MOON DAO
OPEN LUNAR FOUNDATION
avs
TIME CARD

Cislunar Open Clock Synchronization System (CLOCSS)

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

Sept 25 2023 | LunA-10 TA-1

A vibrant cislunar economy, built on time

Scalable, accessible PNT frameworks are critical for the future cislunar economy

Navigation, Orbit Determination & Ephemeris, and Communications all depend on timing precision

LunaNet and Moonlight both assume a precision timing signal will be available

Leveraging today’s technology

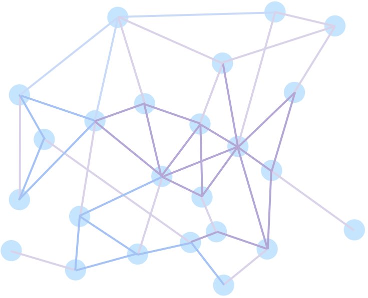
Robust Lunar PNT are possible with existing technology and novel approaches

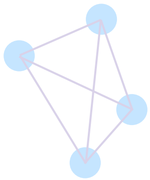
Democratization of services catalyzes coverage and distributes the capital investments across the population

A vibrant cislunar economy, built on time

Wireless comms are central to cislunar conops, all missions will carry comms equipment.

Precise timekeeping uses comms signals achieve <1 ns timing and <1 mm ranging between peers to maximize coverage, resilience of PNT service.





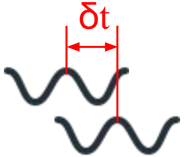
Complement Lunar GNSS initiatives with a bottom-up approach that distributes investment.

Service infrastructure grows with the population, improves with participation, and distributes load.

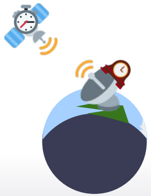
Democratized capability makes decentralized service models viable, incentivizes interoperability.

Timing & ranging from carrier frequency phase

Wireless two-way interferometry (Wi-Wi) enables sub-nanosecond timing and millimeter ranging is achievable if most nodes have stable clocks and a shared communications band using the carrier frequency phase difference.



$$\delta t \approx 1\text{ns}$$
$$c \cdot \delta t = \delta x$$
$$\delta x \approx 3\text{mm}$$



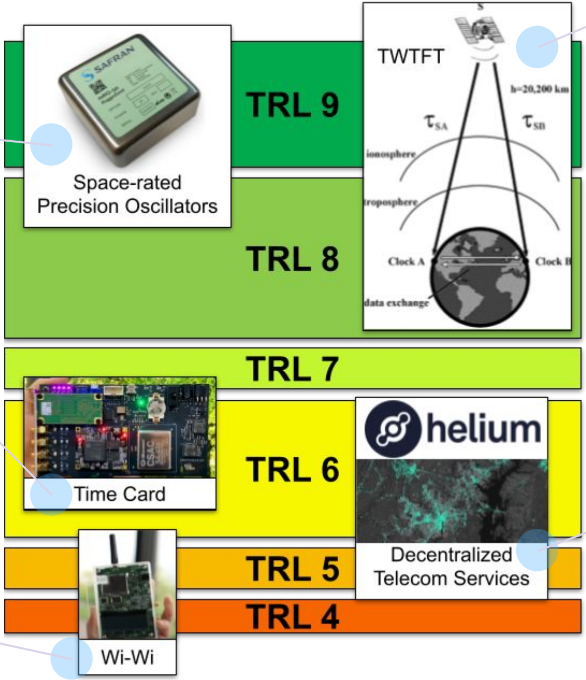
All comms double as PNT nodes with the addition of precise timekeeping

Based on robust, proven technologies

(2022) Space-rated clocks are commercially available and capable of 6×10^{-11} variation at 1s holdover, 6×10^{-12} at 100s holdover.

(2021) Time Card (IEEE P3335) provides designs for precision timekeeping devices with an open specification and third-party builds.

(2019) Wi-Wi demonstrated experimentally with COTS RF Chips.



(1991) Two-Way Time and Frequency Transfer (TWTFT), which is the predecessor of Wi-Wi, demonstrated with satellite to ground links.

(2021) The Helium network successfully commercialized a decentralized machine network for internet connectivity and geolocation.

Completed Work & State of the Art

Time Card
Accessible, inexpensive sub-nanosecond timekeeping with COTS components

Wi-Wi
sub-nanosecond time sync,
sub-millimeter ranging using comms carrier signal with COTS components

Lunar GNSS
First-principles analysis of a minimally viable, optimal cost Lunar GNSS network and cost estimates vs DSN

Helium
Commercially deployed architecture of decentralized machine network & internet

On-orbit Uses of TWTFT
Ground-to-space and space-to-space time transfer and ranging successfully performed in space by prior missions.

Optimal Constellations are Well Studied
There is an abundance of prior art on the optimal constellation configurations for comm. and PNT service coverage

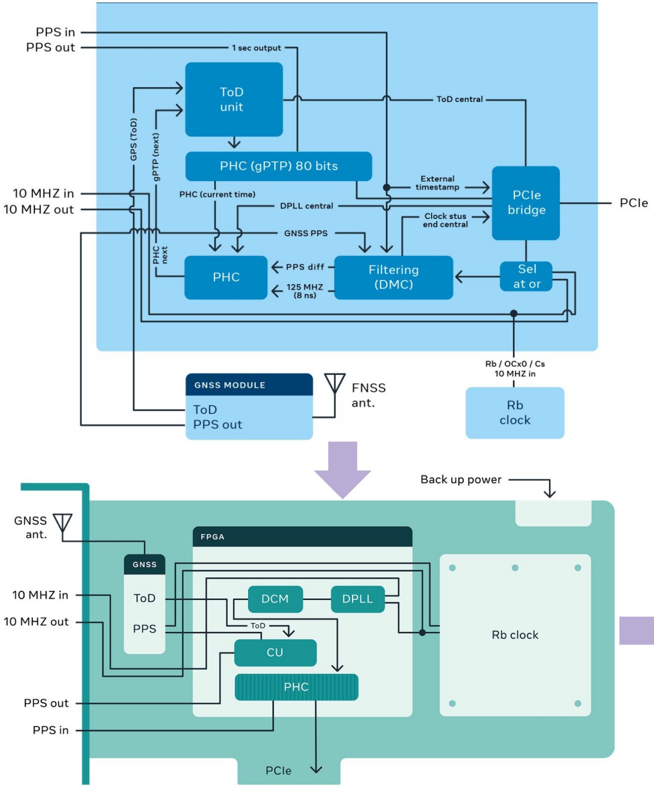
Completed Work

Time Card

Time Card creates an open specification build on commercial off the shelf components with GNSS-disciplined sub-nanosecond precision timekeeping.

Time Card is compatible with space-rated OCXO, Rb, and CSAC clocks.

Third-party integrators develop cards w/ specialized form factors & interfaces.

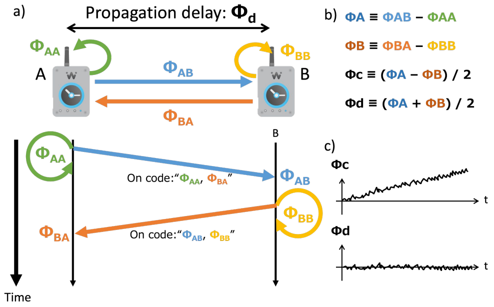


Time Card with Chip-Scale Atomic Clock

Completed Work

Wireless Two-Way Interferometry (Wi-Wi)

The key principle 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.

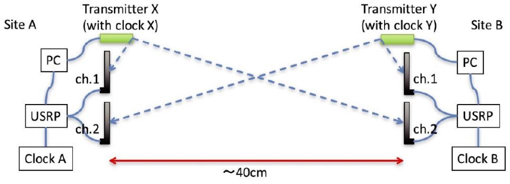


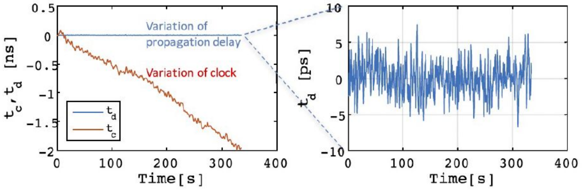
$$\Phi A \equiv \Phi AB - \Phi AA$$

$$\Phi B \equiv \Phi BA - \Phi BB$$

$$\Phi c \equiv (\Phi A - \Phi B) / 2$$

$$\Phi d \equiv (\Phi A + \Phi B) / 2$$



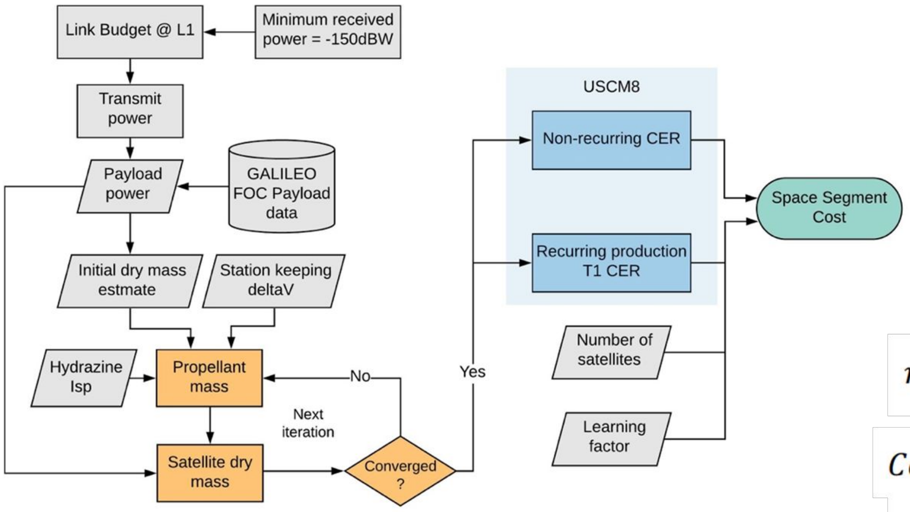


Above: Wi-Wi devices packaged into commercial wireless communication modules, software-defined radios, and Rb clocks.

Left: Wi-Wi experimentally demonstrated with a clock comparison precision of 2.2 ps and distance variation measurement of better than 1 mm.

Completed Work

Lunar GNSS cost derived from first principles



- Space segment cost SEE = 47% inside m_{dry} range of validity: 114 –5127 kg.
- Learning factor = 95%.
- Satellite dry mass estimate obtained from an empirical model derived from data about past communication and navigation satellites [2]

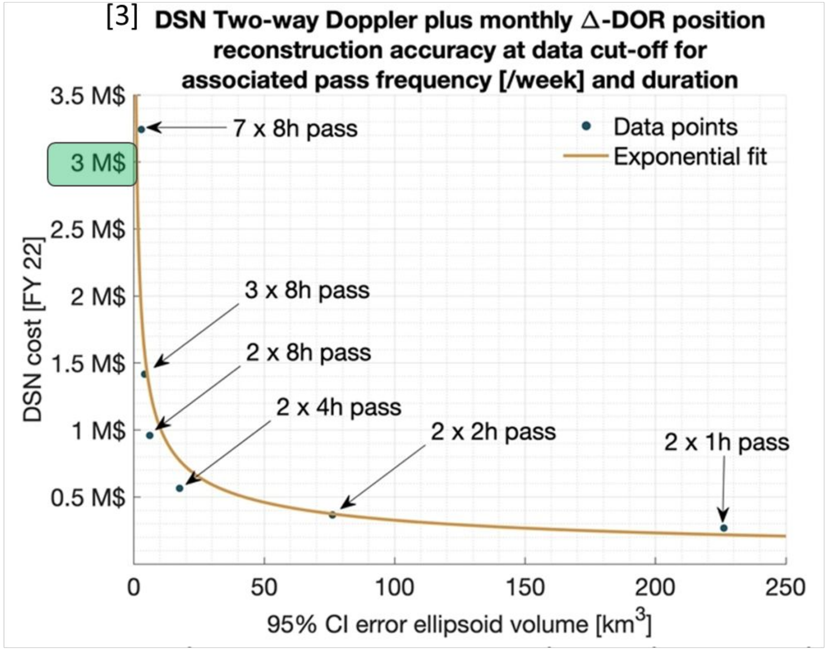
$$m_{dry} = 38\left(0.14 \cdot P_{PL} + m_{prop}\right)^{0.51} - m_{prop}$$

$$Cost_{space\ segment}[FY2010\ \$k] = 110.2 \cdot m_{dry} + \left(289.5 \cdot m_{dry}{}^{0.716}\right) \cdot N^{(1+\log S/\log 2)}$$

[1] P. J. J. Wertz James R., Everett David F., Space mission engineering: the new SMAD. Microcosm Press, 2011.
[2] P. N. Springmann and O. L. De Weck, “Parametric Scaling Model for Nongeosynchronous Communications Satellites,” J. Spacecraft and Rockets, vol. 41, no. 3, pp. 472–477, May 2004.

Completed Work

Lunar GNSS vs Deep Space Network costs


[3] DSN Two-way Doppler plus monthly Δ-DOR position reconstruction accuracy at data cut-off for associated pass frequency [/week] and duration

95% CI error ellipsoid volume [km^3]

DSN

- Assuming : 2-way Doppler + monthly Δ-DOR
- One 8h pass per day : **2.93**
- **Cost : 3 M$ [FY22]**

8-sat Lunar GNSS

- Assuming Walker constellation
  - a = 5730km (h $\approx \sim 2R_{☾}$), e = 0.0057, i = 89.32 deg
  - T = 24, P = 3, F = 0
- [OD error σ = 100m, TCXO] : **0.017** [95 PCTL]
- **Cost : 349 M$ [FY22]**

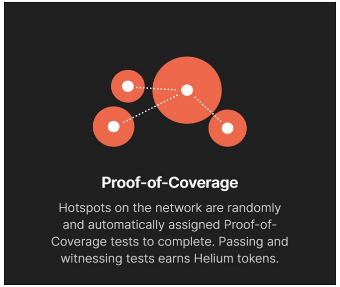
8-sat Lunar GNSS costs can be amortized in 15 years assuming 5–7 mission/year

[3] J. Stuart and L. Wood, “SmallSat navigation via the deep space network: Lunar transport,” in Proceedings of the International Astronautical Congress, IAC, 2017, vol. 9.

Decentralized Networking: Helium

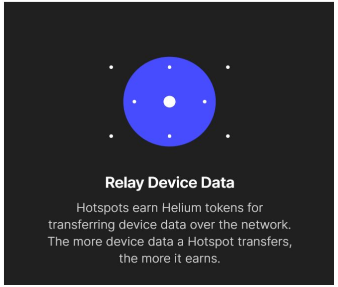
- The Helium network successfully commercialized a decentralized machine network for telecommunications, including internet connectivity and geolocation.
- Protocols and applications that enable compatibility with existing telecom hardware are published open source software, and hardware devices are sold by third party device vendors.

helium



Proof-of-Coverage

Hotspots on the network are randomly and automatically assigned Proof-of-Coverage tests to complete. Passing and witnessing tests earns Helium tokens.



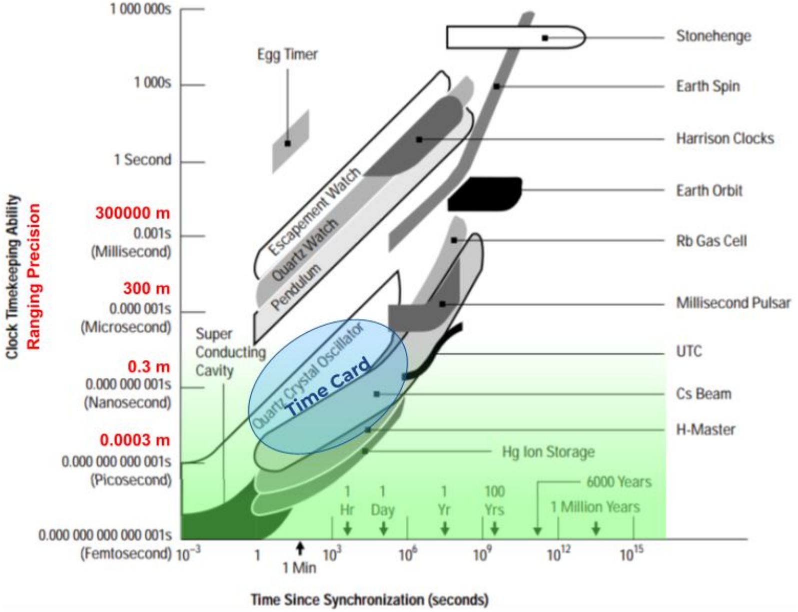
Relay Device Data

Hotspots earn Helium tokens for transferring device data over the network. The more device data a Hotspot transfers, the more it earns.

Proposed Approach

1. With Wi-Wi, ranging precision is proportional to timing precision.
2. Time Card provides suitable capability at a low cost.
3. Democratized PNT service compliments traditional GNSS approaches at a fraction of the cost

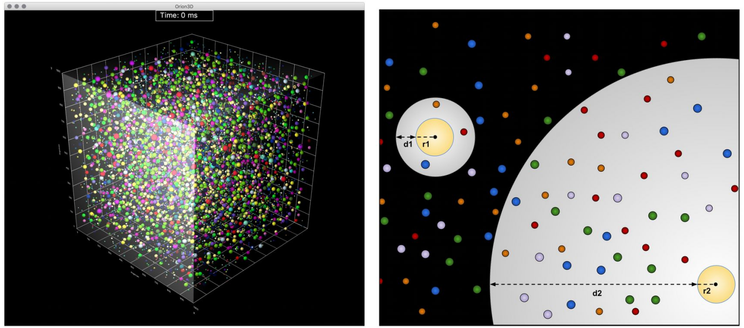
Our study analyzes Wi-Wi as an alternative method to traditional GNSS constellations to implement a PNT service, assessing both approaches against a set of proposed metrics.



Agent Based Modeling

- 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.

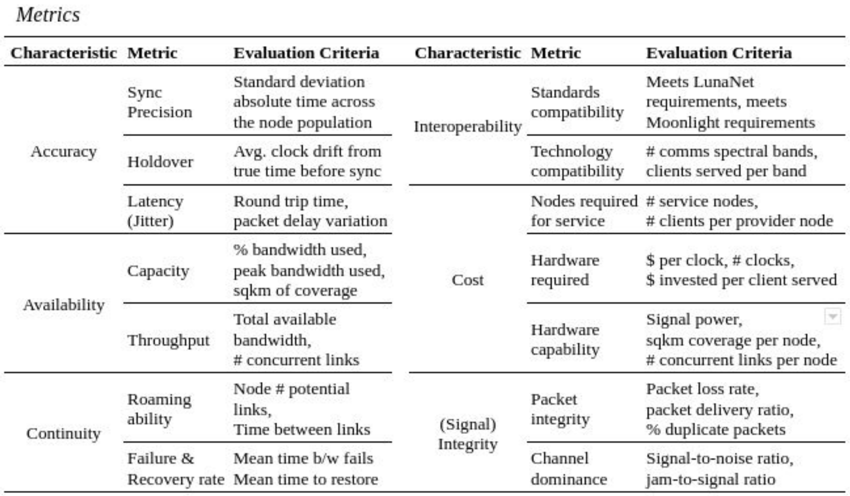
- Modeling network topologies representative of near-term lunar missions and large future populations of cislunar actors will predict the relative performance, “critical mass” of assets required for service, and coverage of Wi-Wi based decentralized PNT services and/or GNSS-like beacons providing PNT to lunar missions.



(a) (b)

Proposed Metrics

- We expect our proposed solution will be dramatically lower cost per client served
- Our core metrics are accuracy, availability, continuity and integrity, in addition to costs, timeline and technology development requirements of implementing each system in a cislunar context.



Metrics

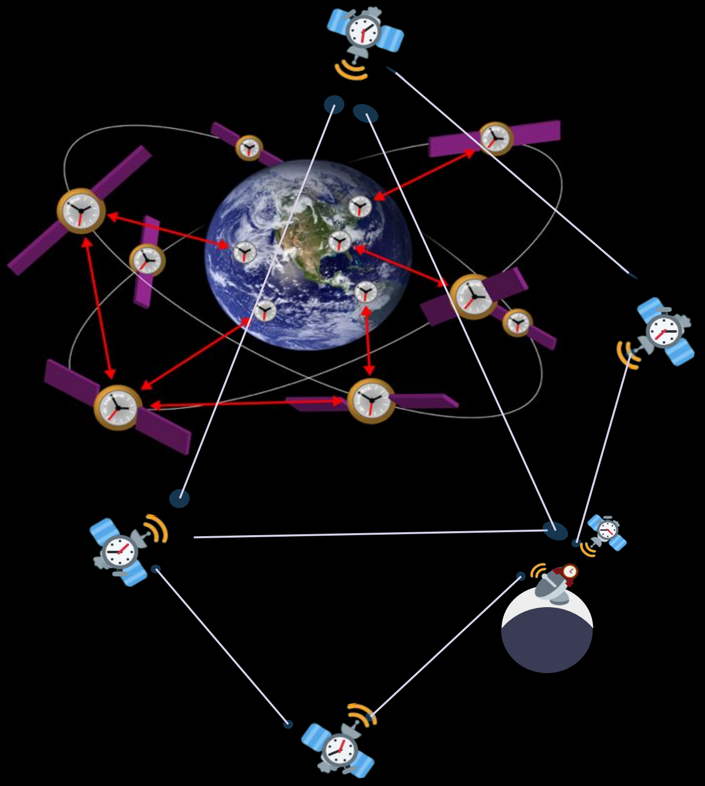
Characteristic	Metric	Evaluation Criteria	Characteristic	Metric	Evaluation Criteria
Accuracy	Sync Precision	Standard deviation absolute time across the node population	Interoperability	Standards compatibility	Meets LunaNet requirements, meets Moonlight requirements
	Holdover	Avg. clock drift from true 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	Node # potential 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.

Proposed Approach

Metric Analysis

- The proposed study seeks to evaluate Wi-Wi based decentralized networks as alternatives to centralized GNSS-like services for cislunar PNT.
- 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.



Market Analysis

- Position, Navigation and Timing services for Earth and Space currently represent approximately 50% of the space industry yearly revenue. Given the very high number of terrestrial users, a very large infrastructure cost can still be economical and provide a large ROI.
- With a much more limited number of users and total expected revenue generated in cislunar space in the medium term being 2 orders of magnitude lower, PNT infrastructure complexity and cost must also be scaled down to be provided in a viable commercial manner.

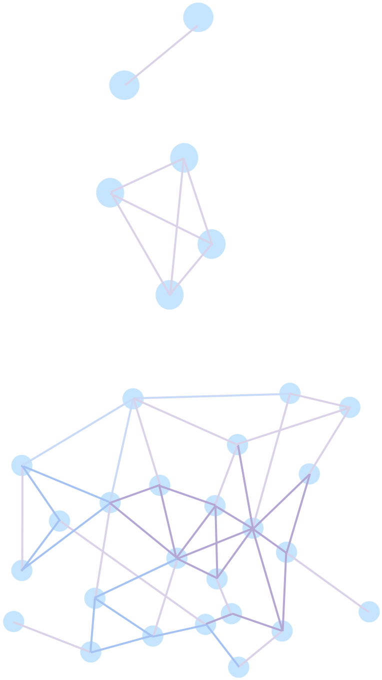
GNSS System	Estimated Total Cost ($ Billion)	Estimated Annual Cost ($ Billion)
GPS	44.5	1.95
Galileo	40	1.65
GLONASS	20	1
BeiDou	25	1.5
Total	**129.5 +/- 20%**	**6.1 +/-20%**

Commercialization

To commercialize this technology, our approach is a peer-to-peer services network for PNT, rather than a server-client architecture.

We aim to bootstrap a robust network of Wi-Wi hardware integrated into the majority of spacecraft deployed to cislunar space through a fee distribution incentive.

Future users in cislunar space purchase space-grade Wi-Wi hardware with precision timekeeping that allows them to not only receive precision PNT and access telecommunications, but also be a provider in a robust and antifragile PNT and telecommunications environment.



Scaling

In a world of ubiquitous Wi-Wi nodes with accurate clocks, telecommunications congestion becomes bounded dramatically.

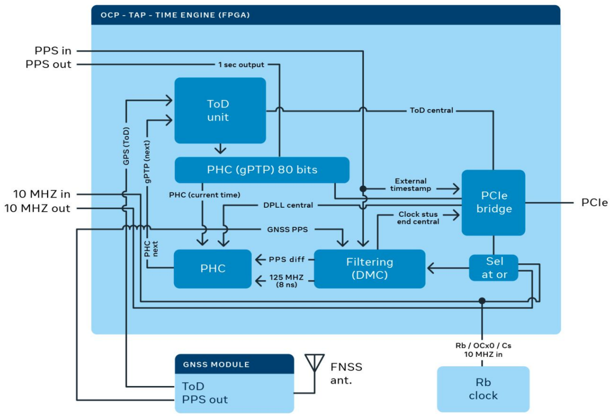
Graph-based routing for messages with several paths means that communications are resilient, fast, and cheap.

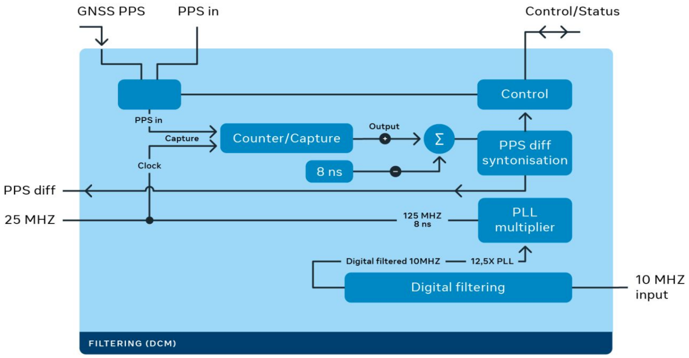
The network would self organize whereby nodes located in the most trafficked areas for PNT or communications services would receive a larger utilization fee, so coverage bootstrapping for PNT and communications relays becomes a free-market endeavor.

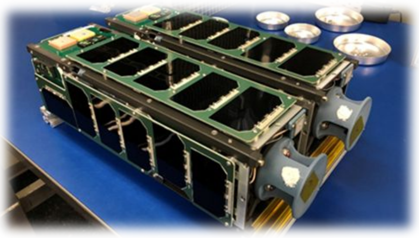
Minimum Viable Experiment

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

1. Upgrade Time Card designs for space-rated applications, and validate the designs in representative environments.
2. Deploy 2x3U 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.







Risks

Low Adoption of Precise Clocks: The primary risk is the potential failure to achieve a sufficient density of precise clocks deployed with cislunar missions to support the system adequately. (Likelihood: High, Impact: High)

Dependency on Node Population: The proposed study may reveal that a sufficient PNT service relies on a large population of nodes within the system. (Likelihood: Moderate, Impact: High)

Performance Issues at High Velocities: There's a risk that the system may not function as expected or could provide inaccurate results when nodes experience rapid relative velocities. This risk could have a high impact if not mitigated. (Likelihood: Low, Impact: High)

Challenges

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.

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.

Unproven Technology for Rapid Distance Changes: Wi-Wi has not been demonstrated under rapidly changing distances between nodes.

Conclusion

Scalable, accessible PNT frameworks are critical for the future cislunar economy

Complement Lunar GNSS with a bottom-up approach that distributes investment.

Democratized capability makes decentralized service models viable, incentivizes interoperability.

Agent-based modeling and simulations explore how centralized and decentralized PNT service network topologies evolve in a growing lunar ecosystem for many configurations and heterogeneous ecosystems.

Core metrics are accuracy, availability, continuity and integrity, in addition to costs, timeline and technology development requirements of implementing each system in a cislunar context.