A Brief on Lunar Coordinated Time

Philip Linden[1] & Chris Rabotin[2] - April 2024

Implementing Lunar Coordinated Time (LTC) is more complicated than you think. Doing it right means involving all stakeholders—public, private, military, civilian, and commercial—and allowing it to be independent of UTC.

Key points

1. ***LTC is not a time zone, it is a time scale.*** *It will continuously diverge from Coordinated Universal Time (UTC), but they have a relationship that we can predict and use to convert between the time scales.*

2. ***This is not the first time*** *science has defined a time scale outside of Earth's gravity well. Dynamic Barycentric Time (TDB) is defined at the barycentre of the solar system and progresses at a different rate than UTC which varies over time. LTC, too, will deviate from UTC at different rates over time.*

3. ***Including all stakeholders is key*** *to defining an equitable, useful, and lasting timing infrastructure in the cislunar space. Timing is a mission-critical resource for navigation. It's not just the definition of the time scale—the time still needs to be distributed to Lunar actors.*

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Contents

Cooperation Depends on Coordinated Time

The white paper, Possibilities for a Local Lunar Time Standard, expands on this subject, including an examination of past efforts at global coordination and possible implementations to distribute a local time standard to the cislunar ecosystem.

On April 2, 2024, the office of the President of the United States released a statement on their new policy toward time standardization in the context of upcoming Lunar missions with the Artemis program. In the announcement, the office explains the need for a standardized time scale, local to the Moon, that can scale with the future cislunar economy and remain traceable back to Earth time. A fully defined time scale on the Moon enables navigation satellites at the Moon without the need for constant synchronization with Earth systems.

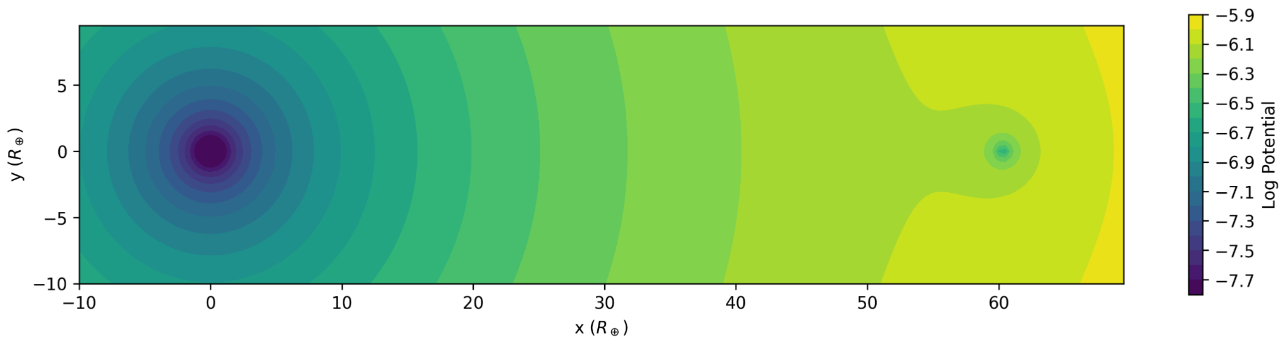
With the USA's declaration of enacting a Lunar Coordinated Time (LTC), the clock is ticking for Lunar consensus in Positioning, Navigation, and Timing (PNT) service architectures.

Celestial time scales aren't new

Astronomers and astrodynamicists already have a time scale for deep space, Barycentric Coordinate Time (TCB). TCB is equivalent to a hypothetical clock that has exactly the same movements as the barycenter of the Solar System, except outside the Solar System gravity well and hence it is not affected by time dilation from gravity. Since TCB isn't affected by gravity, it ticks faster than Earth time by about 490 milliseconds per year.

TCB is converted to Geocentric Coordinate Time with a complex equation that includes the effects of relativity and time dilation. This equation includes intricate mathematical components, such as two integrals, one of which is nested within a derivative. The full equation spans multiple lines and utilizes a significant portion of the alphabet. Despite its complexity, the equation has a closed form and is accurate to 5×10^{-18} seconds.

LTC isn't so lucky. Lunar time must be realized in an area near the Moon, so it has to account for dilation. Lunar trajectory designs account for the gravity of Earth, Moon, Sun, and Jupiter. Since time dilation changes with the gravitational potential, so too must LTC include influences from all of these bodies. And to make matters worse, the potential field is always changing with their orbits!



Time is warped with more intense (more negative) potential, but the potential field anywhere in the Solar System is continuous. This plot only shows the idealized potential field from the Earth-Moon system. The real potential field is lumpy, warped by the Sun and Jupiter (and every other body, at least a little).
Image credit: Original work (code) inspired by Eric Meyers, Visualization of the Cislunar Potential

The future of space activity will be mostly autonomous

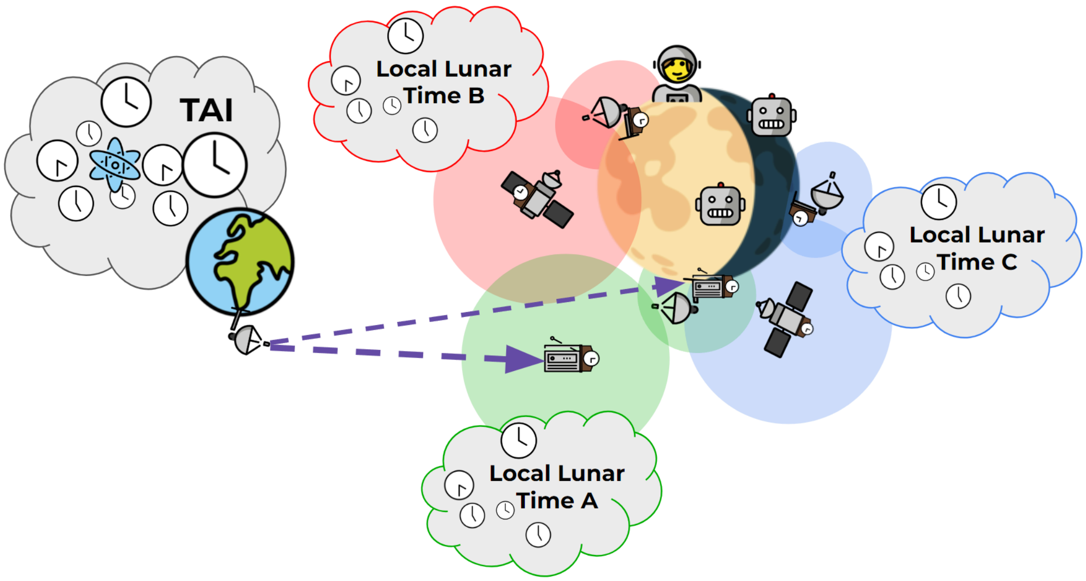
Spacecraft clocks today are routinely re-aligned with Coordinated Universal Time (UTC) regardless of how much time was experienced by the spacecraft itself. This is just fine for historical deep space missions that don't need to coordinate with anywhere but Earth. This is not sustainable for a bustling economy of thousands of spacecraft operating autonomously across the solar system when a message to Earth can take seconds to cross the distance each way. Imagine if every computer on the internet had 1 second of network latency each way—most online applications today would be unusable.

Current spacecraft missions to the Moon synchronize the on-board clocks between the Earth and the Moon. This works fine for short engineering missions because we effectively assume that there is no time difference between the gravity wells. However, if one wanted to perform measurements of the same phenomenon at the same time between an instrument placed on the Moon and one placed on the Earth, then one would need to know exactly at what time each measurement was taken. For this, two options exist:

1. Synchronize the Lunar spacecraft's clock immediately before the measurement is taken. This allows a reasonably accurate approximation that the clock has not drifted enough to impact the scientific data.
2. Define the Lunar time scale in a way that is consistent with physics and the gravity difference between both places. This enables long-term science and engineering activities on the Moon because we will know exactly how to convert the time between one celestial object and another.

Exquisite million-dollar clocks are the norm for GPS satellites today, but projects like Meta's open-source Time Card show that there is a path to nanosecond-precise timekeeping devices for less than $10,000 using commodity components. This kind of technology is already at the basis of new standards for timekeeping in data centres and is maturing rapidly. Commoditized precision time at the nanosecond level could profoundly impact the industry, like how CubeSats transformed the satellite market over the last decade.

It is not unreasonable to imagine the future Solar System is full of “time-spaces” where agreed-upon regions in 3D space have their own local time scale maintained by a subset of the population and commoditized precision clocks. Actual deviations in time can be measured and predicted by physics, so all of these time scales could be converted between each other as needed. Like how UTC zones organize the day for humans on Earth, these interplanetary time spaces would simplify interactions at the local level. This opens the door for local areas in cislunar space to become “neighbourhoods” of activity where local coordination emerges without rigorous planning and coordination between the humans on Earth.



Commoditized precision clocks open the door for local areas in cislunar space to become "neighbourhoods" of activity with their own local time scales.
Image credit: Open Lunar Foundation, *Possibilities for a Local Lunar Time Standard*

Doing it right means involving all stakeholders

Agreeing on the definition of LTC isn't the only obstacle to using it in the field. After it is defined, it must be distributed. Operators of the hundreds of expected Lunar spacecraft will need to share and coordinate this common time reference. This will require establishing time sources, agreeing on communication protocols, and potentially appointing an oversight authority. Clearly, there's a lot to be decided before LTC can be incorporated into Lunar mission designs. In the near term, simply defining the LTC and mandating its use on Lunar missions may be sufficient for most needs. Synchronization of time is crucial for PNT, which would unlock large deployments at the Moon.

The best way to accelerate the implementation of the LTC time standard would be to democratize precision timekeeping among the many missions headed to the Moon in the next two years. Democracy takes time, and time takes democracy.

There are a few examples of standards and missions with plans for serving and sharing time with the cislunar community already. NASA's LunaNet includes a provision for a (to be determined) time standard as part of its protocol, and the European Space Agency's Moonlight project has also been working toward precision timekeeping at the Moon. Multiple or competing time scales would undermine much of the interoperability efforts being proposed today.

Toward a Solar System Internet

Beyond Earth and the Moon, a distinct time scale independent of UTC is absolutely necessary. All spacecraft trajectories rely on another time scale called Dynamic Barycentric Time (TDB) where each second is set to the duration of one second at the centre of the solar system. The TDB time scale is referenced to January 1, 2000, at noon. If this upcoming Lunar Coordinated Time has the same reference epoch, then the time on Earth and the Moon would have approximately drifted by 520 ms between then and 02 April 2024.

As mentioned before, spacecraft clocks have traditionally aligned with UTC, suitable for historical deep space missions coordinating solely with Earth. However, this approach is unsustainable for the emerging economy of autonomous spacecraft across the solar system. Communication delays of seconds or minutes each way make it impractical to continuously synchronize all spacecraft clocks to a distant Earth reference.

This is a solvable problem, and the best solution is very unlikely to involve a homogenous network. Groups like the Internet Society Interplanetary Chapter (IPNSIG) are already thinking about architectures that scale the Internet beyond Earth.

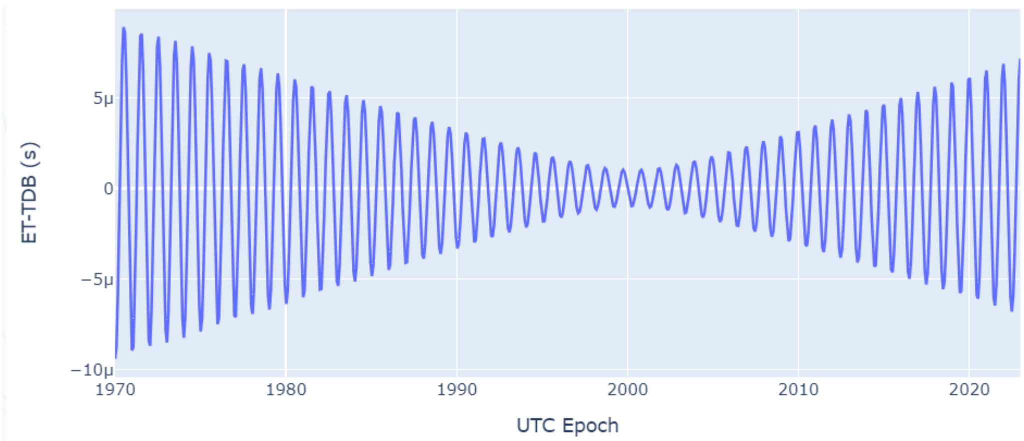
Astronomical Timekeeping for the Impatient

Time *zones* are not time *scales*

LTC is a time scale, not a time zone!

Time zones are for humans to coordinate relative to the local position of the Sun. All time zones use the same time scale, UTC, but with a fixed amount of time added or subtracted based on how many degrees of longitude are between you and UTC, all to make 12:00:00 approximately line up with the moment the Sun is highest in the sky at your location. The internet, on the other hand, mostly operates on UTC because computers don't care if the sun is up or not. All of these times still refer to UTC. One second elapsed for me is the same elapsed duration for you. No matter how much "actual time" has elapsed for a computer according to physics, we update the time so it matches UTC.

Time scales are used to define a given instant at a particular place. Time scales allow us to correct for the gravity difference between the different places where we measure time. The important thing about time scales is that they are defined relative to each other, so any instant can be described in any time scale. It's kind of like converting between Imperial and International units, except instead of multiplying scalar constants, it's a more complicated equation that depends on the instant you put in. For example, an engineer calculating when a signal from Earth will reach a spacecraft in deep space needs to account for the differences due to the spacecraft's clock ticking at the rate of TDB instead of the rate of UTC, in addition to accounting for light time. If that spacecraft was travelling particularly fast, the TCB time scale should be used instead of TDB.



Earth Time (ET) and Dynamic Barycentric Time (TDB) have a complicated situationship. They're just… drifting apart. 😅
Image credit: Nyx Space and Christopher Rabotin.

How much does LTC change compared to UTC? It depends…

Time scales are necessary when it comes to space travel. The presence of gravity warps spacetime. The more warp, or the deeper the gravity well, the slower each second is for that point in space. Remember, the influence of gravity (the amount of spacetime *warpage*) increases with the mass of a body and lessens with distance from it.

The Moon is about 380,000 km away from Earth, so if you measure the total gravity on the Moon (and NASA has done this with the GRAIL mission!), it will be much less than what you'd measure on Earth's surface. High school physics uses balls rolling on hills to describe potential energy. Well, there's a reason why it's called a *gravitational potential field!*

The same idea applies to anywhere else in the Solar System, from Mars to Pluto and beyond. At any point in the Solar System, time might pass faster or slower than what we observe on Earth, depending on how much gravity there is in that spot and how fast the object is moving relative to the observer.

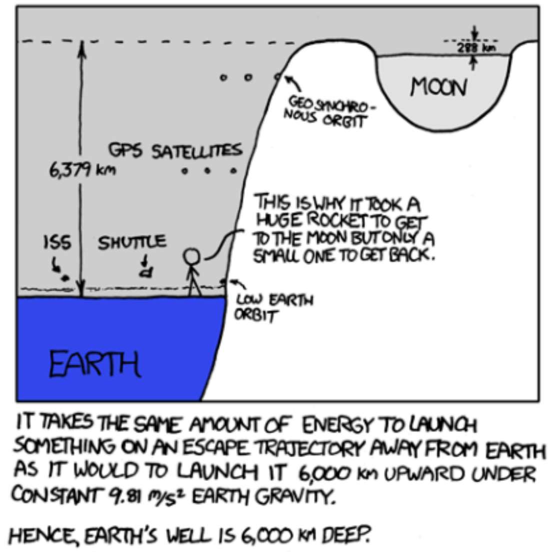
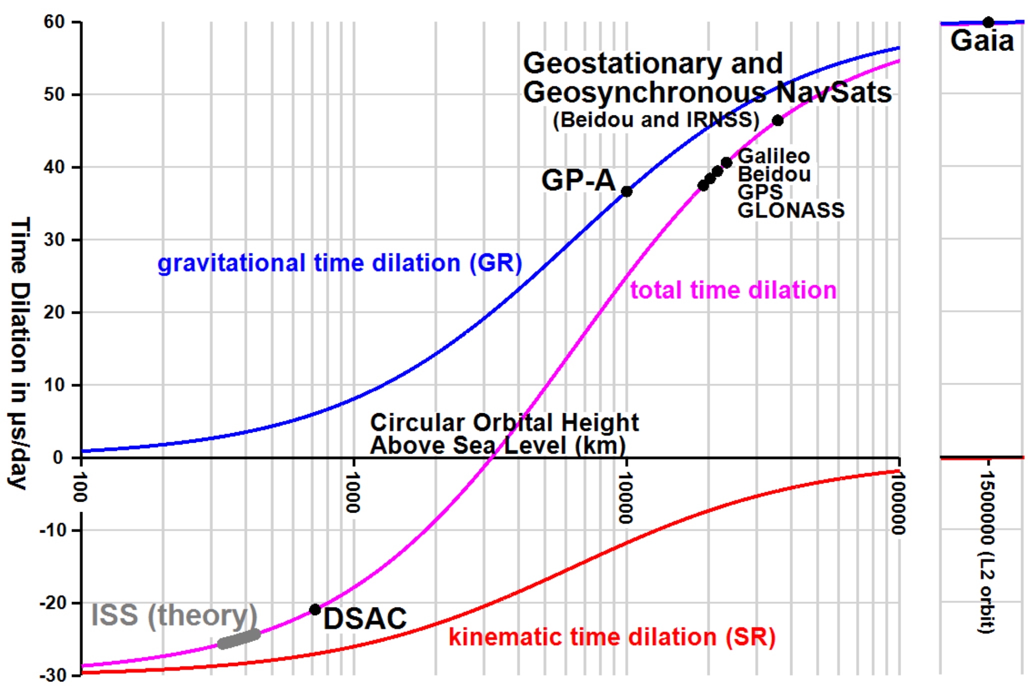


Image credit: xkcd 681: Gravity Wells

Speed also plays a role, but it's trickier. A clock moving relative to an observer appears to be ticking slower than the observer's clock. Weirdly, this works the other way too. From the clock's perspective, the observer's clock slows down. Both are correct! As brain-melting as it seems, this effect is measurable and predicted using special relativity and is enough to consider for cislunar orbits.



While mission-agnostic gravitational time dilation could be mapped out with astrodynamics, kinematic time dilation is subjective to the observer. Image credit: Prokaryotic Caspase Homolog - Own work, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=76468566

Analogies for important concepts

Analogy: phone a friend

Imagine you and a friend are talking on WhatsApp and want to watch a video together. You count to three and press play at the same time. If both of you were on Earth, you might not even notice any delay. If your friend was on the Moon, however, it would be like your friend's video player was stuck in slo-mo. To your Lunar friend, they'd see the video at normal speed, but to them, your video was stuck in fast-forward. That's general relativity at work. The playback speed of your video is your time scale, and your friend's playback speed is their time scale.

Now your little brother wants to watch the video too. He starts watching on another screen in the same room as you. Both of your videos play at 1x speed, but your brother's video started 2 minutes behind yours. The two videos are separated by a constant duration, like a time zone.

Analogy: a race against time

You, me, and a geosynchronous satellite are in a race against each other. The catch is, that no relative motion is allowed between the three contestants. Each contestant has a *perfect* clock at our respective locations. These clocks are programmed to begin at *exactly* the same time and run at *exactly* the same rate. When we check our clocks tomorrow, your clock and my clock will still be in sync. The time readout for the clock on the satellite would read a time around 45 microseconds ahead of our clocks. All of the clocks are correct—this is general relativity at work.

The satellite is pulling ahead, could we still win with special relativity? If we move toward or away from the satellite, its clock will appear to get slower than ours. So to catch up to the satellite's clock with special relativity alone, we'd have to move at... the speed of light times 0.999 999...we'd need a pretty big turbo.

Analogy: frozen assets

Santa Claus has cornered the ice cream market and defends it with a gold-hoarding dragon. His ice cream shop at the North Pole exclusively serves the whole world's demand for ice cream. In this analogy, Santa represents Earth's mission operators and infrastructure, and ice cream cones represent a freshly calculated time relationship between UTC and LTC.

If you want to buy an ice cream cone:

1. you convert your dollars to equivalent ounces of gold,
2. mail the gold to the store,

3. they send a letter back asking what the value of gold was at the time that you sent it,
4. you mail a response,
5. and then they finally mail you your ice cream. Enjoy your milk soup.

If only we could convince Santa to allow remote franchises to make ice cream locally in different regions, or better yet, ice cream trucks for each neighbourhood...