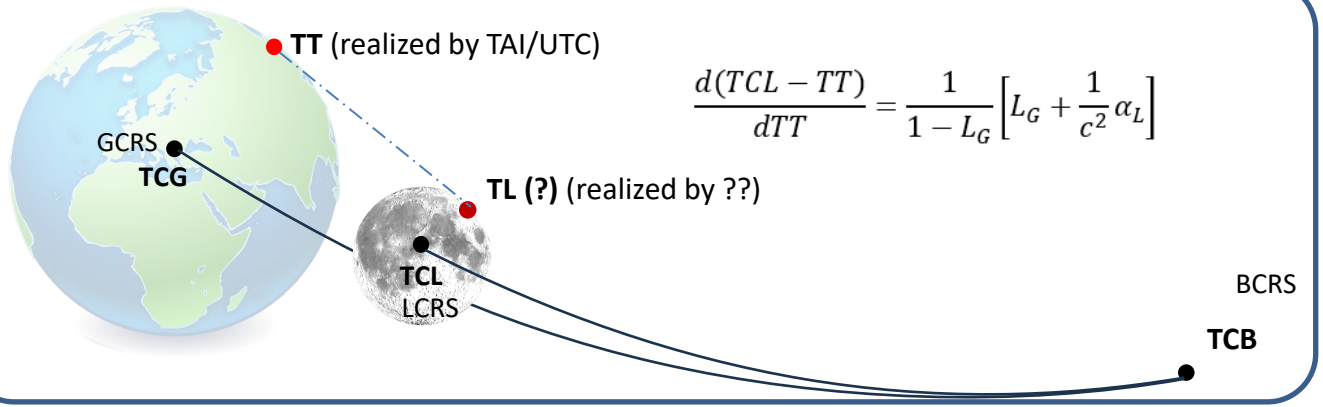
$L_G \overset{\text{def}}{=} 6.969290134 \times 10^{-10}$

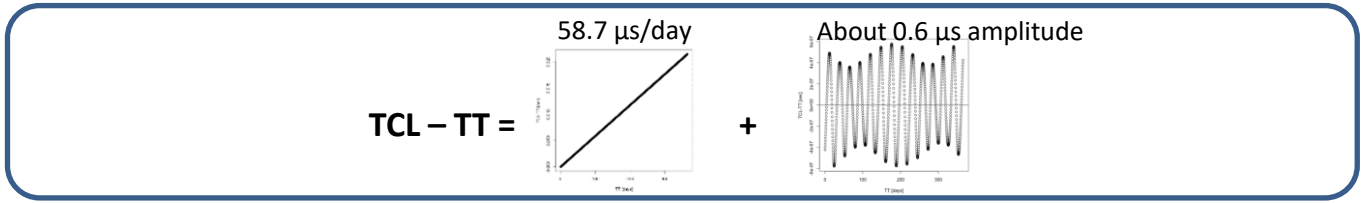
$(\simeq GM_\oplus/(c^2 R_\oplus))$

- TT and TDB designed to have $\sim$ the same rate as a clock on the geoid
- All coordinate transformations between systems are 4-dimensional

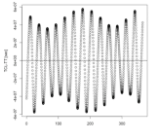
# Defining a Lunar Timescale

TT: Time at geoid (TAI and therefore UTC are realizations of TT)
TCG: Time at Earth barycenter
TCL: Time at Moon barycenter
TL: Lunar time




Define TL : TT plus the lunar periodic terms (?)

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# What does it mean?

- All clocks on or around the Moon will tick their **proper time**
- If we compare two clocks on the Moon (fixed in the LCRS) we will see only a small drift if they are at different altitudes (1.8E-17/m or 1.5 ns/1000m/day), but **no periodic variations**
- If we compare a clock on the Moon equator and a clock on the Earth equator, we will see a difference of **~56 µs/day + periodic terms**

See e.g. Ashby & Patla, 2024, https://arxiv.org/abs/2402.11150

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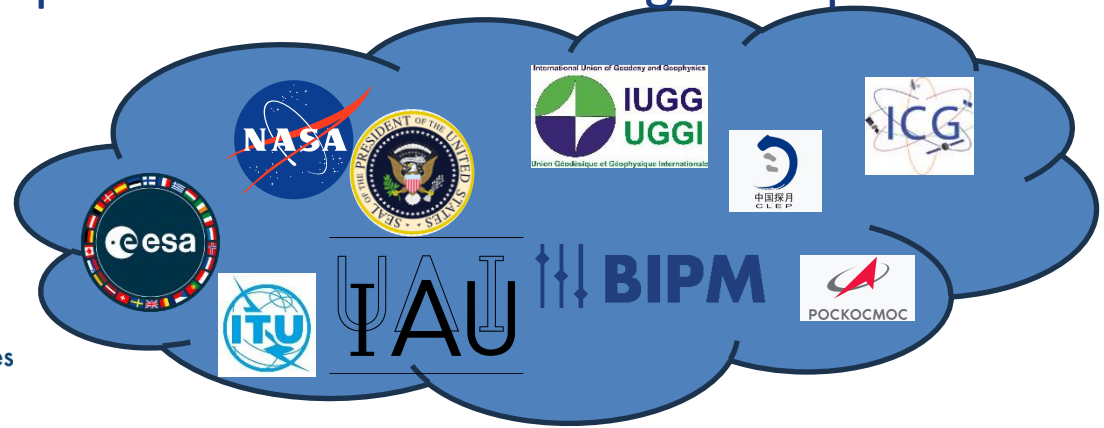
# Not only a scientific issue...

- Staying in geocentric reference frames allows some approximations that are no longer valid on the Moon. (And what about Mars ?)
- Still, navigation systems will need a common time scale
- Also a political matter involving multiple actors

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# Comparison of 2 possible approaches

| | Lunar Time = TT + periodic terms | Lunar Time = TT + $L_L$(t-t0) + periodic terms |
|---|---|---|
| Realization (=physical reference) | UTC + [periodic terms (from ephem)] $_{\text{num cor}}$ | UTC + [$L_L$(t-t0) + periodic terms]$_{\text{num cor}}$ |
| Difference to UTC | Remains within the periodic terms | Secular Increase (~57µs/day) |
| Uniqueness of time scale | YES: UTC frequency is the reference | NO: new time scale with t0, and Long term deviation between LT and UTC, **risk of confusion** |
| Time system aligned with the LCRS | **NO** | YES |
| Direct interoperability with Earth's GNSS | YES | **NO** |

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# Time for the Moon and TF metrology in the BIPM/CCTF


Two recommandations:

- **Work together with concerned International Organization for common agreement:** decision on reference time scales impacts several fields of applications and activities in the realm of different international organizations. It is important to work together and define common and agreed reference standards ensuring interoperability and comparability of measurements, since the beginning.
- **Any time scale on the Moon (or anywhere) should be connected to UTC:**
  - the theoretical behavior versus TT/UTC is known (mathematical equations in the frame of General Relativity)
  - when feasible, their difference is measured and the contributions to uncertainty evaluated (issue in the theoretical expectations, retrace of the clock frequency, steering)

# Time for the Moon
# and TF metrology in the BIPM/CCTF (continued)

**Activity:**

- stimulate contacts between metrology institutes and (inter)national space agencies
- Based on our timekeeping expertise we can help in identifying the key issues in time dissemination, synchronization, and uncertainty evaluation

**Collaboration with other International Organizations:**

- **IAU**
  - Commission A3 Standards
  - WG "Time Metrology Standards", and subgroup on lunar timescale
  - IAU Symposium: “Advancing Reference Systems, Ephemerides, and Standards: from the Earth and the Moon to solar system bodies” August 2025
- **IAG**
  - WG1.1.3: Lunar Reference Frames
- **ITU**
  - Contacts with WP7A and 7B «time and frequency services » and « science »

# Takeaway

- Agencies and private companies are coordinating **now** in order to be ready for their future missions
- "Correct" answer not completely clear yet
- International Organizations can/should play a major role in reaching a globally accepted consensus
- Time and Frequency community may help with the experience in clocks, synchronization, time scale, and time transfer
- Let's exchange information and ideas among time laboratories, space agencies, and international organizations