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Possibilities for a Local Lunar Time Standard

Promoting Cooperation and Bootstrapping Early Lunar Operations

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Possibilities for a Local Lunar Time Standard that Promotes Cooperation and Bootstraps Early Lunar Operations

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The establishment of a local lunar time standard or a shared and openly accessible reference timing signal can greatly enhance the positioning, navigation, and timing (PNT) capabilities of lunar missions without the need for direct links to Earth or precision instruments to be a requirement for every mission to the Moon. This paper proposes the concept of a local lunar time standard that can be accessed using technology that is likely to be included in most lunar missions for nominal activities. Even if the local lunar time standard exhibits drift or variations from terrestrial time, its existence would be a significant step towards lunar coordination. Unlike terrestrial synchronized time, a fully usable lunar reference time can be implemented proactively before the activity that necessitates it occurs. This paper discusses the potential benefits and challenges of establishing a local lunar time standard and its implications for lunar missions, including its compatibility with existing lunar initiatives such as LunaNet, Moonlight, and upcoming lunar missions. The proposal highlights the opportunities and considerations for stakeholders in the cislunar ecosystem, including options for missions to ignore, participate in seeding, or consume the proposed timekeeping protocol. The proposal is expected to contribute to the evolving landscape of timekeeping technologies and methods in cislunar space, and stimulate further research and discussion on this topic.

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Painted picture: lunar operations 10+ years from now

It is 2035. Many governments, non-governmental organisations, universities, and commercial ventures own and operate spacecraft in lunar orbit and on the lunar surface. Orbital platforms occupy a variety of trajectories, including Near-Rectilinear Halo Orbits, circular orbits and eccentric orbits, while surface operations are clustered near favourable zones such as the lunar South Pole.

Most local infrastructure systems (navigation, communications networks, resource management, etc.) were overseen carefully by terrestrial human operators at first, then increasingly operated autonomously as machine systems improved. Constituent systems now interact and coordinate autonomously. Humans interface and act amid a broader autonomous ecosystem.

A dynamic network of heterogeneous clock devices autonomously and opportunistically synchronize their time using a decentralized protocol. This protocol allows all clocks in cislunar space to contribute to a single reference time that can then be used for navigation and communications, as well as to update the clocks themselves. As a trusted, neutral time source, this lunar time standard is relied upon for activities ranging from registration to coordination of assets between geopolitical rivals to small CubeSats from emerging space actors who wouldn't otherwise have access to good quality time references.

The protocol is managed by a group of experts representing diverse stakeholder groups that all have an interest in accurate and resilient time sources. Over 100 clocks now participate in the system. This system has become the de facto Lunar Standard Time and is the reference for Cislunar space. It has also become a reference case study regarding equitable governance approaches for shared utilities. Time synchronization and update events are transparent to the entire lunar community.

In an effort to support innovation and university research seeking to operate at the Moon, an academic group developed an open hardware design for a clock that was sufficiently dependable, accurate, and affordable such that they have become commodity devices flown on missions to integrate with the time dissemination network. The devices are also interoperable with dissimilar devices using the common protocol.

Lunar positioning, navigation, and timing (PNT) is made accessible thanks to the commoditized clock devices, and many additional actors participate in the time network, further improving the accuracy of the global lunar reference time. The size, weight, power, accuracy, and cost of interoperable clocks improve as innovators improve upon the open standard and experimental techniques are explored.

PART I: Introduction

In this paper, the characteristics of a common reference timing signal to serve future lunar operations are explored. The history of time standards on Earth is also examined in order to understand the potential impacts and consequences of such a reference time. The goal is to identify a low-cost, transparent approach to the development of a Local Lunar Time Standard.

Motivation

Today, missions beyond Earth orbit receive time-transfer signals over direct links to ground stations on Earth. Spacecraft on the Moon are operated remotely from Earth. There is currently little to no autonomous coordination between actors in cislunar space,[4] so the need for an in situ timekeeping function is still low. But there are a plethora of missions to the Moon planned in the next decade (see *Relationship to Upcoming Missions & Programs*, below), many of which are expected to involve autonomous operations and real-time coordination between activities.

Time transfer to the cislunar environment directly from Earth-bound antennas will not meet the need for clock alignment, the efficiency of access to timing information and commensurate coordination needs required for lunar missions expected to be in operation by 2030 [2]. These missions can reasonably be expected to depend on a time standard and synchronization service local to the lunar environment, without requiring a direct, simultaneous connection between Earth and each participant.

Space-based Positioning, Navigation, and Timing (PNT) systems in Earth orbit known as Global Navigation Satellite Systems (GNSS)[5] have benefited from massive investments and mature space organizations [3]. NASA has demonstrated that it may be feasible to operate a very precise atomic clock in deep space [4]—to the tune of tens of millions of dollars each. It would take significant time and investment to create a GNSS-like network in cislunar orbit. There is an opportunity, however, to incrementally develop PNT infrastructure grown out of the burgeoning lunar ecosystem that demands it.

[4] One example of coordinated operations in lunar orbit is GRAIL, in which a pair of lunar satellites operated in tandem around the Moon to map variations in the lunar gravitational field by measuring relativistic effects on each spacecraft's timekeeping system as they orbited the Moon [1].
[5] Global Navigation Satellite Systems (GNSS) are constellations of satellites that beacon high-precision time signals toward Earth. Commoditized receivers enable low-cost and low-power systems to maintain timing accuracy to UTC with up to nanosecond precision, and ranging accuracy within a few meters. Examples of GNSS networks include GPS (USA), GLONASS (Russia), and BeiDou (China).

A single trusted, shared time source local to the lunar environment is the simplest solution to bridge the gap in PNT services as the lunar ecosystem develops, especially in the near-term. However, a single source is unlikely to meet the needs of all missions simultaneously. Importantly, it would serve as a useful baseline for a local lunar timing service while lunar activities are still nascent.

In the medium- and long-term, a cooperative network of timekeeping devices could offer an agile and affordable approach to supporting an ecosystem of diverse actors in cislunar space. A cooperative network would support incremental improvements while building in elements of transparency and coordination that will be important for long-term stability in the lunar environment. This enables the network to grow and benefit from innovations in technology and CONOPS as the community of lunar operators develops in terms of population, autonomy, and PNT needs.

Lunar timekeeping is a complex and evolving field that requires further research, experimentation, and collaboration among space agencies, researchers, and industry stakeholders to establish a robust and reliable lunar timekeeping framework for future missions.

A local lunar time reference is necessary

PNT is difficult without a precise reference signal for timing [1], [5], [6]. In the absence of a reference system, each operator has to stand up their own approach, either with terrestrial ground station links, intermediate commercial systems or rely on timekeeping devices on board each vehicle. Depending on the capabilities required, these options may involve significant cost and/or engineering expertise to implement. Lack of a shared time source may contribute to misunderstandings, conflict, and difficulty in conducting basic operational coordination necessary for effective lunar activity.[6]

A local lunar time standard, or a shared and openly accessible reference timing signal, bootstraps lunar missions with PNT capability without requiring direct links to Earth or precision instruments. Such a signal would be accessible using technology already likely to be included with most lunar missions for nominal activities. The existence of a shared local time standard would be an important step for lunar coordination, even if it exhibits drift or variations from terrestrial time. Unlike

[6] An example of this can be seen during the First Gulf War, often dubbed the first “space war” due to the reliance of coalition forces on space-based infrastructure like GPS. At the time, the GPS network was not as comprehensive in coverage as today, and the commander of the British Army’s 7th Division noted that his battle group would “get lost” out in the desert for a full fifteen minutes every morning and every evening as the satellite network went out of range [7]. From a military-security perspective, this left them highly vulnerable and could have jeopardized operations. In other contexts, a similar sparse orbital population could see a range of activities put at risk or, at best, become inefficient.

terrestrial synchronized time, there is an opportunity to implement a fully usable lunar reference time *before* the activity that necessitates it occurs.

An open, collaborative approach fosters growth

An open and collaborative time standard sets an important precedent for lunar activity. These traits increase access to and accuracy of PNT as more operators participate and contribute to the time standard, thus rewarding cooperation and transparency. The CubeSat standard, for example, provided an open, albeit imperfect, standard to bootstrap low-cost, experimental satellites in Low Earth Orbit (LEO) when it was first published in 1999 [8]. The standard provided unprecedented access to spacecraft design for new organizations and individuals at the time. With contributions from academia and industry and a decade of iteration and collaboration, the CubeSat standard brought a paradigm shift to the satellite industry and catalysed innovations toward commoditized satellite components and access to low-cost orbital platforms [9], [10]. Likewise, an open lunar time standard has the potential to bootstrap developing lunar activities. The time standard should therefore be implemented as an open standard.

Openness is central to providing a shared common service, like a time standard. International recommendations to design such standards have already taken root at government space agencies.[7] An open time standard would reward adoption and, in the case of a cooperative protocol, would increase access to the service in turn.

Objectives

There is an opportunity to set a positive precedent by establishing a time standard that embodies the following values:

Open to all. The reference time may be used by anyone who follows the protocol.

Apolitical. The reference time and time dissemination system are operated transparently to all clients, especially when the value of the time is adjusted. Certain governments are unlikely to trust or unilaterally rely upon foreign governments' time sources, especially those with geopolitical rivalries. Commercial operators are unlikely to be relied upon by any government unless they are well-resourced and experienced operators, which would likely raise similar issues with foreign governments. Therefore, a local lunar time standard should be coordinated by a neutral third party, much like the Bureau of International Weights and Measures coordinates UTC on Earth.

[7] LunaNet [11], Moonlight [12], and other leading standards for lunar missions are all intended to be interoperable. This follows recommendations published by the international space community.

Reference hardware designs. An open, freely available hardware specification is available for any actor who wishes to contribute to the reference time. This standard is developed and maintained by an independent, apolitical organization. Reference protocol, service, and/or device designs are based on well-understood technologies.

Leverage contributions from distributed sources. The reference time is made up of contributions from many participant nodes. The aggregated reference time is statistically-based, the best estimate derived from many observations from multiple clocks.

The following are envisioned as key characteristics of an open time standard for lunar operations that fulfils these objectives:

- Access to a *shared* time source is more useful than a supremely accurate time source early on. Importantly, it doesn't matter if a shared reference is synced to any other actor, as long as all the participating actors are coordinated.
- Every actor that participates in the network contributes to the source.
    - While community contributions are not necessary to achieve the technical goals of a reference time service, such contribution imbues values such as cooperation and openness that reinforce the system's utility, trust, and longevity. Therefore, this trait is necessary for broad, sustainable, and long-lasting adoption of such a system.
- The entire cooperative network benefits when future missions participate.
    - Early missions likely won't require very accurate timekeeping, but would benefit from access to a time service. Later missions will likely require accurate timekeeping. If the existing accuracy isn't good enough, missions can bring their own clock. When a more precise clock participates in the cooperative network, the stability and accuracy of the entire network improve.
    - More precise clocks could be introduced with additional missions, supporting existing missions by participating in the timekeeping network. This reduces risk by incrementally improving the timekeeping network as it is necessary for future activities, and doesn't lock the network into legacy technology.

The following characteristics of a time standard are relevant to lunar operations, but not necessarily required in order for a local lunar time standard to be effective:

- Synchronizing to an outside reference time, such as UTC,[8] is NOT a requirement for a successful lunar reference time. Actors in lunar space only need to synchronize to a terrestrial time reference if they are coordinating with an Earth-based actor [15].[9]

- The timescale is decimated in a linear scale elapsed from an epoch, *i.e.* an "origin" moment in time, and is NOT organized into buckets of time like days, weeks, months, or years [16], [17].
    - Of course, lunar reference time can be translated into UTC (or any other Earth-based time decimation system) for an equivalent Earth day, hour, or year to describe a given moment. This is commonplace today, with computer systems converting between UTC and Unix Epoch time.
    - It may be useful for some lunar missions to keep track of the lunar synodic day (time for the sun to reach the same position in the local sky) or lunar sidereal year (time for the Moon to return to the same spot in the solar system reference frame, *i.e.* stars returning to the same position in the local sky). Neither of these time frames bears importance to lunar operations en masse, especially with missions that transit between the Earth and the Moon.[10]
    - Using a continuous timescale also avoids problems that may occur due to "leap seconds" or "rollover" events [2], [18].[11]

Relationship to Upcoming Missions & Programs

The proposal for lunar timekeeping, including the approaches mentioned such as LunaNet, Moonlight, and upcoming technology demonstration missions, especially spacecraft with precision navigation or communications capabilities, will likely be

[8] Coordinated Universal Time (UTC) is based on International Atomic Time (TAI), but it is adjusted by leap seconds to account for the difference between the definition of the second and the rotation of Earth [13]. Distinctions between these timescales are not relevant to the discussion presented in this paper, but it is useful to understand the relationship between the timescales used for deep space missions throughout history [14].

[9] Practically speaking, it is very likely that lunar actors will want to coordinate with earth actors. This is not an inherent requirement to use a local lunar standard time, however. In other words, the *ability to synchronize* with UTC or another timescale is more important than actually *being synchronized* to a terrestrial reference time [2].

[10] Missions that operate on Mars typically count the number of synodic Martian days, or Sols, since operations are dictated by the available solar energy. The same premise can be applied to lunar missions. Importantly, the lunar reference time is just a moment in time that can be agreed upon, so it is not necessary to encode information about the day/night cycle in the measurement. If the lunar synodic or sidereal is needed for a mission, it can be derived from the lunar reference time using a calendar designed for this purpose.

[11] These are examples of "jumps" present in some timescales that lead to discontinuities in the reported time, usually to align a timescale like UTC to the observed solar time on Earth. This practice has fallen out of favor in recent years because of problems that commonly arise from such discontinuities in modern networks and computer systems [19].

influenced by the wider ecosystem of capabilities that are being developed in cislunar space.

As the ecosystem matures, there may be opportunities for integration, competition, and interoperability among different timekeeping technologies and protocols. For example, LunaNet and Moonlight initiatives could potentially collaborate or compete in providing timekeeping services and may offer complementary or competing capabilities for lunar positioning, navigation, and timing in the overall timekeeping framework.

The involvement and input from relevant entities involved in lunar missions and their interests will be important in understanding how the proposal for lunar timekeeping may be received and adopted. Incentives for missions to participate in the proposed timekeeping protocol, such as benefits in terms of accuracy, reliability, interoperability, or cost savings, may influence their decision to adopt or support the proposed approach.

Options for missions in the ecosystem may include ignoring the proposed timekeeping protocol, actively participating in seeding and developing the protocol, or simply consuming the services provided by the protocol. The adoption and evolution of the proposed timekeeping framework will depend on a variety of factors, including stakeholder interests, technological advancements, regulatory frameworks, and market dynamics in the cislunar ecosystem.

Overall, the proposal for lunar timekeeping will likely be influenced by the wider ecosystem of capabilities that are being developed in cislunar space, and the approach may need to evolve and adapt as the ecosystem matures and stakeholders navigate the landscape of incentives, options, and opportunities presented by the evolving cislunar ecosystem.

PART II: Benefits of Synchronized and Standardized Time Local to the Moon

Synchronized and standardized time has been historically driven by the need to broaden and better facilitate economic and social interactions, security, and transparency. In the short term, it helps facilitate the growth of economic and social activity "at scale" while in the longer term, it is fundamental to create communities at scale through the provision of a shared point of reference.

In the case of the Moon, a standardized time utilized by all interested actors would:

> **Over the short term,** provide safety and security through a common point of reference not subject to misinterpretation that could be highly valuable in an environment where landing sites and points of interests are comparatively limited, and interests and operations steadily increasing from a myriad of stakeholders.
>
> **Over the long term,** help those actors with semi-permanent or persistent missions on the Moon (crewed or uncrewed) operate more effectively with regard to one another. Especially at a point in time when adherence and respect to conceptions like safety zones is an unknown quantity between major competing stakeholders.

Need and Benefits of Local Lunar Time

From a socio-political perspective, the flow of time is not actually a concept which is experienced universally in the same way by all peoples and geographies. Its telling is mediated and represented by different types of clocks and calendars, whose reach is determined by socially constructed institutions and protocols, and the agreement or at least acquiescence of those affected [20].

For this reason, the expansion of a standardized time on earth synchronized between key actors was both driven by and also facilitating an increasingly connected globe.

A major step towards this was the 1884 International Prime Meridian Conference hosted by the US, in Washington DC and attended by twenty-six countries, which at the time were all the major political and economic powers. The aim was to establish a Prime Meridian to standardize time and longitude, from which the rest of the world could synchronize [21].

The reason for this, in the words of Britain's delegate, was to "secure the greatest convenience of the whole civilized world" [22]. Whilst this is steeped in the rhetoric of the time, what it meant to the delegates in practice, was the wish by all parties to secure a standardized international time to facilitate and support more effective development in four key areas. This earth-based context, as shall be highlighted, is directly relevant to the developing lunar environment.

Economy

At the 1884 conference, it was noted that the "exactness of time reckoning is an imperative necessity in the conduct of business" [22]. Economic activity was made more efficient, or even—over larger distances—facilitated by a shared framework of time. Meetings and other communications could be arranged, and transactions and deliveries scheduled with accuracy.

In a lunar context, while economic activity is nascent and will be minimal for some time yet, it is firmly on the agenda for most lunar-interested actors [23]–[25]. Establishing a shared sense of time between actors could alleviate a multitude of problems which might occur in what is a physically hostile, capital-intensive, and highly risky environment, and so aid in its start-up. For instance, it could ensure efficiency and transparency surrounding where actors are operating. With comparatively (for the foreseeable future) limited landing sites and points of interest [26], and an increasingly competitive political and economic environment both globally [27] and in regard to the Moon itself [28]. Being able to broadcast accurate time and positioning information to state or private sector actors in a way that does not cause confusion, when a mission is taking place (both in terms of time and GNSS) and what it is doing at a given time is all the more important to avoid misunderstandings or issues.

An example of the difficulty of not having a transparent, shared, and synchronized time basis can be found in the Antarctic, where in 2020 a Russian fishing vessel was alleged, to the Commission for the Conservation of Antarctic Marine Living Resources, by New Zealand to be operating in a zone that had been "closed" for the fishing season. Russia claimed that New Zealand had got the location data (which is derived from time signals via GNSS systems) wrong, and offered up its own interpretation (which it refused to share publicly). Both sides escalated, stating the other had doctored the evidence [29].

Attempting to head off such risks in the short term for the lunar environment through a neutral standardized and synchronized time would aid in establishing a stable and sustainable commercial environment before stakeholders have become established and invested in heterogeneous systems, making them more reluctant to cooperate with other systems. Indeed, longer term, it could help stave off the inefficiencies that medieval merchants faced with the existence of "city time"—this being where individual local authorities had their own conceptions of time (and based regulations around them) which then external stakeholders had to adapt to separately [30].

Society

The “common good of mankind” was a persistent reference from all delegates [22] at the Prime Meridian Conference. This means that a synchronized and universally-agreed reference of time could facilitate the national and international activity of all manner far more efficiently, and indeed make it possible for connectivity over truly global distances. While a fully-fledged lunar society remains a far-distant aim for many lunar stakeholders, establishing a framework now would likely prove more politically expedient. Especially as time can prove to potentially be a heavily politicized concept wielded by authorities to create a sense of national or community cohesion and identity— as, for example, Beijing and Delhi have done by basing their nations' time on that in the capital, despite spanning multiple timezones. [31].

In the more immediate term, a standardized and synchronized lunar time system would help inter-lunar communications between different missions on the lunar surface; i.e. between any semi-permanently crewed Artemis team in the 2030s and Chinese equivalent through a common frame of reference [32], [33].

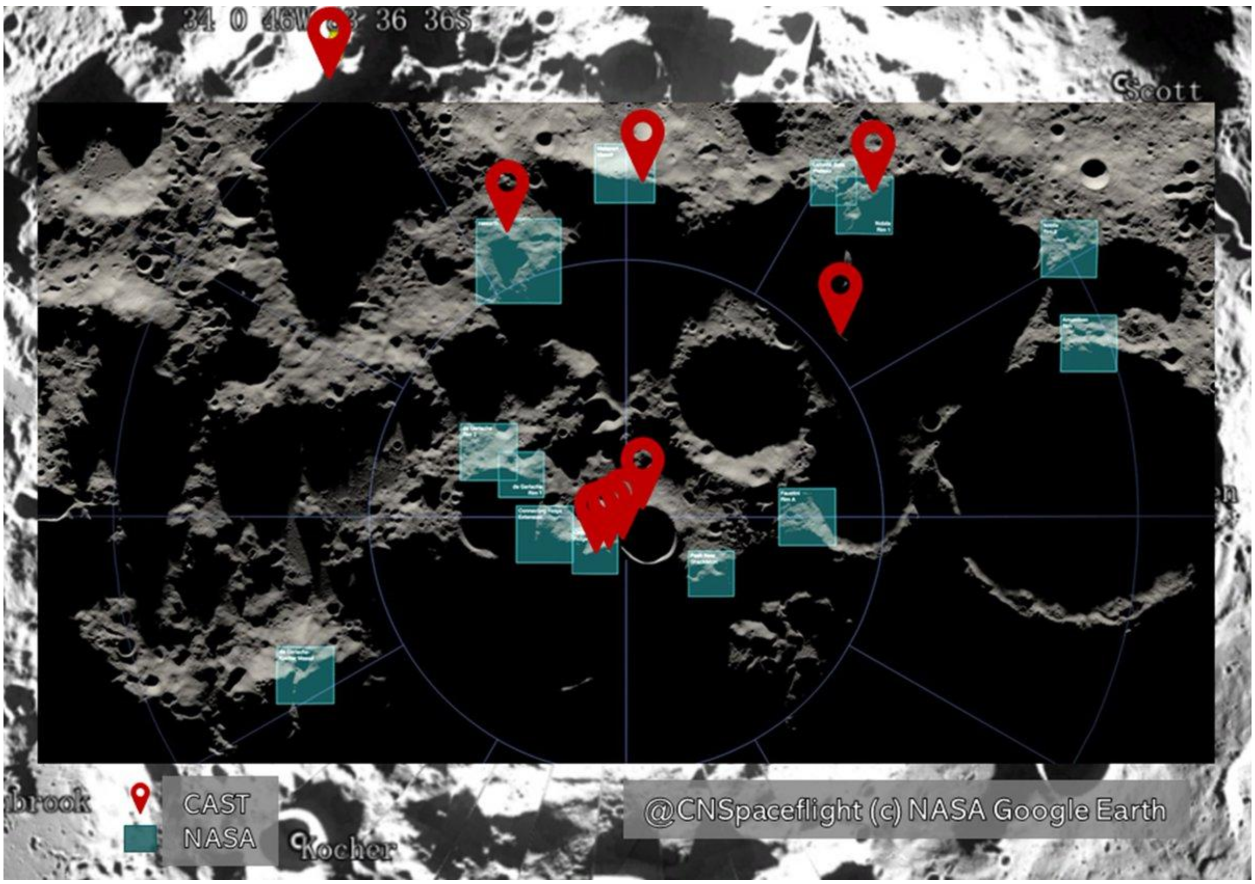
Security

The British delegate at the 1884 Meridian Conference noted that as technology shrank the globe, and humanity became an ever-closer-knit community, while great progress, cooperation, and positive activities were facilitated, there were “evils” to that also “must greatly increase rather than be lessened” [22]. These evils are two-fold;

Firstly the direct issues, inconveniences, and dangers of an interconnected world having different conceptions of time; for instance, as seen in the 1851 New England train crash, in which 14 died due to the two trains’ conductors having aligned their clocks with differing local times [34].

In the foreseeable future on the Moon, there is a slight, though increasingly real, political and operational risk that Actors X and Y have long-term crewed or uncrewed missions operating near the same point of interest (courtesy of the comparatively limited landing zones and areas of interest such as at the lunar South Pole) [35]. Actor X is an Artemis Accord Signatory, and so claims a safety zone. Actor Y is not a signatory but follows a similar practice of utilizing a zone of operations as a safety and/or regulatory measure. Actor X courtesy of the NASA clarification wants to make sure that it respects the zone of Actor Y in that area [26], and also that Actor Y respects its safety zone, lest the legitimacy of the Artemis Accords be pulled into question (if enforcement is lax, the Accords are just paper). A lot of political capital is at stake with significant spill-back potential on Earth, not to mention the operational safety implications at play. A shared and synchronized time reference utilized by both Actors will avoid misunderstandings and difficulties—both politically (as in the example mentioned previously of Russia's 2020 Antarctic fishing vessel) and from an operational safety perspective.

Such a scenario indeed may not be too distant into the future. Already, there is a growing potential for mission overlap regarding lunar areas of interest for the US' Artemis Programme and China's counterpart [36];



Blue squares are candidate locations for the Artemis Program's operations at the lunar South Pole. Red marks are those proposed by CAST scientists. Data and image courtesy of CNSpaceflight, 22 August 2022 [37].

Secondly, as the British delegate at the Prime Meridian Conference also references, the difficulties that not having a shared sense of time (and so place) can lead to politics between nations and actors on a wider scale; for example, a common source of tension between states was over claims and borders [38].

The 1967 Outer Space Treaty's Article II expressly forbids the sovereign claiming of celestial bodies, and while we would not suggest that a lunar time standard should or would be used for contravening this, it can help defuse potential disagreements over a safety zone or operating area through reference to a standardized time of who is there when, and who "found" the point of interest first (which can play a role in de-escalating disputes between actors over which should be allowed to operate in a given area). For example, a major part of legitimizing the ownership of a claim was the date, and often time it was "discovered". For example; In the Antarctic, the lack of an indigenous population and its incredibly hostile environment (a context shared by the lunar environment) meant that the typical means of legitimizing a territorial claim, such as being recognized as a new authority by those currently occupying the land, physically colonizing the area, or setting up the economic, political, and security infrastructure to exert pressure in defence of that claim were impossible [39]. As such, "discovery" was given a lot of weight legally and politically to compensate by several significant claimants [40]; and the point of discovery was disputed due to a lack of permanent markers [41]. Britain, France, the US, and Russia particularly did not recognize one another's claims, leading from the late 19th century until 1959 to a growing geopolitical competition over the Antarctic and rising tensions. Including, despite its unknown and disputed strategic and economic value-shots being fired, and military assets deployed [42]–[44].

With such precedents in mind at the time, and from competition elsewhere, an agreed framework for a synchronized and standardized lunar time could be an important tool, especially looking towards a future where already "the application of science to the means of locomotion and to the instantaneous transmission of thought and speech have gradually contracted space and annihilated distance" [22]. In this context, being able to accurately reference political events or safety zones could mean a key difference between escalation and mediation.

Governance

An underlying concern at the conference was that a standardized framework was required to allow states to police and government at national and international levels effectively the above three categories of activities, but also there was a recognition that a splintering of the world into contradictory time frameworks would be very damaging for international cooperation, peace, and prosperity.

This is the same for the Moon. In our current moment of geopolitical competition, the threat that the lunar environment becomes a new frontier for competition rather than cooperation, much like the Arctic and Antarctic have become. Despite being internationally or multilaterally governed, and pegged as areas of successful cooperation, competition is starting to change them away from this [45]. It is important, then, that any pragmatic, low-hanging fruits of cooperation are established sooner rather than later. Indeed, the 1884 conference expressly aimed to "[throw] aside national preferences and inclinations" in pursuit of getting consensus regarding a standardized time. This was maintained, and the delegations agreed that Greenwich should be recommended as the prime meridian— courtesy of it already being utilized as such by 65% of global shipping, compared to 10% for its nearest competitor, Paris [22]. This was against the backdrop of increasing global imperial competition between these very powers at the time over territory, resources, "national honour", prestige, and security. A very similar context to the geopolitical competition we are facing now; particularly between the US and China [46], and their space-related rivalries [28].

Pragmatic steps, such as a standardized time, are low-hanging fruit for cooperation to form. Certainly, it provides a basis to mitigate somewhat the political and security difficulties that may arise. This is arguably needed at a time when making binding multilateral treaties regarding space and the Moon seems an impossibility due to their politicization [47]. Establishing a standardized and universally utilized lunar time system has, at this point in time, much to commend it.

Challenges for Local Lunar Time

Delaying the consideration of a shared lunar time standard will make it even more difficult to achieve this low-hanging, pragmatic fruit for cooperation, as actors invest in their own frameworks. This would compound several issues that already need to be overcome in the near future.

Astropolitical Competition

While a standard and synchronized lunar time holds the potential to be a key and easily accepted tool of international cooperation, both in its forming and in its mitigation of aforementioned political, security, and economic risk, it must be recognized that we are already in a "post-ISS" era [48], both physically but also astropolitically. The globe, much like during the 1884 Meridian Conference, is experiencing a period of increasing multipolar geopolitical competition which has spilled over into the politicization of most international spheres such as supply chains, and legally binding treaties [49]. While in 1884 this environment was overcome due to the pragmatism and clear advantage to all actors in having global time, this cannot simply be taken for granted as happening again; history often rhymes, but never repeats. Certainly, in what should be other low-hanging regulatory fruit, such as agreeing to ban kinetic anti-satellite weaponry whose use could damage the infrastructure of friend, foe, and neutral parties alike, no real progress has been made as China and the US refuse to compromise from their respective propositions [50], [51].

Establishing a shared lunar time system then requires more than simply passively waiting for stakeholders to deem it useful. There needs to be a clear conversation surrounding potential systems (as this paper provides), and ideally, a politically neutral push towards getting either, major stakeholders interested, or, providing for a grassroots adoption by smaller actors and commercial enterprises.

Interestingly, it is during this period of astropolitical competition that there might be an advantage for NGOs and other politically neutral actors in pushing for alternative governance frameworks. While competition potentially prevents actors from compromising and forging cooperative agreements between themselves as easily as might be hoped, as in the case of the Anti-satellite (ASAT) negotiations, this does provide space for democratization of space and lunar governance. Where state actors might be, for a variety of interest-related reasons, unable to compromise, non-government and "neutral" parties have greater leeway and potential support in offering a way forward that might be taken seriously by competing state actors to break the deadlock in a way that both sides may want, but neither can accept directly from the other.

Reluctance to Participate

Not all actors will wish to give up the advantages that a flexible approach to timekeeping may provide—for instance, in being a way of giving up control, and self-reliance regarding data fundamental to politically-charged incidents, such as with the 2020 Russian fishing vessel [29]. Here, the accusation by Russia that New Zealand "fiddled" with the GPS data to make them look bad provided a degree of deniability, while also interestingly providing an "off-ramp" potentially for further escalation regarding the incident as it was a denial that, perhaps in a different circumstance where more is at stake, one side would like to accept and could publicly present. An accurate and universal conception of time-shared by all parties, however, might make even "implausible deniability" just plain implausible—removing an element of the escalatory "off-ramp" from actors. As such, maintaining this degree of political freedom might be deemed more important for now, by actors engaged in astropolitical competition.

Likewise, state actors may be attached to their own time systems that are wielded to help foster a sense of shared national or community identity [52] and national pride.

Prominent states like China continue to adopt this approach, despite the drawbacks it presents from a social and economic perspective [31].

In these contexts, the approach to mitigation will need to be considered on a case-by-case approach and the concerns of all lunar stakeholders acknowledged.

PART III: Essential Characteristics

Assumptions

Lunar operations are still nascent, and many dimensions of the trade space for developing a useful time standard are nebulous or unknown. This paper identifies several reasonable assumptions to set up a lens for analysing this topic.

Lunar actors are willing and able to communicate with each other

Lunar activities planned today ubiquitously have telecommunications as an aspect to nominal operations. A direct telecommunications link to Earth is not trivial, however, so we shall assume that surface-to-orbit or intersat links are possible, but a direct link to Earth might not be feasible. Interacting with a time standard should therefore piggyback upon these existing transmitters and/or receivers sized for lunar-orbit-to-lunar-orbit or lunar-surface-to-lunar-orbit telecommunications.

We assume that actors are willing and able to communicate with the service that operates the time standard. The design of the time standard should encourage this!

A time reference does not need to be an observation of nature

It would be best to have a stable clock signal that was universally observable and independently verifiable. A commonly observable natural phenomenon at the heart of the time standard would be ideal, but it's not a necessary element of a useful service for early lunar operations.

- PNT needs a time signal that is stable in the short term. Even a clock derived from observations of natural phenomena needs to include a local oscillator in order to keep the time between observations of the external source.
- Users of the time standard interact with it the same way, regardless of the true frequency source that the time standard is based on. The origin of the frequency source does not change the protocol for how time is shared between nodes. Coordination requires a time signal that is shared between actors.

A locally hosted oscillator could be just as trustworthy as an external, observable source for a spacecraft. For example, the internationally maintained TAI time standard is composed of measurements from many certified oscillators—most of the constituent clocks that comprise TAI don't observe natural or extrasolar phenomena [53]. As another example, UTC is itself a so-called "paper clock"—there is no physical clock or oscillator that is a single instantiation of UTC. Instead, individual time laboratories steer their clocks to an estimate of where UTC is going to be, and the International Bureau of Weights and Measures (BIPM) takes all the individual time lab contributions, applies a weighted algorithm to the contributions, then publishes the difference between each lab and UTC on a regular basis [54].

Lunar communications network topology is inherently dynamic

Unlike most terrestrial networks, where clients and servers are joined over long distances by a well-established infrastructure of wired and wireless connections, the topology of nearly all lunar networks will be inherently dynamic and evolving over time. Not only is there no existing communications infrastructure on the Moon, but all planned lunar telecommunications architectures are based on long-range, wireless surface-to-orbit or orbit-to-orbit links, and many missions with relatively short lifespans [55], [56].

Whether a server or client is in orbit or on the lunar surface, its communications system has coverage limits to its transmission and reception fields of view/fields of regard. Entire regions of orbital and surface selenography[12] may be partitioned from other members of the network, especially early on.

An agile approach to lunar operations in the near term must account for the expectation of most missions having a short mission life. Technology is still being developed, and new technology often has performance issues with reliability and/or ageing. Further, new technologies will continue to push the ecosystem forward and break new ground. Going from no infrastructure to a developing ecosystem will inherently involve diverse hardware and have frequent turnover as missions come and go—in terms of coverage and operating life. On the other hand, this can be an opportunity to constantly improve the time source itself [57].

Timekeeping accuracy must be within tens of nanoseconds

All navigation algorithms are grounded on the basis of events happening over time, which means that timekeeping accuracy impacts nearly every other aspect of PNT calculations. For this reason, the lunar reference clock must have excellent long-term

[12] We define *selenography* as a general term for areas on and around the Moon, similar to how the word *geography* is used to describe regions on Earth.

stability. The reference clock does not need to "tick" every nanosecond, but every "tick" (once per second, for example) must remain consistent on the order of tens of nanoseconds for a long period of time.

Space missions typically require timing accuracy ranging from microseconds (10^{-6} s) to nanoseconds (10^{-9} s) for communications, precise navigation, and other activities [2]. Therefore, a useful reference clock should maintain timing accuracy of at *least* 1.2×10^{-5} PPM (about 1 microsecond error per Earth-day).[13, 14]

Suitable Timekeeping Technologies

It is important to thoroughly evaluate the accuracy, stability, reliability, and suitability of different timekeeping technologies based on the specific needs and constraints of the cislunar space mission for positioning, navigation, and timing purposes. Additionally, considering factors such as mission duration, cost, and availability of resources will also play a crucial role in selecting the best technology for timekeeping in cislunar space.

Oscillators suitable for deep space

The best technology for timekeeping in cislunar space, which includes the region between the Earth and the Moon, for the purpose of positioning, navigation, and timing (PNT) depends on various factors such as accuracy requirements, mission objectives, and available resources. Some potential options to consider are:

Deep Space Atomic Clock (DSAC): DSAC is considered to be the best option for a singular time source due to its high accuracy and stability. It is capable of providing precise timing information for PNT applications in cislunar space.

Chip-Scale Atomic Clock (CSAC): CSAC is known for its long-term stability and can be a suitable option for timekeeping in cislunar space. It offers good accuracy and can be utilized in missions that require reliable timekeeping over extended durations.

Rubidium Atomic Frequency Standard (RAFS): RAFS is another option for timekeeping in cislunar space. While it may be considered overrated by some, it can still provide accurate timing information for certain mission requirements.

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[13] Some napkin maths: the precision needed to maintain 1 μs of error between communications with terrestrial operators, conservatively assuming 1 communication session per Earth-day, translates to an error of ~1.2×10^{-5} parts-per-million (PPM).
[14] For example, 1 microsecond (10^{-6} s) of timing error for a craft in polar orbit around the Moon such as the Lunar Reconnaissance Orbiter (LRO) travelling at 1600 m/s [58] corresponds to an accumulation of about 1 mm of position error per second. At this rate, LRO's estimated position could drift by more than 7 meters after just one orbit!

Using Multiple Clocks on a Single Board: To reduce risk and improve resilience, employing multiple clocks on a single board can be considered. This approach can enhance redundancy and reliability in timekeeping systems for cislunar space missions. Time laboratories on Earth are often made up of ensembles of clocks—frequently caesium and hydrogen maser, or caesium and rubidium [59]–[62]—that are complementary. A time system that incorporates observations from a variety of timekeeping devices and technologies, some with better short-term stability and others with better long-term stability, might keep a more accurate time overall compared to a single clock.

These technologies and more are discussed further in the *Timekeeping technologies & methods* section of the Appendix.

Suitable time transfer protocols

There are various time transfer protocols available, such as Precision Time Protocol (PTP), which offers nanosecond-level synchronization. Further research is needed to determine the best protocol for specific mission requirements.

These and other time transfer protocols are discussed further in the *Time transfer protocols* section of the Appendix.

PART IV: Possible Implementations

Today, nearly all[15] lunar PNT occurs by sending time-transfer messages from Earth over direct links or simply not at all. Consider a concept of operations where an actor needs to perform PNT activities while it is transiting across the far side of the Moon. There are no precision time sources local to lunar space today designed to disseminate time to peers, so each new mission must maintain its own clock to a high degree of precision or rely on DSN.

Relegating the duty of timekeeping to each individual actor or to time-transfer from direct links to Earth is not sustainable to support widespread lunar activities [63], [64]. Although GNSS or GNSS-like signals could be detected on the Moon and used for PNT in limited circumstances [65], the utility of GNSS diminishes greatly at the Moon due to the geometry at play. On Earth or in LEO, GNSS satellites are widely separated across a user's field of regard and provide accurate PNT service. At lunar distances, however, GNSS satellites have very narrow angular separation, hindering the timing and positioning accuracy of GNSS signals for users in cislunar space [66].

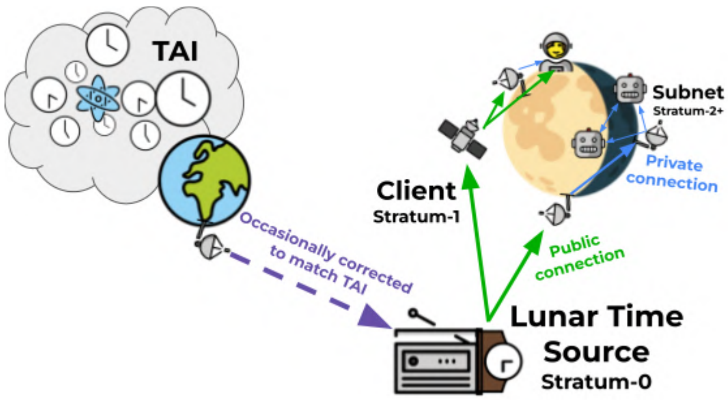
It is clear that a time service local to cislunar space is needed for PNT, but what would it need to do in order to independently and apolitically maintain a local lunar reference time?

Part IV presents four possible implementations of a local lunar reference time, in order of ascending complexity. Open questions are identified for elements of each option presented.

Option 0: Singular Time Source

As a baseline, consider a single time source (clock) deployed to the lunar environment by a specific lunar operator.

[15] One recent example of a lunar mission that does *not* use direct time transfer from DSN is CAPSTONE, a technology demonstrator specifically designed to explore this situation [5].



A singular time source is deployed in a south pole-focused orbit. It is orbital rather than ground based to provide visibility to the most users. It is in a south pole focused orbit to target the concentration of lunar activities planned for that region. The clock operates according to an open protocol. Missions operating in the South Pole environment would be able to use it. The clock's host spacecraft occasionally communicates with an independent operator on Earth to send and receive commands/telemetry, and updates the time to synchronize with TAI.

The orbit for a single time source could be a polar circular orbit or perhaps a highly elliptical orbit like a near-rectilinear halo orbit—the optimal orbit depends on a number of specific mission parameters, and is itself fertile territory for future research [67]–[69].

The main advantage to this kind of architecture is that it could be implemented today with existing technologies and protocols, since this paradigm is likely to lead to many distinct subnets that terminate at the reference time source, much like modern terrestrial networks. On the other hand, operating a single time source loses out on the opportunity to disseminate risks among an ensemble of devices and instrument technologies.

Design trades have an outsized impact

Access to the system is the main limiting factor—it may not be feasible to access the time source from every mission profile. Thus, every design trade has a significant impact on the utility of the time source.

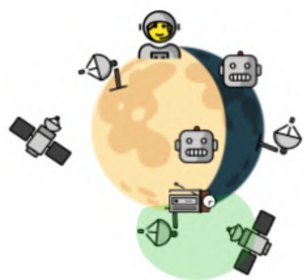
Like cell phone coverage on Earth, there is a trade-off in access between connecting to a signal transmitted located on the surface versus one in orbit. On the Moon, where there is no existing infrastructure, it is not obvious whether a surface-based or orbital time source is best suited to serve missions in the lunar environment.

The choice of location also impacts the clock's technical performance. The local gravity in cislunar space is not uniform. These non-uniformities lead to relativistic effects that speed up or slow down the time of a clock with respect to an observer on

Earth, even with an ideal clock [70]. While relativistic effects are still significant on the surface of the Moon, it is easier to correct for them because the clock wouldn't be moving across the Moon's gravity field and the local gravity would be consistent.

Surface Node

Although the vast majority of lunar surface activity will be localized to a reasonably small area [71], a single time source on the lunar surface would have a limited range of service. Even at the poles, access to an orbiting time source is limited, depending on the orbit [67]–[69].

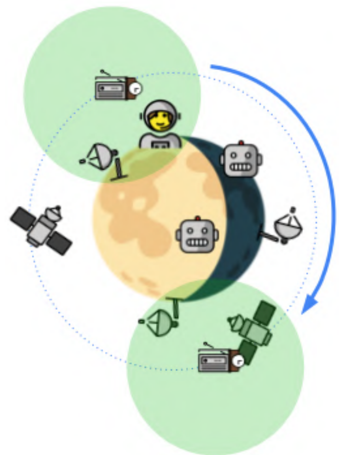


Access to a surface-based time source requires line-of-sight, leaving faraway surface activities out of luck. Orbiting clients may still have access, depending on their orbit. Therefore, choosing an optimal location of the node is critical to its usefulness.

Power availability and maintaining the temperature of components in their operating range is of paramount concern for any spacecraft. Lunar synodic day, or the time it takes for the Sun to return to the same spot in the local sky, is 2,551,443 seconds (29.5 Earth-days) long. A surface-based lunar spacecraft must be equipped to continue operation in complete darkness during a lunar night, when temperatures can reach -130 °C, for nearly two Earth-weeks on end. Surviving the lunar night is anything trivial, but not an impossible task for a system designed for such extreme environments [72]–[74].

Orbital Node

An orbital time source would provide access to the most users, thanks to broad visibility of the lunar surface from above. An orbiting time source is more prone to relativistic effects degrading the time accuracy because it is travelling at high speeds and transiting through gravity fields. The power and thermal environment is not as extreme, since an orbit can be selected where the spacecraft spends just a few hours in lunar eclipse per orbit.



Access to an orbiting time source also requires line-of-sight, however the node covers more areas as it transits around the Moon. The drawback is that access is consequently intermittent for most clients.

A single time source or a sparse population of orbital nodes may lead to intermittent coverage. Orbiting time sources would always have periods of blackout as the spacecraft goes behind the Moon. This may or may not be of concern, depending on the activities and orbital period: there are many South Pole orbits which could provide revisit times well within desired update frequencies [69].

Open Questions

- What is the optimal location for a single-source time standard?
- What signal transmission power is required from the source (or the sensitivity of the receiver at the client) to supply a reliable timing signal?[16]

Technically and politically fragile

In a centralized architecture, the responsibility of maintaining the time service falls upon the operator(s) of constituent nodes. In order to maintain the values of independence, apoliticalness, and being in the best interest of all, the time service operator must embody these values and be held accountable to them.

A single source would present a single point of failure to dependent systems, meaning its design would need to be robust and expensive (if not immediately superseded by constellation designs).

Certain governments are unlikely to trust or unilaterally rely upon foreign governments' time sources, especially those with geopolitical rivalries. Commercial operators are unlikely to be relied upon by any government unless they are well

[16] The system requirements here vary with system designs: distance to target and beam spread determine required power/sensitivity—remember, a signal's power is spread over its cross-sectional area.

resourced and experienced operators, which would likely raise similar issues with foreign governments. In this regard, a single centralized source would be difficult to achieve international trust and reliance.

Open Questions

- How is confidence in its reliability established? What happens if this service goes away?
- Who controls this service? What jurisdiction are they associated with?
- Who pays for this spacecraft, and how would they recoup their costs?

Fragility increases at scale

In a dynamic network topology like we expect to find among lunar actors, this architecture is likely to become fragile at scale. As more missions with specialized or unique needs and profiles seek access to the time source, the more likely it is that the established single-source time standard is insufficient. In addition, demand for the time is anticipated to grow over time, but the clock's hardware performance is expected to degrade with age.

Two-way time transfer[17] presents a vulnerability wherein a surge in demand floods the service with connections or requests, causing it to fail [75]. This failure mode could arise as a result of usage exceeding the designed capacity of the system or from an intentional DDoS attack.

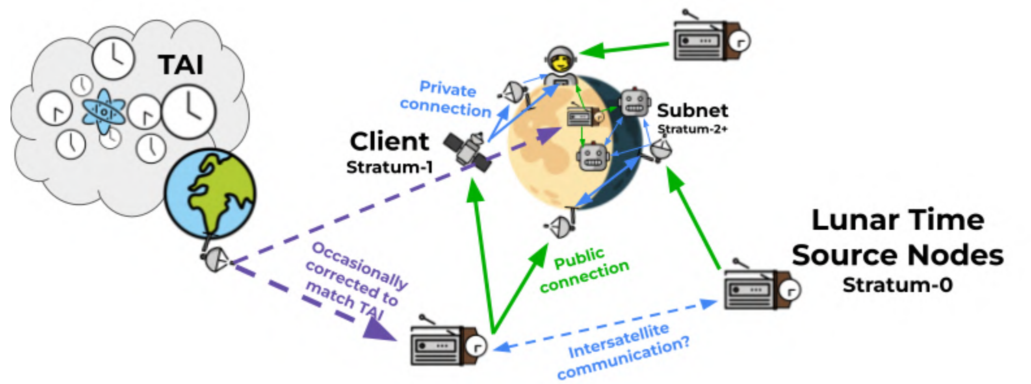
Open Questions

- What if a group of actors cannot resolve a path to the standard?
- How many clients is too many?

Option 1: Centrally Controlled Network of Time Sources

Consider a fleet of reference clocks, akin to Option 0, deployed by a single operator in many lunar orbits and/or surface locations. Using many time sources extends the reach/accessibility of the centralized time service by providing a structured pathway for any actor to synchronize to the clocks belonging to that service.

[17] One-way and two-way time transfer are explained in the *Impact of time transfer approach on host architectures* section of the Appendix.



Many time sources are deployed in a variety of orbits, and to surface locations that provide visibility to regions that see high levels of activity. All the clocks operate according to an open protocol. The clocks' host spacecraft occasionally communicate with an independent operator on Earth to send and receive commands/telemetry, and update the time to synchronize with TAI. Each clock is operated as an independent time source.

Since this paradigm is an extension of *Option 0*, it shares the advantage of being feasible to build with existing technology and protocols. Further, a *constellation* of time sources addresses key weaknesses to a single-source approach:

- Instead of needing to *trade* mission requirements for a one-size-fits-all solution, multiple time sources can be operated, with each tailored to a different area of the trade space.
- The system is more resilient to failures, since a client is more likely to have multiple time sources available to choose from. This has the secondary benefit of relaxing mission reliability constraints for the operator of the time sources.
- Accuracy and reliability of the system can improve over time. As new time sources are developed, additional nodes using the latest technology can be added to the system (and older or poor-performing time sources can be phased out).

A centralized service needs a dedicated operator

A centralized system places the investment/effort load of maintaining the time standard solely on the operator.[18] This means growth and performance of the time standard is proportional to the level of investments from the operator, which are sure to not scale in the same manner as the number of potential clients demanding services. The business model for such a service is unclear: even if you charged for the time service, it is doubtful you could actually recoup mission costs—unless a major

[18] While the time service itself is not decentralized in this paradigm, the operator could be.

government funds such a mission. Even so, funding for major missions is extremely competitive, and there are plenty of other concepts being advanced. More so, Artemis program and mission funding itself is uncertain in outyears.

Similarly, a centralized time service does not encourage cooperation between actors. If the open time service is inaccurate or unstable, influential organizations (like government space agencies or large commercial operators) would prefer to build their own closed networks. There is little incentive for an operator that has invested in expensive and superior timekeeping technology to contribute to a centralized time service infrastructure in ways that benefit other users.

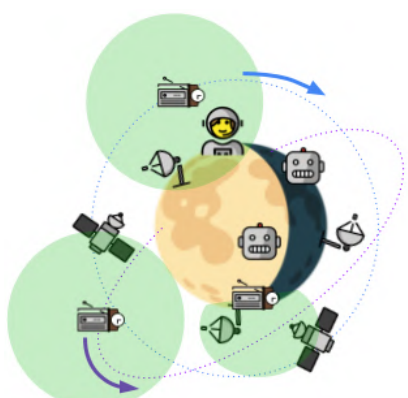
Open Questions

- How is confidence in its reliability established? What happens if this service goes away?
- Who controls this service? What jurisdiction are they associated with?
- Who pays for this service, and how would they recoup their costs?

The optimal number of nodes is unclear

Adding more nodes in the time service network would lead to increased access to the service by a wider variety of mission profiles.

Moreover, the resilience of multi-satellite fleet operations has been demonstrated time and again by Earth-orbit constellations [76], and similar benefits would be expected from a fleet of many time sources.



The benefits of a time utility really emerge in force when there are multiple nodes, but more nodes means more complexity and cost for the operator.

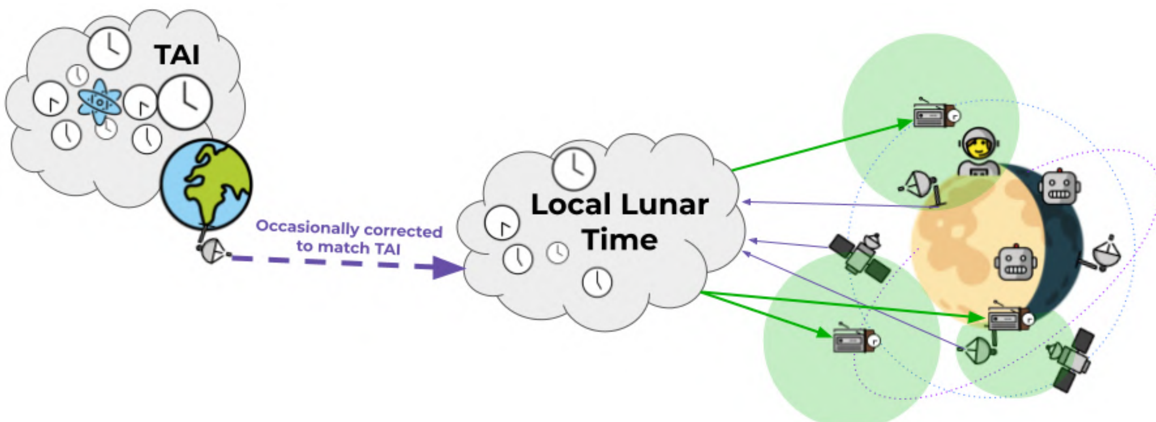
A single node might be sufficient at first, but it is essential to organize the system in a manner that lends itself to easily scale to include many server nodes in addition to many client nodes to prepare the system for growth.

Open Questions

- What is the optimal number and distribution of nodes? How does this change as the lunar ecosystem evolves?
- What is the trade-off between access and cost/complexity associated with operating a fleet of many time sources?

Option 2: Time Sourced from Community Contributions

Helping to distribute the time is only one aspect of cooperative participation in a community time service. Nodes can also contribute their time source to be used to derive the reference time itself, similar to how many clocks contribute to TAI on Earth [53], [62].[19] The adoption and accuracy of a time utility depends on how member contributions to the reference scale as more participants join the network.



Many time sources are deployed in a variety of orbits, and to surface locations that provide visibility to regions that see high levels of activity. The clocks' host spacecraft are independently operated and maintained as independent time sources.

All the clocks operate according to an open protocol. The time signal from each clock is provided to an apolitical steward, which estimates the average local lunar time from all participating clocks. This reference time is used as the "true" time by participating time sources. Community contributions to the time standard set the foundation for an open and diverse time service that is resilient to bad-faith actors and improves alongside development of lunar activities.

Adopting a time standard that is sourced from peers lifts this burden from a single operator. Implementing an open clock design as a specification or turnkey component using standard hardware and software interfaces would catalyse this even further. Like the CubeSat Standard, operators may choose to design and build

[19] While TAI does use contributions from many sources, BIPM has technical prerequisites for a time lab to participate [77]. Participation in the lunar time standard may be a useful incentive for actors to participate in an information sharing program like registries proposed by Open Lunar Foundation [78].

custom clocks completely anew or based on an open reference design that meets the timing contribution criteria [9].

Averaging

With multiple nodes keeping the time, the local lunar time can be averaged across all nodes for more stable network time. Simply averaging the time across the entire population weighs the contribution of every clock equally. If a contributor introduces a more accurate clock, every participant benefits. The caveat to a true average is that there should be a minimum acceptable clock accuracy to prevent the time standard from degrading below the required level.

When the time sources are operated by a diverse community, the accuracy and stability of contributing clocks is sure to vary. A Kalman filter could be used to incorporate this variety of sources into a "best estimate" for a common lunar reference time that would in turn be asserted to all the clock nodes. The Kalman filter attributes more influence over the estimate to sources with more accuracy and/or more stability, making the estimate robust to underperforming sources [79]. For decades, the time from trusted clock operators has been combined in this way to maintain TAI as a global time basis [53].

Voting

Consider instead a voting system in which nodes reach a common time by voting toward a given time value, and each node's influence is proportional to their respective accuracy or contributions to the standard. The local time would be determined by reaching a distributed consensus [80], [81]. This is especially important when considering a stratified or delegate-based topology.

A democratic paradigm invites collaboration because more accurate clocks would have more influence over the time standard. Relating voting influence to participation encourages actors to engage with the time standard in ways that improve the time standard itself. As actors compete for influence by introducing better clocks, the overall accuracy of the time service improves and every participant benefits.

Decentralized governance is an active field of study and a diverse ecosystem of Decentralized Autonomous Organizations (DAOs) are already experimenting with governance models based upon web3 infrastructures [82], [83]. A public registry of contributions to the time standard is critical for establishing trust in a collaborative environment among actors that may not be on friendly terms [84].

Open Questions

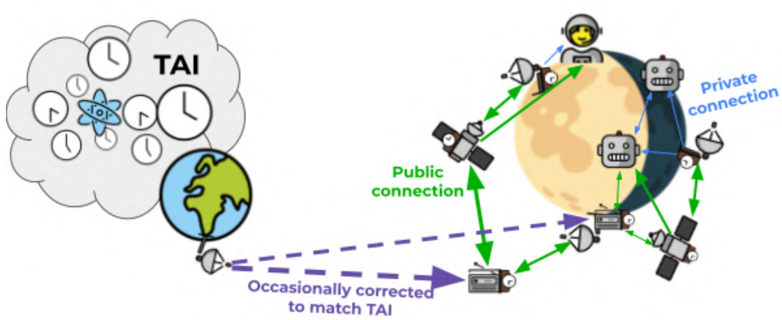
- How do clients retrieve the standard time? Is this approach compatible with *Option 0* or *Option 1*?

- Who controls this service? What jurisdiction are they associated with?
- How do community members contribute? What measures are needed to prevent abuse or misuse

Option 3: Decentralized Time Between Peers

A decentralized approach invites collaboration and encourages openness—the time standard itself would embody the desired values for an open, independent lunar time discussed in *Part I*. This concept is the most complex and unorthodox of the presented implementation options, but most closely exhibits these values.

Consider a network of heterogeneous time sources where no single time source designated as the reference time, nor is there a steward who maintains the "true" local lunar time. Instead, all lunar actors use an open protocol to determine a shared common time between them [85]–[87]. With this approach, there is no "global" lunar reference time—rather, each area of activity maintains a synchronized, shared, and coordinated time reference derived from the open time synchronization protocol.



The local lunar time emerges as the shared timing signal used by many actors coordinating in an area. Some nodes in the local environment may be occasionally synchronized to TAI or other external time sources. Over time, the shared local time in an area converges to a stable timing signal.

The common paradigm of operating distinct subnets that terminate at a time reference would still be possible, as long as one member of the subnet interfaces with others outside the subnet, but would not contribute to the success of the service as a whole and is not in the spirit of a decentralized service. In a dynamic environment, it may be more beneficial for secondary nodes to also (re)distribute the time, rather than waiting for more subnet infrastructure to be established.

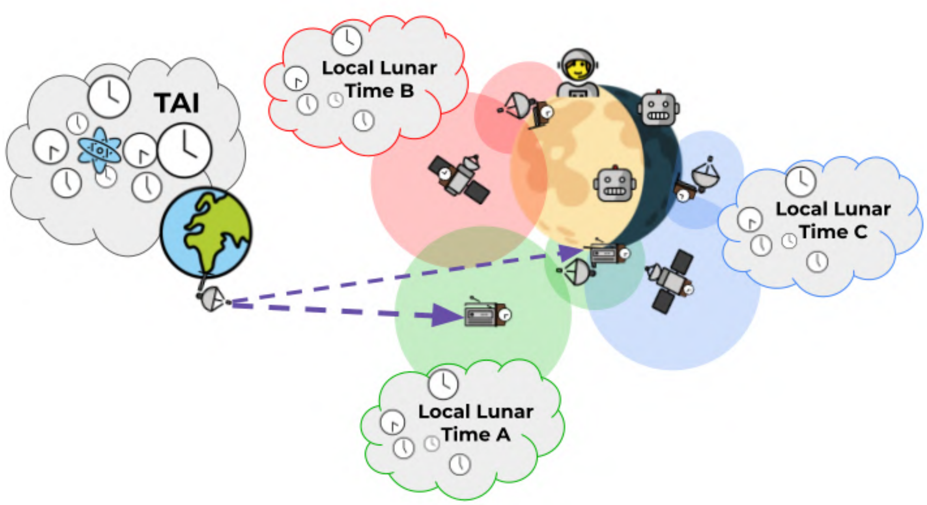
As more actors participate, the stability of timing synchronization is expected to improve. As adoption increases, access to a nearby time source and overall timing stability would increase in turn [88]. On the other hand, such a system might be very unstable and inaccurate until a critical level of adoption is reached—with mass adoption, however, it may prove to be even more resilient than a centralized service.

Open Questions

- Is it necessary to have a "global" lunar time reference? Could dynamic local lunar "time zones" be manageable?
- What is the critical level of adoption above which this approach becomes stable and accurate in the long-term?
- Will actors be willing to synchronize their time with anonymous or antagonist nodes? How resilient is this approach to abuse or misuse?

Proximity-Based Synchronization

In a proximity-based decentralized model, nodes adjust their oscillation phase to match the phase of neighbouring nodes. Eventually, the wider population becomes synchronized since all constituent nodes are coupled [85], [86], [89]–[94].



Clocks adjust frequency to match its neighbours, little by little. Actors close to each other will be more tightly synchronized as compared to actors far away.

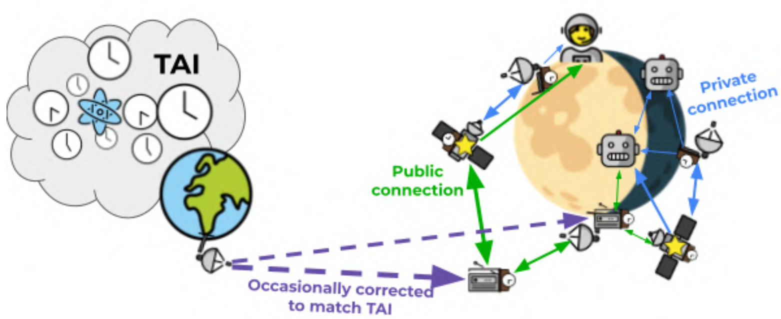
Under the Kuramoto model, neighbouring oscillators "nudge" each other toward the average between them and the phase of each member in the population eventually converges to be synchronous [95]. The drawback is that this topology is very loosely grounded to a reference time, if at all, because it is only concerned with peers synchronizing to each other. Synchronization between distant clusters is weak. While two distant members may not be exactly in phase, neighbouring members will be tightly coupled—this could be sufficient for coordinated PNT in localized areas [88].

Open Questions

- What are the minimum communication requirements for a node to participate? Would every member be expected to support intersatellite links?

Local Synchronization Clusters with Delegates

Consider a modified proximity-based approach, where at least one member of a local node cluster is delegated to occasionally synchronized with distant peers or reference times. The local cluster would synchronize to the "barycentric centre" time between them [96]–[98]. The delegate node would attempt to keep the cluster synchronized to an external source to prevent the cluster from deviating too far from the "global" reference [92].



Nodes in proximity adjust their phase to match their neighbours, and some "delegate" nodes in the local cluster reach out to other clusters to synchronize with their respective delegates.

This model is useful to establish a diverse cooperative network of potentially antagonistic actors because it allows a group of actors to channel inter-cluster communications through a special peer, perhaps one with increased encryption capability. Distributed consensus algorithms are often used in cloud computing to achieve similar objectives [99]. Unlike cloud computing infrastructure, however, nodes in the lunar network are subject to relativistic effects from gravity and orbital speeds [100].

Open Questions

- What are the minimum communication requirements for a node to be a member of a cluster? A delegate?
- How are delegates selected or designated? A vote from the cluster? Pick the node with the best communications capability

PART V: Conclusion

In conclusion, lunar timekeeping is a critical aspect of positioning, navigation, and timing in cislunar space. Establishing a local lunar time standard is necessary to ensure accurate and reliable timekeeping for future lunar missions. However, determining the best approach for lunar timekeeping is not clear-cut and requires further research and experimentation.

The paper proposes the establishment of a local lunar time standard that can be accessed using technology likely to be included in most lunar missions. This local lunar time standard would not require direct links to Earth or precision instruments, and its existence could significantly enhance the positioning, navigation, and timing capabilities of lunar missions. Unlike terrestrial synchronized time, a local lunar time standard can be implemented proactively before the activity that necessitates it occurs. This proactive implementation would enable lunar coordination and enhance the capabilities of lunar missions without waiting for specific activities to trigger the need for timekeeping.

There are several potential approaches to lunar timekeeping, including establishing a reference specification for a reliable timekeeping device, implementing a centrally managed source or network of sources for time synchronization, or developing a protocol for distributing time among peers in a distributed network. Each approach has its advantages and challenges, and finding the optimal solution requires careful consideration of various factors, such as accuracy, resilience, interoperability, and scalability. In selecting an approach, one must take into account the opportunities and considerations for stakeholders in the cislunar ecosystem, including options for missions to ignore, participate in seeding, or consume the proposed timekeeping protocol.

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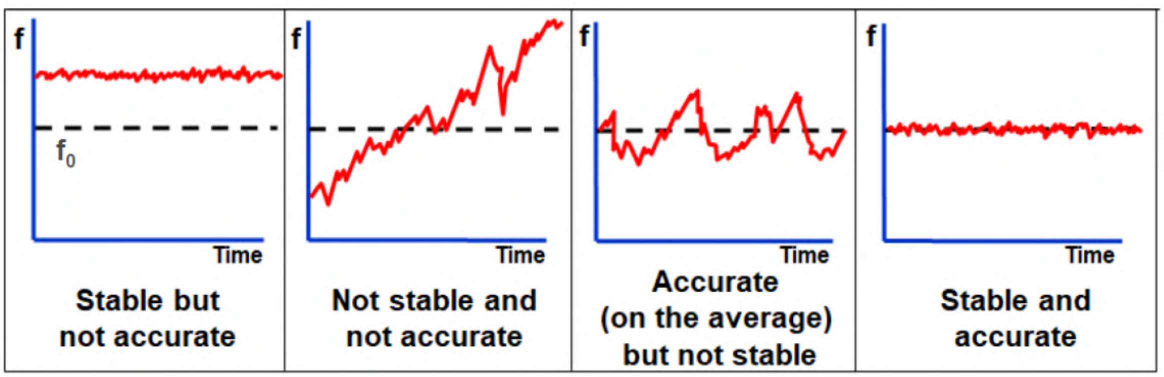
APPENDIX

Terminology

A *time standard* or *reference time* is basically a clock that serves as a common reference to many actors. A *clock* observes a frequency signal and monotonically counts intervals as they occur. Accuracy has an instantaneous error component (*phase offset*), deviation in the separation between pulses, and an integrated error component (*drift*), or the accumulated separation between two timing signals. Clocks in space also tend to drift due to relativistic effects that become significant at orbital speeds and long distances between objects in cislunar space [70]. *Stability* is a measure of the signal's variation from the ideal. International Atomic Time (TAI), Coordinated Universal Time (UTC), and Unix Epoch Time are examples of common time standards used today.



Example of signal accuracy versus stability [101].

Time standards have the special role of being a shared reference for situations where observations or information packets are time-critical, such as in telecommunications, time-transfer, and ranging. Actors (machines, people, computers, etc.) must share a common understanding of the time in order to coordinate time-critical actions, often by synchronizing their clocks to one another and/or a common standard time.

Time transfer is the term used to describe the process of multiple actors coordinating to use a shared timing frequency. In a *one-way* time transfer system, one actor communicates its time to another. In a *two-way* time transfer system, the two peers will both transmit, and will also receive each other's messages, thus performing two one-way time transfers to determine the difference between the remote clock and the local clock [15].

A *protocol* is a method by which actors interact to agree on the time. A *node* is a clock that shares the time with other clocks. The network *topology*, or the arrangement of connections between nodes, is shaped by the protocol. Choosing a time synchronization protocol and network topology that best serves all participants is pivotal to bootstrapping open, cooperative, and agile timekeeping services in the lunar environment.

Network time-server hierarchy as a baseline model

Typical network time is stratified by how far removed a clock is from the “true” time.

We can look to internet time-servers as a model for how time is distributed in a network of devices. A time-server in a time-transfer system typically consists of different strata, or layers, that represent the hierarchy of time sources and their reliability. These strata are commonly referred to as Stratum-0, Stratum-1, Stratum-2, and so on, with Stratum-0 being the most accurate and reliable source of time and higher strata representing lower levels of accuracy and reliability.

Stratum-0 is the topmost layer in the time-server hierarchy and represents the most accurate and reliable source of time. It typically consists of atomic clocks or other highly precise timekeeping devices that generate a reference time signal. These devices are directly connected to a primary reference time source, such as a national time standard or a GPS satellite, and provide a highly accurate and stable reference for timekeeping.

Stratum-1 represents the second layer in the time-server hierarchy and consists of servers that synchronize their time with one or more Stratum-0 sources. These servers act as primary time-servers and are commonly used as reference time sources for other devices and systems. Stratum-1 servers typically use precision timekeeping methods to synchronize their time with the Stratum-0 sources with little-to-no delay. *Stratum-1* time appliances are precision devices with synchronized to *Stratum-0* clocks Time servers like `pool.ntp.org` are *Stratum-1* time appliances [102].

Stratum-2 (and higher) represent(s) the next layer(s) in the time-server hierarchy and consists of servers that synchronize their time with one or more servers at the Stratum above. These servers act as secondary time-servers and are used as time sources for devices and systems that do not have direct access to Stratum-0 or Stratum-1 sources. Stratum-2 servers rely on Stratum-1 servers for time synchronization and may introduce additional network latency or errors in timekeeping. There can be higher strata in the time-server hierarchy, such as Stratum-3, Stratum-4, and so on, which represent lower levels of accuracy and reliability. These servers synchronize their time with higher-level stratum servers and may introduce further delays or errors in timekeeping.

Timekeeping technologies & methods

There are many timekeeping instruments and methods that could potentially serve as the basis for a lunar time standard. Comparisons between them must navigate a treacherous trade space composed of stability, cost, complexity, size, mass, power, sensitivities to disturbances, and more. Below, we identify the characteristics and potential implementations of existing timekeeping technologies that could be used beyond Earth orbit.

Listening to existing signals

All deep space missions today have their clocks synchronized to terrestrial time standards by asserting it with commands sent directly to the spacecraft. For satellites without precise onboard timekeeping, PNT operations can be performed by remotely tracking a spacecraft's position and velocity and then sending commands or instruction sets, accounting for the communication delay. Between asserted time synchronizations, these spacecraft keep time using a local oscillator.

There are few instances where synchronous activities are performed by multiple deep-space actors, so this is usually an acceptable approach. This method is not viable for synchronous activities between autonomous actors where a link to Earth is not always available.

Asserting the time directly from Earth

Earth is home to the most precise clocks known to humanity. The reference time can be regularly updated on a lunar spacecraft with the Earth's reference time. Time transfer can be performed any time a lunar spacecraft establishes a communication link to a terrestrial ground station. Time-transfer with a communications link requires consent from all parties involved.

Direct links to cislunar spacecraft are not trivial to accomplish [4], [5]. The sheer distance from Earth to the Moon requires a significant amount of power and/or pointing accuracy to deliver messages across the divide, not to mention relativistic interactions between Earth's gravity field and the Moon's gravity field (neither of which are uniform), and actors travelling at thousands of meters per second. Both ends of the link (spacecraft and ground station) must contend with these challenges.

The main communications system today capable of time transfer to missions outside Earth orbit is NASA's Deep Space Network [2], [103], [104], which is already saturated with demand [105]. Even with additional resources invested in terrestrial networks with the express purpose of communication with lunar missions [106], a time transfer umbilical to Earth will likely inhibit the growth of an autonomous lunar ecosystem.

Catching GNSS signals that "missed" Earth

GNSS satellites are in medium Earth Orbit. The "shadow" of those signals may be detectable or even usable from lunar orbit [63]. GNSS is widely held to be the de facto Stratum-0 time source for terrestrial applications, including satellites orbiting Earth, but even GNSS-disciplined clocks must contend with environmental sources of error [107]."shadow"

If a spacecraft in cislunar space could detect GNSS signals, it could use them for clock synchronization in the same manner as satellites in Earth orbit [108]. These signals are beaconed "in the blind" and can be observed and used by the public.

Access to GNSS signals has not yet been tested in cislunar space, but experiments to use GNSS for lunar PNT are included in upcoming missions [12], [109]. Since all GNSS constellations continuously orient their transmitters toward Earth, Earth often gets in the way. There is a relatively strong signal that propagates to the side of GNSS transmissions, called "side lobes" that are also detectable on the Moon. The GNSS signals that do make it to the Moon are likely hard to detect thanks to the inverse-square law.

Supposing that all GNSS signals are measurable at the Moon, the position and timing accuracy derived from these signals is diminished further due to the narrow angular separation between GNSS sources in a lunar user's field of view [66].

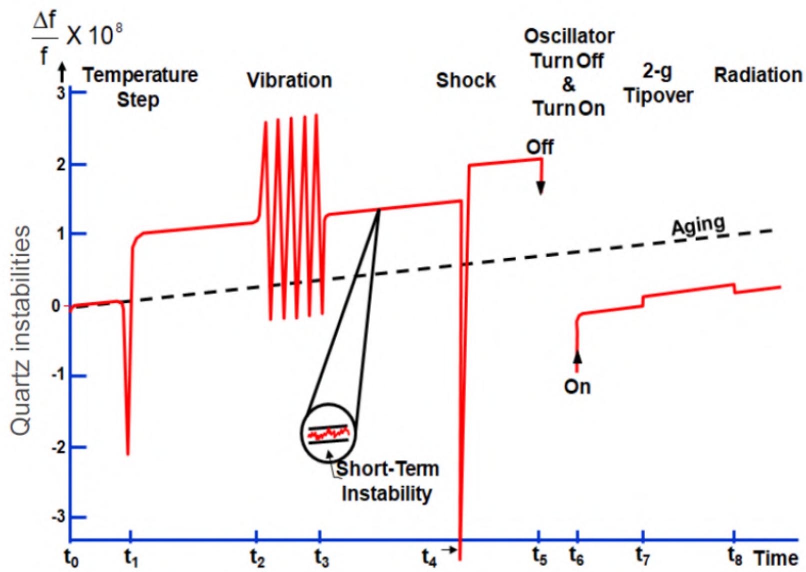
Using a local oscillator ("clock")

A local oscillator is a self-contained device that emits a signal of a measurable frequency, where each oscillation is quantized into "ticks." By counting how many ticks have elapsed, you can keep time—as long as you know the length of each tick. No oscillator is perfect, and errors accumulate over time as drift. A local oscillator can only be observed by its host, and sharing the time is up to the host's discretion.

Crystal Oscillator

Crystal oscillators are the timing basis for nearly all modern digital electronics [110]. They have excellent short-term accuracy, but are vulnerable to drift and usually require regular syncing with a "time reference" that is known to have greater precision.

Crystal oscillators are prone to drift as a function of temperature and ageing. More advanced clocks, called Temperature-Compensated Crystal Oscillators (TCXOs), include a temperature sensor and feedback control loop that adjusts the input voltage to the crystal to compensate for temperature-dependent frequency variations to keep the output stable, independent of the local environment's temperature.



The accuracy of quartz oscillators is affected by the environment and component ageing but is generally stable within tens of microseconds [101].

Radiation-tolerant TCXOs designed for use in space applications are commercially available [111]. A free-running high-precision oven-controlled quartz oscillator can drift at a rate of about 0.5 PPM unless disciplined by GPS; a common quartz wristwatch may drift at a rate of 2.75 PPM [112].

Rubidium Atomic Frequency Standard (RAFS)

GPS satellites are highly regarded for their timekeeping precision and stability [113], [114]. Fortunately, their clocks are commercially available—at a price (thousands to millions of dollars) [115]–[118].

Plug and play rubidium-based chip scale atomic clock, originally developed for GNSS satellites. Works just like a CSAC, because it is one. However, RAFS are usually orders of magnitude more expensive and heavier than a typical CSAC due to extensive measures taken to make the device resilient in a space environment and validate its performance against strict standards [119].

RAFS oscillators require more power to operate than TCXOs and are generally less stable in the short-term, but have excellent long-term stability and accuracy over time [114], [120].

Deep Space Atomic Clock (DSAC)

A quartz crystal oscillator is connected to a feedback control loop that locks the output frequency to the atomic resonance of the ion used in the instrument. This “trapped ion” technique is very, very stable because it uses a special method to isolate the resonator from outside disturbances [4], [121].

Trapped ion clocks (like DSAC) electromagnetically constrain atoms to mitigate interactions between the atoms and the confinement chamber's walls. The ultra-stable Local Oscillator or LO is a mechanical oscillator such as a quartz crystal, used as a reference for a synthesizer, which generates the 40.5 GHz ion resonance interrogation frequency. Ion measurements described in the text determine the error in this frequency and feed this back as a correction to either the LO or a user output synthesizer. In this way, the user output frequency is locked to the ion resonance.

Big, complicated, power-hungry, and built as a one-off—but it is exceptionally precise and accurate, even in deep space [122]. At least one future deep space mission will use an evolution of DSAC for PNT [123].

Chip Scale Atomic Clock (CSAC)

A quartz crystal oscillator is connected to a feedback control loop that locks the output frequency to the atomic resonance of the ion used in the instrument [101]. The whole device with supporting electronics fits in the palm of one's hand.

Commercially available CSAC devices are not as accurate as DSAC or RAFS, but probably “good enough” for most space missions and much less expensive [115], [124].

Watching celestial objects

There are periodic signals that originate outside the solar system. A time standard derived from observations of these signals would be independently verifiable and inherently apolitical—a tempting proposition, but one that proves to be as technically difficult as it is philosophically agreeable.

Sundial

A flat plate or prism with a special, calibrated orientation to the sun.

The geometric relationship between the Sun and Moon is periodic. Use the shadow of projected sunlight to trace the progression of time as the shadow of a calibrated geometric surface changes over time.

The primary element of a sundial, the part that casts a shadow, is purely geometric and has no moving parts. Unfortunately, a sundial at the Moon won't be directly observable with human eyes, unlike the sundials on Earth. A measurement system to quantize the shadow as a unit of time is likely possible, such as using an array of photodiodes, but would introduce a significant amount of complexity.

Pulsar Detector

Pulsars are rotating extrasolar objects that emit jets of energy, detectable as pulses of electromagnetic waves, like a lighthouse. The locations of these pulsars and their pulse characteristics are well-characterized and catalogued. Timing can be deduced from measuring the frequency of a pulsar signal time series [6], [125], [126].

A time series of observations of a pulsar are made and corrected for the proper motion of the spacecraft with respect to the solar system barycenter (SSB). A pulse profile (pulse phase histogram) of the observations represents the temporal emission characteristics of the pulsar. Also: the phase difference between the observed and predicted pulse phase can be used to determine relative motion from the SSB—observations of 4 distinct pulsars provide a 3D fix on position and velocity.

Radio signals from pulsars are weak and require large antenna arrays; X-ray detectors are about 1 square meter, but are exquisite. Young pulsars exhibit “glitches,” or abrupt changes in rotation frequency, but this is rare in older pulsars. All pulsars exhibit inherent timing noise, with RMS residuals between 0.1 to 1 microsecond.

Synthesizing a “virtual” clock from many other clocks

A “virtual” clock is a time signal that is derived from the combination of other time signals [127], [128]. Virtual clocks can be synthesized at any level in a system—each node used to form the virtual clock may itself be a virtual clock.

One or more CSACs are hosted onboard as the primary timekeeping devices. Many TCXOs would also be hosted onboard to make the system even more robust. Locally, the CSACs and TCXOs would have their noise characteristics calibrated and combined with a Kalman filter (basically a weighted average based on instrument precision). The host platform would connect to GNSS as often as possible for time steering and include GNSS as a member of the Kalman filter. The output signal from the Kalman filter is a composite “best guess” that would act as a high-precision virtual clock node.

Time transfer protocols

The manner of time transfer bounds the system requirements for a time source's host platform. This section explains major differences between methods of time transfer and existing time transfer protocols.

Impact of time transfer approach on host architectures

Beaconed (one-way) signal from the time standard

In a manner similar to GPS, where a reference signal is broadcasted across an area and the responsibility of positioning, navigation, and timing (PNT) lies with the receiver or listener, the beacon for lunar timekeeping passively broadcasts the timing signal. The beacon must remain stable over time and synchronize with a grounded reference, such as Earth time. Unlike ranging, where multiple time standards and simultaneous connections are required, timing only requires one time standard. However, a drawback is that the accuracy of timing depends solely on the participants, and it does not improve the timing between nearby actors. If one actor has a better clock, the neighbour with a worse clock may not be aware or affected.

Another challenge is the issue of power and isolationism. Broadcasting a time signal across a large area requires significant power, and the signal may not be useful in areas where there are no receivers. Lower power results in a shorter effective range as the signal spreads out over distance. However, on the positive side, receivers can use low power and commoditized technologies to bootstrap newcomers in the lunar ecosystem with accurate PNT, even though the required power from the transmitter is substantial. Despite these challenges, a beaconed time signal has the potential to enable accurate PNT for lunar missions with low power receivers, contributing to the evolving landscape of timekeeping technologies and methods in cislunar space [129].

Direct link (two-way) to the time standard

It takes much less power to send a focused beam to a target and communicate with it, rather than a wide-beam broadcast. Doing so requires more specialized equipment (a radio that can direct the beam) and knowledge of the location of peers (so the beam is pointed in the right direction) [130]. A direct link is much more likely to establish a reliable connection.

In a diverse ecosystem with potentially antagonistic actors, it is especially difficult to implement an interoperability standard based on direct links.

Peers as signal repeaters (one-way or two-way)

The APRS system is a decentralized communication network in which each participant listens to all signals, checks if it is the desired recipient, and if not it rebroadcasts the signal [131]. This system allows many lower power transmitters to relay messages over long distances without a direct communication path between the originator and the desired recipient. On Earth, APRS is a heterogeneous system with some repeaters connected to the internet. A high altitude balloon with an APRS module, for example, could send data to a nearby radio tower that's connected to the internet and forwards the data across the world to an operator on another continent.

A cooperative network of repeaters bridges the gap. Actors can bounce signals between nodes across large distances by only having to talk to their neighbours, lowering the power barrier to entry. Nodes can cooperate using direct links OR beacons. Friendly actors can directly link, and can also cooperate with antagonistic actors with an interoperable beacon. As a bonus, this repeater architecture establishes a foundation for a cooperative data relay network for more than just time transfer!

The drawbacks are that each "hop" introduces more timing error, and the path between a time source and a client is not direct. While data, commanding, and telemetry may use delay/disruption-tolerant networking (DTN) and communication relays [132], time transfer messages inherently require a direct connection since the messages are naturally time-critical.

Network Time Protocol (NTP)

The Network Time Protocol (NTP) is a familiar topology, since it's how most of the internet coordinates the time [133]. The basis of NTP is simple: a server's time is communicated to clients on the local network, along with statistics about the time source such as frequency error, stability, phase offset[20] so that clients may choose to ignore unreliable time sources. There exists a reference clock (*Stratum-0*) that provides the best possible time to servers directly connected to it (*Stratum-1*). Time-servers may synchronize to peers on the network.[21]

Synchronization with NTP is best summarized by the NTP-FAQ [134]:

[20] If we think about clock ticks in terms of angles around the unit circle, *phase offset* is the angular distance between the two signals, while *drift* keeps track of how many times the difference was "wound" around the unit circle.
[21] For example, time-server A is a *Stratum-n* time source and maintains a time signal that is *n*-synchronizations removed from the reference time. Time-server B searches for a reference time on its local network (or a time-server with the lowest stratum) and finds A. After B syncs to A, B updates its status to become a *Stratum-(n+1)* time-server for other peers on the local network.

> Synchronising a client to a network server consists of several packet exchanges, where each exchange is a pair of request and reply. When sending out a request, the client stores its own time (*originate timestamp*) into the packet being sent. When a server receives such a packet, it will in turn store its own time (*receive timestamp*) into the packet, and the packet will be returned after putting a *transmit timestamp* into the packet. When receiving the reply, the receiver will once more log its own receipt time to estimate the travelling time of the packet. The travelling time (*delay*) is estimated to be half of *"the total delay minus remote processing time"*, assuming symmetrical delays.
>
> Those time differences can be used to estimate the time offset between both machines, as well as the *dispersion* (maximum offset error). The shorter and more symmetric the round-trip time, the more accurate the estimate of the current time.
>
> Time is not believed until several packet exchanges have taken place, each passing a set of sanity checks. Only if the replies from a server satisfy the conditions defined in the protocol specification, the server is considered valid. Time cannot be synchronised from a server that is considered invalid by the protocol. Some essential values are put into multi-stage filters for statistical purposes to improve and estimate the quality of the samples from each server. All used servers are evaluated for a consistent time. In case of disagreements, the largest set of agreeing servers (*truechimers*) is used to produce a combined *reference time*, thereby declaring other servers as invalid (*falsetickers*).

In a stratified system, accuracy and stability degrades as time is transferred through devices and becomes further removed from the Stratum-0 time source [57]. Distributed clock synchronization networks are resilient, however, in terms of connectivity and failure recovery [88]. Yet if the stable source of the "true time" reference is cut off from the NTP network, time-server peers are prone to "death spiralling" where peers are caught in a loop of syncing to one another and incrementing their degree of separation until they are all at the lowest quality stratum.

In a terrestrial context, GNSS satellites are considered to be *Stratum-0* clocks, and the highest accuracy (*Stratum-1*) time-servers use GNSS receivers to synchronise very precise local oscillators to the signal broadcast from the GNSS satellites. For most computers connected to the internet, timing accuracy with NTP ranges from about 5ms to 100ms, varying with network delays [134].

Precision Time Protocol (PTP)

Precision Time Protocol (PTP), also known as IEEE 1588-2019, is a network timing protocol capable of synchronising clocks on a local network with nanosecond accuracy [135]. PTP is designed around the concept of a Grand Master clock that disciplines clocks on its local network.

PTP derives its accuracy by using *hardware* timestamps, unlike NTP, which uses software timestamps. PTP also keeps track of delays incurred by the device itself (NTP only accounts for network delay) [136].

Peer-to-Peer/Distributed Clock Synchronization

Peer-to-peer or distributed clock synchronization protocols reach a “consensus” synchronization among participants rather than maintaining the population's time with respect to an external reference [89], [91], [94], [96], [98].

Peer-to-peer clock synchronization is not widely used in distributed systems, but it is an active field of study.

Bundle Protocol

Bundle Protocol v7 (BPv7) is a communication protocol that is designed for use in space environments, including cislunar space. It is specifically designed to enable efficient and reliable communication in scenarios where there may be disruptions, delays, or limitations in network connectivity [137].

In the context of time transfer in cislunar space, BPv7 can be utilized to facilitate the exchange of timing information between different lunar missions or spacecraft. Time transfer in cislunar space involves establishing a common reference time among different lunar missions or spacecraft to enable coordinated operations, navigation, and positioning.

BPv7 can be used to package and transmit time-related data, such as timestamps, clock synchronization information, or timing messages, in bundles. These bundles can be sent between lunar missions or spacecraft using available communication links, such as lunar orbiters, lunar landers, or lunar surface communication systems.

BPv7 provides features such as store-and-forward, which allows bundles to be temporarily stored and forwarded by intermediate nodes until a reliable communication link is available, even in the presence of disruptions or delays. This ensures that time-related data can be reliably exchanged even in challenging communication scenarios in cislunar space.

Additionally, BPv7 supports various types of bundle custody transfer, which allows ownership and responsibility for bundles to be transferred between spacecraft or lunar missions. This feature can be utilized for time transfer in cislunar space to ensure that the correct timing information is properly received and maintained by the intended recipients [138].

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