Discussion about candidates of international lunar reference time scale

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Contents of this talk

1. Background and needs of International Lunar Reference Time
2. How much time scale will be different between Earth and Moon?
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    b. General relativity
5. Three options of Lunar Reference Time
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    b. If it is applied to the Mars
6. Conclusion

Activities in Lunar Exploration mission

Lunar Gateway: Communication hub on lunar orbit to be constructed as a part of Artemis project of NASA to be launched from 2027. Multiple space agencies [CSA(Canada), ESA, JAXA, MBRSC (Mohammed Bin Rashid Space Centre: Dubayy), …] are contributing.

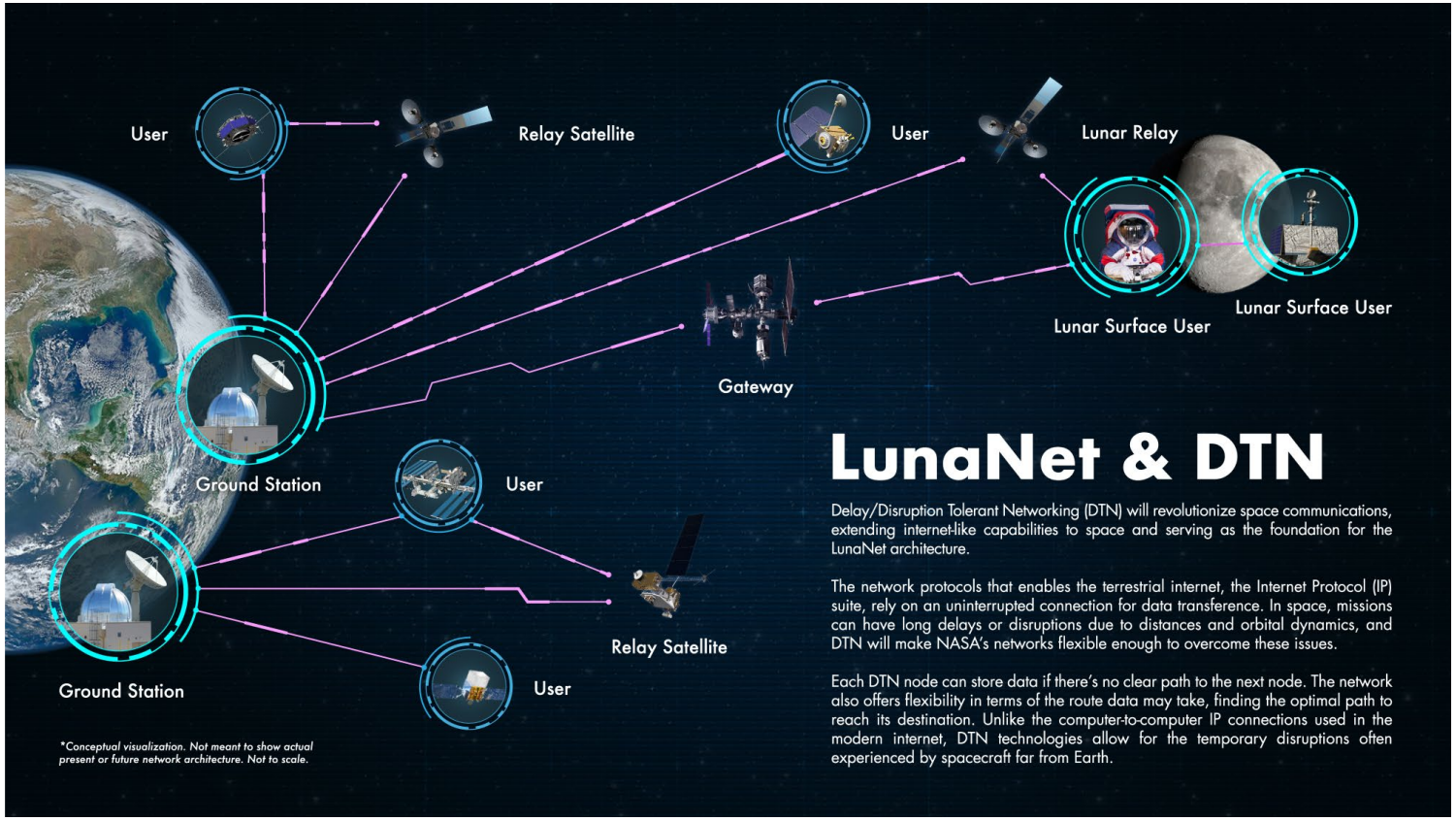
Lunar Net: Specification for communication and Navigation interoperability conducted by ESA, NASA, JAXA and other space agencies.

ESA: Moonlight initiative project contains lunar orbiting five navigation satellite system.

China:Chang'e program contains moon orbiting satellite, landing, and sample return (2020).

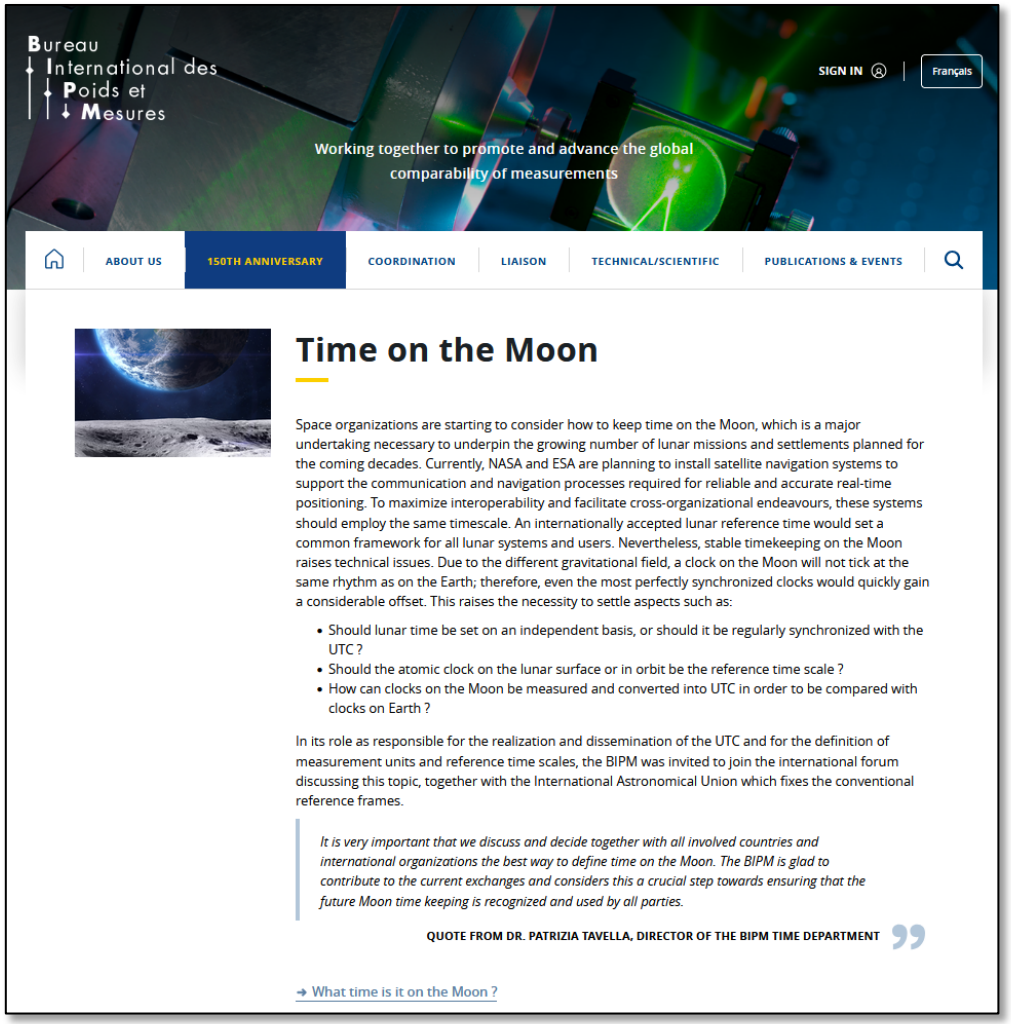
ISRO: Chandrayaan programme succussed landing on the moon in 2023. They plans human landing by 2040s.

JAXA: Participation to Artemis project. Development of rober, and



Citaed from Wikipedia
https://www.esa.int/Applications/Connectivity_and_Secure_Communications/Moonlight

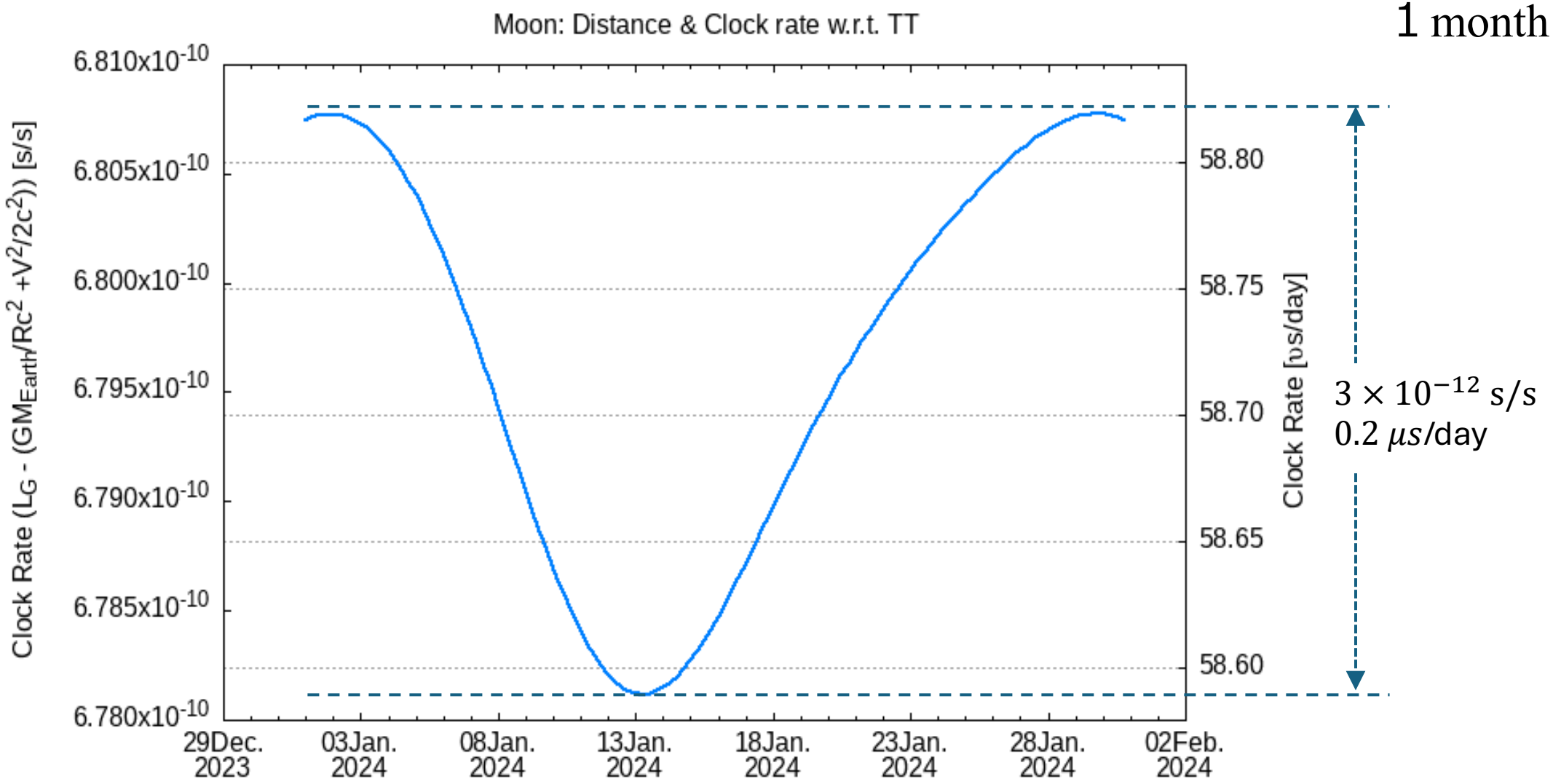
Role of BIPM



https://www.bipm.org/en/-/2023-05-22-moon-time

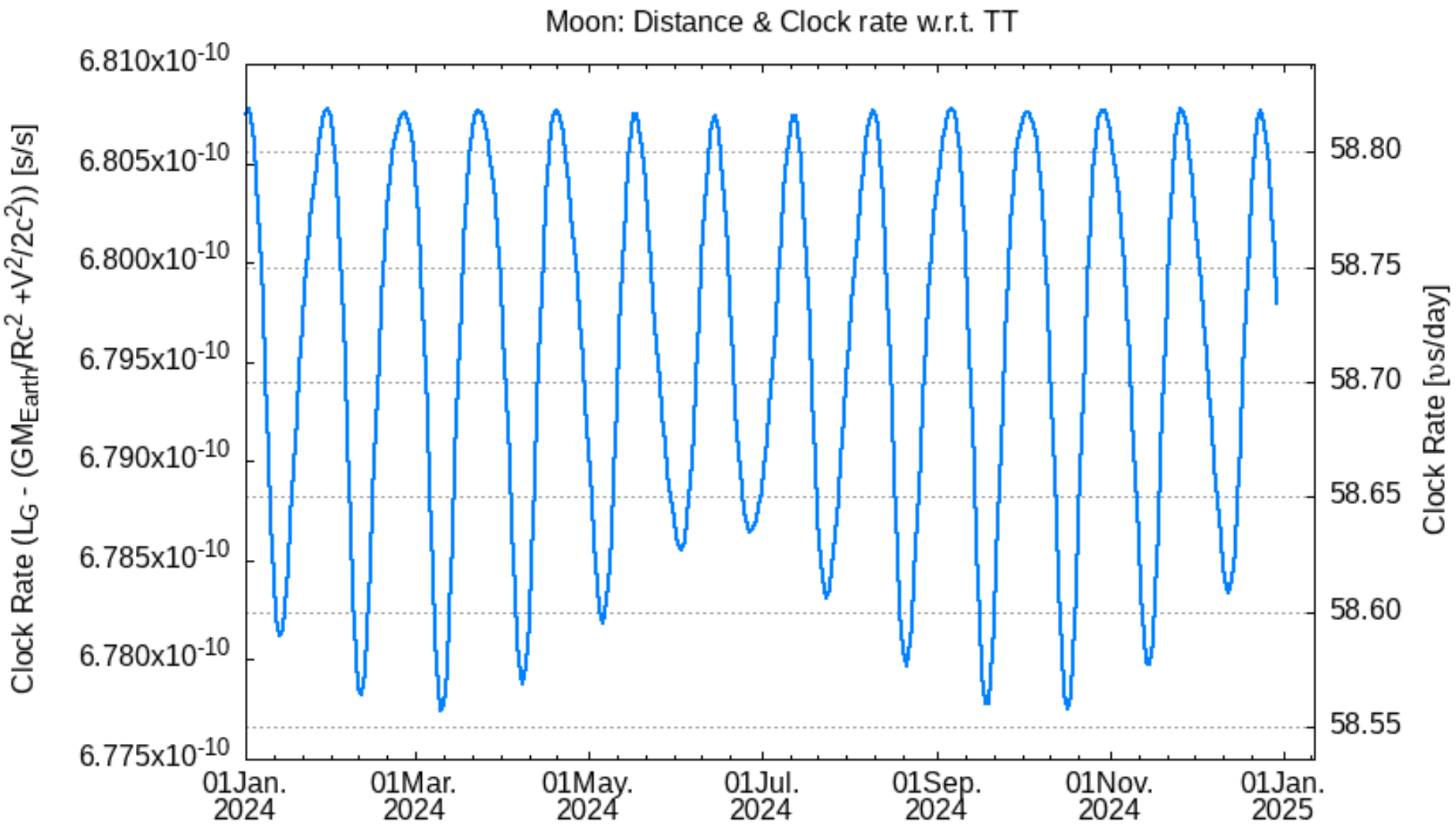
- Currently, NASA and ESA are planning to install satellite navigation systems to support the communication and navigation processes required for reliable and accurate real-time positioning. To maximize interoperability and facilitate cross-organizational endeavours, these systems should employ the same timescale. An internationally accepted lunar reference time would set a common framework for all lunar systems and users. Nevertheless, stable timekeeping on the Moon raises technical issues. Due to the different gravitational field, a clock on the Moon will not tick at the same rhythm as on the Earth; therefore, even the most perfectly synchronized clocks would quickly gain a considerable offset. This raises the necessity to settle aspects such as:
- In its role as responsible for the realization and dissemination of the UTC and for the definition of measurement units and reference time scales, the BIPM was invited to join the international forum discussing this topic, together with the International Astronomical Union which fixes the conventional reference frames.

Variation of Time Scale difference between TCL–TT due to change of earth-moon distance.



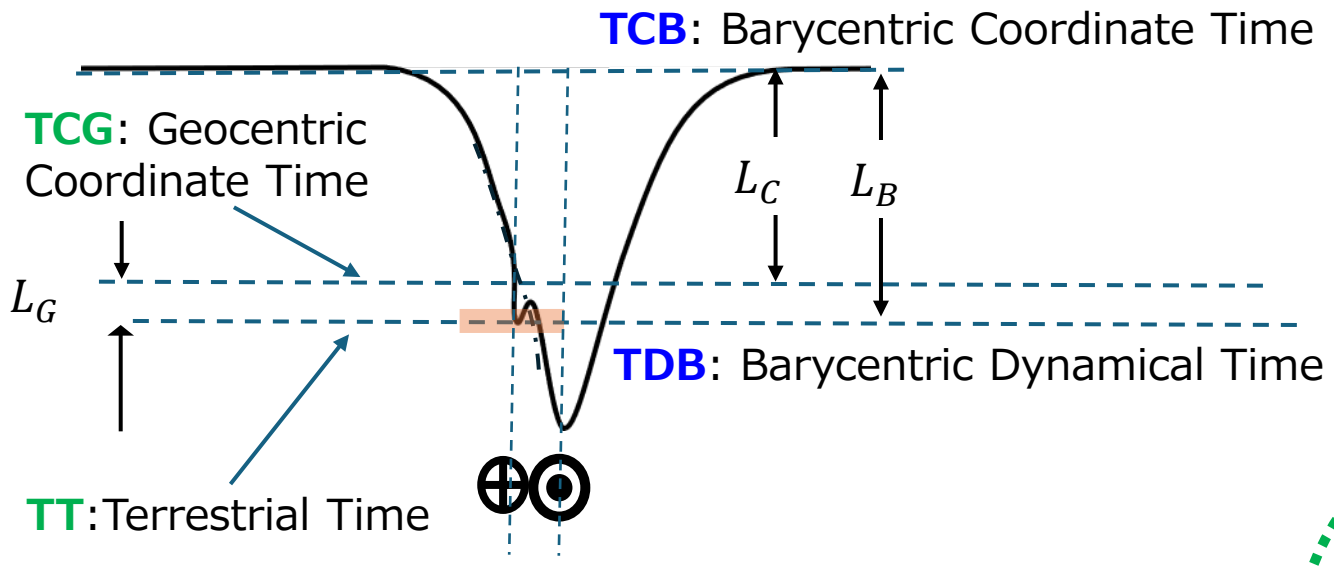
Variation of Time Scale difference between TCL–TT due to change of earth-moon distance.

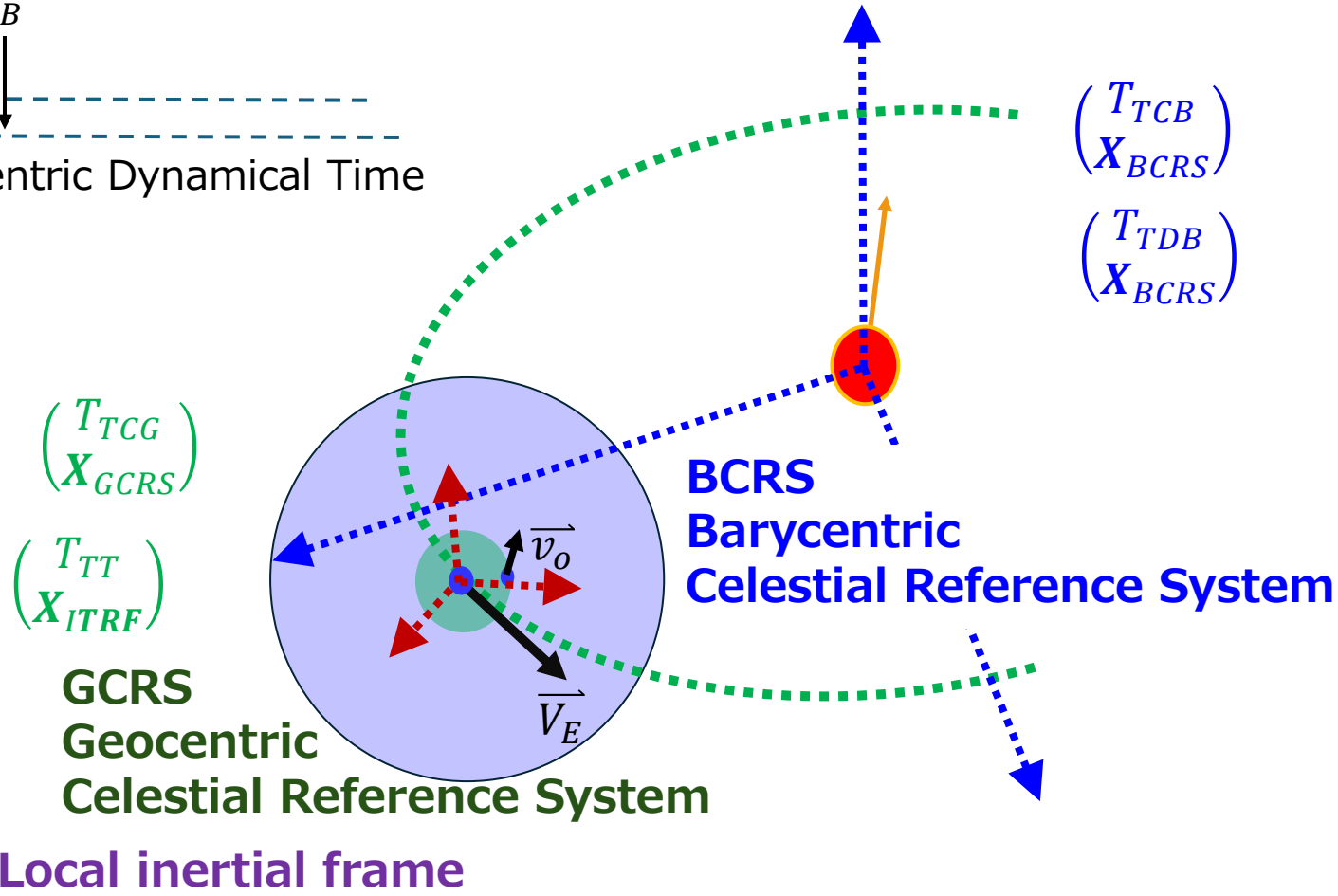
1 year



Reference frame and Coordinate time

Schematic diagram of Coordinate time and potential





Reference frame and Coordinate time

Reference frame

BCRS: Barycentric Celestial Reference System.
Its coordinate time is Barycentric Coordinate Time (**TCB**), or Barycentric Dynamical Time (**TDB**)

GCRS: Geocentric Celestial Refence System
Its coordinate time is Geocentric Coordinate Time (**TCG**), or Terrestrial Time (**TT**) as scaled time scale to be the same rate with clock on the geoid.

ITRS(ITRF): International Terrestrial Reference System (realization). It is fixed to the crust of the Earth.

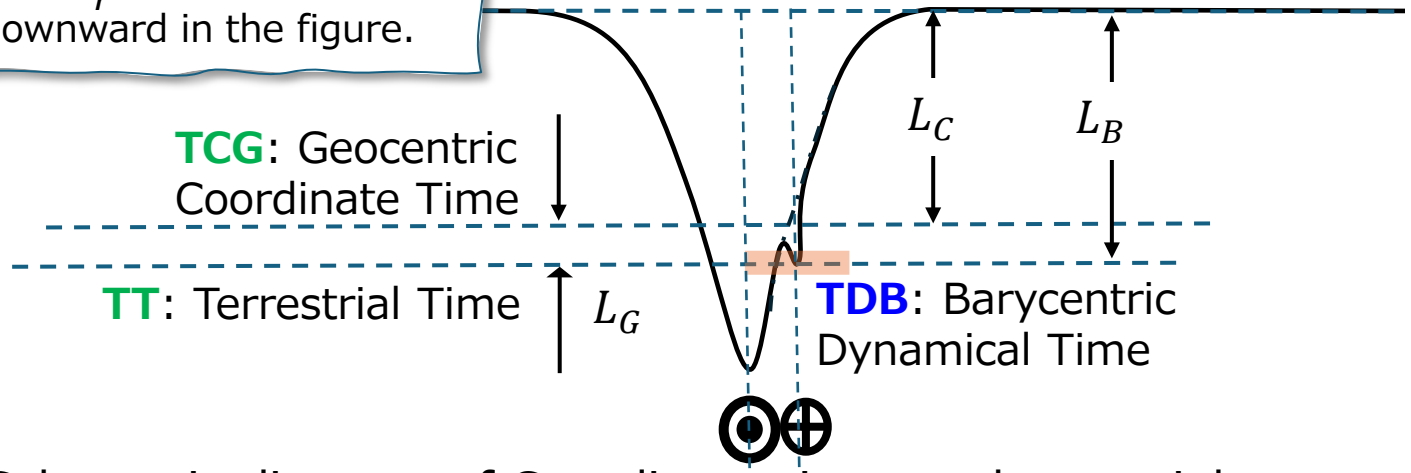
Time system related with TT

TT(Terrestrial Time): a coordinate time of scaled TCG to be the same rate with proper time of clock on the Geoid. TT=TAI+32.184 s

TAI (Temps Atomique International): Time system as weighted average of primary frequency standards in the world. It is regarded as realization of TT.

UTC (Coordinated Universal Time):Time system with offset to TAI to be aligned with UT1 within 0.9 s.

Gravitational potential $U = \frac{GM}{r}$ is larger as downward in the figure.



Schematic diagram of Coordinate time and potential

$$\frac{d\tau}{dt} = 1 - \frac{U}{c^2} - \frac{1}{2}\left(\frac{V}{c}\right)^2 \Rightarrow 1 - \left\langle \frac{U}{c^2} + \frac{1}{2}\left(\frac{V}{c}\right)^2 \right\rangle$$

$= 1 - L_B$: (TCB ↔ TDB)

$= 1 - L_G$: (TCG ↔ TT)

$$L_B = 1 - \frac{d(TDB)}{d(TCB)} = 1.550519768 \times 10^{-8}$$

$$L_G = 1 - \frac{d(TT)}{d(TCG)} = 6.969290134 \times 10^{-10}$$

Time systems on the Earth: UTC, TAI, TT, TCG, TDB, TCB

Why new time scales?

ASTRONOMY AND ASTROPHYSICS

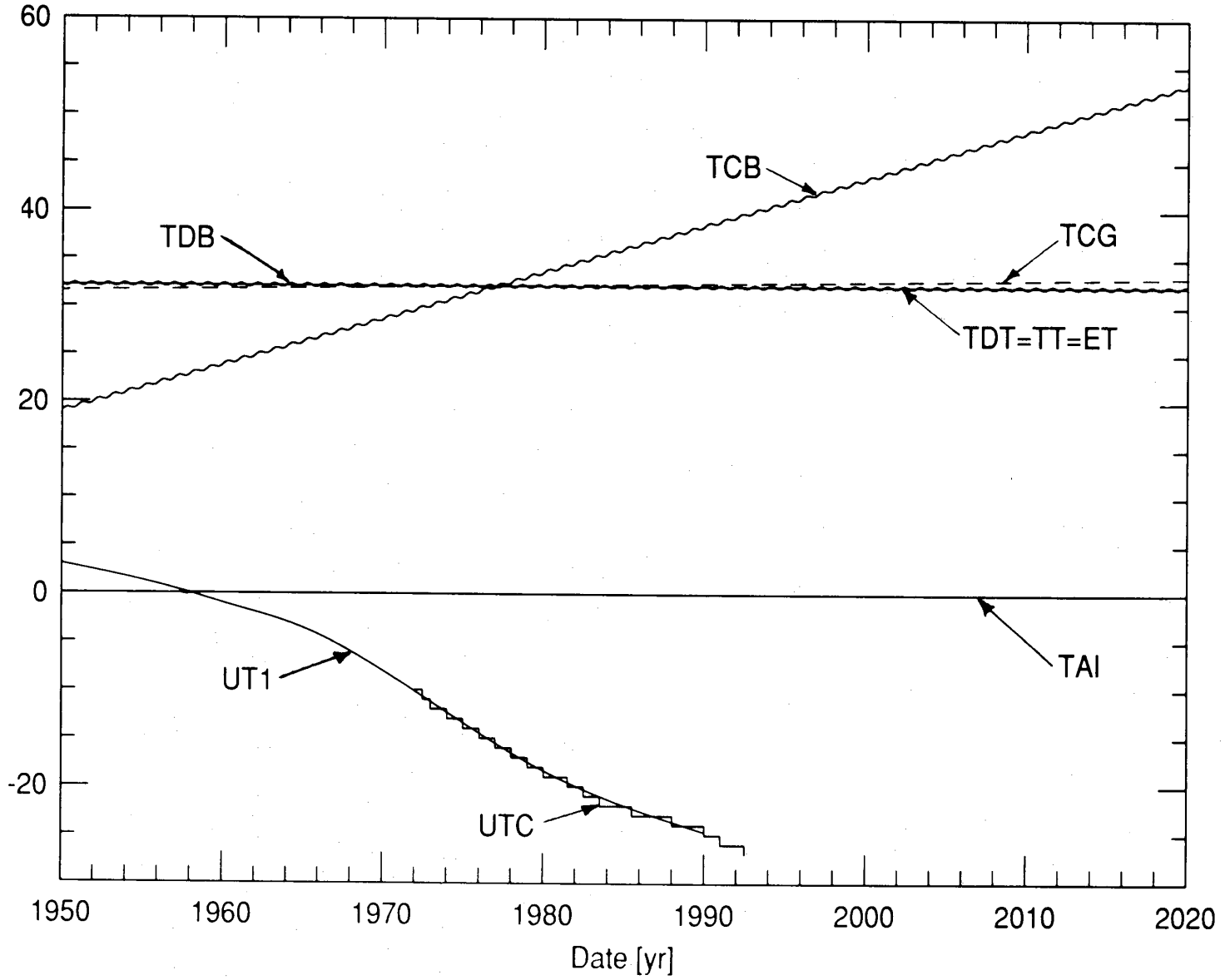
P.K. Seidelmann[1] and T. Fukushima[2]

[1] U.S. Naval Observatory, Washington, DC 20392-5100, USA
[2] National Astronomical Observatory, 2-21-1, Ohsawa, Mitaka, Tokyo 181, Japan

Received March 16, accepted May 27, 1992

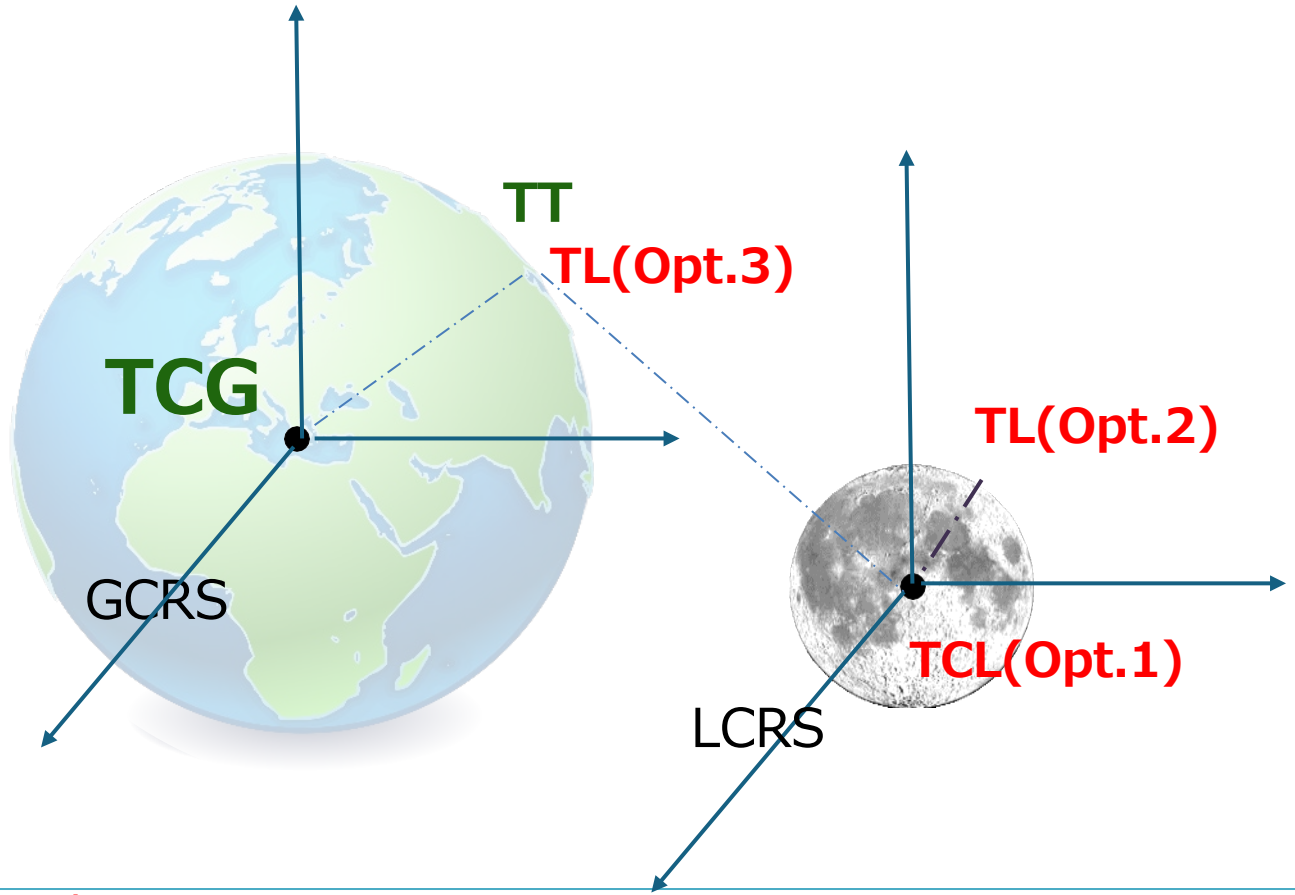
In the **IAU General Assembly held at Kyoto in 1991,** new time scales for space-time coordinate system were recommended with considering framework of general relativity.

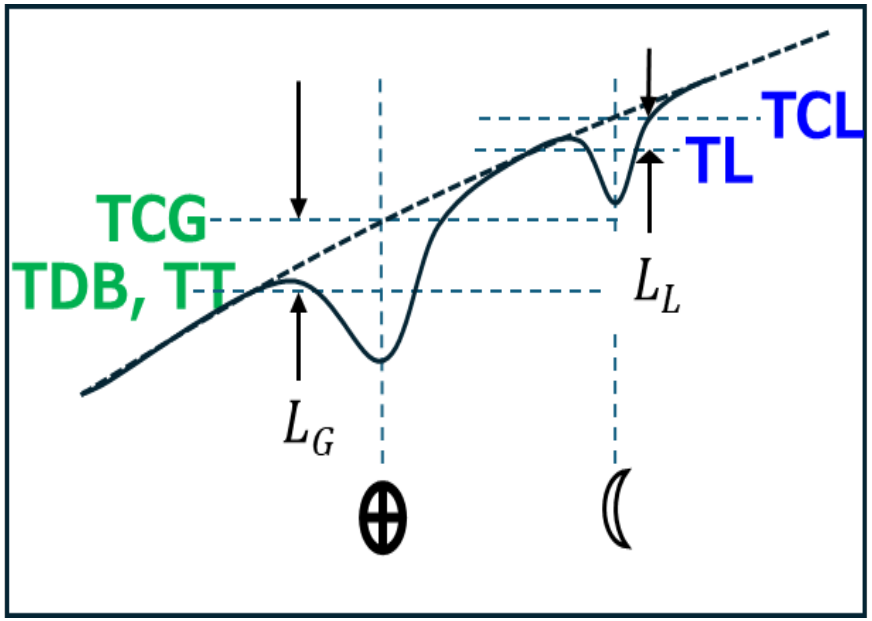
Explanatory paper was published by P.K.Seidelmann and T.Fukushima in 1992.



Introduction of Relativity

Three options of Lunar Reference Time





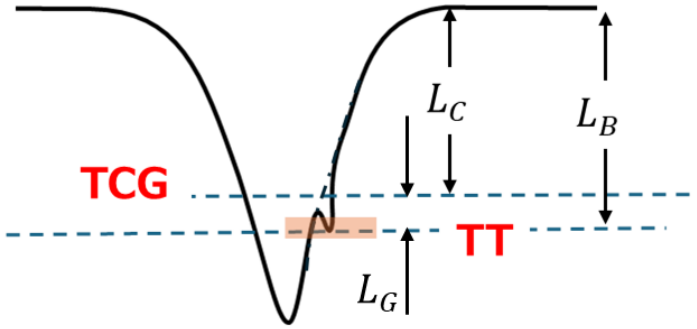
Opt.1) Lunar Coordinate Time (TCL) as time coordinate of Lunar Celestial Coordinate System (LCTS)*
Opt.2) Scaling TCL so that its rate is the same with proper time on lunar reference surface.
Opt.3) Scaling TCL so that its rate is the same with TT

*)TCL(Lunar Coordinate Time):IAU 2024 GA resolution https://www.iau.org/Iau/Iau/Publications/List-of-Resolutions.aspx

What is Scaling of Reference Frame and Space Time

GR: Invariant event distance ds

$$ds^2 = g_{\mu\nu}x^\mu x^\nu$$
$$= -c^2dt^2 + dx^2 + dy^2 + dz^2 \quad \cdots\cdots \text{Minkwski metric}$$
$$= \left[-\left(1 - 2\frac{U_E}{c^2}\right)c^2dt^2 + \left(1 + 2\frac{U_E}{c^2}\right)\sum_{i=1}^{3} dx^{i2}\right] \quad \cdots\cdots \text{Post Newtoni metric}$$



$$\frac{1}{c^2}ds^2 = -d\tau^2 = \frac{\mathbf{1}}{\mathbf{(1-L_x)^2}}\left[-\left(1 - 2\frac{U_E}{c^2}\right)dt'^2 + \frac{1}{c^2}\left(1 + 2\frac{U_E}{c^2}\right)\sum_{i=1}^{3} dx'^{i2}\right]$$

Proper time

$$\approx -\frac{\left(1-2\frac{U_E}{c^2}-\left(\frac{V_E}{c}\right)^2\right)}{(1-L_x)^2}dt^2$$

Coordinate time

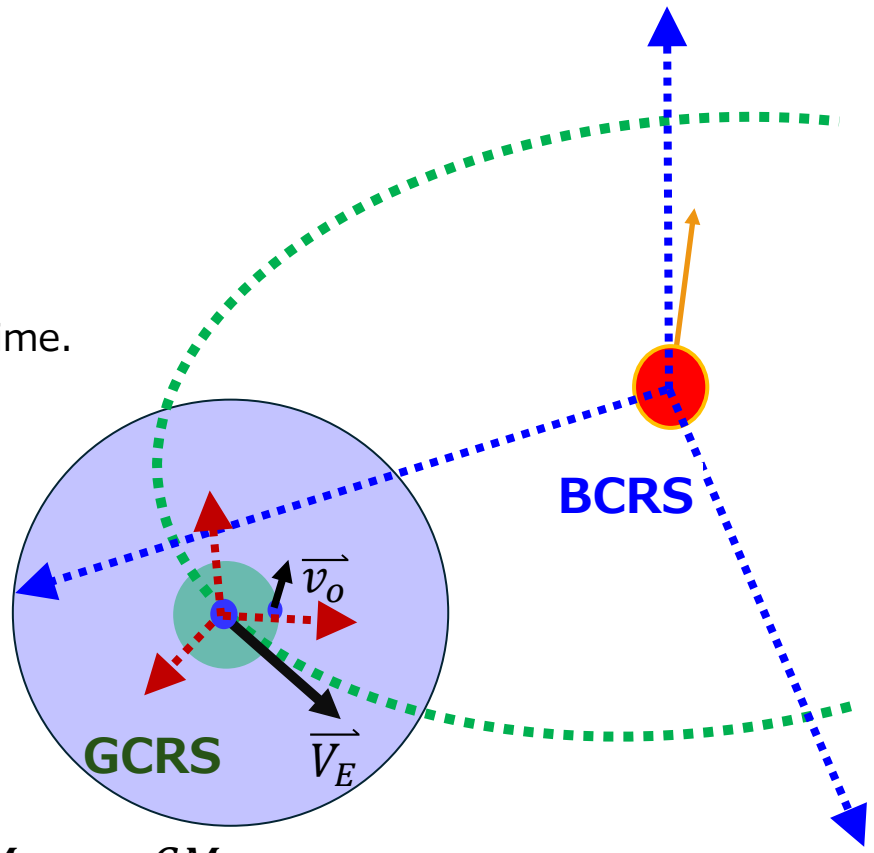
Scaling factor L_x is determined so that the coordinate time to be same rate with proper time.

Then

$$dT_{TDB} = (1 - L_B)dT_{TCB}$$
$$d\vec{x}_{TDB} = (1 - L_B)d\vec{x}_{TCB}$$
$$GM_{TDB} = (1 - L_B)GM_{TCB}$$

And similarly

$$dT_{TT} = (1 - L_G)dT_{TCG}$$
$$d\vec{x}_{TT} = (1 - L_G)d\vec{x}_{TCG}$$
$$GM_{TT} = (1 - L_G)GM_{TCG}$$



Length and Time scale is Scaled. Consequently, Mass parameter GM is also scaled by $(1 - L_x)$ in case of TT and TDB.

But this is not the case for TCG and TCL. Why?

$$GM_{TCB} = GM_{TCG} = GM_{TCL}$$

Mass parameter GM is scaled in case of TT and TDB, But this is not the case for TCG and TCL. What is difference?

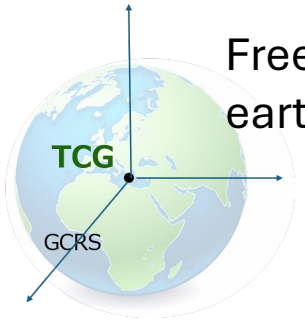
Evaluation of event distance at the center of Earth

$$ds^2 = g_{\mu\nu}x^\mu x^\nu$$

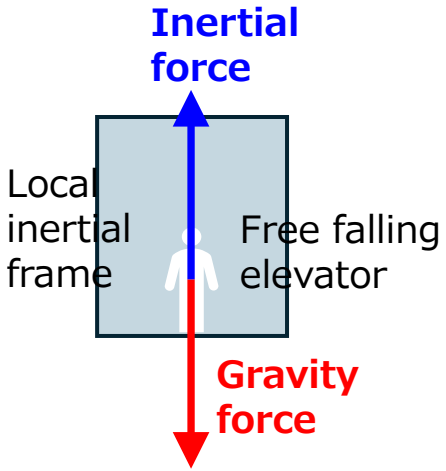
$$= -\left(1 - 2\frac{U_E}{c^2}\right)c^2 dt_{TCB}^2 + \left(1 + 2\frac{U_E}{c^2}\right)\sum_{i=1}^{3} dx_{TCB}^i{}^2$$

$$= -c^2 dT_{TCG}^2 + \sum_{i=1}^{3} dX_{TCG}^i{}^2$$ (Local inertial frame around the center of the Earth)

Mincowski space-time is valid local in the narrow region around the point of interest.



Free falling earth



Evaluation of event distance on the geoid of Earth

$$ds^2 = -\left(1 - 2\frac{U_{geoid}}{c^2}\right)c^2 dT_{TCG}^2 + \left(1 + 2\frac{U_{geoid}}{c^2}\right)\sum_{i=1}^{3} dX_{TCG}^i{}^2$$

$$= \frac{1}{(1 - L_G)^2}\left[-\left(1 - 2\frac{U_{Geoid}}{c^2}\right)c^2 dT_{TT}^2 + \left(1 + 2\frac{U_{Geoid}}{c^2}\right)\sum_{i=1}^{3} dX_{TT}^i{}^2\right]$$

Parameter L_G is determined so that coordinate time T_{TT} to be coincide with proper time except for periodic term.

$$-c^2 d\tau^2 = \frac{-1}{(1 - L_G)^2}\left(1 - 2\frac{U_{Geoid}}{c^2} + \left(1 + 2\frac{U_{Geoid}}{c^2}\right)\frac{V^2}{c^2}\right)c^2 dT_{TT}^2 \approx c^2 dT_{TT}^2$$

Pros and Cons of the three options of Lunar Time

Opt.3: Lunar Time $t_{LT,3}$ coincide with TT except for periodic term.

Time scale difference due to gravitational potential and velocity between surface on the moon and Earth is $\sim 6.4 \times 10^{-10}$

Thus, proper time on the lunar surface differs from TT by the same amount. When reference oscillator is brought from the earth, that rate need to be adjusted by that amount to generate $t_{LT,3}$.

Extension to the Mars: Time scale difference between Mars surface and Earth surface is $\Delta U/c^2 \sim 5.9 \times 10^{-9}$.

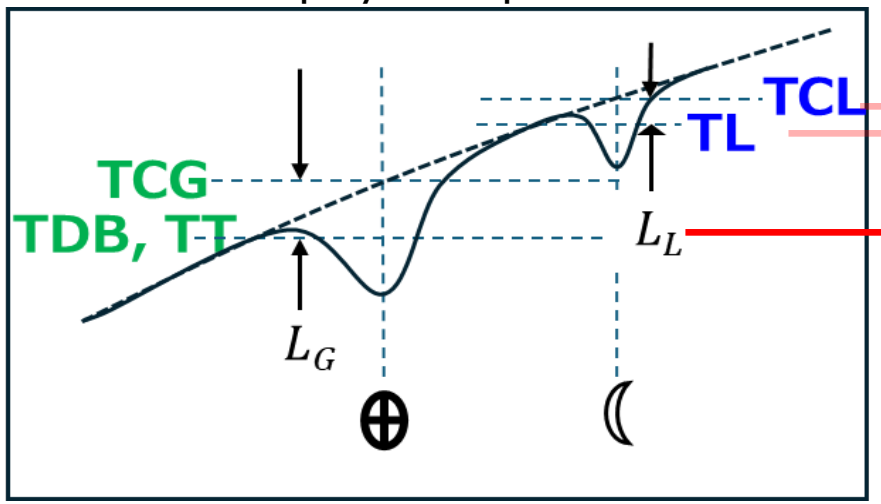
Thus, pre-launch rate adjustment is significant, and new scaled physical parameter GM is introduced.

Pros:

1. $t_{LT,3}$ *does* not depart form TT in average as time goes.

Cons:

1. Oscillator brought from the earth needs rate adjustment 6.4×10^{-10} for moon and it is 5.9×10^{-9} for the case of Mars.
2. Scaling causes additional GM parameters every time when same scheme is applied to planets and satellites.



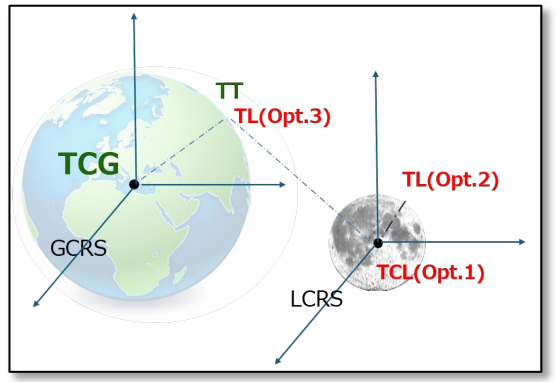
Opt.1

Opt.2

Opt.3

3.1×10^{-11}

6.4×10^{-10}



$$\frac{dt_{LT,3}}{dTT} - 1 \approx 0$$

Pros and Cons of the three options of Lunar Time
Opt.1: Lunar Time $t_{LT,1}$ is TCL defined by IAU-GA 2024.

Time coordinate of LCRS is used. There are no physical parameter scaling.
Gravitational potential at the center of Moon differs from Earth geoid by $\Delta U/c^2 \sim 6.7 \times 10^{-10}$ and potential difference between surface and center of the moon is $\Delta U/c^2 \sim 3.1 \times 10^{-11}$.
Thus, proper time on the lunar surface differs from $t_{LT,1}$ by 3.1×10^{-11}. When reference oscillator is brought from the earth, that rate need to be adjusted by 3.1×10^{-11} to generate $t_{LT,1}$.

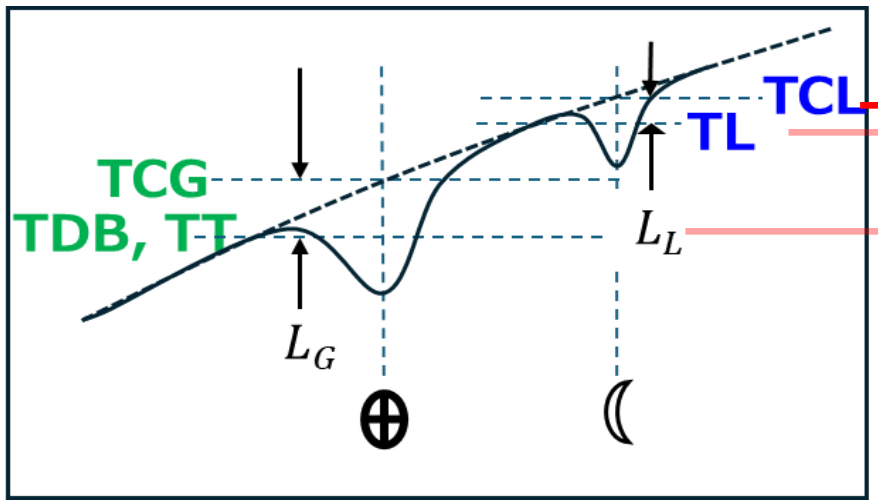
Extension to the Mars: TCM as time coordinate of Mars celestial reference system will be introduced. Potential difference between surface and center of Mars is $\Delta U/c^2 \sim 1.4 \times 10^{-10}$.
Then, this amount of pre-launch rate adjustment is necessary for reference oscillator used for time standards.

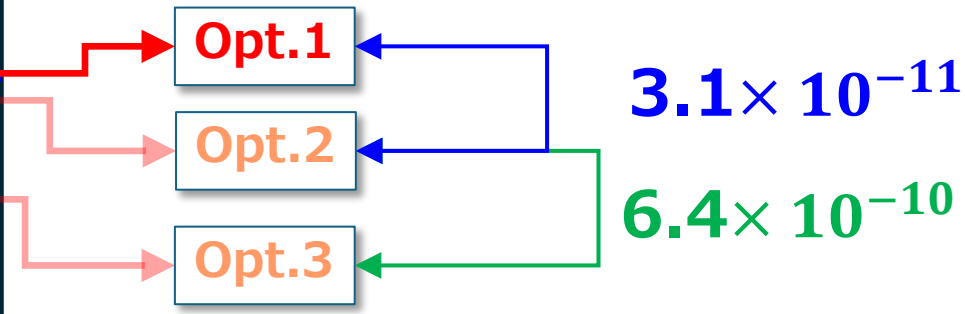
Pros:

1. No needs of scaling. Thus, no proliferation of physical parameter (e.g. GM).

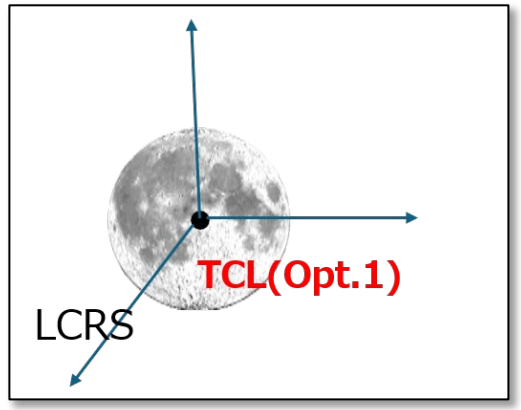
Cons:

1. Oscillator brought from the earth needs rate adjustment 3.1×10^{-11} for moon and it is 1.4×10^{-10} for Mars.





$\frac{dt_{LT,1}}{dTT} - 1 = 6.7 \times 10^{-10} = 21$ ms/year
~ 1 s/47 yeas



Pros and Cons of the three options of Lunar Time
Opt.2:Lunar Time $t_{LT,2}$is scaled TCL by lunar reference potential.

$t_{LT,2}$ is scaled TCL so that its rate coincide with proper time on the reference potential (lunar geoid). Potential difference from moon center to the surface is $\Delta U/c^2 \sim 3.1 \times 10^{-11}$. Rate adjustment is not necessary, when reference oscillator is brought from the earth to the moon surface to generate $t_{LT,2}$. Effect of height difference on the moon surface is approximately within 3×10^{-13}. Scaled new physical parameters (e.g. GM) are introduced.

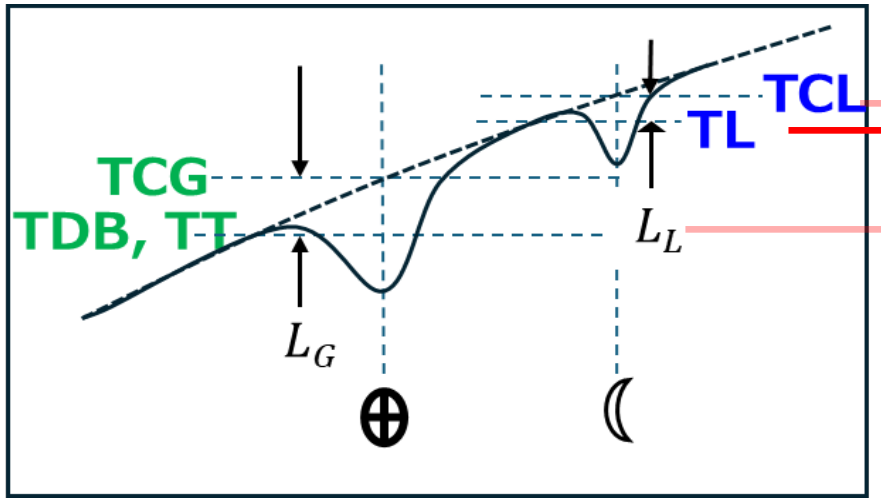
Extension to the Mars: As the same with moon, new scaled GM parameter is introduced. Pre-adjustment of frequency rate is not necessary for reference oscillator used on the Mars surface.

Pros:

1. Rate adjustment is not necessary, when reference oscillator is brought from the earth to the moon surface. This is the same for Mars case.

Cons:

1. Scaling causes additional GM parameters every time when same scheme is applied to planets and satellites.



Opt.1

Opt.2

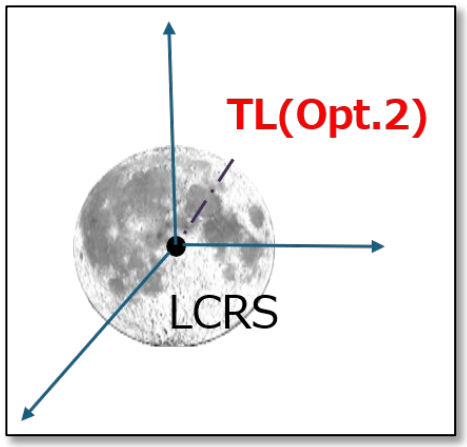
Opt.3

3.1×10^{-11}

6.4×10^{-10}

$\frac{dt_{LT,2}}{dTT} - 1 = 6.4 \times 10^{-10} = 20$ ms/year

~ 1 s/50 yeas

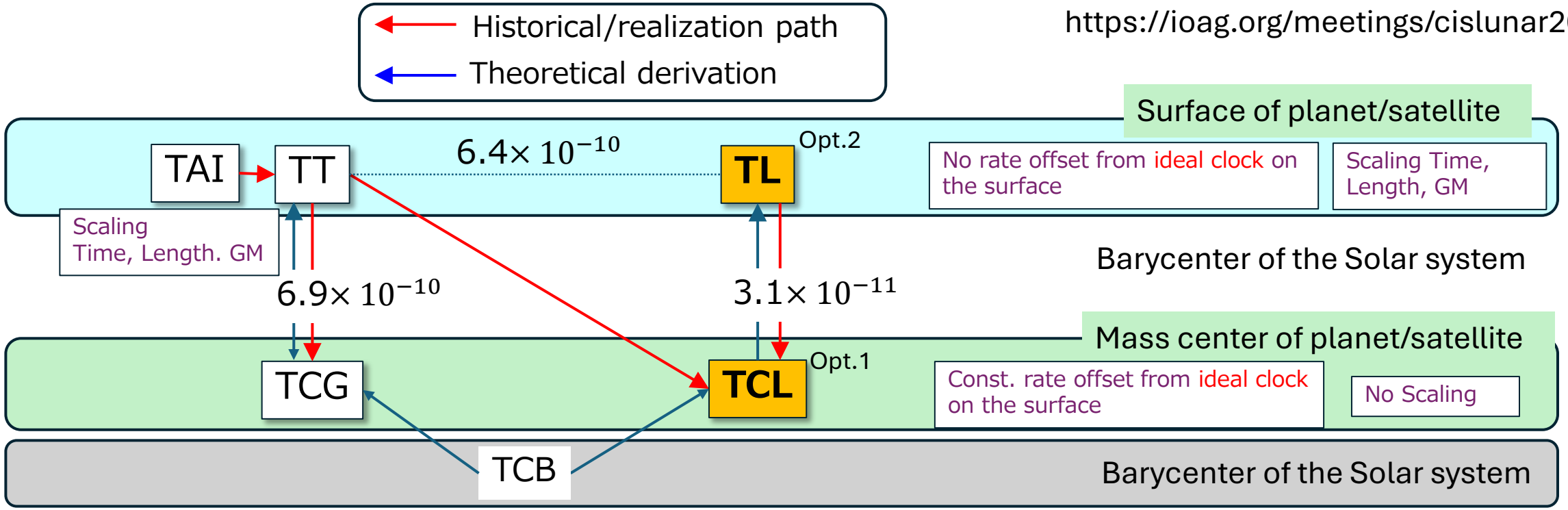


Viewpoint of NASA/LunaNet on Lunar Time

1. Traceability to UTC
2. Sufficient Accuracy
3. Resilience to loss of contact with the Earth
4. Scalability beyond the Moon



https://ioag.org/meetings/cislunar2026/



Which option of Lunar Time is easier to be realized with a clock on the lunar surface ? (1)

1. No clock realizing TCL/TL on the Moon:

Using UTC(k) on Earth and relativistic corrections:

TCL/TL as obtained from UTC(k) transported to the Moon: $TCL_{UTC(k)}$ / $TL_{UTC(k)}$

$[clock - UTC(k)]_{measured}$ – Relativistic corrections → clock-$TCL_{UTC(k)}$ / clock-$TL_{UTC(k)}$

→ steer the lunar clock to align it on $TCL_{UTC(k)}$ / $TL_{UTC(k)}$
→ clock stability to maintain the reference between contacts with the Earth

→ no advantage of using TL or TCL

Which option of Lunar Time is easier to be realized with a clock on the lunar surface ? (2)

2. Autonomous realization of TCL / TL:

Requires :

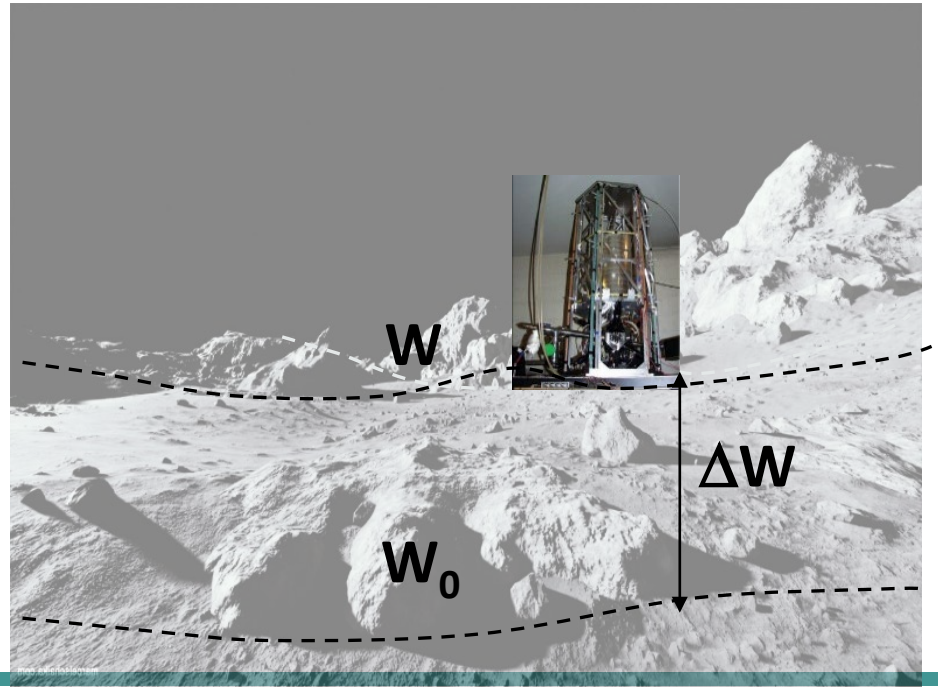
- an accurate frequency standard (PFS)
- an accurate local gravity potential (W) determination

Scale of TCL = f(PFS) – W/ c^2

Scale of TL = f(PFS) – (W-W_0)/ c^2

W «measured»
W_0 convention

→ no advantage of using TL or TCL



Conclusion

- Opt.3 may not be appropriate, because
  - Time/Freq. comparison and adjustment to trace TT is required,
  - Thus it has more difficulty for extension to other planets.]
- Opt.1 (TCL) and Opt.2(TL) are candidates for lunar reference time.
- Opt.1 (TCL) has advantage at free from scaling of space-time and physical quantity. Physical realization requires rate offset from ideal clock (proper time).
- Opt. 2 (TL) may be realized by taking advantage of primary Frq. Std. located close to lunar reference potential. Drawback is introducing Space-time scaling. But, its applicable space region is limited in local inertial reference frame.

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)	μ*= (1-L_B) μ	μ** = (1-L_G) μ
	L_B= 1.550519768 × 10^{-8}	L_G = 6.969290134 × 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.

“Risk of complexity and ambiguity” ?

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	$dTT/dTCG = 1 - L_G$	$6.969\,290\,134 \times 10^{-10}$	60.2146 μs d^{-1}	IAU 2000 B1.9
L_C	$\langle dTCG/dTCB \rangle = 1 - L_C$	$1.480\,826\,867\,41 \times 10^{-8}$	1.279 434 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 ms d^{-1}	IAU 2006/2009
L_L	$dTL/dTCL = 1 - L_L$	$3.1390541 \times 10^{-11}$	2.712143 μs d^{-1}	this work, Eq. (A5)
L_H	$\langle dTCL/dTCB \rangle = 1 - L_H$	1.4825362×10^{-8}	1.280 911 ms d^{-1}	this work, Eq. (A8)
L_M	$\langle dTL/dTCB \rangle = 1 - L_M$	$1.485675294 \times 10^{-8}$	1.283 624 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

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

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)

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