Workshop on Lunar Time : AGENDA

- Introduction (P. Tavella, F. Meynadier) ---------- 15 min
- needs and constraints for a Lunar time scale from Space agencies
  - JAXA
  - NASA
  - ESA ---------- 40 min
  - CNSA
  - ROSCOSMOS
- Steering (P. Defraigne) ---------- 10 min
- Scaling (S. Klioner) ---------- 15 min
- Joint IAG IAU WG (K. Sośnica) ---------- 10 min
- Discussion (all) ---------- 30 min

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Context

Space agencies → GNSS-like Positioning Navigation and Timing (PNT)

→ Need to fix the reference systems for interoperability

→ Reference time scale for Moon operations ?

This depends on the necessary accuracy:

- UTC will remain the international reference timescale
- Most of the Moon missions till now needed less than 1 microsecond accuracy.
- PNT like GNSS require nanosecond accuracy. On the Moon, relativity cannot be ignored.
  → A Moon time reference is needed for such high precision applications

IAU resolution on Lunar coordinate Time

IAU (Resolution II-2024) defines the theoretical framework

- 4D Lunar Celestial Reference System (LCRS) (x,y,z,t) with t in **Lunar Coordinate Time TCL**
- 4D transformation from Barycentric Coordinate Time TCB to TCL

$$TCB - TCL = c^{-2}\left\{\int_{t_0}^{t}\left[\frac{v_l^2}{2} + W(\vec{x_l})\right]dt + \vec{v_l}\,.\,(\vec{x} - \vec{x_l})\right\} + O(c^{-4})$$

t_0= *1977 January 1, 0h 0m 32.184s*

IAU (Resolution III-2024) recommends collaborative **agreement** among the relevant **international organizations** for the reference time scale **for practical use**,
quoting Coordinated Universal Time (UTC), as established by the Bureau International des Poids et Mesures (BIPM), based on international collaboration and coordination, a successful worldwide reference time scale for operational systems in the near-Earth environment.

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Also the "International Committee on GNSS" WG L asks for collaboration with BIPM
BIPM is member of the joint IAG IAU WG 1.1.3 on Lunar Reference Frames

Workshop on Lunar Time

CCTF Task Group on Lunar Time started in 2024

Dr Mamoru Sekido, NICT (co-chair)
Dr Pascale Defraigne, ORB, (co-chair)
Dr Frédéric Meynadier, BIPM (secretary)
Dr Ashish Agarwal , NPLI
Dr Adrien Bourgoin , LNE-OP
Dr Fang Fang , NIM
Dr Myoung-Sun Heo , KRISS
Dr Tetsuya Ido , NICT
Dr Noël Dimarcq , CNRS, Univ. Côte d'Azur, Obs. Côte d'Azur
Dr Artem Karaush, VNIIFTRI
Dr Judah Levine , NIST retired
Mr Andrey Naumov , VNIIFTRI
Dr Bijunath Patla , NIST
Dr Steven Peil , USNO
Dr Ilaria Sesia , INRIM
Dr Patrizia Tavella , BIPM
Dr Dongshan Yin , NTSC

CCTF Task Group on Lunar Timing : main goals

- Understanding and clarifying the possible options for a reference time on the Moon and its realization based on our timekeeping experience
- NMIs in contact with space agencies -> future collaborations
- Exchanges with the space agencies about possible operational constraints
- Exchanges with the experts in General Relativity about implications of different options of a Lunar Reference Time
- Ensure the possibility to have traceability to UTC and uncertainty evaluation

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The General Conference on Weights and Measures (CGPM) in Oct 2026 will adopt a resolution

Draft CGPM resolution:

- UTC is the international reference timescale and will be used for most of operations at the Moon, as there will be intense communication with the Earth.
- A specific Lunar reference time is needed for high precision applications as PNT
- TCL (**Lunar Coordinate Time)** has already been defined by IAU
- Proliferation of time scales should be avoided
- Scaled version of TCL → additional scaling and risk of confusion. Reference values are needed by other bodies
- As on the Earth, most clock frequency on or around the Moon will need to be steered
- Operational and practical constraint may justify another Lunar time scale?

Further steps before a consolidated CGPM draft resolution

- Draft already discussed at the CCTF in Sept 2025
- Session devoted to “Lunar ref frame and timing” at the ICG in October 2025
- **Workshop on Nov 18** organized by the CCTF task group:
  - Space agencies
  - Future scientific users of Time on the Moon

  → **Define the list of open questions**

- CCTF task group participation to bilateral and ICG WG L meetings in Dec 2025
- 2nd workshop IOAG/ICG in Vienna in Feb 2026 *(time session under organization)*
  https://www.unoosa.org/oosa/en/ourwork/icg/working-groups/l/CislunarPNT2026.html
- Complete CGPM draft resolution published on the BIPM web in Feb 2026
- Oct 2026 meeting of the General Conference on Weights ad Measures for adoption by BIPM member states

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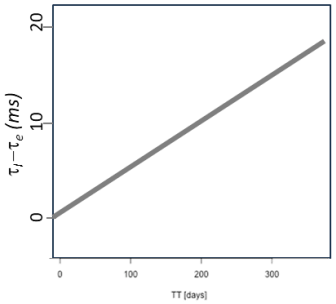
All presentations (if agreed) available on
https://www.bipm.org/en/committees/cc/cctf/wg/cctf-tgmt/2025-11-18

Expected difference for [Moon clock – Earth clock]

~ 56 µs/day
(1s after 50 yr)



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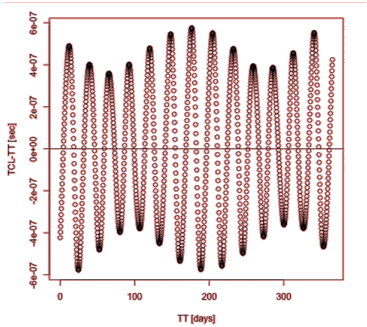


Depends on the
- Coordinate system
- Clock positions

τ_e

Using on the Moon a linear function of UTC : only valid at the µs level
No unique relation UTC-TL as coordinate time differences are 4-D

τ_l

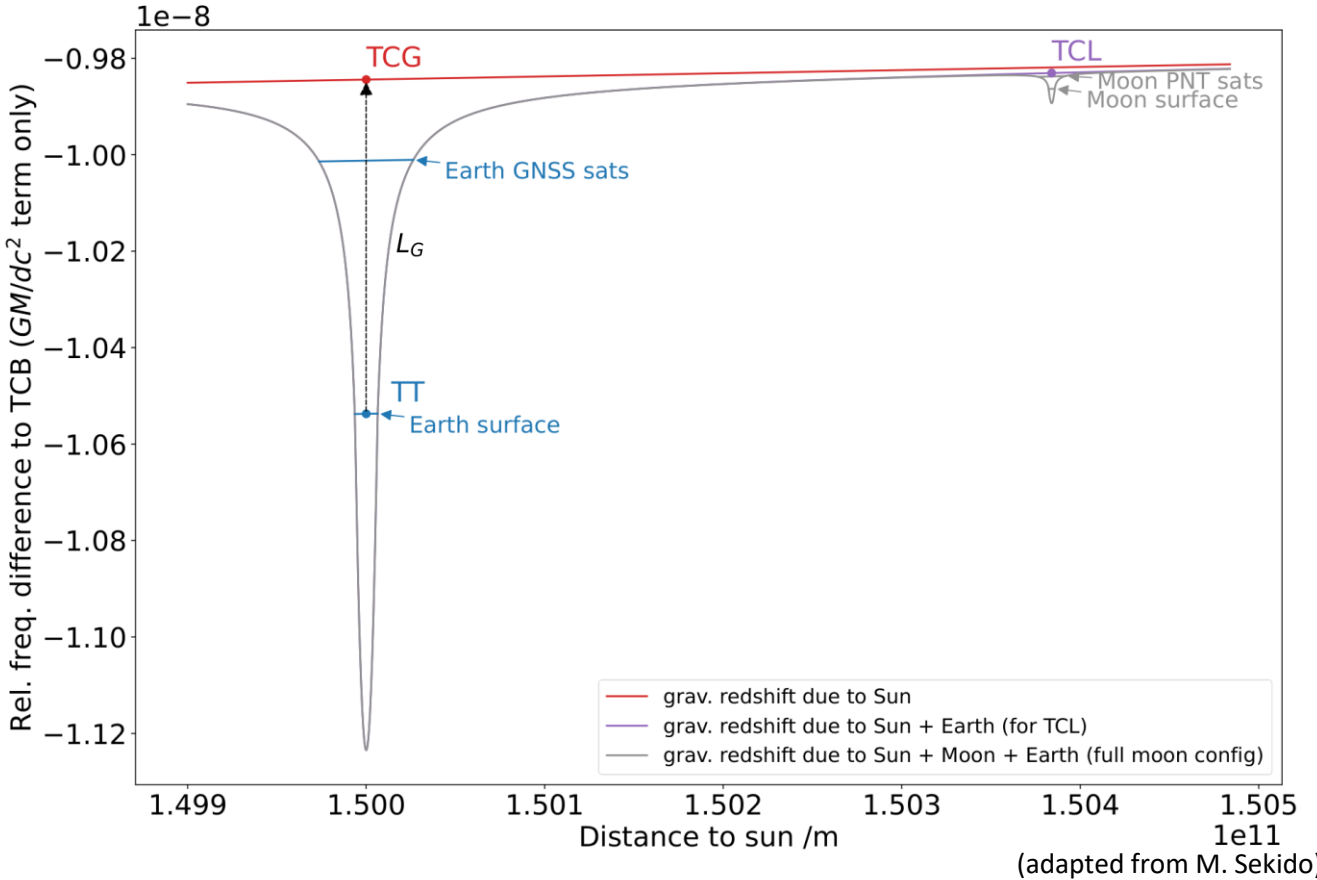
Recent papers on the Moon timing in relativistic frame:

Ashby & Patla : https://arxiv.org/abs/2402.11150
Kopeikin & Kaplan : https://arxiv.org/pdf/2407.04862
Bourgoin, Defraigne, Meynadier : https://arxiv.org/abs/2507.21597
Biju and N. Ashby (on Mars time): https://arxiv.org/abs/2507.21388

Gravitational redshift : orders of magnitude

TCG and **TCL**:
already defined by IAU, coordinate times at the barycenter of Earth (resp. Moon) *not taking into account its own gravitational potential well*

L_G = rate difference between **TT** and **TCG**, fixed by convention

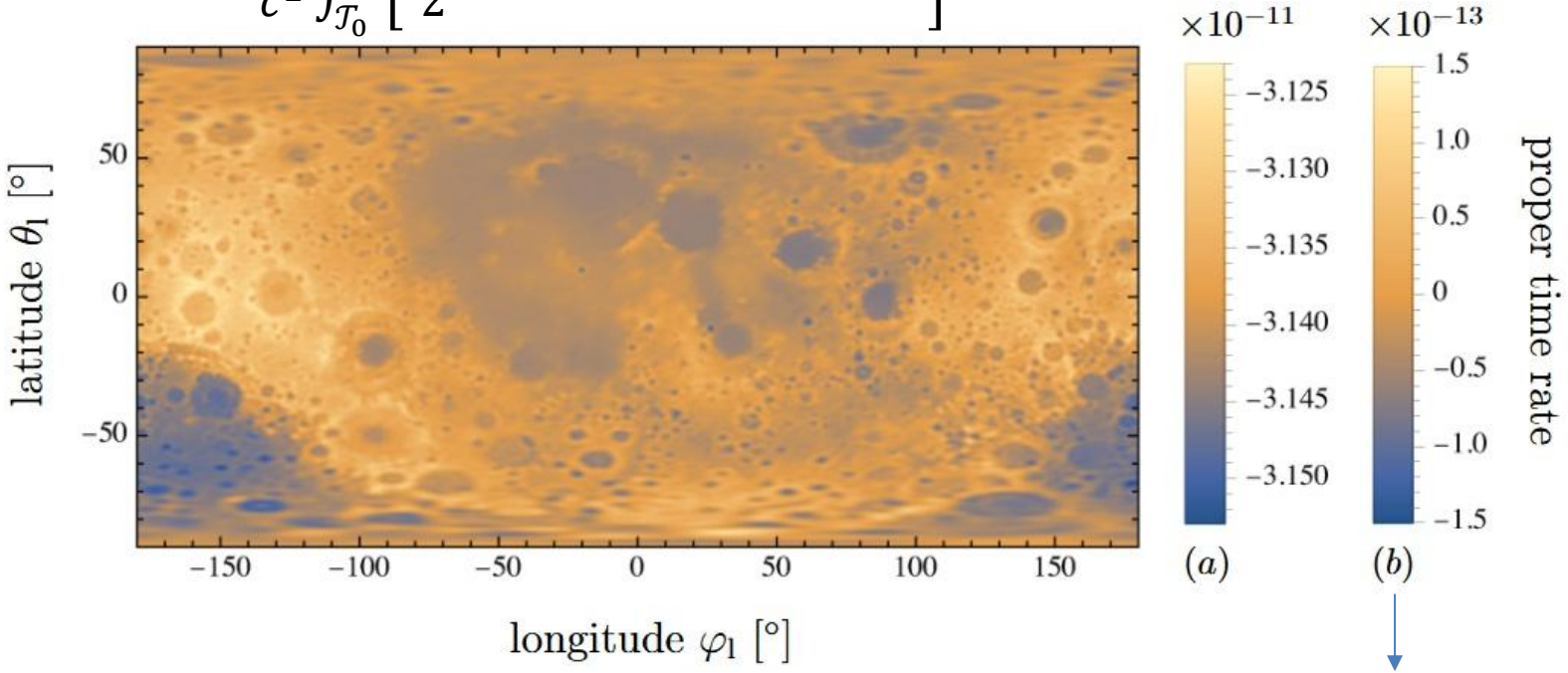


(adapted from M. Sekido)

Time rate differences on the Moon surface

$$\tau_l - TCL = -\frac{1}{c^2}\int_{\mathcal{T}_0}^{\mathcal{T}} \left[\frac{v_l^2}{2} + \mathcal{W}_L(\vec{x_l}) + \mathcal{W}_{tidal}(\vec{x_l})\right] d\mathcal{T}$$

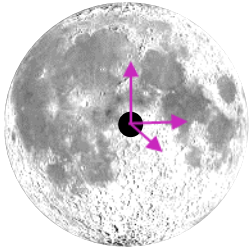
(~25 ns/day)



After fixing a $W_{L0}=2.82 \times 10^6$ m^2 s^{-2}

[Bourgoin, Defraigne, Meynadier, 2025]

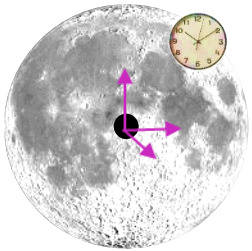
3 options were considered



TL time scale of the LCRS (Lunar Celestial Reference System)

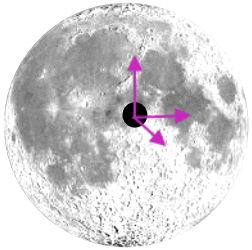
TL(1) = TCL (no need to use the naming TL)

or TL(1) = TCL + dt_0



TL ~ rate proper time of a clock on the Moon surface

TL(2) = TCL – $\Delta f \times (t\text{-}t_0) + dt_0$ $\Delta f \sim 3.14 \times 10^{-11}$



TL – TT has only periodic terms, no secular drift

TL(3) = TCL – $\Delta f \times (t\text{-}t_0) + dt_0$ $\Delta f \sim 6.8 \times 10^{-10}$

Scaled TCL (options 2 and 3)

Scaling of coordinate time → scaling of masses and distances

$TL = TCL - \Delta f \times (t - t_0)$ → $x^* = (1 - \Delta f)\, x$ (Spatial coordinates)

$\mu^* = (1 - \Delta f)\, \mu$ ($\mu = Gm$ with m the mass)

IAU already defined two scalings: $TDB = (1 - L_B)\, TCB + t_0$ & $TT = (1 - L_G)\, TCG$

Additional scaling (and later for Mars, and other planets)

→ risk of complexity and ambiguity → risk of errors.

(see S. Klioner presentation)

Option 1: TL = TCL

PROs

- No additional time scale defined, TCL (as time coordinate of the LCRS) is anyway needed for geodesy.

- No additional scaling of masses & distances

CONs

- An ideal clock located on the Moon surface would have a frequency offset about 2μs/day (3.14×10^{-11}) with respect to the reference

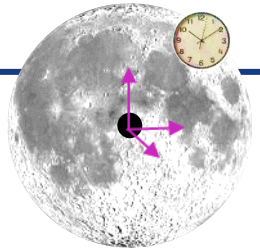
  → only clocks with accuracy better than 3.14×10^{-11} would see this offset

  All other clock should be steered anyway

OTHER:

- No need to call it TL.

Option 2: TL ~ rate proper time of a clock on the surface



PROs

- system similar as for the Earth.

- Clocks on the surface, due to the topography, would have a frequency offset of maximum 5×10^{-13} with respect to the reference

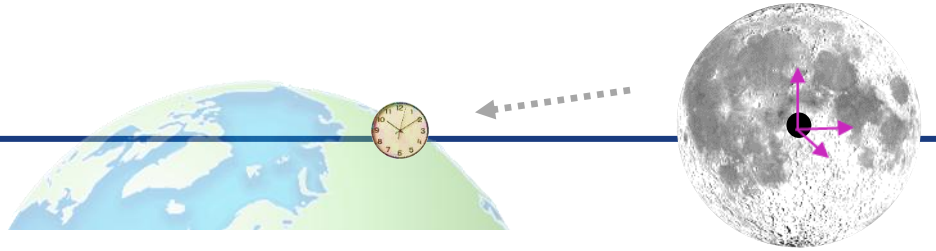
CONs

- Introduce a new space-time reference system, which would imply another scaling by 3.14×10^{-11} of masses, distances,
  about 1 cm on the Earth-Moon distance *

- No selenoid is defined to date.

* doing the same for Mars → yet an additional scaling, here by 1.4×10^{-10}

Option 3: TL – TT only periodic



PROs

- no linear drift between the lunar reference and TT (or TDB)

CONs

- Clocks with accuracy better than ~7×10^{-10} would see a frequency offset (~56 µs/day) with respect to the reference
- This new scaling (TCL-TL) would induce a new scaling by ~7×10^{-10} of masses, distances (~30 cm on the Earth-Moon distance).

* doing the same for Mars → yet an additional scaling, here by 5.8×10^{-9} !

(~ several km on the Earth-Mars distance, 1.5 cm on Mars radius !)

Different approach Earth-Moon

Earth

Humanity **used** day, h, min, sec
from Sun/stars observations

For Astronomical and high precision applications
Introduction of GR → (GCRS, TCG), (BCRS, TCB)

→ Obliged to define TT (scaled TCG) which is what was used by Humanity.

Moon

What time scale will be **used** ?
UTC for all communication with Earth
→ Most probably also UTC there for "daily life" (like for Apollo missions)

For high precision applications (< µs)
UTC not enough
→ need for a Lunar Time, but no real need that it corresponds to a clock on the surface. TCL is sufficient (?). Depending on implementation, impact on length/mass measurements, LCRS realization coordinates.