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Lunar PNT: Enabling a Resilient and Accessible PNT Infrastructure for Lunar Exploration

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Introduction

With the growing interest in Lunar exploration, there have been international efforts on building fundamental technologies. Lunar Position, Navigation, and Timing (PNT) is one of such technologies that will provide key PNT services to Lunar missions. PNT plays a vital role in the success of lunar exploration. PNT supports spacecraft and rovers to safely land and operate on the Moon by accurately determining their position and navigating its difficult terrain. PNT also enables seamless coordination among landers, orbiters, and astronauts, helping reduce the risk of collisions and communication gaps. In addition, PNT also underpins autonomous systems, allowing robotic vehicles to carry out tasks with minimal human oversight, especially important for extended missions or activities in hard-to-reach areas like the lunar far side or permanently shadowed regions. In short, reliable PNT is fundamental to safe, efficient, and productive lunar operations.

This paper overviews the current state of Lunar PNT, analyzes the use cases and gaps, and proposes future capability needs among the international efforts.

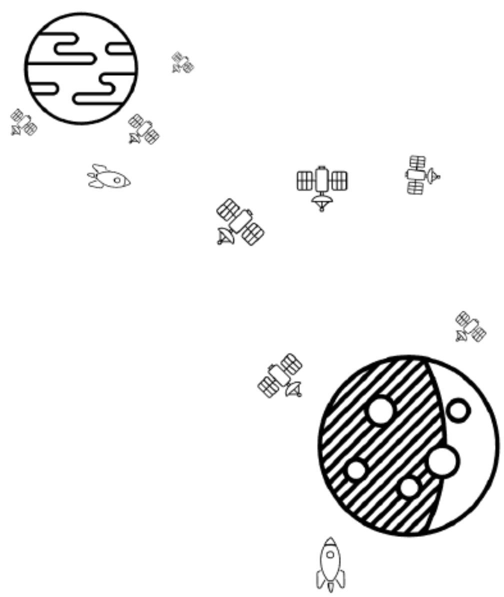

Fig. 1: An illustration of the Lunar PNT infrastructure

Current State of Lunar PNT

The Global Navigation Satellite System (GNSS) provides essential PNT services for a wide range of Earth-based applications. Major GNSS constellations with global coverage include GPS (United States), Galileo (European Union), and BeiDou (China). Terrestrial-based PNT systems, such as Enhanced Long-Range Navigation (eLORAN), serve as complementary and resilient alternatives to satellite-based systems. These ground-based systems are particularly valuable in GNSS-denied or degraded environments, such as indoors or areas with significant signal obstructions.

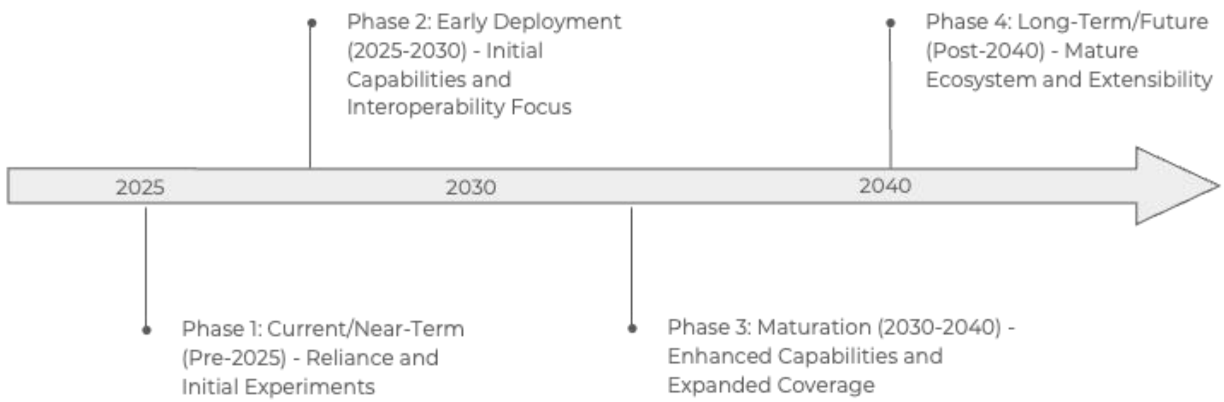

Fig. 2: Lunar PNT evolution roadmap

As shown in Fig. 2, the PNT roadmap outlines a four-phase progression toward a mature and autonomous lunar navigation system.

Phase 1: Current/Near-Term (Pre-2025) focuses on reliance on Earth-based tracking systems such as NASA's Deep Space Network (DSN), with initial experiments using weak GNSS signals. A study [6] in 2018 explored the high-altitude GPS Space Service Volume (SSV) in the NRHO. It derives the number of satellites visible as a function of altitude and the received signal carrier-to-noise spectral density at the high-altitude GPS receiver in a special orbit close to the Moon, the near-rectilinear halo orbit (NRHO), with the Orbit Determination Toolbox (ODTBX) simulator. Navigation during this phase remains basic and constrained. Apollo-era techniques such as orienteering underscore the limitations of relying on Earth-based systems alone. Ongoing experiments, such as Lunar Pathfinder and LuGRE, aim to understand GNSS signal propagation at lunar distances, while weak-signal GNSS receiver technologies are under development. Key research efforts are centered on assessing signal availability, enhancing ground station performance, understanding navigation accuracy limits, and exploring how lunar missions can benefit from GNSS for orbit determination.

Phase 2: Early Deployment (2025–2030) marks the beginning of deploying dedicated lunar PNT infrastructure. Key orbiting infrastructures include NASA's Lunar Communication Relay and Navigation System (LCRNS), ESA's Moonlight Lunar Communication and Navigation System (LCNS), and Japan's Lunar Navigation Satellite System (LNSS). These systems aim to demonstrate initial PNT capabilities and to focus on interoperability through a collaborative effort known as the Lunar Augmented Navigation Service (LANS). Standards for interoperability are being defined under the LunaNet framework. Early services will mimic terrestrial GNSS broadcast signals, targeting real-time positioning accuracy of less than 10 meters for lunar rovers. Research questions in this phase revolve around system effectiveness, challenges of interoperability, achievable accuracy for surface users, and optimal signal design.

Phase 3: Maturation (2030–2040) envisions full operational capability with expanded service coverage across the lunar surface. Moonlight and LNSS aim to achieve full deployment in the early 2030s. Enhancements include the addition of more satellites, integration of Lunar Surface Stations for improved local signal distribution, and advanced algorithms leveraging Digital Elevation Maps (DEMs) for higher accuracy. High-performance space atomic clocks are introduced to support autonomous operations, and there is growing interest in establishing a lunar time standard, UTC for Moon. Research efforts will focus on the optimal global architecture for PNT, integration of surface infrastructure, long-term clock stability, increased navigation autonomy, and the specific PNT needs of sustained lunar presence and infrastructure.

Specifically, the European Space Agency's (ESA) Lunar PNT roadmap [3] is structured into three phases to progressively develop a comprehensive lunar PNT infrastructure. In Phase 1 (2025 onward), ESA plans to leverage existing Earth-based GNSS signals, such as Galileo and GPS, using high-sensitivity receivers to provide initial lunar navigation capabilities. A key milestone in this phase is the launch of the Lunar Pathfinder mission by Firefly Aerospace, which will carry a GNSS payload to demonstrate the feasibility of using Earth GNSS signals in lunar orbit. Phase 2 (2027–2035) introduces the Moonlight

NAV Initial Services, which will deploy a GNSS-like constellation to support navigation in cislunar space and at the Moon's South Pole. These services will be coordinated with Japan's LNSS and evolve toward Full Operational Capability. Phase 3 (2035 onward) aims to enhance this system with a full constellation and lunar surface infrastructure to provide global lunar coverage and high-accuracy PNT services. This phase aligns with NASA's CPNT architecture, focusing on scalable infrastructure for long-term lunar operations. The roadmap includes building a robust communications network—using direct-to-Earth links, orbital relays, and lunar surface networks—while preserving scientifically important lunar regions.

The Lunar Node-1 Navigation Demonstrator (LN-1) [4], delivered as part of the Commercial Lunar Payload Services (CLPS) Flight: IM-1 by the Intuitive Machines mission in February 2025, represents a major step forward in establishing autonomous navigation on the lunar surface. Designed to support future exploration, LN-1 enables landers, rovers, surface systems, and astronauts to determine and verify their relative positions on the Moon without reliance on Earth-based systems. This compact, CubeSat-sized S-band radio beacon utilizes the Multi-spacecraft Autonomous Positioning System (MAPS) along with pseudo-noise one-way ranging and Doppler measurements to provide local positioning, velocity, and timing data. When activated on the lunar surface, LN-1 functions as a navigation aid, broadcasting state and timing information to assist nearby robotic and human assets in independently determining their location. IM-1 also carries a laser retroreflector (LRA) payload, consisting of eight cube-prism retroreflectors, which will be deployed on the lunar surface to enable precise distance measurements between orbiting or landing spacecraft and the LRA on the lander. Another version of the LRA payload with 48 corner cubes will be equipped to ESA's Lunar Pathfinder in 2026. The LRA on ESA's Lunar Pathfinder will interact with ground-based laser stations [5], as part of the International Laser Ranging Service, which fires short laser pulses at the spacecraft. The LRA's corner-cube reflectors return the light directly to its source. By measuring the round-trip travel time of the pulses, scientists can determine the spacecraft's distance to within centimeters or better. While Lunar Pathfinder relies on weak Galileo and GPS signals to determine its orbit, the LRA provides an independent geodetic measurement, enabling verification and calibration of the satellite's onboard position solutions.

China National Space Administration (CNSA) launched the initiative in 2017 for building the International Lunar Research Station (ILRS) [1], which is a facility that can support human participation and robotic operation jointly constructed by multiple countries on the Moon. The ILRS supports lunar surface activities ranging from operations in localized station areas to the lunar south pole region and across the entire Moon. Positioning accuracy will reach meter- or centimeter-level precision, with velocity measurements accurate to the decimeter per second (dm/s) or centimeter per second (cm/s) level. To enable long-range scientific activities at the south pole and across the Moon, the system will provide positioning and timing accuracies at the 10-meter level, velocity measurement accuracy better than 0.1 dm/s, and timing accuracy at the 100-nanosecond level.

In [2], authors proposed a Chinese cislunar space infrastructure designed to provide both Lunar PNT and data communication services. This integrated system aims to support a wide range of lunar activities, including scientific exploration, crewed missions, and future lunar infrastructure, by ensuring reliable navigation and continuous communication between the Moon, cislunar space, and Earth. In the first phase, satellites would be placed in stable, oval-shaped orbits around the Moon to begin building the system. The second phase would add more of these satellites, along with others positioned at key balance points between the Earth and Moon (called Lagrange points) in NRHO and in a fixed position relative to Earth, serving as a cislunar space station. The third and final phase would expand the system further by placing satellites in distant, stable orbits that loop far around the Moon. Together, these would create a network covering both the area near the Moon and the wider space between the Earth and Moon. The system would also be supported by a network of facilities on Earth to manage operations and communication.

Use Cases and Gaps

Security, Resilience, and Interoperability Capability Assessment

The advancement of lunar exploration and the establishment of sustainable human presence on the Moon necessitate robust PNT services tailored specifically for the lunar environment. Critical use cases for lunar PNT include precise landing and descent guidance for crewed and robotic missions, surface navigation for astronauts and autonomous rovers, timing synchronization for scientific experiments, and coordination of communication and resource logistics within lunar bases or between Earth and the Moon. For instance, accurate PNT capabilities will enable efficient traverse planning over the challenging lunar terrain, improve the safety of extravehicular activities (EVAs), and support autonomous operations by providing reliable positional data in the absence of direct Earth-based navigation aids.

Despite the importance of lunar PNT, current capabilities reveal significant gaps. One of the primary challenges lies in the limited availability and coverage of PNT infrastructure on the Moon. Unlike Earth, which benefits from multiple GNSS constellations and diverse frequency bands, lunar PNT depends heavily on a sparse network of space assets and communication links, mainly operating in the S-band. This scarcity creates vulnerabilities in redundancy and fault tolerance, limiting the system's resilience to failures or interference. Furthermore, lunar environmental factors such as solar radiation, regolith dust, and orbital perturbations introduce unique threats that conventional terrestrial GNSS systems do not face, potentially degrading signal integrity and receiver performance.

Security gaps also pose critical risks to lunar PNT. Current approaches such as Satellite-Based Augmentation Systems (SBAS) and military-grade M-code signals offer some protection against spoofing, jamming, and replay attacks; however, they rely on precise time synchronization and secure key management, both of which are challenged by the lunar environment and emerging technologies such as quantum computing. No experimentation has yet validated M-code's viability for high-altitude or lunar PNT applications, leaving a significant gap in assured, secure navigation for lunar missions. The lack of standardized authentication protocols for lunar-specific navigation signals further exacerbates these vulnerabilities. In addition, encryption methods currently used for anti-spoofing need enhancement to resist future quantum threats, highlighting an urgent need for post-quantum cryptographic solutions and robust key distribution frameworks.

Interoperability between lunar PNT and Earth-based GNSS systems presents another area with considerable opportunities and risks. While compatibility with Earth GNSS provides a starting point for navigation on the lunar surface, signal blockage and degradation in lunar polar regions or rugged terrain could limit the effectiveness of GNSS-dependent methods. Obtaining raw GNSS data from missions like NASA's LuGRE and conducting comparative analyses across various lunar regions will be essential to understand these limitations and develop complementary solutions. Moreover, international collaboration frameworks such as NASA's LunaNet and the Artemis Accords set a foundation for standardization, but political and policy hurdles remain a concern for widespread adoption of neutral, interoperable PNT standards.

Overall, closing the gaps in lunar PNT capabilities will require a holistic approach combining technological advancements, such as infrastructure redundancy and enhanced signal authentication, with international policy coordination to foster interoperability and resilience. Leveraging emerging technologies like post-quantum cryptography, advanced error correction, and radiation-hardened hardware, alongside comprehensive environmental mitigation strategies, can ensure that lunar PNT systems meet the demanding needs of future missions. These improvements will be instrumental in enabling safe, reliable, and efficient lunar exploration and utilization in the years ahead.

Architectural options

When considering the overall architecture for lunar PNT services, there are three main options: an infrastructure-based architecture (such as one anchored by the Lunar Gateway as shown in Fig. 3), an ad-hoc architecture relying on commercial orbiters or landers, and a hybrid architecture that combines both.

Fig. 3: Illustration of Gateway lunar space station orbiting the Moon

An infrastructure-based architecture is ideally suited for providing sustained, high-integrity, and secure PNT in priority regions, such as the lunar South Pole, where long-term exploration and scientific activities are expected to concentrate. The Gateway, with its stable orbit and advanced capabilities, can serve as the backbone of lunar navigation, offering consistent coverage, robust security, and a platform for future expansion.

In contrast, an ad-hoc architecture, leveraging commercial orbiters, landers, or mission-specific relays, offers significant agility and flexibility. This approach can deliver targeted PNT capabilities for specific missions or regions on relatively short timelines. However, without overarching policy guidance and standardization, ad-hoc systems may face challenges in ensuring long-term continuity, interoperability, and consistent service quality across different providers and mission types.

A hybrid architecture presents a compelling path forward. In this model, the Lunar Gateway provides the core, high-assurance PNT service, while commercial orbiters and landers complement this by extending coverage, filling capability gaps, and supporting operations in regions beyond the Gateway's primary service area. This blended approach could harness the strengths of both models — combining resilience, scalability, innovation, and cost-effectiveness — while mitigating the weaknesses inherent in relying solely on either infrastructure-heavy or ad-hoc solutions.

Simulation-based assessments of the PNT architectures and services

The need for dedicated simulation software has been identified as a critical gap in ongoing Lunar PNT research and development efforts. Current tools do not sufficiently address the complex requirements of cislunar and lunar surface operations, particularly in areas involving communication resilience, interoperability, and precise navigation under challenging lunar environmental conditions. To address this gap, we have proposed a set of software requirements that are structured across three progressive phases as shown in Fig. 4. Each phase is designed to incrementally advance the capability, fidelity, and operational relevance of the simulation environment, supporting both near-term technology development and long-term mission planning for lunar and cislunar domains.

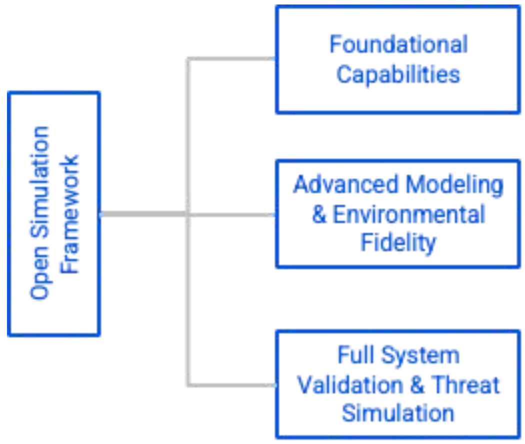

Fig. 4: Proposed open simulation framework for lunar PNT

Phase I focuses on establishing the foundational system-level capabilities and supporting early-stage risk assessment activities. This includes the development and integration of a high-precision orbit propagator capable of accurately modeling lunar and cislunar orbiter trajectories, as well as tools for simulating basic radio frequency (RF) communication payloads and coverage scenarios. These will enable analyses of both orbiter-to-orbiter and orbiter-to-lunar region communication links. Additionally, this phase provides functionality for simulating signal jamming and disruption effects on PNT signals, supporting the assessment of fundamental interoperability scenarios among space-based assets and laying the groundwork for future resilience studies. Existing simulators such as ODTBX, GMAT, and Orekit can be utilized to achieve various functionalities.

Phase II builds on this foundation by introducing more sophisticated models and simulation capabilities. Enhanced communication payloads operating in S-band and Ka/Ku-band frequencies will be supported, with configurable antenna patterns and communication protocol settings to reflect realistic mission architectures. High-fidelity environmental models, such as those accounting for solar radiation effects, will enable more accurate evaluation of cislunar and near-lunar orbiter dynamics. Advanced visualization tools will provide detailed representations of PNT-related spacecraft, offering valuable insights into coverage and geometry considerations. This phase also incorporates support for PNT payload signal reception across both lunar surface vehicles and stationary facilities, as well as orbiters, enabling integrated analysis of end-to-end PNT service delivery. A reporting mechanism will facilitate evaluation of different interoperability scenarios, and the simulation will have the capability to ingest and utilize real-world data collected from high-altitude GNSS experiments and missions, such as LuGRE and the Lunar Pathfinder GNSS payload, to enhance model realism and credibility.

Phase III delivers a comprehensive environment for full PNT scenario validation and experimentation. This includes generating detailed performance metrics aligned with a wide range of PNT-supported services, prioritized according to mission-criticality. The software will support creation and analysis of communication scenarios that evaluate system resilience and security under various threat and degradation conditions. Detailed communication modeling will account for realistic lunar terrain features—such as permanently shadowed regions (PSRs), wrinkle ridges, and expansive plains like Mare Crisium—that could impact signal propagation and coverage. Furthermore, the software will address the communication modeling needs associated with digital twin architectures, enabling integration with broader mission system simulations. Crucially, simulation outputs will be validated against published data and operational benchmarks to ensure reliability and applicability for mission planning and technology development.

Together, these three phases define a robust and scalable simulation framework aimed at closing critical gaps in lunar PNT research and development. By supporting rigorous system analysis, risk assessment, and design validation, the proposed software will play a key role in enabling future lunar exploration and sustained operations on and around the Moon.

Future Capability Needs

In a future 2027 scenario, NASA's Commercial Lunar Payload Services (CLPS) mission [7] would deliver a suite of scientific instruments and autonomous rovers to the Moon's South Pole — a region of high scientific interest due to its permanently shadowed craters and potential water ice deposits. Precise and reliable PNT services would play a critical role in enabling mission success and maximizing scientific return.

For example, upon landing, the lunar lander and rovers would immediately initialize their onboard navigation systems, which integrate lunar PNT signals transmitted from a newly deployed local lunar navigation satellite constellation supplemented by Earth-based GNSS augmentation. These signals provide high-accuracy positioning data critical for safely maneuvering on the challenging and rugged terrain of the South Pole, where visual landmarks are scarce and communication with Earth suffers from delays and intermittent line-of-sight.

The rovers would rely on continuous lunar PNT signals to autonomously navigate across cratered surfaces, avoiding hazardous slopes and coordinating their movements with stationary instruments distributed across the landing site. Timing synchronization enabled by lunar PNT ensures that data collected from temperature sensors, spectrometers, and seismometers are precisely time-stamped, enabling correlation and integration of measurements across multiple locations.

In addition to navigation and timing, lunar PNT's robust anti-spoofing and encryption capabilities protect the integrity of command and telemetry signals exchanged between the lunar assets and mission control on Earth. This security is vital to prevent malicious interference that could jeopardize the mission's scientific objectives.

The redundancy and fault tolerance built into the lunar PNT infrastructure enable continuous operations despite harsh environmental factors such as solar radiation and lunar dust. When solar storms momentarily disrupt direct communication links, local lunar PNT satellites maintain timing synchronization and positional awareness, allowing autonomous systems to operate safely until Earth communication is restored.

By providing accurate, secure, and resilient navigation and timing services, lunar PNT services could empower future NASA CLPS missions and beyond to conduct complex scientific experiments, safely explore the South Pole's unique environment, and pave the way for sustainable lunar exploration infrastructure.

Recommendations

In the short term, **policymakers and regulators** should focus on establishing clear, comprehensive regulatory frameworks that address the unique security and interoperability challenges of lunar PNT systems. This includes mandating authentication standards for navigation signals, enforcing encryption protocols, and encouraging transparency through the sharing of vulnerability assessments. Initial investments and funding support for pilot projects and technology demonstrations are critical to accelerate development and build foundational capabilities. Over the medium term, regulatory bodies need to facilitate the development of international agreements that promote harmonized standards and compliance mechanisms to ensure interoperability and prevent signal interference or malicious attacks. Establishing certification processes for lunar PNT technologies will enhance trust and safety, while incorporating lunar PNT into broader space policy agendas—such as space traffic management—will provide holistic governance for sustainable lunar operations. In the long term, policymakers should lead efforts to negotiate binding international treaties governing lunar PNT infrastructure deployment, sharing, and security to foster collaboration and reduce geopolitical risks. Sustained resources for the development of resilient, multi-constellation lunar navigation architectures will be crucial. Additionally, proactive policies supporting research into post-quantum cryptography and advanced communication security will future-proof lunar PNT systems against emerging threats.

Technology developers should prioritize the short-term creation of lunar-specific hardware and software that address immediate environmental and security challenges. This includes enhancing time synchronization mechanisms critical for anti-spoofing, developing radiation-hardened and dust-resistant navigation receivers, and beginning integration of post-quantum cryptographic algorithms to safeguard future communications. Early prototyping and rigorous testing under simulated lunar conditions will help identify performance gaps. In the medium term, developers must scale these technologies toward interoperable lunar PNT systems capable of working seamlessly with Earth-based GNSS and local augmentation networks. This stage involves building redundancy into system architectures, improving fault tolerance, and developing resilient communication channels among lunar assets. Close collaboration with policymakers will ensure that technological solutions meet evolving regulatory requirements and security standards. Looking further ahead, long-term innovation should focus on deploying scalable, autonomous lunar navigation constellations that provide continuous, high-accuracy coverage and can dynamically adapt to threats or failures. Integrating AI and machine learning for real-time anomaly detection and self-healing capabilities will significantly enhance system resilience. These advanced solutions will underpin the sustainable navigation infrastructure needed for extensive lunar exploration and commercialization.

In the short term, **multilateral coordination bodies** can play a critical role by organizing workshops and expert panels that bring together diverse stakeholders to assess lunar PNT requirements, identify gaps, and share best practices. Publishing open-access reports on vulnerabilities and threat landscapes will promote awareness and collaborative risk mitigation. Initial multinational pilot projects can serve as testbeds for interoperability and security protocols. During the medium term, these organizations should facilitate the creation and adoption of unified lunar PNT standards developed through consensus, ensuring neutral frameworks acceptable to all parties. Coordinating joint exercises that simulate spoofing, jamming, and fault scenarios will strengthen collective preparedness. Promoting transparent data-sharing agreements and collaborative threat intelligence networks will improve overall system security and reliability. Over the long term, multilateral bodies should establish permanent governance structures responsible for overseeing lunar PNT infrastructure and resolving disputes among participants. They can also champion multinational funding programs to build and maintain shared lunar PNT assets. Continuously evolving standards and policies to keep pace with technological advances and emerging threats will be essential for sustained cooperation and safe lunar operations.

The Open Lunar Foundation should, in the short term, act as an impartial convener, bringing together governments, industry, researchers, and international agencies focused on lunar PNT. By publishing foundational guidance documents that highlight key challenges and best practices, Open Lunar can set a baseline for coordinated development. Early coalition-building efforts will identify key stakeholders and foster initial collaborative momentum. In the medium term, Open Lunar should organize recurring forums and working groups aimed at creating shared roadmaps for lunar PNT advancement, emphasizing interoperability and security improvements. Supporting pilot projects and demonstrations that validate collaborative solutions will build trust and accelerate adoption. Providing training and capacity-building resources will empower emerging lunar actors with the knowledge necessary to contribute meaningfully. Looking to the long term, the Foundation's role should evolve into a continuous hub for innovation, knowledge exchange, and standards evolution. By maintaining open-source toolkits and an accessible knowledge base, Open Lunar can lower barriers to entry for new participants and encourage broad adoption of best practices. The Foundation can also champion equitable access to lunar PNT services, ensuring that future lunar infrastructure supports a wide range of scientific, commercial, and governmental users globally.

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