Lunar Time
Different options for a reference

Pascale Defraigne, Adrien Bourgoin, Frédéric Meynadier
and the **CCTF Task Group on Lunar Time**

Bureau International des Poids et Mesures

CCTF

What is already defined

by IAU

TCB = Coordinate Time at the Barycenter of the Solar System

TCL = Coordinate Time at the Center of the Moon

TCG = Coordinate Time at the Center of the Earth

TT = Coordinate Time on the geoid, scaled version of TCG

TDB = Barycentric Dynamical Time: scaled version of TCB

so that TDB-TT = only periodic terms

by BIPM

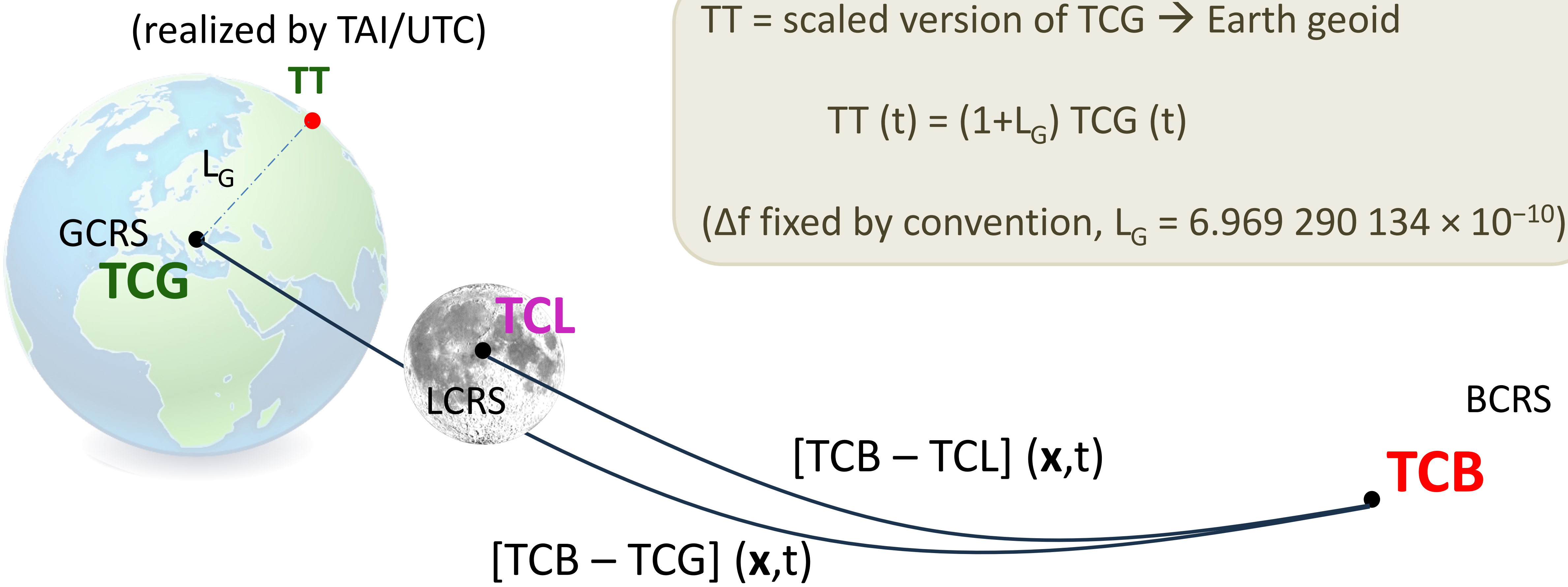
Resolution 2 of the 26th CGPM (2018): On the definition of time scales

TAI = realization of TT

UTC = TAI + leap second

A brief reminder about Coordinate time scales

IAU conventions



TT = scaled version of TCG → Earth geoid

$$TT\,(t) = (1+L_G)\ TCG\,(t)$$

(Δf fixed by convention, $L_G = 6.969\ 290\ 134 \times 10^{-10}$)

Proper Time / Coordinate Time

PROPER TIME τ

The time as measured by a clock

A 

$$\tau_A - TCG = -\frac{1}{c^2}\int_{t_0}^{t}\left[\frac{{v_A}^2}{2} + U_E(\overrightarrow{x_A}) + W_{tidal}(\overrightarrow{x_A})\right]dt$$

2 events are synchronous in a space–time coordinate system if they have the same coordinate time.
Ex. 2 clocks on the geoid are synchronous in the GCRS
(!! if neglecting the tidal effects)

Synchronization is entirely dependent on the chosen space–time coordinate system

COORDINATE TIME t

One of the 4-D coordinates of an event in theory of relativity.

Proper Time : the natural time of a clock ?

YES but only if the clock realizes “by construction” the definition of the second at the required level of accuracy !

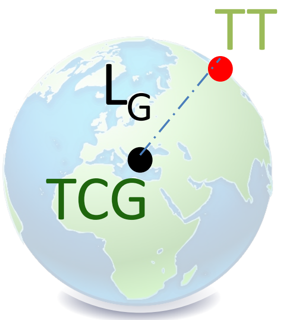
All other clocks have their frequency adjusted on a reference frequency anyway.

→ Currently, the best realizations of the SI second at a given location are Primary Frequency Standards.

As a reminder : TAI = average of clocks (EAL)
then steered on the primary frequency standards

→ Except for clocks with better free-running performances than the user needs, we will have to adjust their frequency to align them on the reference, whatever the reference

TT on the Earth ⟹ ? TL on the Moon ?



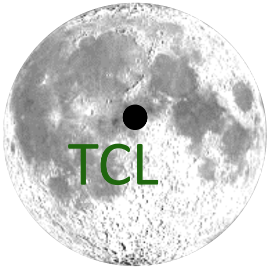
W(A) = $-\frac{GM}{r} + \frac{GMa^2J_2}{2r^3}(3\sin^2\phi - 1) - \frac{1}{2}\omega^2 r^2 \cos^2\phi + \ldots$

Geoid definition = fixed W_0

Clock **on the geoid**:

$$\tau_e - TCG = -\frac{1}{c^2}\int_{t_0}^{t} [\, W_0 + W_{tidal}(\overrightarrow{x_e})\,]\, dt$$

Only periodic terms
< 5×10^{-17}



Same reasoning:
Selenoid definition = fixed W_{L0}

Clock **on the selenoid**:

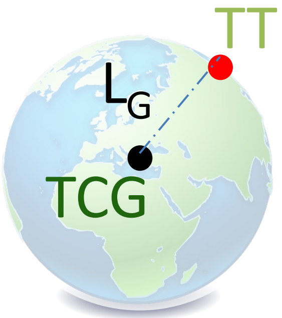
$$\tau_l - TCL = -\frac{1}{c^2}\int_{t_0}^{t} [\, W_{L0} + W_{tidal}(\overrightarrow{x_l})\,]\, dt$$

Due to synchronous rotation of the Moon

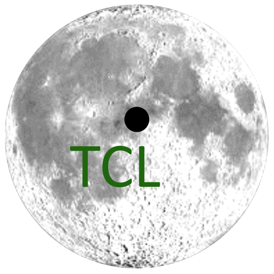
Constant + periodic terms
~ 2×10^{-16}

(A. Bourgoin, 2025)

TT on the Earth ⇒ ? TL on the Moon ?



Difference between 2 clocks on the geoid



Difference between 2 clocks on the selenoid

~7 ns/yr (depending on clock locations)

CONSEQUENCE
If a LT (Lunar TT equivalent) is defined, any W_{L0} equivalent must take this constant tidal term into account (= not the usual selenoid)

On the link between Earth time and Moon time

Difference between an Earth surface clock and a Moon surface clock:

Linear term (~56 µs/day)

+ periodical variations which depend on where the observer is…

Observer at the Solar System Barycenter : oscillations ~120 µs

Ashby and Plata (2024) approach : observer at the Earth-Moon barycenter

Kopeikin and Kaplan (2024) approach : Observer on the Earth

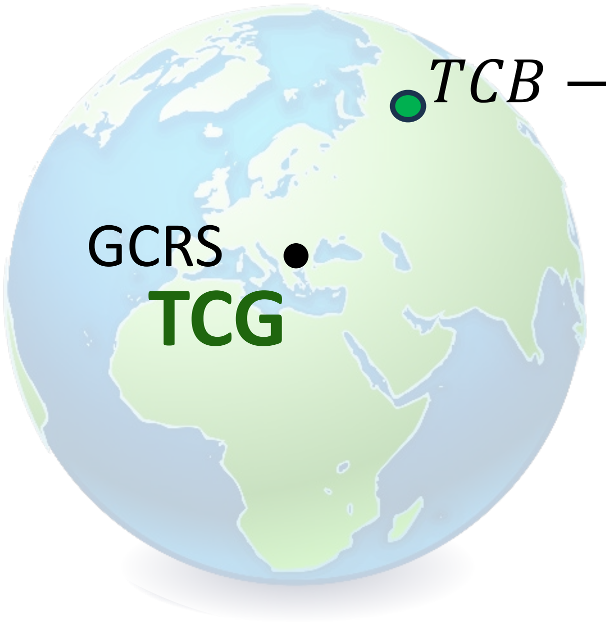
oscillations ~0.5 µs

CONSEQUENCE:

Differences between Moon Reference Time and TT, to be transmitted to the user, depend on the 4-D reference frame in which the time transfer Moon-Earth is computed.

TCB-TCG (and TCB-TCL) are 4-dimension relations

$$TCB - TCG = c^{-2}\left\{\int_{t_0}^{t}\left[\frac{v_e^2}{2} + U_{ext}(\vec{x_e})\right]dt + \vec{v_e}\,.\,(\vec{x} - \vec{x_e})\right\} + O(c^{-4})$$



$TCB - TCG\ (t, x_1)$

$TCB - TCG\ (t, x_2)$

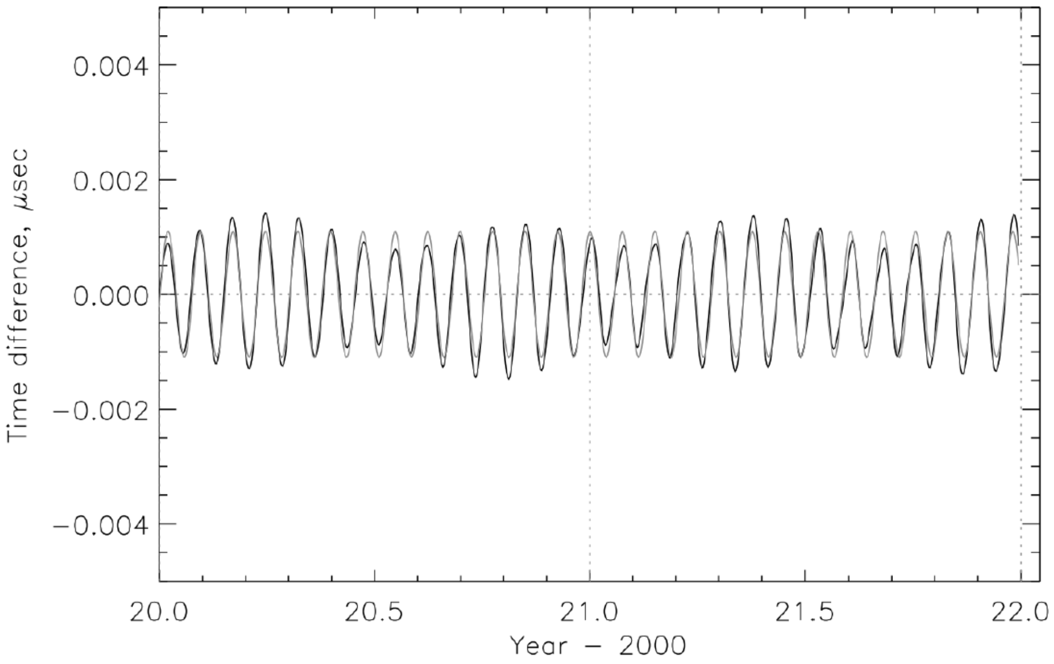
CONSEQUENCE:

Differences between TCL and TT (or TCG) depend mainly on the ephemerids but also on the clock locations on Earth and on the Moon.

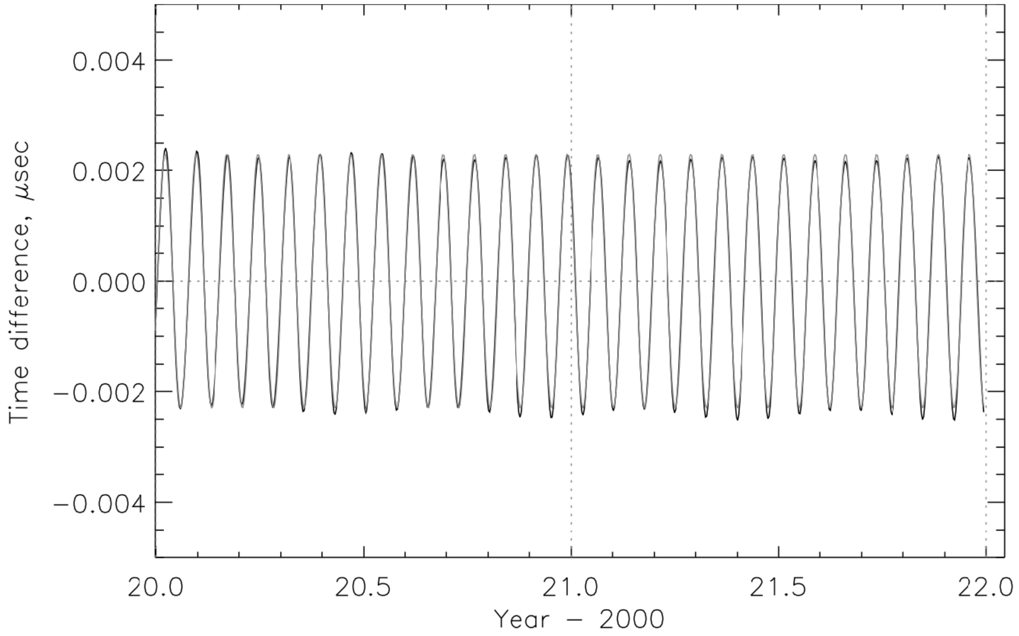
→ NO UNIQUE RELATION between TCL and TT (or TCG)

Non-unicity of the relation TCL-TCG

TCL-TCG Terms depending on the position on the Moon-clock:
(Figures 5 et 6 from Kopeikin and Kaplan, 2024)



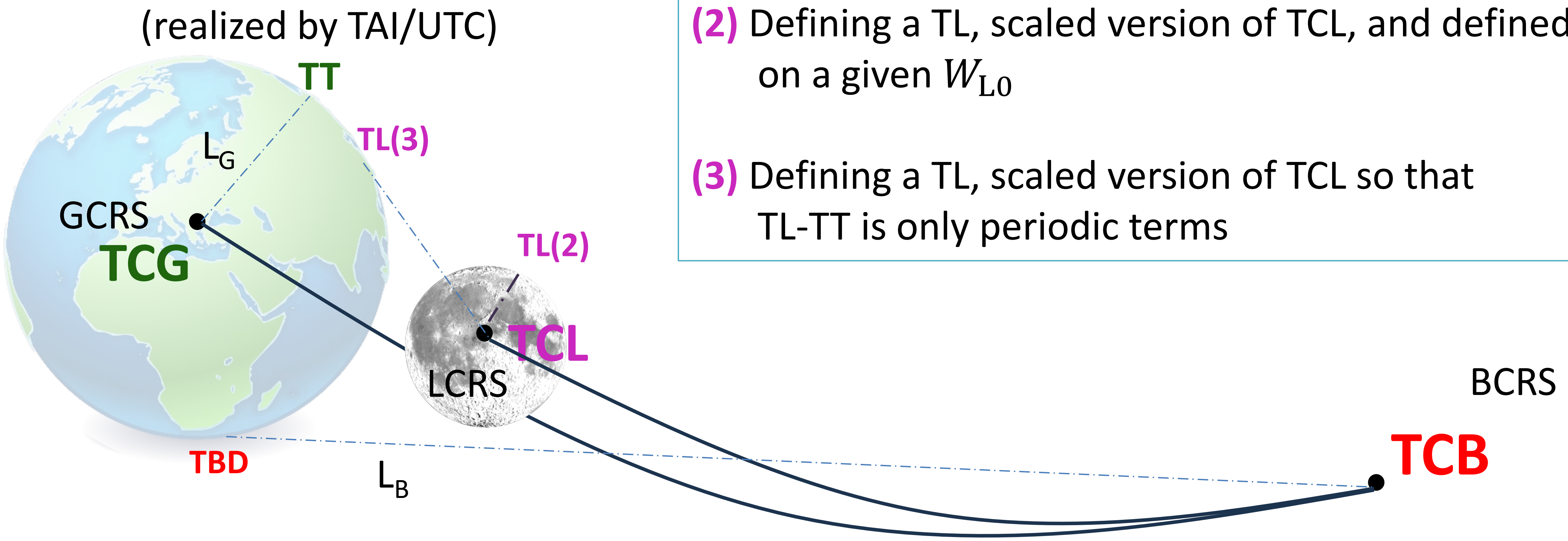
Difference Moon-clock at the Equator / at the center



Difference Moon-clock at the South Pole / at the center

Order of magnitude : a couple of ns over a 1 month period

3 options for a reference time on the Moon



(1) Using TCL

(2) Defining a TL, scaled version of TCL, and defined on a given W_{L0}

(3) Defining a TL, scaled version of TCL so that TL-TT is only periodic terms

Option (1): Defining only a coordinate time TCL

PROs

- No additional time scale defined, TCL (as time coordinate of the LCRS) is anyway needed for geodesy
- Also means that we do not introduce a new space-time reference system, which would imply another scaling of masses, distances (as is already the case with TCB, TDB, TT…)

CONs

- An ideal clock located on the Moon surface would have a frequency offset about 2µs/day (2.3×10^{-11}) with respect to the reference
- significant linear drift between the lunar reference and TT (or TDB): ~58 µs/day or 6.7×10^{-10}

Option (2): Defining a reference coordinate time TL near the lunar surface

PROs

- An ideal clock located on the surface defined by a lunar W_{L0} would have no frequency offset with the reference time scale.

CONs

- The link between an Earth clock realizing TT and a Moon clock realizing TL would anyway depend on the clock location through TCL-TCG(**x**,t)
- For theoretical developments, this new scaling (TCL-TL) would induce a new scaling of masses, distances (E.g. the Earth Mass has already different values if using TCB, TDB, TT).
- There is still a significant linear drift (~ 56 µs/d or $6.5\mathrm{x}10^{-10}$) between the lunar reference and TT (or TDB)

Option (3): Defining a TL = scaled version of TCL aligned on TT/TDB

PROs

- Only periodic terms between TL and TT: no linear drift between the lunar reference and TT (or TDB)
- Direct compatibility between Lunar and Earth GNSS (same time reference, on average)

CONs

- An ideal clock located on the Moon would have a frequency offset about 56 µs/day (6.6×10^{-10}) with respect to the reference
- The link between an Earth clock realizing TT and a Moon clock realizing TL would anyway depend on the clock location through TCL-TCG($\mathbf{x}$,t)
- For theoretical developments, this new scaling (TCL-TL) would induce a new scaling of masses, distances (E.g. the Earth Mass has already different values if using TCB, TDB, TT).

Realization of the reference

In the first decade(s), a link with Earth will be unavoidable:

(τ_E -TCG) Earth ground clock to center of Earth

+ (TCG – TCL) (not unique ! Depends on the clock positions)

+ (TCL - τ_L)

… all depending on the exact position of the clocks (at the ns level for TCG – TCL)

If there is an autonomous network of clocks on the Moon:

Local synchronisation within this network “like UTC(k)s on Earth” is possible, but any time transfer with Earth will require the above calculations anyway.

This could then be a local realization of the Lunar reference time scale. LNSS satellites could broadcast their offset to it.

BIPM could publish a difference to UTC (with an ad-hoc time transfer convention) ?

Questions for the discussion

1. What do you think on the 3 possibilities to **DEFINE** a lunar reference time scale?

2. How will you **REALIZE** the definition and have a physical signal realizing lunar time:
   a) On the Moon?
   b) On a station orbiting around the Moon?
   c) On a GNSS-like navigation satellite around the Moon?
   d) From Earth?
   e) And during travel to the Moon?

3. For the interoperability of GNSS-like navigation systems around the Moon should a common lunar time **realization** be used as common pivot? Could each navigation system broadcast the offset of its system time versus this common lunar time realization?

Session 3: Proposed Summary and Conclusions

1. IAU formally adopted definitions for (locally inertial) lunar reference frame & it's coordinate time August 2024
   - LCRS centered on lunar center of mass
   - TCL coordinate time
   - Needs approximation for TCB → TCL for ease of use

2. IAU recommended a coordinated lunar time, traceable to UTC to be determined by collaboration between relevant international organizations.

3. IAU to hold Symposium in August 2025 on Solar System Standards, including lunar.

4. IAU plans to update standard terms to include cislunar terminolgy

5. IAG WG for unified standard lunar body-fixed (surface) reference system (LRS)
   - Coordinate system – Mean Earth and/or PA and transformations
   - Reference frame, ellipsoid, topography, gravity model, "geoid," etc.
   - Recommendations at IAU symposium and IAG Scientific Assembly Sept 2025.

The CCTF Task Group on Moon Timing will:

- finalize the evaluation of the various options taking into account the needs of Moon PNT providers and other users.
- promote contacts with other international bodies and agencies so that this work leads to a consensus.
- support the development of methods ensuring traceability to UTC of whichever Lunar reference time is chosen
- submit a recommendation proposal to the CCTF in Sept 2025 for adoption by BIPM member states at the General Conference (CGPM) in Oct 2026

Contacts for
CCTF Task Group on Moon Timing :

Patrizia.Tavella@bipm.org

Frederic.Meynadier@bipm.org

TCB-TCG and TCB-TCL depend - on ephemerides
- on the observer position

$$TCB - TCG = c^{-2}\left\{\int_{t_0}^{t}\left[\frac{v_e^2}{2} + \left(\sum_{a\neq e}\frac{GM_a}{R_{ea}} + \cdots\right)\right]dt + \vec{v_e}\,.\,(\vec{x} - \vec{x_e})\right\} + O(c^{-4})$$

Earth/Moon velocity in BCRS

Distances between Earth/Moon and the other bodies

$$TCB - TCL = c^{-2}\left\{\int_{t_0}^{t}\left[\frac{v_l^2}{2} + \left(\sum_{a\neq l}\frac{GM_a}{R_{la}} + \cdots\right)\right]dt + \vec{v_l}\,.\,(\vec{x} - \vec{x_l})\right\} + O(c^{-4})$$

Traceability to UTC

When TCL is realized on the Earth:

- Ground-clock - UTC(k) would give the traceability to UTC

On the Moon:

- Compare Moon-clock realizing TAL(k) with a UTC(k) via time transfer between the Moon and the Earth.
  Corrects for (TT-TCL) at the clock location,
  So that the difference to UTC(k) does no more contain relativistic contributions.