Lunar Reference Time

Proposal by the Consultative Committee Time & Frequency

Bureau International des Poids et Mesures

What was already defined:

IAU (Resolution II-2024) defines the theoretical framework

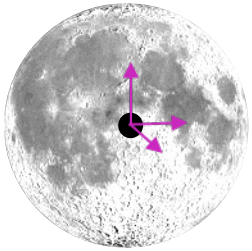
- 4D Lunar Celestial Reference System (LCRS) (x,y,z,t)
  with t in Lunar Coordinate Time TCL
- 4D transformation from Barycentric Coordinate Time TCB to TCL

Position-dependent

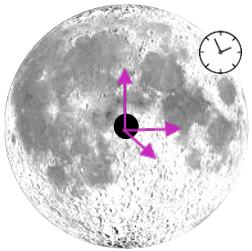
$$TCB - TCL = c^{-2}\left\{\int_{t_0}^{t}\left[\frac{v_l^2}{2} + \left(\sum_{a\neq l}\frac{GM_a}{R_{la}} + \cdots\right)\right]dt + \vec{v_l}\,.\,(\vec{x} - \vec{x_l})\right\} + \mathrm{O}(c^{-4})$$

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

3 options were proposed and discussed:

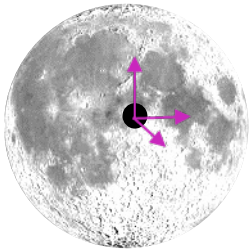


Use TCL
= the coordinate time scale of the LCRS (Lunar Celestial Reference System)



Use a scaled version of TCL ~ rate proper time of a clock on the surface

$TL(2) = TCL - \Delta f_{x} (t-t_0)$ $\Delta f \sim 3.14e\text{-}11$



Use a scaled version of TCL ~ no secular drift (only periodic) with UTC

$TL(3) = TCL - \Delta f_{x} (t-t_0)$ $\Delta f \sim 6.8e\text{-}10$

Impacts of the choice of the reference

- Scaling
- Time scale realization
- Steering of the clocks
- What if the link for steering is lost
- What about the link with the SI second
- …

Frequently asked questions

- Why is TCG not used as reference time on the Earth?
- Are the UTC(k) (and clocks on Earth) corrected for the local gravity ?
- Which option of Lunar Time is easier to be realized with a clock on the lunar surface?
- Where is the SI second defined (SI second = 9192631770 oscillations observed from Cs emission)?
- What is the relation between the TAI (or UTC) scale unit and the SI second ?
- If TL or TCL becomes a standard lunar time, does one second measured with a clock indicating the standard time deviate from SI second?
- SI meter and its measure
- is TL easier in case of Loss of connection with Earth / Lunar PNT satellites ?
- Equations and models to convert from TCL to TCB/TCG/TT
- How is the Moon Reference Time realized?
- How should interoperability between different lunar PNT systems be ensured?
- Traceability of the Moon Reference Time to UTC

- … please ask additional questions you would have …

What about the scaling (options 2 & 3)

Time	TDB = $(1-L_B)$ TCB + t_0*	T T = $(1-L_G)$ TCG
Spatial coordinates	$x^* = (1-L_B)\, x$	$X^{**} = (1-L_G)\, X$
Mass of the bodies (μ=Gm)	$\mu^* = (1-L_B)\, \mu$	$\mu^{**} = (1-L_G)\, \mu$
	$L_B = 1.550519768 \times 10^{-8}$	$L_G = 6.969290134 \times 10^{-10}$

Mass and coordinates must be specified: TCB-compatibe, TDB-compatible, TT-compatible, ….

Introduce new scaling → μ^{***} for the Moon, μ^{****} for Mars etc…
→ risk of complexity and ambiguity → risk of errors.

Exemple of the complexity with a scaling

TABLE I. Reference time-scale constants and implied mean rates (IAU/IERS defining constants used in this work).

Symbol	Definition	Value (s/s)	Mean rate per day	Note
L_G	$d\mathrm{TT}/d\mathrm{TCG} = 1 - L_G$	$6.969\,290\,134 \times 10^{-10}$	$60.2146\,\mu\mathrm{s\,d}^{-1}$	IAU 2000 B1.9
L_C	$\langle d\mathrm{TCG}/d\mathrm{TCB}\rangle = 1 - L_C$	$1.480\,826\,867\,41 \times 10^{-8}$	$1.279\,434\,\mathrm{ms\,d}^{-1}$	IAU 2000 B1.5
L_B	$1 - L_B = (1 - L_G)(1 - L_C)$	$1.550\,519\,767\,72 \times 10^{-8}$	$1.339\,649\,\mathrm{ms\,d}^{-1}$	IAU 2006/2009
L_L	$d\mathrm{TL}/d\mathrm{TCL} = 1 - L_L$	$3.1390541 \times 10^{-11}$	$2.712143\,\mu\mathrm{s\,d}^{-1}$	this work, Eq. (A5)
L_H	$\langle d\mathrm{TCL}/d\mathrm{TCB}\rangle = 1 - L_H$	1.4825362×10^{-8}	$1.280\,911\,\mathrm{ms\,d}^{-1}$	this work, Eq. (A8)
L_M	$\langle d\mathrm{TL}/d\mathrm{TCB}\rangle = 1 - L_M$	$1.485675294 \times 10^{-8}$	$1.283\,624\,\mathrm{ms\,d}^{-1}$	this work, Eq. (A10)

Expression (A11) allows us to formulate (TDB − TL) as a function of TL. To achieve this, we use (11), (A10), and (A11), to express TDB − TL as a function of TL as shown below

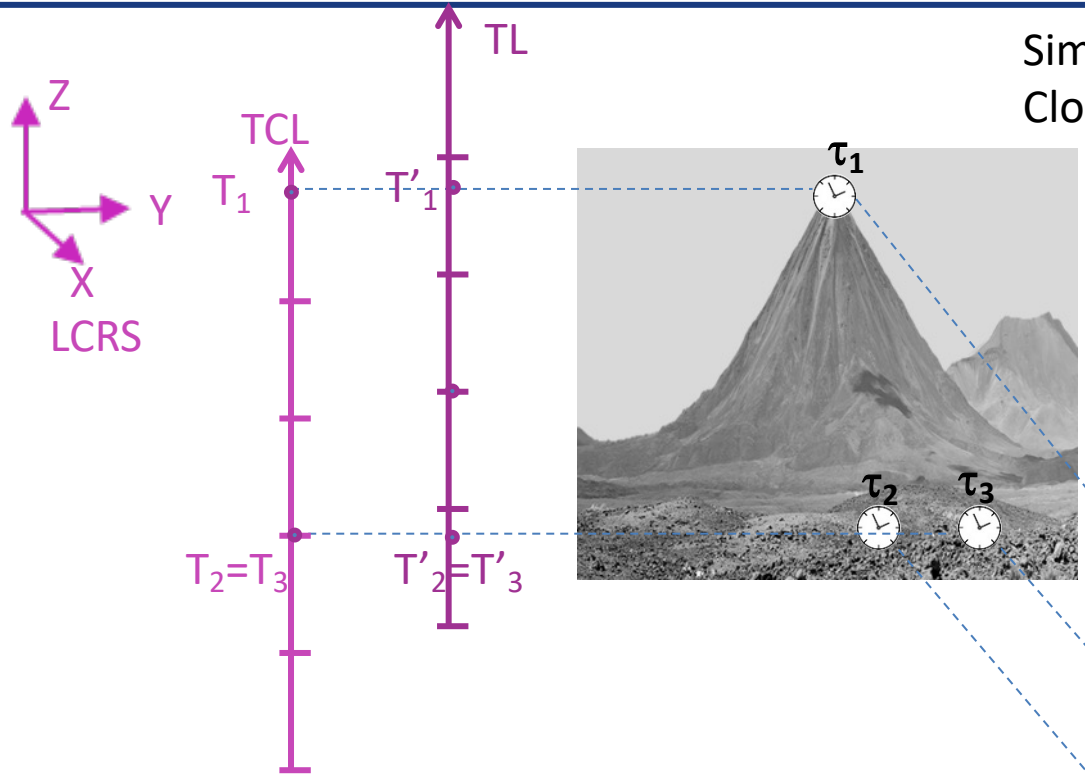
$$\mathrm{TDB} - \mathrm{TL} = \mathrm{TDB}_0 - \frac{L_B - L_L}{1 - L_L}(\mathrm{TL} - \mathrm{T}_0) + L_B(\mathrm{T}_0 - \mathrm{T}_{L0}) + \\ + \frac{1 - L_B}{1 - L_M}\left\{\frac{1}{c^2}\int_{\mathrm{T}_{L0}}^{\mathrm{TL}}\left(\tfrac{1}{2}v_M^2 + \sum_{B\neq M}\frac{GM_B}{r_{BM}}\right)d\mathrm{TL} + \frac{1}{c^2}(\mathbf{v}_M \cdot \mathbf{r}_{OM\mathrm{TL}})\right\} + \mathcal{O}(c^{-4}). \quad \text{(A12)}$$

It is useful to express the difference (TDB − TL) as a function of TDB. This can be achieved by applying (11), (A6), (A7), and (A10), resulting in the following expression (see details in [8, 21]):

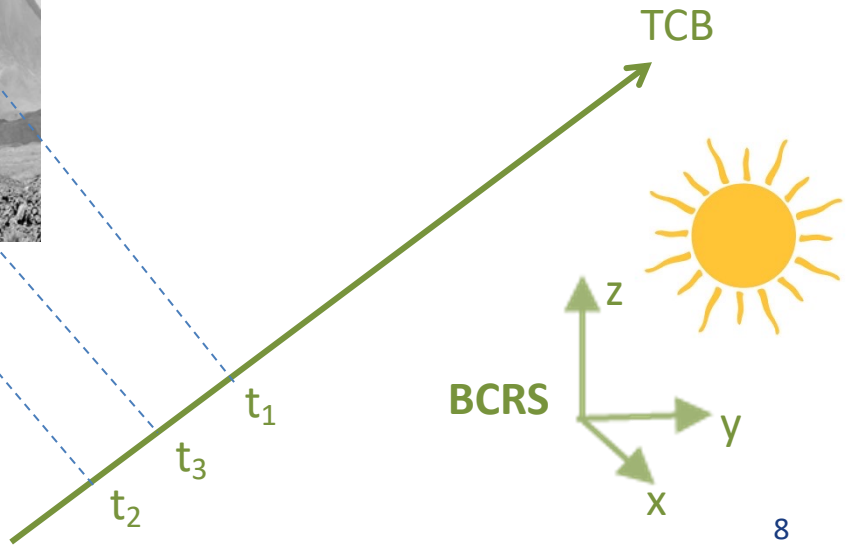
$$\mathrm{TDB} - \mathrm{TL} = \frac{1 - L_L}{1 - L_B}\mathrm{TDB}_0 - \frac{L_B - L_L}{1 - L_B}(\mathrm{TDB} - \mathrm{T}_0) + L_L(\mathrm{T}_0 - \mathrm{T}_{L0}) + \\ + \frac{1 - L_L}{1 - L_B}\left\{\frac{1}{c^2}\int_{\mathrm{T}_0 + \mathrm{TDB}_0}^{\mathrm{TDB}}\left(\tfrac{1}{2}v_M^2 + \sum_{B\neq M}\frac{GM_B}{r_{BM}}\right)d\mathrm{TDB} + \frac{1}{c^2}(\mathbf{v}_M \cdot \mathbf{r}_{OM\mathrm{TDB}})\right\} + \mathcal{O}(c^{-4}). \quad \text{(A13)}$$

From Turyshev et al.
(https://arxiv.org/pdf/2511.12058)

Proper time / coordinate time



Simultaneity: same coordinate time
Clocks 2 and 3 simultaneous in TCL
in TL
but not in TCB



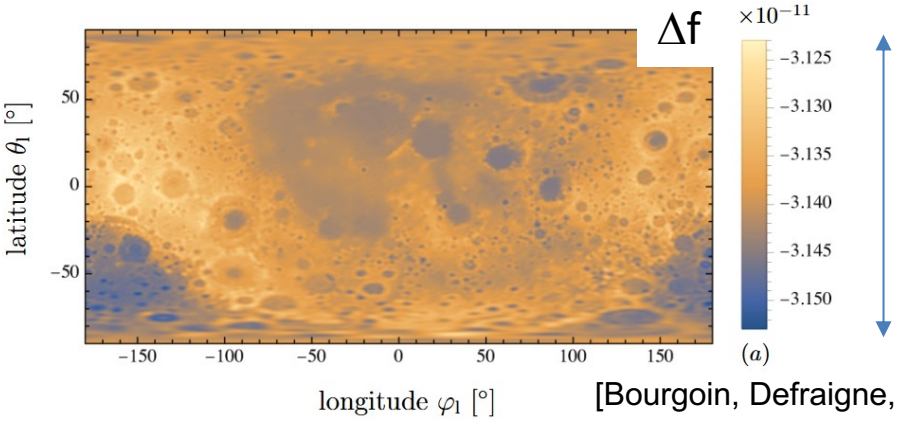
Simultaneity: same in TCL and TL

Proper Time rate differences (measured in TCL)

$$\frac{d\tau_{clock}}{dTCL} - 1 = -\frac{1}{c^2}\left[\frac{{v_{clock}}^2}{2} + \mathcal{W}_L(\overrightarrow{x_{clock}}) + \mathcal{W}_{tidal}(\overrightarrow{x_{clock}})\right]$$

x and v in the LCRS

On the surface:

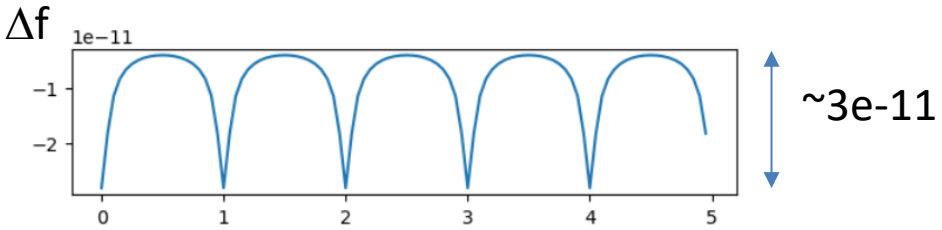


~3e-13

~25 ns/day

[Bourgoin, Defraigne, Meynadier, 2025]

In a satellite :



~3e-11

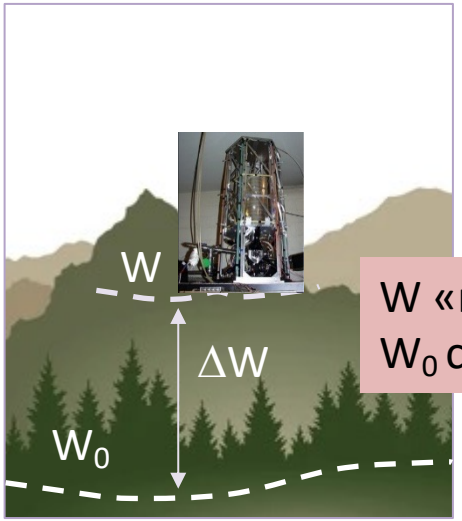
PRIMARY Realization of the reference coordinate time

- UTC realizes TT , with TT = (1- W_0/c^2) x TCG - W_0/c^2 x T_0
- the scale unit of UTC is close (~10^{-17}) to the SI Second of a clock on the Earth at a gravity potential = W_0

UTC scale unit is determined from primary frequency standards **unsteered**,
Using their **proper frequency** corrected by (W-W_0)/ c^2

Scale of UTC = f(PFS) - ΔW/ c^2

For continuity between PFS measurements,
UTC uses a clock ensemble **steered** on PFS measurements.



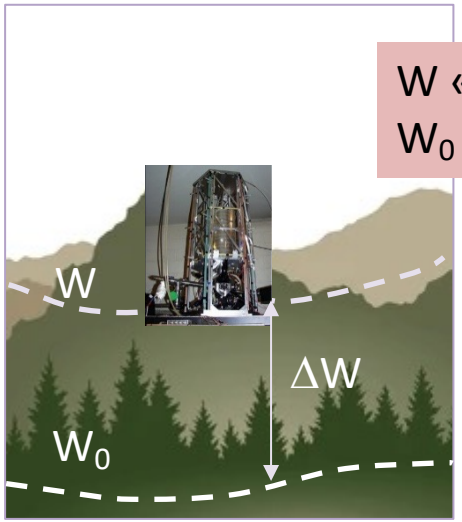
W «measured»
W_0 convention

PRIMARY Realization of the reference coordinate time

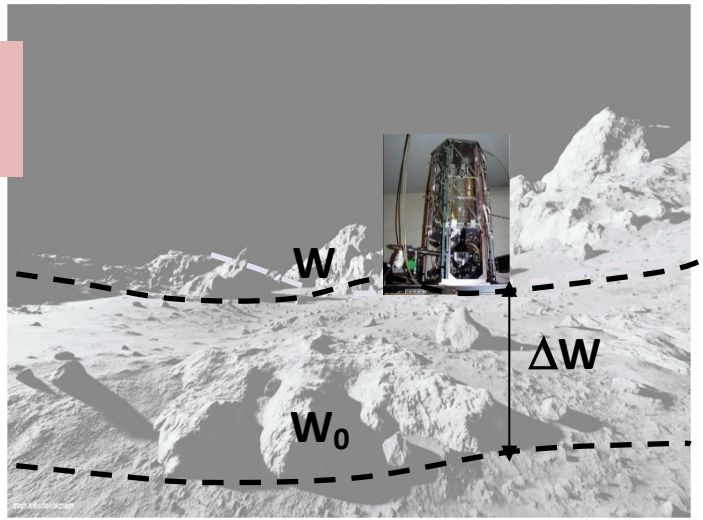
Scale of UTC = f(PFS) - (W-W_0)/ c^2

Scale of TCL = f(PFS) – W/ c^2

Scale of TL = f(PFS) – (W-W_0)/ c^2



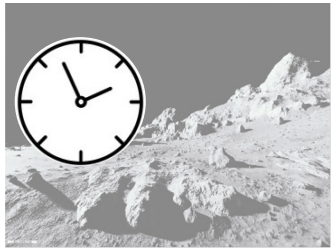
W «measured»
W_0 convention



For both options 1 and 2:
Same approach, same W measurement needed

What if a clock is on the Moon?

Clock is ticking its proper time
+ Clock Frequency error (*uf*)
due to inaccuray and instability



TCL

Quartz-Rb ($uf \geq 10^{-11}$) : clock-TCL~ *uf*

Cesium,
AHM, ($uf \leq 10^{-12}$) : clock-TCL~ 10^{-11}
optical

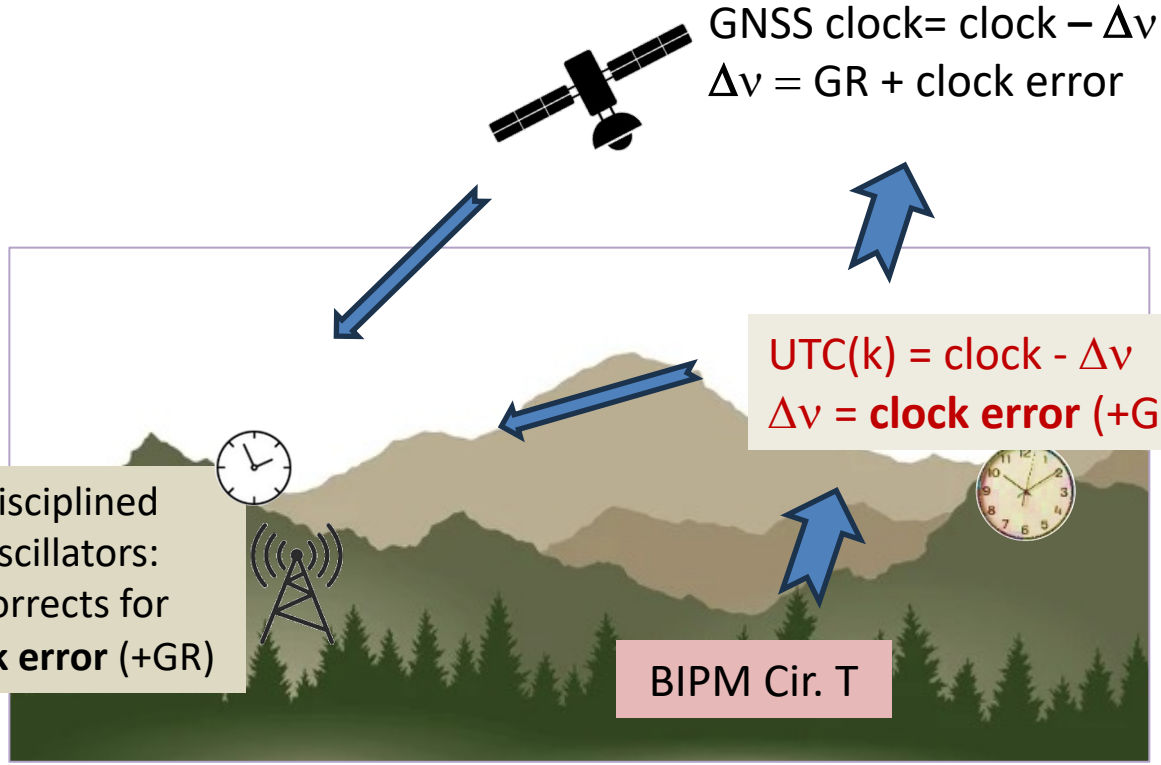
TL

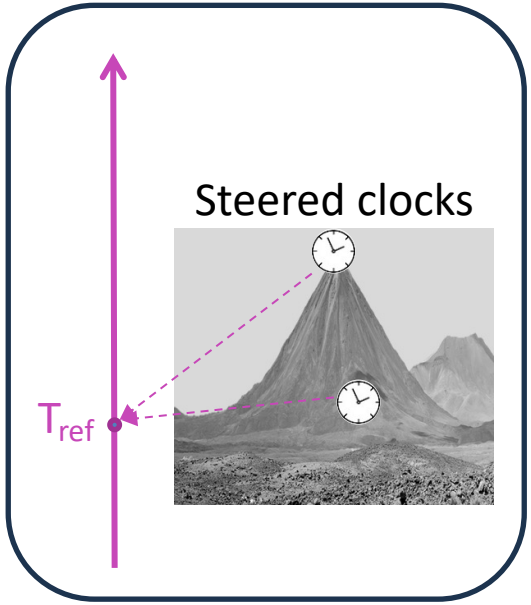
Quartz-Rb ($uf \geq 10^{-11}$) : clock-TL~ *uf*

Cesium,
AHM, ($uf \leq 10^{-12}$) : clock-TL~ (10^{-12}-10^{-13})
optical

If better is needed : steer the clock

Operational clocks : Steering=Aligning on the reference





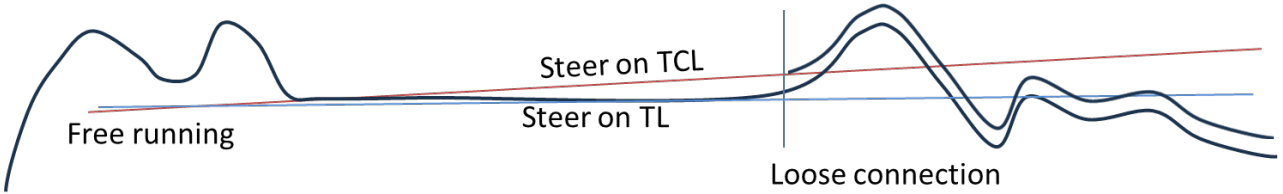
(No measure of W)

(GR = General Relativity = proper time – ref coord time)

What if the connection for steering is lost ?

Holdover : depends on the stability of the clock !

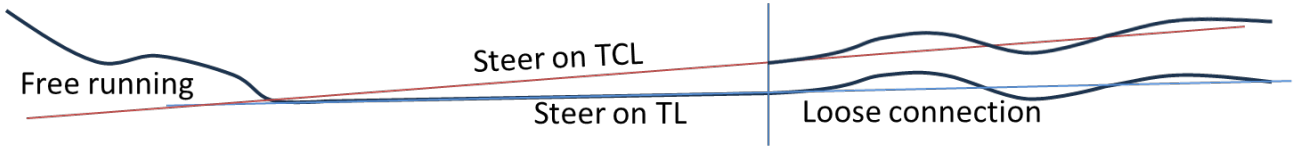
Quartz-Rb: $(uf \geq 10^{-11})$ clock-TCL~ uf and clock-TCL~ uf



Not closer to one or another reference

Cs, AHM : $(uf \leq 10^{-12})$

Steering done by synthesizers able to maintain the last frequency correction



Stay aligned on the chosen reference

Why TCG is not used on the Earth ?

Earth

Historical aspects:
Humanity **used** solar days
divided in 86400 s

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

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

Moon

Historical aspects:
UTC used for all communication with Earth
(e.g. Apollo missions)

TDB for precise applications (e.g.GRAIL)

No specific time use there,
No link with the Moon rotation

No such a need for TL as was the need for TT

Conclusion

- Up to now, the works of the Task Group show that

  - both options TL and TCL fulfill the metrological requirements
  - Primary realization of both options is equivalent
  - Scaling like TL = TCL – Δf_x (t-t_0) induces risk of complexity and errors (options 2 and 3)

Future work of the Task Group

- Prepare the set of FAQ
- Continue the interaction with space agencies to answer their questions, and consider their operational needs

Thank you