Memorandum for understanding Options of Lunar Time

8 June 2025

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1 Introduction

Lunar navigation system using lunar orbiters are insvestigated and planned by space agencies around the world. The BIPM CCTF has also launched a Lunar Time Working Group to study an internationally common lunar standard time system, with Pascal et al. [1] proposing three options. This is a memorandum for better understanding on these options.

In Section 2, we review the relationship between the coordinate times TCB, TCG, TDB, and TT in the solar barycentric coordinate system and the Earth barycentric coordinate system. In Section 3, we derive the relationship between the lunar time TCL, TL by analogy with the Earth case, and the coordinate time TL* scaled so that TL*-TT contains only periodic terms as shown in Option 3 of Pascal et al. [1]. In Section 4, we focus only on the special relativity effect due to the relative motion between the Moon and the Earth, and show that the synchronization of time and frequency depends on the location. In Section 5, we consider the advantages and disadvantages of the three options based on [2].

2 Relation among TCB, TDB, TCG, and TT

In the following description, variables in lowercase Roman letters represent coordinate variables in the Barycentric Celestial Reference System (BCRS), and those in uppercase Roman letters represent coordinate variables in the Geocentric Celestial Reference System (GCRS).

The BCRS metric tensor defined in the IAU General Assembly Resolution B1.9 in 2000 is given as follows using the scalar potential $w(t,\vec{\mathbf{x}})$ at the position of the clock and the vector potential $w^i(t,\vec{\mathbf{x}})$[4].

$$\begin{aligned} g_{00} &= -1 + 2\frac{w}{c^2} - \frac{2w^2}{c^4} + O(c^{-5}) \\ g_{0i} &= -\frac{4}{c^3}w^i + O(c^{-5}) \\ g_{ij} &= \delta_{ij}(1 + 2\frac{w}{c^2}) + O(c^{-4}), \end{aligned} \tag{1}$$

where G is the gravitational constant. The scalar potential, and the vector potential are given as follows:

$$w(t,\vec{\mathbf{x}}) = G\int d\vec{\mathbf{x}}' \frac{\sigma(t,\vec{\mathbf{x}'})}{|\vec{\mathbf{x}}-\vec{\mathbf{x}}'|} + \frac{1}{2c^2}G\frac{\partial^2}{\partial t^2}\int d^3x'\sigma(t,\vec{\mathbf{x}}')\,|\vec{\mathbf{x}}-\vec{\mathbf{x}}'|\,, \tag{2}$$

$$w^i(t,\vec{\mathbf{x}}) = G\int d^3x' \frac{\sigma^i(t,\vec{\mathbf{x}}')}{|\vec{\mathbf{x}}-\vec{\mathbf{x}}'|}. \tag{3}$$

Here, $\sigma(t,\vec{\mathbf{x}}), \sigma^i(t,\vec{\mathbf{x}})$ denote the mass density and mass flux density, respectively. For simplicity, in the transformation of the following equations, we approximate it to the order of c^{-2}, ignoring the effects of tides, and writing the scalar potential w in equation (2) as $U = \sum_j \frac{GM_j}{R_j}$. This is the sum of the gravitational potential at the target position with respect to j (=gravity source).

The Barycentric Coordinate System (BCRS) is a four-dimensional coordinate system whose origin is barycenter of the solar system, and whose spatial coordinate axes are defined in the direction of distant radio celestial bodies (such as quasars). Barycentric Coordinate Time (TCB) is a time system based on a virtual clock that is located at the origin of the BCRS but is not affected by gravitational potential. Another BCRS coordinate time is Barycentric Dynamical Time (TDB), which is obtained by scaling TCB to have the same time scale as TT on average. TCG is a time system of an ideal clock placed at the center of the Earth, and is coordinate time in the Geocentric Coordinate System (GCRS).

Let us consider a clock placed at the center of the Earth by using coordinates $(t_{\mathrm{TCB}}, \vec{\mathbf{x}}_{\mathrm{TCB}})$ in the Barycentric Solar System (BCRS). Let the coordinate scaled by a factor

$$l = (1-L)^{-1} \tag{4}$$

be $(t', \vec{\mathbf{x}'})$. Let us express the line elements between infinitesimal four-dimensional events at the center of the Earth in both TCB-compatible and TCG-compatible coordinates.

$$
\begin{aligned}
ds^2 &= (g_{\mu,\nu} dx^\mu dx^\nu) \\
&= -\left(1 - 2\frac{U_{\mathrm{E}}}{c^2}\right) c^2 dt_{\mathrm{TCB}}^2 + \left(1 + 2\gamma\frac{U_{\mathrm{E}}}{c^2}\right) \sum_{i=1}^{3} {dx^i_{\mathrm{TCB}}}^2 \qquad (5) \\
&= l^2 \left[-\left(1 - 2\frac{U_{\mathrm{E}}}{c^2}\right) c^2 dt'^2 + \left(1 + 2\gamma\frac{U_{\mathrm{E}}}{c^2}\right) \sum_{i=1}^{3} {dx'^i}^2\right]. \qquad (6) \\
&= -c^2 dT_{\mathrm{TCG}} + \sum_{i=1}^{3} {dX^i}^2_{\mathrm{TCG}}, \qquad (7)
\end{aligned}
$$

where, $U_{\mathrm{E}} = \sum_{\mathrm{j} \neq \mathrm{E}} \frac{GM_j}{r_{Ej}}$ is the gravitational potential of a celestial body other than the Earth evaluated at the center of the Earth.

The relationship between the reference coordinate systems (BCRS, GCRS) and their coordinate times TCB, TDB, TCG, and TT has been discussed and described in several publications [3, 4, 5, 11]. Here we introduce expression from the supplementary paper on Resolution of IAU General Assembly 2000[4]:

$$
\mathrm{TCB} - \mathrm{TCG} = \frac{1}{c^2}\left[\int_{t_0}^{t} \left(\frac{v_{\mathrm{E}}^2}{2} + U_{\mathrm{E}}(\vec{\mathbf{x}}_{\mathrm{E}})\right) dt + \vec{\mathbf{v}}_{\mathrm{E}} \cdot \vec{\mathbf{r}}_{\mathrm{E}}\right] \qquad (8)
$$

TT is sometimes expressed as "a clock defined on the geoid", but the clock (proper time) on the geoid on the surface of a rotating Earth moves with the Earth's rotation. Hence, clock by that definition is not at rest with respect to the local inertial coordinate system, accordingly it is not regarded as coordinate time. TT can be regaded as a coordinate time when it is considered as time of a clock at rest to the Geocentric Coordinate System, scaled from TCG by the factor of gravitational potential (W_0) on the geoid surface. Rate difference between TCG and is expressed as:

$$
\begin{aligned}
dT_{\mathrm{TT}} &= (1 - L_{\mathrm{G}}) dT_{\mathrm{TCG}} \qquad (9) \\
d\vec{\mathbf{X}}_{\mathrm{TT}} &= (1 - L_{\mathrm{G}}) d\vec{\mathbf{X}}_{\mathrm{TCG}}, \qquad (10)
\end{aligned}
$$

where, $L_{\mathrm{G}} = W_0/c^2$ is the defining constant [7]. TCG-TT is expressed as follows[4]:

$$
\begin{aligned}
\mathrm{TCG} - \mathrm{TT} &= L_{\mathrm{G}} \times (\mathrm{JD} - 2443144.5) \times 86400, \\
L_{\mathrm{G}} &= 6.969290134 \times 10^{-10}. \qquad (11)
\end{aligned}
$$

TDB is the coorinate time of BCRS, in which space-time coordinates is scaled so that TDB-TT contains only periodic terms. To uniquely define TDB, the constant L_{B} was formally defined at the 2006 IAU General Assembly[8], and the relationship between TCB and TDB is

$$
\begin{aligned}
\mathrm{TCB} - \mathrm{TDB} &= L_{\mathrm{B}} \times (\mathrm{JD} - 2443144.5) \times 86400, \\
L_{\mathrm{B}} &= 1.550519768 \times 10^{-8}. \qquad (12)
\end{aligned}
$$

Derivative expressing of time scale difference between TCG and TCB is

$$
\frac{d\mathrm{TCG}}{d\mathrm{TCB}} = 1 - \frac{1}{c^2}\left(\frac{v_{\mathrm{E}}^2}{2} + U_{\mathrm{E}}(\vec{\mathbf{x}}_{\mathrm{E}}) + \vec{\mathbf{v}}_{\mathrm{E}} \cdot \vec{\mathbf{V}}_{\mathrm{obs}} + \frac{d\vec{\mathbf{v}}_{\mathrm{E}}}{dt} \cdot \vec{\mathbf{r}}_{\mathrm{E}}\right), \qquad (13)
$$

where $\vec{\mathbf{v}}_{\mathrm{E}}$ is the velocity vector at the center of the Earth in the BCRS, and $\vec{\mathbf{V}}_{\mathrm{obs}}$ is the velocity vector of observer in the GCRS. For the scale ratios between TT and TCG, and TDB and TCB are represented respectively as follows:

$$
\frac{d\mathrm{TT}}{d\mathrm{TCG}} = 1 - L_{\mathrm{G}} \qquad (14)
$$

$$
\frac{d\mathrm{TDB}}{d\mathrm{TCB}} = 1 - L_{\mathrm{B}}. \qquad (15)
$$

From these relation,

$$\frac{d\mathrm{TT}}{d\mathrm{TDB}} = \frac{1-L_\mathrm{G}}{1-L_\mathrm{B}}\left[1-\frac{1}{c^2}\left(\frac{v_\mathrm{E}^2}{2}+U_\mathrm{E}(\vec{\mathbf{x}}_\mathrm{E})+\vec{\mathbf{v}}_\mathrm{E}\cdot\vec{\mathbf{V}}_\mathrm{obs}+\frac{d\vec{\mathbf{v}}_\mathrm{E}}{dt}\cdot\vec{\mathbf{r}}_\mathrm{E}\right)\right] \tag{16}$$

is derived. Gravitational potential in the above formula is evaluated at geocenter. The last term in equation (11) and the last two terms in equation (13) and (16) are terms associated with the Lorentz transformation (difference in simultaneity) from the BCRS to the GCRS, which is moving relative to it.

In a TDB-compatible coordinate system, where the TDB is the coordinate time, physical constants such as the mass parameter GM are scaled, e.g., $GM_\mathrm{sun}^\mathrm{TDB} = (1-L_\mathrm{B})GM_\mathrm{sun}^\mathrm{unscaled}$. Similarly, a TT-compatible coordinate system uses different mass parameters (e.g., $GM_\mathrm{E}^\mathrm{TT} = (1-L_\mathrm{G})GM_\mathrm{E}^\mathrm{unscaled}$) from the unscaled TCB and TCG -compatible coordinate systems.

Fig. 1 is schematic view of relation between time systems and gravitational potential.

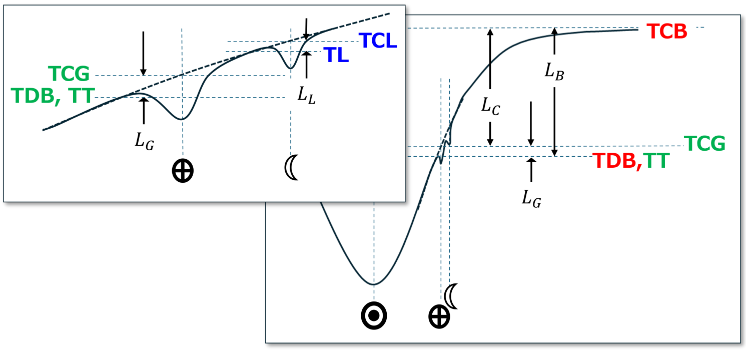

Figure 1: Schematic image of relation between coordinate time scale and gravtational potential.

3 Lunar Time and coordinate systems

Similar to the process of deriving the Earth's time system in the previous section, let us consider the lunar time system shown in [1]. The 2024 IAU General Assembly Resolution [9] defines the Lunar Centric Reference System (LCRS) and its coordinate time, Lunar Centric Coordiante Time (TCL)[9]. This corresponds to the TCG on Earth. Similarly, a lunar version corresponding to TT could be Lunar Time (TL), which is a coordinate time obtained by scaling TCL and making the rate almost the same as that of the clocks on the surface of the moon. Pascal et al. [1] have proposed the following three options for the lunar standard time system:

1. Using TCL (Lunar Centric Coordinate Time)
2. Defining a TL, scaled version of TCL and defined on a given W_L0
3. Definiing a TL, scaled version of TCL so that TL-TT has only periodic term

Let us compare the time scales of the Moon with those of the Earth (TCG⇔TCL, T⇔TL) and show the difference in time scales for each case.

Lunar Time (TL) is defined by scaling TCL with constant $L_\mathrm{L} = W_\mathrm{L0}/c^2$, where W_L0 is standard potential at lunar surface.

$$\frac{d\mathrm{TL}}{d\mathrm{TCL}} = 1 - L_\mathrm{L}. \tag{17}$$

The rate differences of TCL and TL with respect to TDB can be derived with referring to the equations (13) and (16) as

$$\frac{d\mathrm{TCL}}{d\mathrm{TDB}} = \frac{1}{1-L_\mathrm{B}}\left[1-\frac{1}{c^2}\left(\frac{v_\mathrm{L}^2}{2}+U_\mathrm{L}\right)\right] \tag{18}$$

and

$$\frac{d\mathrm{TL}}{d\mathrm{TDB}} = \frac{1-L_\mathrm{L}}{1-L_\mathrm{B}}\left[1-\frac{1}{c^2}\left(\frac{v_\mathrm{L}^2}{2}+U_\mathrm{L}\right)\right]. \tag{19}$$

Here, $U_\mathrm{L} = \sum_{j \neq L} \frac{GM_j}{r_{Lj}}$ is the gravitational potential of a celestial body other than the Moon evaluated at the lunar center of mass, and v_L is the Moon's velocity in the BCRS. For simplicity, we assume that the observer (clock) is rest at the lunar center of mass, and omit the position-dependent terms that correspond to the final two terms in equations (13) and (16).

Scale difference between TT-TCL and TT-TL are derived as follows:

$$\begin{aligned} \frac{d\mathrm{TCL}}{d\mathrm{TT}} &= \frac{d\mathrm{TCL}}{d\mathrm{TDB}} \cdot \left(\frac{d\mathrm{TT}}{d\mathrm{TDB}}\right)^{-1} && (20) \\ &= \frac{1}{1-L_\mathrm{G}} \left[\frac{1 - \frac{1}{c^2}\left(\frac{v_\mathrm{L}^2}{2} + U_\mathrm{L}\right)}{1 - \frac{1}{c^2}\left(\frac{v_\mathrm{E}^2}{2} + U_\mathrm{E}\right)} \right] && (21) \\ &\cong 1 + \frac{1}{c^2}\left(\frac{v_\mathrm{E}^2 - v_\mathrm{L}^2}{2} + U_\mathrm{E} - U_\mathrm{L}\right) + L_\mathrm{G}, && (22) \end{aligned}$$

$$\begin{aligned} \frac{d\mathrm{TL}}{d\mathrm{TT}} &= \frac{d\mathrm{TL}}{d\mathrm{TDB}} \cdot \left(\frac{d\mathrm{TT}}{d\mathrm{TDB}}\right)^{-1} && (23) \\ &= \frac{1-L_\mathrm{L}}{1-L_\mathrm{G}} \left[\frac{1 - \frac{1}{c^2}\left(\frac{v_\mathrm{L}^2}{2} + U_\mathrm{L}\right)}{1 - \frac{1}{c^2}\left(\frac{v_\mathrm{E}^2}{2} + U_\mathrm{E}\right)} \right] && (24) \\ &\cong 1 + \frac{1}{c^2}\left(\frac{v_\mathrm{E}^2 - v_\mathrm{L}^2}{2} + U_\mathrm{E} - U_\mathrm{L}\right) + L_\mathrm{G} - L_\mathrm{L}. && (25) \end{aligned}$$

Option 3 proposes time system TL*, which differs from TT only by periodic term. In this case, scaling constant is different from $L_\mathrm{L}(= W_{\mathrm{L}0}/c^2)$, but new sacaling constant is defined as

$$L_\mathrm{L}^* = \left\langle \frac{1}{c^2}\left(U_\mathrm{E} - U_\mathrm{L} + \frac{v_\mathrm{E}^2 - v_\mathrm{L}^2}{2}\right)\right\rangle + L_\mathrm{G}, \tag{26}$$

where <> denote long term average. By using this constant L_L^*,

$$\left\langle \frac{d\mathrm{TL}^*}{d\mathrm{TT}} \right\rangle = 1. \tag{27}$$

The above formulas are only rough outlines, and more detailed consideration including higher-order terms have been done by other literatures[10, 11].

In addition, the comparison of time systems shown in this section is based on time systems evaluated at the center of the Moon, and if the observer is on the surface of the Moon or above the Moon, note that the term expressed in the last terms of equation (8), equation (13) or equation (16) in the case of the Earth must be taken into account. These terms are associated with differences in simultaneity between coordinate systems moving relatively. This point will be discussed more simply in section 4 by only using special relativity.

4 Time comparison and synchronization between the Moon and Earth is location dependent

In the previous section, we considered the difference in rate (scale) between the time systems evaluated at the barycenters of the Earth and the Moon. However, when comparing clocks on the surface or in the air of the Earth (proper time) with clocks on the surface or in the orbit of the Moon (proper time), it depends on their locations. To show this simply, in this section, we will only consider the effects of special relativity.

The Moon revolves around the Earth at a speed of about 1 km/s, and a Lorentz transformation is necessary between the Earth GCRS coordinates $(T, \vec{\mathbf{X}})$ and the Moon LCRS coordinates $(T', \vec{\mathbf{X}}')$. Let us suppose that $\vec{\mathbf{V}}_{\mathrm{L}}$ is the Moon's velocity in GCRS, $\gamma = 1/\sqrt{1-(V_{\mathrm{L}}/c)^2}$, and $*^T$ denote transpose of matrix, $(\vec{\mathbf{A}} \otimes \vec{\mathbf{B}})_{ij} = A_i B_j$, then the Lorentz transformation can be written as follows.

$$\begin{pmatrix} cT \\ \vec{\mathbf{X}} \end{pmatrix} = \begin{pmatrix} \gamma & \gamma \frac{\vec{V}_{\mathrm{L}}^T}{c} \\ \gamma \vec{\mathbf{V}}_{\mathrm{L}}/c & \mathbf{I} + (\gamma - 1)\frac{\vec{V}_{\mathrm{L}} \otimes \vec{\mathbf{V}}_{\mathrm{L}}}{V_{\mathrm{L}}^2} \end{pmatrix} \begin{pmatrix} cT' \\ \vec{\mathbf{X}}' \end{pmatrix} \tag{28}$$

Epochs of two events simultaniously happened on the Moon (LCRS) $(dT' = 0)$ will have time differences in the coordinate system on the Earch (GCRS) by the amount evaluated with following equation:

$$dT = \gamma \frac{\vec{\mathbf{V}}_{\mathrm{L}} \cdot d\vec{\mathbf{X}}'}{c^2}. \tag{29}$$

Magnitude of this difference is about 19 ns at maximum in the case of spatial separattion btween two events is Moon radius (1700 km) in direction of Lunar motion, for instance. When two points as subject of time comparison are moving fast, two time systems will have scale difference by an amount of

$$\frac{dT}{dT'} = \gamma \frac{\vec{\mathbf{V}}_{\mathrm{L}} \cdot \vec{\mathbf{V}}_{\mathrm{obs}}}{c^2}. \tag{30}$$

The maximum value of this quantity is evaluated as 4×10^{-11} by using vecolcity of moon ($V_{\mathrm{L}}/c \sim 3.3 \times 10^{-6}$) and case of GPS satellite $V_{\mathrm{GPS}}/c \sim 1.3 \times 10^{-5}$. This reaches 3.5×10^{-10} when counter part is International Space Station (ISS) orbiting 400 km altitude of Earth.

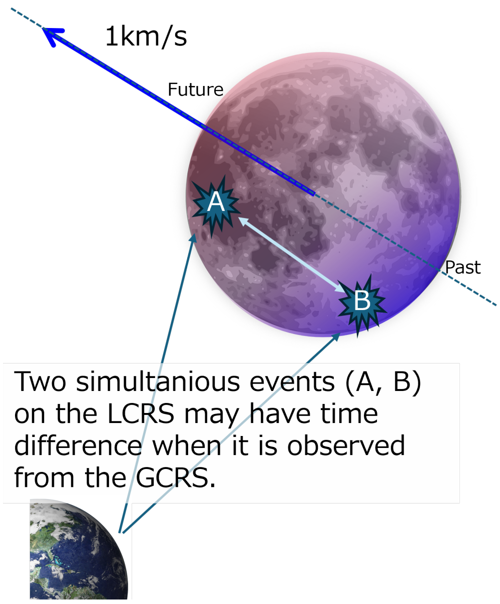

Figure 2: Since the Moon and the Earth move relatively each other, the simultaneity differs, so locations of both sides have to be spcified for synchronizing the time. For example, simultaneous events on the lunar surface (LCRS) separated by a distance of about the radius of the moon will have about 20 ns time difference at maximum in the Earth's coordinate system (GCRS).

5 Pros and cons of Lunar Time options

Below we consider the options proposed by Pascal et al.[1]. The advantages and disadvantages of the three options have already been discussed in [2], and we will review them below.

5.1 Option1

This is the case using the TCL for the Lunar standard time.

Pros

1. TCL is the LCRS coordinate time defined by the IAU[9], so there is no need to define a new time system.
2. Because it is an unscaled coordinate time, physical quantities (length, mass parameters, etc.) are the same as unscaled TCB-compatible and TCG-compatible physical quantities, so there is no need to introduce a new space-time reference system.

Cons

1. An atomic clock placed on the surface of the moon has a rate (frequency) offset of 2μs/day (2.3×10^{-11} s/s) relative to the TCL.
2. Comparing TCL and TT, there is a rate (frequency) offset of about 58μs/day (6.7×10^{-10} s/s).
3. In order to compare and synchronize time between the TT on Earth (including the sky) and the surface of the Moon (including the sky), it is necessary to take into account the difference in special relativity between the coordinate systems that are moving relatively. Therefore comparison of time depends on the location. This point is common to all options.

5.2 Option2

This is the case using TL, which is scaled version of TCL via standard Lunar gravity potential (W_{L0}/c^2) on the surface of Moon. (TL $= (1 - L_L)$TCL)

Pros 1. When an ideal atomic clock is located at the reference potential on the suface of the moon, it ticks as a realization of TL.

Cons 1. Introducing $1 - L_L$ scaling means introducing a new space-time coordinate system with scaled physical quantities (length, mass parameters, etc.)[12].

2. When comparing TL and TT, there is a rate (frequency) offset of approximately 56μs/day (6.5×10^{-10} s/s).
3. In order to compare and synchronize time between the TT on Earth (including the sky) and the surface of the Moon (including the sky), it is necessary to take into account the difference in special relativity between the coordinate systems that are moving relatively. Therefore comparison of time depends on the location. This point is common to all options.

5.3 Option3

This is a case using TL*, which is scaled TCL so that TL*-TT has only veriodic variation ($\langle d\mathrm{TL}^*/d\mathrm{TT}\rangle = 1$).

Pros 1. Since TL* and TT are identical except for the periodic term, TL* can be regarded identical with TT and TDB within an accuracy of less than xxx seconds. Time difference will not grow with elapsed time.

2. Since it has the same time scale as the signals from GNSS satellites on Earth on average, it looks easy to handle.

Cons 1. Relative to an ideal clock placed on the surface of the moon, TL* deviates at a rate of 56 μs/day (6.6×10^{-10} s/s).

2. Introducing the $1 - L_L^*$ scaling means introducing a new space-time coordinate system with scaled physical quantities (length, mass parameters, etc.).
3. In order to compare and synchronize time between the TT on Earth (including the sky) and the surface of the Moon (including the sky), it is necessary to take into account the difference in special relativity between the coordinate systems that are moving relatively. Therefore comparison of time depends on the location. This point is common to all options.

6 Summary

- In the case of Options 2 and 3, a new coordinate system with scaled physical quantities (length, mass parameters, etc.) is introduced. The theoretical treatment of quantities observed in this time system and equations of motion using this time system are complicated to handle.
- For celestial bodies with ocean, such as the Earth, the equipotential surface of the celestial body can be easily defined as the "mean sea level". However, since the Moon does not have ocean, it is difficult to easily define the equipotential surface in a simple manner (disadvantage of Option 2).
- As discussed in the section4, the time simultanity and clock rate difference depend on the position and motion of the comparison targets between Earth and Moon. This is common for all three options, and it is necessary to take into account relativistic space-time coordinate transformation to compare and to synchronize time and frequency with the TT on Earth.

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