Cislunar Open Clock Synchronization System (CLOCSS)

PNT Infrastructure for Cislunar Ecosystems via Wireless 2-Way Interferometry & Time Card

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Statement: *No team members from this proposal work for DARPA as SETA, A&AS, or similar support services. Our contracting staff acknowledges the LunA-10 TA-1 program's timelines and can negotiate an OT award within 30 days. An ACA is acceptable: Yes. Our technology will not require an ACA.*

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Summary of Proposed Approach

Recent advancements in space technologies have prompted a surge in lunar missions, both crewed and uncrewed. Such an influx demands scalable, commercially-accessible Positioning, Navigation, and Timing (PNT) frameworks for the development of a cislunar economy. In order to bring PNT infrastructure to the lunar ecosystem and have it be as ubiquitous and as useful as Global Navigation Satellite Systems (GNSS) are in the interoperable Space Service Volume (SSV), there needs to be accurate, traceable and accessible timing and ranging infrastructure that is also resilient, reliable and flexible. NASA's LunaNet and ESA's Moonlight are two major initiatives to promote interoperability and connectivity in cislunar space by providing a common communications framework and standards. Lunar constellations equivalent to terrestrial GNSS are one approach to delivering a cislunar PNT [1], [2] but it is not the only solution.

Existing technology can be used to leverage the carrier signal of communications links to obtain sub-nanosecond timing and millimeter ranging. Thus, traditional communication avenues can be revamped to serve dual purposes by equipping two distinct entities in cislunar space with stable clocks and a shared communication bandwidth, and synchronization becomes a streamlined process. This synchronized environment then facilitates accurate relative ranging using Wireless Two-Way Interferometry (Wi-Wi) with the communication link's carrier signal. Essentially, all Wi-Wi demands is a standardized bandwidth and a precision clock. This permits PNT using communication links that are likely to already be established, and minimizes the volume of data exchanged. With terrestrial systems as a benchmark, our focus is to craft a comprehensive system tailored to the lunar ecosystem's challenges and the constraints of cislunar operations. Wi-Wi uses existing COTS RF chips to achieve phase-lock between precision clocks to achieve time synchronization and ranging. This approach does not require complex new technology development. The addition of a single component (Time Card, standardized by IEEE P3335) can be used to integrate a LEO platform (or terrestrial vehicle) with the cislunar PNT utility over its own pre-existing communications channels. Thus, communications nodes become PNT nodes.

In this study we will assess lunar PNT commercial user requirements and analyze Wi-Wi as an alternative method of implementing a PNT service to traditional GNSS constellations. We will compare the proposed method with metrics known from the current PNT solution such as accuracy, availability, continuity and integrity [3], in addition to costs, timeline and technology development requirements of implementing each system in a cislunar context. The goal is to develop the proposed solution up to System Concept Review (SCR), to a level mature enough to predict the system's performance relative to the number and distribution of interconnected assets, and quantitatively demonstrate that our approach becomes more robust and performant as it scales to service the anticipated demands of a thriving lunar ecosystem. The study will consider specific lunar PNT user needs and infrastructure combination opportunities, as well as requirements for Earth / Earth Orbit systems to be usable with minimum changes for lunar applications. Like GNSS, passive receivers can obtain the time and position in reference to the PNT node's position by observing the transmitted signal so long as the receiver's clock is synchronized to the node. These metrics will be used to evaluate opportunities to improve PNT offerings for the cislunar ecosystem. As a result, it is expected that the study will demonstrate that the proposed alternative PNT infrastructure solution is superior to existing GNSS technology in scalability, cost of operation, resilience, composability, and versatility.

Summary of Current State of the Art

This proposal seeks to evaluate two-way PNT architectures against traditional GNSS-like services for anticipated needs of the lunar ecosystem. The landscape of cislunar networks will grow and change rapidly in the next decade [4]–[6]. Modeling interactions between actors as the population size and distribution changes over time is necessary to characterize the capabilities of an essential utility like PNT services. Agent-based modeling is an established technique for evaluating network dynamics and geographical information systems [7]–[11].

There is an abundance of lunar mission profiles and optimal constellation designs for communications coverage in cislunar space [12]–[23]. Two-way interferometric ranging between spacecraft was demonstrated in LEO and lunar orbit with GRACE [24] and GRAIL [25], respectively. The ESA Lunar Pathfinder [12], [26] offers lunar communications for commercial and institutional customers in support of prospecting, exploring, and ultimately utilizing the far side of the Moon. NASA's Lunar GPS Received Equipment (LuGRE) [27] will demonstrate GNSS-based PNT in transit to the Moon and on the lunar surface. NASA's Lunar Reconnaissance Orbiter (LRO) is currently orbiting the moon in an eccentric polar orbit to map lunar poles [28]. In the private sector, Lockheed Martin subsidiary Crescent has announced Parsec [13], a system of coordinated small satellites designed to provide data relay and PNT services to cislunar space by 2025. Parsec will implement GPS-like satellites in a cislunar context to offer services as a subscription or similar agreement.

The key principle in two-way time and frequency transfer (TWTFT) [29], [30] and its modern evolution, Wireless Two-Way Interferometry (Wi-Wi) [31], [32], is to measure the clock difference and propagation time of two remote clocks in a single measurement by transmitting a signal in both directions and comparing the difference between internal clock (phase) and received clock signal (phase) at both ends. Precise clock difference and propagation time measurements are two sides of the same coin, and TWTFT is a protocol that can measure them both at the same time. The carrier phase comparison improved the precision of the time and clock signal comparison from ns to ps accuracy [32]. Applying the same protocol to commercial wireless communication modules, software-defined radios, and Rb clocks, Wi-Wi has demonstrated a clock comparison precision of 2.2 ps [31] and distance variation measurement of better than 1-mm precision [33]. This capability has been packaged into a single module, achieving simpler, cheaper, more convenient use of the Wi-Wi technology [34], [35]. Sub-nanosecond precision timekeeping is available with Time Card [36], [37], [37], [38], an open specification of timing platform built on commercial off the shelf (COTS) components, chosen for its simplicity and low cost. Time Card is implemented as third-party commercial and open-source architectures [39]–[41] that are compatible with space-rated clocks [42]–[44].

Proposed Design and Unique Insights

Two-way satellite time and frequency transfer is a well-developed technology and capable of measuring clock differences with picosecond precision. Instead of using a satellite microwave transmitter and a receiver as in TWTFT, Wi-Wi uses a wireless communication module to achieve the same performance with much lower cost, power consumption, and volume [31], [34]

Time Card (mRO-50)	
precision	6×10^{-11}@1s 6×10^{-12}@100s
mass	< 0.90 kg
power	< 2 W
volume	< 40 cm^3
cost	< $5,000

Wi-Wi	
required stability for mm-precise ranging	6×10^{-11}@1s
data tx for sync	4 bytes
required SNR	> 10
precision of sync	< 1 ns
ranging precision	$\delta t \times 10^8$ m

Table 1: *above, left:* Characteristics of Time Card w/mRO-50 [39], [43].
Table 2: *above, right*: Timing and ranging capability using Wi-Wi.

Figure 2 shows the Wi-Wi carrier phase comparison protocol between two modules A and B where the clock phase and propagation delay phase of the carrier wave are calculated from the measured phases. Each module includes their previous measurements of the phase on their payload, and therefore, both modules share each other's measurements.

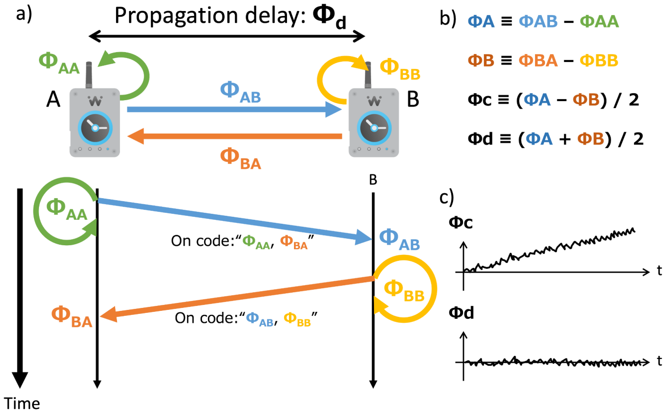


Figure 2: System model of Wi-Wi. a) Range and angle measurement sequence. b) Calculation of Φc and Φd from the measured phases. c) In the experiment reported in [34], the accuracy of ϕc and ϕd was 7 deg at 20 Hz. Accuracy of ϕd is limited by signal-to-noise ratio (SNR) of the phase measurement.

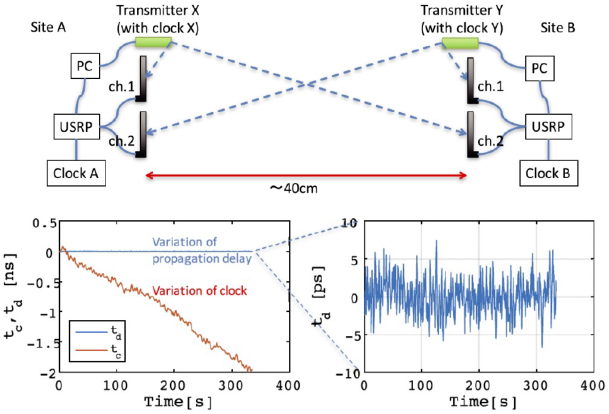


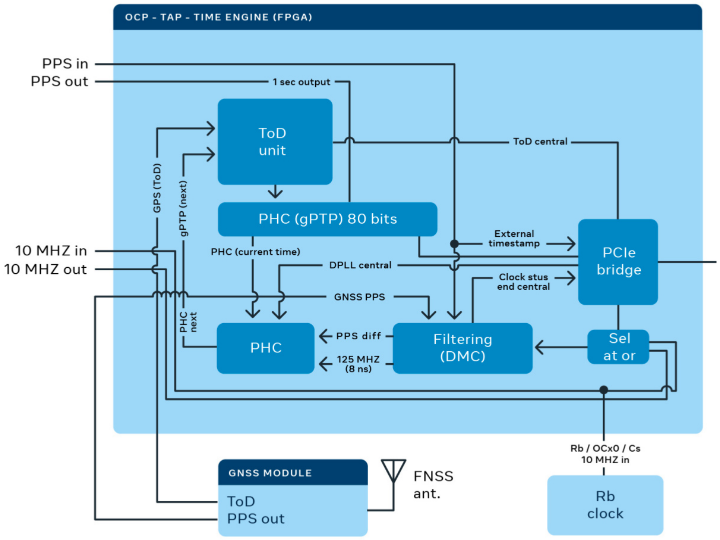
Figure 3: Wi-Wi time synchronization demo in which Site A and Site B use Wi-Wi to wirelessly maintain ~5 ps synchronization despite their clocks drifting by ~ 2 ns over the experiment duration [34].

Time Card offers an inexpensive and ready-made design for a precise clock capable of supporting TWTFT and Wi-Wi and providing high stability and holdover with COTS hardware. The Time Card acts as a bridge between a GNSS signal receiver and the clock, and can be implemented in software or hardware. This proposal considers a Time Card as a hardware bridge between a Chip-Scale Atomic Clock (CSAC) and a generic PNT signal, and assumes parts, interfaces, and form factors that are compatible with spacecraft buses.

Since the signal being measured is the carrier frequency of the link, ranging is a byproduct of observing the time difference between synchronized clocks, as shown in Figure 2. Thus ranging accuracy is proportional to the time precision of participant clocks, as shown in Equation 1.

Equation 1:

$$c\Delta t = \Delta x \qquad c = \text{speed of light}$$



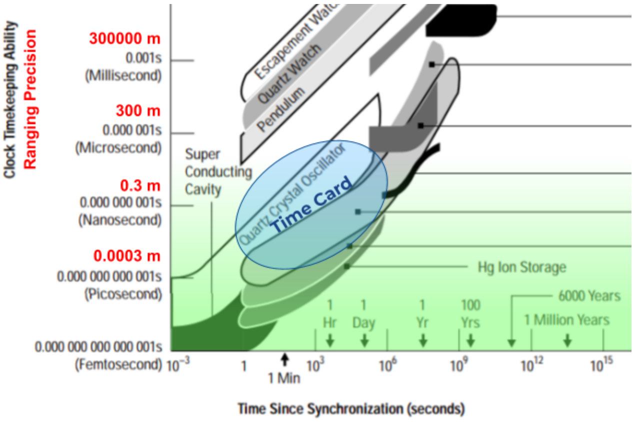


Figure 4: *above:* Block diagram of the Time Engine (FPGA) that drives all Time Cards [38].
Figure 5: *right:* Typical timekeeping stability [45] and corresponding ranging precision of clock technologies.

Positioning and navigation are particularly sensitive to timing instability, as shown in Figure 5. A PNT service should maintain precision of at least $5{\times}10^{-9}$s for days or weeks before syncing to an external reference [46]. Space applications must also contend with very high relative velocities between nodes, which leads to significant Doppler shifts in the transmitted signals. Doppler impacts both time synchronization and estimated time of arrival (ranging) but the receiver should be able to track the changes in the carrier frequency and adjust the local oscillator frequency accordingly. Compensation for Doppler in space communications is not a new problem, and mitigation strategies that apply to satellite communications may also be applied to the proposed PNT architecture [47], [48].

The core technology behind distributed time synchronization is heavily biased toward software development, with nearly all core hardware technology available commercially today. This proposal aims to use agent-based modeling and simulations to explore how centralized and decentralized PNT service network topologies evolve in a growing lunar ecosystem. Modeling network topologies representative of near-term lunar missions and large future populations of cislunar actors will predict the relative performance, “critical mass” of assets required for service, and coverage of Wi-Wi based decentralized PNT services and/or GNSS-like beacons providing PNT to lunar missions. There is an abundance of prior art describing optimal orbit configurations for such systems that can also be evaluated in this way [16], [21]–[23], [49], [50].

The model will feature a population of agents, where each agent has a Stratum, a location and velocity, a clock with drift, and a communications system with a spectral band and radiation power. Agents belong to one of three groups based on their behavior: Transmitters, Receivers, and Peers. Transmitter agents radiate signals but do not listen for incoming signals. Receivers listen for incoming signals but do not radiate. Peers are capable of listening for and radiating signals. Agents move in space independently along orbits or surface routes around a sphere in the simulation space representing the Moon. Terrestrial communications systems are modeled as a Stratum 0 Transmitter. Every node reports measurements of each metric described in the subsequent *Metrics* section at every step of the simulation period.

The described model also permits the simulation of multiple PNT services coexisting, such as Parsec, weak-GPS, and the proposed decentralized network. The model also accounts for the evolution of competing providers as the populations of servers and clients grow. Insights obtained from models will then be applied to create an optimal mission profile for a constellation of cislunar spacecraft equipped with space-rated Time Cards that enable the proposed capability of a publicly available minimum viable PNT service. Estimating PNT users for each service configuration over the next 5 to 15 years, it is clear that the total users will be orders of magnitude lower than current terrestrial users of GNSS, which has worldwide yearly cost of over 5B$ considering all deployed networks; if similar infrastructure architectures are considered for such a lower number of users it would lead to prohibitive cost/user to provide the service with a very substantial need for subsidies; through our analysis, a realistic cost per user for commercial lunar applications will be computed and the associated maximum infrastructure cost to implement and deliver the service commercially will be derived so that data-driven investment decisions related to deploying new PNT fleets in cislunar space are possible.

Scaling

All cislunar missions will be equipped with some form of wireless communications equipment [14], [15], [51]. If two actors in proximity each have stable, precise clocks and can communicate on a common band (S-band, X-band or L-band, UHF-band, or optical links for example), these actors can phase-lock their clocks and derive relative ranging using a wireless two-way interferometry with the communications link's carrier signal. Existing spacecraft architectures may save power, mass, bandwidth, and cost by obtaining PNT from their wireless communications by adding a precise timekeeping device to the system. Neither actor requires a-priori knowledge of the other, so long as they maintain a shared communication channel and possess a precise clock, so today's missions will benefit from and support future missions.

Since two-way communications lends itself to PNT service, there is greatly reduced friction for any node to act as a PNT node for peers, dramatically improving coverage and access to PNT. All nodes in the network with precise clocks and a line-of-sight connection to one another may use Wi-Wi for time synchronization and positioning relative to each other node. This means that local groups may still coordinate and synchronize even when isolated from a broader network. In an environment where signals are detectable but data cannot be exchanged, ranging between nodes is still possible by comparing the carrier phase of the detected signal [52]. Clock synchronization requires both nodes to exchange timing data with each other, but positioning and navigation are possible by passively observing a signal and measuring the carrier phase difference over time. Ranging precision from such one-way measurements depends on the timing precision of the least stable clock involved, as shown in Figure 5. Thus, Wi-Wi and proliferation of precise clocks naturally yield a resilient PNT service capable of mixed modes of operation.

In a cislunar context, especially under the LunaNet interoperability standard [53], spacecraft will send and receive data across Delay-Tolerant Network (DTN) protocols like Bundle Protocol Version 7 (BPv7) [54], [55]. BPv7 encapsulates data (TCP/IP packets, for example) with another packet structure. This allows relays to forward the packet to its destination without ever reading the contents. Including Wi-Wi clock synchronization data in the BPv7 packet allows every message exchanged between nodes to double as a timing and ranging measurement without requiring every node to read the contents of the encapsulated packets themselves. Thus the DTN relay nodes become PNT providers so long as the sender and receiver both possess precise clocks. Constellations of simple relays may enter service as highly interoperable PNT nodes with the integration of a device like the Time Card and no other changes to the mission or spacecraft.

Minimum Viable Experiment

The Time Card's architecture is hardware-agnostic. Form factor and component selection decided by the device integrator. Commercially available Time Cards are optimized for data centers, personal computing, or embedded applications [39], [40], [56]–[58]. However, space-rated components are commercially available and only minimal changes to interfaces, form factor, and fault protection are needed to achieve a flight-ready Time Card.

Specific modifications to the open source reference architecture [56] will be:

1. Modify power delivery architecture to add reset and latch-up protection [59].
2. Replace FPGA with a space-rated module [60]–[62].
3. Replace precision oscillator with a space-rated module [42], [43].
4. Modify form factor to be compatible with CubeSat or other spacecraft bus [63], [64].

The minimum viable experiment is an on-orbit experiment in LEO or cislunar space. Such experiments could be performed quickly and inexpensively, within <1.5 years and <3M$.

1. Modify existing Time Card designs for space-rated applications, and validate the designs in representative environments (TVAC tests and/or secondary orbital payloads).
2. Deploy a pair of 3U+ cubesats to LEO to demonstrate Wi-Wi time synchronization and ranging for space-to-ground and space-to-space links. Each spacecraft will be equipped with a Time Card developed in (1), intersatellite communications, GNSS receivers, and capability to change their relative spacing. The pair will perform a number of relevant measurements and compare the position and timing data acquired through each method.

Potential for integration with other program concepts

In the design of a lunar PNT system one important consideration is the definition of a reference frame to allow for absolute position. This time transfer and relative position concept could be used to define a network of realization points (fixed points for the reference frame) to assist in the realization of a Lunar Reference Frame. These lunar realization points would be located on the near side of the Moon and equipped with e.g., laser retroreflectors for accurate ranging from Earth by the existing Lunar Laser Ranging (LLR) stations.

A fundamental characteristic of the proposed design is its peer-to-peer topology, ensuring resilience against centralized points of failure. The structure stands robust against interference, adversarial or accidental. The decentralized nature of the design further augments its flexibility, permitting in-flight mission adaptations and potential as a backup for lunar missions, reducing their dependence on individualized PNT structures. Since Wi-Wi is a protocol that works with any radio band, it is likely that several independent PNT services could emerge on different parts of the spectrum. This allows actors to maintain closed PNT utilities or to offer services for a self-sustaining, monetizable, commercially owned-and-operated lunar infrastructure. Critically, public and private PNT utilities may coexist under this paradigm, like how a single transponder can access both terrestrial open-air radio and encrypted radio channels. In essence, this philosophy aims to nurture a resilient PNT ecosystem that accommodates both public and private ventures. Through a credibly neutral protocol for timekeeping, foreign adversaries would not only have difficulty manipulating the service, but they may use this infrastructure themselves and even work to support its canonization.

Metrics

Characteristic	Metric	Evaluation Criteria	Characteristic	Metric	Evaluation Criteria
Accuracy	Sync Precision	Standard deviation absolute time across the node population	Interoperability	Standards compatibility	Meets LunaNet requirements, meets Moonlight requirements
	Holdover	Avg. clock drift from true time before sync		Technology compatibility	# comms spectral bands, clients served per band
	Latency (Jitter)	Round trip time, packet delay variation	Cost	Nodes required for service	# service nodes, # clients per provider node
Availability	Capacity	% bandwidth used, peak bandwidth used, sqkm of coverage		Hardware required	$ per clock, # clocks, $ invested per client served
	Throughput	Total available bandwidth, # concurrent links		Hardware capability	Signal power, sqkm coverage per node, # concurrent links per node
Continuity	Roaming ability	# available links, Time between links	(Signal) Integrity	Packet integrity	Packet loss rate, packet delivery ratio, % duplicate packets
	Failure & Recovery rate	Mean time b/w fails Mean time to restore		Channel dominance	Signal-to-noise ratio, jam-to-signal ratio

Table 3: Metrics and quantitative evaluation criteria used to evaluate PNT service characteristics.

Commercialization

Position, Navigation and Timing services for Earth and Space currently represent approximately 50% of the space industry yearly revenue valued at $229B in 2022 [3], [65], [66]; compared with GNSS infrastructure cost of ~$5B/yr, it provides a compelling return on investment. With 2 orders of magnitude fewer users and total expected revenue generated in cislunar, PNT infrastructure complexity and cost must also be scaled down to be commercially viable.

Our approach towards commercialization is a peer-to-peer services network for PNT that piggy-backs on existing missions, rather than a top-down server-client architecture that must make strong assumptions about the distribution of its user base. This approach addresses current limitations of GNSS services that are fractured into separate, government-owned fleets due to the enormous capital investment required to deploy them. Ubiquitous precision timekeeping has major implications not only on the PNT market, but the downstream effects of this infrastructure is profound for cislunar telecommunications and the cislunar economy more broadly. The estimated value of a sustainable cislunar market is estimated to be a ~$4B revenue market by 2030 with potential to grow to $21B+ by 2045 as markets and supply chains mature [67, p. 152].

Future users in cislunar space may purchase space-grade Wi-Wi hardware with precision timekeeping that allows them to not only receive precision PNT and access telecommunications, but also become the provider in a network of peer-to-peer nodes that create a robust and anti-fragile PNT and telecommunications environment. Users of the service would pay a small fee for PNT or data services, the fee would be distributed to the specific provider nodes in the network that facilitated the user's PNT or communications request. Therefore, the cost of integrating our hardware will be subsidized over time, and may even become a revenue generator for the spacecraft, subsidizing all cis-lunar space missions for their future economic potential as a PNT or telecommunications service provider with our Wi-Wi technology.

In a world of ubiquitous Wi-Wi nodes with accurate clocks, telecommunications congestion becomes bounded dramatically [68], [69]. Graph-based routing for messages with several paths means that communications are resilient, fast, and cheap. The network would self organize whereby nodes located in the most trafficked areas for PNT or communications services would receive a larger utilization fee, so coverage bootstrapping for PNT and communications relays becomes a free-market endeavor. There is prior art in bootstrapping a hardware network using monetary incentives. Helium is a project that creates global hotspot coverage around the world in which miners on the network purchase the hardware and receive a fee for network utilization [70], [71]. Protocol governance can be operated in a credibly-neutral manner by a Decentralized Autonomous Organization (DAO) to coordinate upgrades and policies in a decentralized fashion.

Technology Challenges

Challenges

1. *Limited Use of Precise Clocks in Space:* There is limited use of precise clocks in space applications today, particularly if the mission profile doesn't demand precise PNT for its objectives. The majority of missions rely on time transfer from the ground or GNSS. A sufficient density of nodes with precision clocks must be deployed with cislunar missions to support a viable PNT service.
2. *Dependency on Clock Precision:* The proposed system's effectiveness depends on actors possessing timekeeping precision, which may hinder its coverage until a sufficient number of network nodes have precise clocks.
3. *Dependency on Node Population:* The proposed study may reveal that a sufficient PNT service relies on a large population of nodes within the system.

Risks

Each risk in Table 4 is mapped to related *Technical Challenges* and *Metrics*. Risks are ranked by Likelihood (1=Highly likely, 3=Unlikely) and Impact (1=Severe, 3=Negligible).

Risk Likelihood: 1 Impact: 1	*Low Adoption of Precise Clocks:* The primary risk is the potential failure to achieve a sufficient density of precise clocks to support the system adequately. The PNT service is not viable until a sufficient density of the network population is equipped with precise clocks.
Related Challenges	*Limited Use of Precise Clocks in Space,* *Dependency on Clock Precision, Dependency on Node Population*
Mitigations	Apply minimal modifications to the Time Card design so it stands on its own as a space-grade device capable of accurate PNT in cislunar space; Publish reference designs for flight-ready Time

	Card (5×10^{-11}@1s or better for millimeter ranging); Demonstrate a plug-and-play solution [60], [64] for precision timekeeping that may be integrated with cislunar missions currently in development with minimal overhead; Deploy this PNT service as strictly a ground segment to accompany GNSS.
Related Metrics	*Sync Precision, Holdover, Throughput, Roaming ability, Standards compatibility, Technology compatibility, Nodes required for service, Hardware capability*
Risk Likelihood: 1 Impact: 3	*Low Adoption of Two-Way Ranging & Sync:* Satellite integrators are accustomed to using GNSS and receiving PNT passively with one-way measurements. The perceived incentive of including hardware capable of delivering PNT is weak for most missions without navigation objectives.
Related Challenges	*Limited Use of Precise Clocks in Space, Dependency on Node Population*
Mitigation	Present incentives to subsidize hardware costs and generate revenue long term for adopters by distributing funds to providers through proof-of-work algorithms; Initial nodes of the proposed network serve as base stations equipped with a sensitive GNSS receiver and a high-gain antenna to perform weak GNSS signal tracking and gain access to any of the GNSS time scales (BeiDou Time (BDT), Galileo System Time (GST), GLONASS Time (GLONASST), and GPS Time (GPST).
Related Metrics	*Sync Precision, Holdover, Capacity, Throughput, Roaming ability, Nodes required for service, Hardware required, Hardware capability*
Risk Likelihood: 3 Impact: 2	*Wi-Wi Performance Issues at High Relative Velocities:* An on-orbit demonstration of Wi-Wi may reveal that it does not function as expected or could provide inaccurate results when nodes experience rapid relative velocities.
Related Challenges	*Dependency on Clock Precision*
Mitigations	Perform two-way interactions such as full-duplex or multiple channels simultaneously to compensate for high relative speeds between nodes; Model worst-case performance to assess the sensitivity of the system to degraded accuracy and reliability of two-way links.
Related Metrics	*Sync Precision, Holdover, Latency (Jitter), Throughput, Packet integrity, Failure & Recovery rate, Channel dominance*

Table 4: Risks mapped to related technical challenges and quantitative metrics.

Team and Teaming

MoonDAO *moondao.com*

Philip Linden phil@moondao.com, US citizen, 65% effort.

Phil's professional experience includes R&D engineering for SpaceX and Lockheed Martin Space, Mission Operations for Planet Labs, and research for Open Lunar Foundation [72]. *Specific Contributions:* Project Lead, Systems Design, Simulation, Software Engineering

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Pablo holds a Bachelor's degree in Mechanical Engineering and Computer Science from the University of Michigan. Pablo's professional experience includes software engineering at Waymo, GoogleX, Youtube, and the founding of MoonDAO, an organization with the mission to accelerate the long-term settlement of the Moon. *Specific Contributions:* Software Engineering, Systems Design, Protocol Design.

Greg Search gsearchent@gmail.com, US citizen, 10% effort.

Greg holds a Bachelor's degree in Mathematics and Aeronautical Engineering, and a Master's in Electrical Engineering. His research includes but is not limited to the Low Cost

Attritable Aircraft Technology (LCAAT) program which became Skyborg, magnetic navigation and laser air data systems. *Specific contributions:* DOD perspectives.

AVS US, Inc (Part of AVS Added Value Solutions) *a-v-s.es/areas/space*

Ramon Blanco Maceiras space@a-v-s.us, non-US person (Spanish, US E2 Visa), 50% effort. Ramon Blanco Maceiras is the US Head of Space at AVS Added Value Solutions, leading the strategic expansion of its space division from Europe into the US market. At Thales Alenia Space he participated in system architecture and R&D efforts for a range of telecoms, EO and SatNav constellations in LEO, MEO, GEO, in multi-Billion dollar projects (Galileo 2nd Generation, Telesat), leading new project acquisition in the 50-500m€ value range. *Specific contributions:* Project Management, Financial Analysis, Strategy, User inputs

Filipe Pereira filipe.pereira@a-v-s.us, US person (Portuguese, US Green Card), 75% effort. Filipe Pereira holds a Ph.D. in Systems Engineering from Cornell University, with research on Multi-objective design for lunar GNSS [1], [2]. Filipe's professional experience includes navigation engineering, flight dynamics and spacecraft operations (ROSETTA mission) for the ESA, Comms lead for the Cislunar Explorers mission (NASA's CubeQuest challenge) *Specific contributions:* GNSS and PNT Expert.

Open Compute Time Appliance Project *opencompute.org/projects/time-appliances-project-tap*

Ahmad Byagowi ahmad.byagowi@ocproject.net, US person (US Green Card), 25% effort. Ahmad Byagowi leads the Time Appliances Project at Open Compute Project. Ahmad received a PhD from Vienna University of Technology in Electrical Engineering (Control Systems) in 2010 and a second PhD from University of Manitoba in Computer Engineering in 2016. *Specific contributions:* Precision Timekeeping, Distributed Systems.

Open Lunar Foundation *openlunar.org*

Rachel Williams rachel@openlunar.org, US citizen, 25% effort. Rachel has over 6 years of experience as COO of commercial space companies, including experience managing multiple government technology contracts. *Specific contributions:* Program Operations Advisor, Risk Assessment, New Missions

Jacob Malthouse jacob@openlunar.org, non-US citizen (Canadian), 25% effort. Jacob holds a Bachelor's degree in Geography and Economics from the University of Victoria. His professional experience includes 5 years at the United Nations Environment Programme Finance Initiative, 2 years at ICANN, and 10 years as CEO of the .eco top-level domain registry. *Specific contributions:* Program Operations Advisor, Economics

Data Rights

This consortium is committed to the principle of open access concerning the intellectual property generated through this project. We believe that such openness will significantly enhance the utility of the infrastructure we are developing. We acknowledge that certain funding bodies, such as DARPA, may have specific stipulations regarding intellectual property rights. We are open to engaging in discussions and adapting our stance to align with the requisite funding guidelines so that our project not only adheres to the ethos of collaborative development but also remains compliant with the necessary regulatory frameworks. All software and simulations developed under the program are designated as Government Purpose Rights (GPR); All integrated system designs will be Government owned, with performers having unlimited rights of use. The proposed solution includes technology protected by patents US10945223B2 and JP6376911B2.

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