Defining a Lunar Reference Time

In order to allow interoperability between different systems of the different actors on the Moon, it is important to define a common reference timescale, exactly as TT (and its realization TAI, or further UTC) has been chosen and commonly adopted for all activities in the vicinity of the Earth. We suggest calling the reference timescale in the Moon environment the Lunar Time (TL).

Several **criteria** must be considered for this lunar timescale to be adopted as a reference.

1. The lunar reference timescale should be TCL or a linear function of it.
2. A physical realization should be available so that all actors could steer their clocks and internal timescales on this reference. Note that this physical realization should be based on Earth's clocks as long as there is no accurate clock on the Moon.
3. This reference should have a clear and documented relationship with UTC. UTC produced by the BIPM, based on TAI, is indeed the only recommended timescale for international reference as stated in the Resolution 2 of the 26th CGPM in 2018 CGP [2019].
4. In the future, the equivalent definition of reference time should be defined for Mars and possibly other planets of the solar system.

Options

The first criteria implies that TL is an affine function of TCL, namely scaled by some constant frequency offset, namely

$TL = TCL + \Delta f\,(TCL - TCL0) + const.$

We considered three options that could make sense for lunar operations:

O1: Δf is such that the rate of TL is exactly the same as TCL, namely $\Delta f = 0$;

O2: Δf is such that the rate of TL corresponds, on average, to the rate of proper time of a clock on a given lunar geoid; (the equivalent of TT on the Earth) - $\Delta f \sim 3.14 \times 10^{-11}$ in this case

O3: Δf is such that there are only periodic variations between TL and TT. - $\Delta f \sim 7 \times 10^{-10}$ in this case

Note on scaling

For O2 and O3, the scaling of the coordinate time is necessarily accompanied by the corresponding scaling of spatial coordinates and mass parameters of celestial bodies so that the form of the equations of motion and light propagation are preserved. The scaled time and spatial coordinates can then be seen as defining a new reference system characterized by its own metric tensor. Presently, two different scalings are recommended by the IAU: the one defining TDB from TCB and the one defining TT from TCG. Defining a lunar reference coordinate time based on a scaling of TCL would thus introduce an additional set of rescaled mass parameters and distances. Applying a similar approach to Mars in the future would again imply another scaling factor and another set of rescaled masses and distances, leading to possible increasing confusion as more scaled coordinate times would be introduced for other planets.

Note on the Topography:

The gravitational redshift associated with the topography on the Moon produces clock relative frequency variations in the range [-1.5×10^{-13}, $+1.5 \times 10^{-13}$] (see Figure 1).

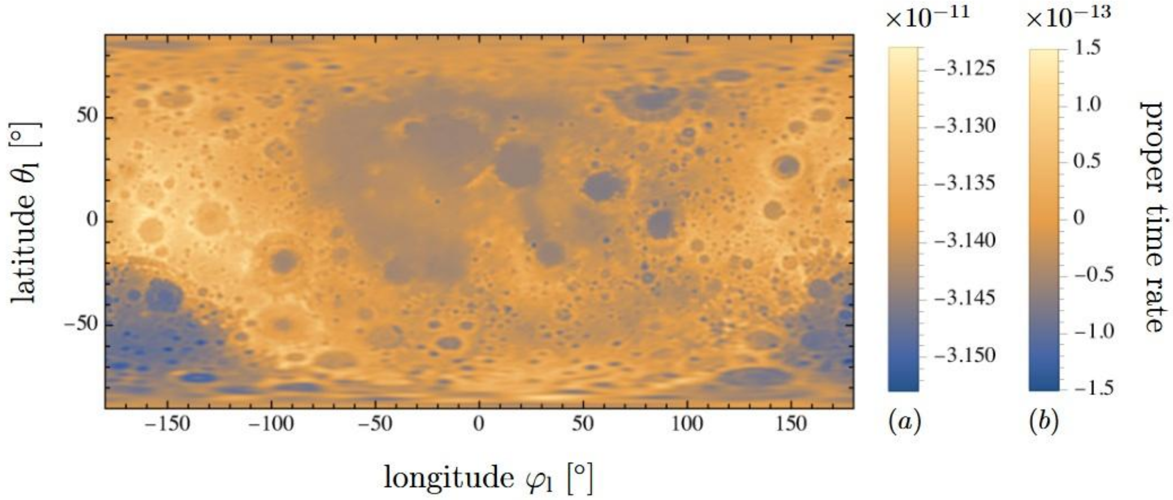

Figure 1: Map of the relative frequency difference between the proper time of a clock at rest on the lunar surface and (a) TCL, (b) a rescaled TCL as in option O2, with a reference lunar potential has been fixed to WL0=2.82×10^6 $m^2\,s^{-2}$.

First PRO/CONS analysis:

O1 +:

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

O1 –:

- An ideal clock located in free running on the Moon surface would have a frequency offset about 2µs/day (3.14×10^{-11}) with respect to the reference (drawback only for clocks with accuracy better than ~3×10^{-11})

O2 +:

- Same logic as for Earth.
- Clocks on the surface, due to the topography, would have a frequency offset of maximum 5×10^{-13} with respect to the reference (advantage only for clocks with accuracy better than ~3×10^{-11})

O2 –:

- Introduce a new space-time reference system, which would imply another scaling by 3.14×10^{-11} of masses, distances (as is already the case with TCB, TDB, TT...)*
- No lunar "geoid" or reference equipotential value is defined to date.
- A similar approach for Mars would induce a new scaling by ~ 1.4×10^{-10} of masses and distances.

O3 +:

- no linear drift between the lunar reference and TT (or TDB)
- Same time reference for Lunar and Earth GNSS

O3 –:

- Clocks with accuracy better than ~7 x 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 x 10^{-10} of masses and distances.
- A similar approach for Mars would induce an additional scaling by ~5.8 x 10^{-9} of masses and distances.

Steering

Concerning the frequency offset of a clock with respect to the reference, let's remind that most clocks, even on the Earth, are steered on the reference, i.e. their frequency is adjusted so that the clock tick that the same rate as the reference (UTC for the Earth). The steering is not needed only if the clock accuracy is sufficient with respect to the user needs. We can therefore see in which cases the clocks on the Moon should be steered on TL.

Table 1 provides, for the different options of TL, the cases when a steering of the clock on TL is needed, depending on the user needs and clock accuracy. The categories have been defined based on the different scaling values: 10^{-9} as about the scaling for option 3, 10^{-11} as about the scaling for option 2, and 10^{-13} as the effect of the gravitational redshift along the topography.

Table 1. Options that require a clock steering, as a function of the user need

	Clock accuracy	User need			
		$> 10^{-9}$	$10^{-9} - 10^{-11}$	$10^{-11} - 10^{-13}$	$< 10^{-13}$
Quartz	$> 10^{-9}$	, ,	1 , 2 , 3	1 , 2 , 3	1 , 2 , 3
Quartz-Rb	$10^{-9} - 10^{-11}$	, ,	, , 3	1 , 2 , 3	1 , 2 , 3
Cs/H-maser/ optical	$< 10^{-11}$	, ,	, , 3	1 , , 3	1 , 2 , 3

We see from this Table that for what concerns the steering:

- there is an advantage of option 2 only when clock accuracy and stability are better than 3×10^{-11} and user needs are in the range ~ [10^{-11}, 10^{-13}].
- for user needs in the range ~ [10^{-9}, 10^{-11}], only option 3 would imply a need for clock steering if the clock frequency accuracy is better than 10^{-9}.
- In all other cases, the need for clock steering is the same for the three options.

Current situation

Space agencies have provided some opinions, but no consensus has been reached to date. The preferred options are clearly O1 and O2.

People from LLR community and experts in General Relativity recommend O1 to avoid the complexity of scaling.

What we expect from you:

Please answer to this question:
As a potential future user/actor on the Moon requiring accurate time measurements, or based on your experience on Earth, is there any advantage or constraints of having the clocks on the Moon aligned on a reference which is one of the three options proposed?

We organize a Workshop on November 18th, you are cordially invited to participate to it.
We would like to collect your answers before November 10th so that we can present the results of this survey to all participants. This will accompany also the presentation from the space agencies on their needs and operational constraints.

Please can you send us your answer (specifying your field of activity) by email to Pascale Defraigne (p.defraigne@oma.be) and Mamuro Sekido (sekido@nict.go.jp) ?

Thank you very much in advance and best regards,

Pascale Defraigne, Mamuro Sekido

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