Interoperable Services to Mitigate Lunar Position, Navigation, and Timing Challenges

Cheryl Gramling*, Juan Crenshaw*, Laurie Mann*

*. National Aeronautics and Space Administration, Goddard Space Flight Center, Greenbelt, Maryland, 20771, United States of America, cheryl.j.gramling@nasa.gov, juan.m.crenshaw@nasa.gov, laurie.m.mann@nasa.gov

*Corresponding Author

Abstract
Across the Earth, both civilian and government endeavors enjoy a built-in reliance on a position, navigation, and timing (PNT) infrastructure to which they are largely blind. Whether walking, driving, flying, or orbiting, Earth-centric PNT systems that have evolved over decades provide a core functionality to which we have grown accustomed for these pursuits. As NASA joins with other government space agencies and commercial partners to return humans to the Moon in a sustained manner within the current decade, expectations for PNT knowledge and timeliness at the Moon rival those on Earth. The need exists to develop a viable lunar-centric PNT infrastructure to support the planned human and robotic exploits. Navigating within the influence of the Moon presents its own set of challenges. Identification, understanding, and use of a unified reference frame and time system on which navigation is based becomes a fundamental need at the Moon. In addition to the unified foundational elements, measurement liability, dynamic conditions that require Earth-independent autonomous operations, and standards for PNT signals and message-based data exchange each represent distinct challenges to navigation in a burgeoning operational lunar environment. The PNT services planned as part of the lunar communications and navigation relay architecture known as LunaNet aid in surmounting the challenges. LunaNet interoperability specifications stipulate standards for signal parameters, messages, and lunar reference systems for PNT services. Within LunaNet’s defined interoperability resides the concept of a Reference Signal to provide communication signals specifically structured to enable measurement of pseudorange, Doppler, and time transfer by the recipient. One such signal type, the Augmented Forward Signal (AFS), functions as the mainstay for LunaNet PNT, while also serving the data needs for ubiquitous broadcast of network access and rapid unscheduled dissemination of alerts and messages. The presence of a geographically distributed network of orbiting nodes transmitting the AFS forms the basis for the Lunar Augmented Navigation System (LANS), that delivers both radio navigation and data to multiple users in the lunar environment simultaneously. After reviewing the challenges associated with lunar navigation, this paper will describe the concepts and rationale behind the LunaNet PNT services. By borrowing techniques from Earth-centric Global Navigation Satellite Services (GNSS), the Tracking and Data Relay Satellite System, and the Consultative Committee for Space Data Standards, PNT from LunaNet aids to overcome challenges faced for accurate lunar navigation.
1. Introduction

It is happening, we are going to the Moon – and we are not alone! Under the auspices of the Artemis Accords, the National Aeronautics and Space Administration (NASA) is part of a multinational cooperation seeking to expand human presence to the Moon. A sustainable presence on the Moon ensures preparation for missions to Mars [1]. The placement or orbit regime of operations for lunar missions will be diverse, including assets in orbit around the Moon, transitioning to and from the lunar surface, as well as assets on the lunar surface. As the volume of sojourns to the Moon increases over the next decade, the needs of the human and robotic missions for accurate position, navigation, and timing similarly increase.

All missions have an essential need for cognizance of their Position, Velocity, and Time (PVT) to realize their objectives, whether for purposes of human exploration, science, resource utilization, servicing, or other space-borne activities. In addition to the commonality in the necessity of PVT knowledge, each element will be influenced by other common environmental aspects, such as a complex lunar gravitational potential distribution, and defining their PVT within a lunar reference frame and time system. Despite the commonalities, missions’ objectives call for varying levels of PVT knowledge and timeliness, and missions may choose to satisfy them in different ways, further adding to the complexity of the solution space. This, along with the difference in placements or orbits for missions will set forth a new set of distinctive challenges in each scenario.

Following a description of the multiple challenges in navigating in the lunar and multi-body arena, this paper discusses an approach to providing a unified, global, ubiquitous PNT system under the framework of LunaNet [2]. This paper provides information on the different LunaNet Position, Navigation and Timing (PNT) services, and the rationale behind them, envisioned to serve the exponential growth for PVT accuracy and application in the lunar and cis-lunar environment. These services aim to address and overcome some of the PNT needs and challenges.

2. Lunar PNT Challenges

Navigation for past and current lunar missions depends on Earth ground station communications and tracking networks, such as the Deep Space Network and the Near Space Network, similar stations from international partners such as the European Space Agency (ESA) and the Japanese Aerospace Exploration Agency (JAXA), and the four Lunar Laser Ranging stations. Generally, two- or three-way radiometric tracking range and Doppler, measured from the communications link between the spacecraft and one or two ground stations, are processed in ground orbit determination software. The Magnetospheric MultiScale Mission (MMS) represents a departure from the traditional construct using onboard autonomous navigation flight software to process pseudorange from a weak signal Global Positioning System (GPS) receiver [3]. However, the ground controllers perform the maneuver planning for MMS, as for other cislunar missions. Hence all observables and processing to date for lunar missions has convened in an Earth-relevant environment, with established coordinate frame, time system, measurement and environment models, and ground software. The Artemis mission elements, including the Artemis objective for a sustained lunar presence, Commercial Lunar Payload Services (CLPS), and envisioned lunar science missions represent a burgeoning lunar mission set to motivate a vibrant lunar economy. This increasing mission set presents a burden to the currently overloaded ground networks. In addition, these upcoming lunar missions differ from the Apollo missions of the 1960’s and even the recent lunar orbiting missions such as the Lunar Reconnaissance
Orbiter (LRO) [4] and Gravity Recovery and Interior Laboratory (GRAIL) [5], because prime objectives reside in the lunar South Polar or far-side regions out of view of Earth, or in preparation for human exploration at Mars that encounter round trip light times to Earth as long as 45 minutes when the view is not occulted. These conditions drive the need for crew and robotic autonomy, and Earth-independent PNT.

The key challenges in the lunar regime for position, navigation, and timing can be categorized into seven areas discussed further in this section: Reference System, Measurement Liability, Autonomy, Timeliness, Resource Constraints, Security, and Standards.

2.1 Reference System

Transit to, orbiting, landing, or operating on a celestial body requires a defined coordinate frame of reference for that body that relates to the International Celestial Reference Frame (ICRF) and to Earth’s inertial reference frame as a fundamental element for navigation. Differences in reference frames introduce significant error; for example, the lunar Mean Earth Rotating and the Principal Axis frames differ by approximately 860 meters at the lunar surface, increasing the offset with distance from the Moon [6]. In addition to the reference frame, the reference time system must be adhered to since offsets in time knowledge directly contribute to radiometric tracking errors that serve as a basic data set for navigation. This includes accounting for relativistic differences between the time system source and the location of the user. For example, on average, a clock on the lunar surface will drift 56 microseconds per day in relation to a clock on Earth. However, the range of the offset varies depending on the lunar distance and libration with respect to the earth and the gravitational density at the lunar clock location. Of utmost importance, all human or robotic assets in the lunar regime must navigate within the same reference frame and time system to land at the correct location, assure situational awareness to avoid collisions, and execute science. Thus, the reference system consisting of the ephemeris of the center of mass, frame axes and orientation including libration parameters, gravitational potential model, definition of a geoid of equipotential gravity, an ellipsoidal shape, coordinate transformations, cartographic products, and synchronized time knowledge must be known, disseminated, and adhered to as a mainstay for safe, accurate, and autonomous navigation operations in the lunar regime. Figure 1 shows the relationship between the ellipsoid, geoid, and topographic surface components of a lunar reference system.

2.2 Measurement Liability

Relying on one measurement source and type to solve navigation introduces risk in achieving accurate observability of any system. Firstly, a single data source may introduce a bias that only becomes observable by incorporating additional data sources. Secondly, the data may not always be available due to occulted line-of-sight, maintenance outage, or system interruption. Thirdly, navigation solutions are highly dependent on relative geometry between observer and that which is observed as well as the accuracy of the observation. For example, measurements solely along a single angular line-of-sight with little to no variation, offer observability in only one dimension. Maps with insufficient resolution hamper their usefulness for navigation. In addition, the lunar landscape, in particular the areas of interest for Artemis exploration and lunar science, incur stark lighting conditions or suffer from illumination deficiencies; Figures 2 and 3 show representative examples of lunar lighting, courtesy of the Johnson Space Center Simulation and Graphics Visualization Team. Low solar elevation angles direct the sunlight along the surface with no atmospheric refraction to diffuse the light. The South Pole and Permanently Shadowed Regions have sustained periods without light. The starkness coupled with lighting variability and long distances of shadows provides challenging conditions for visual- (human eye) or image-based (camera) navigation. Thus, sole dependence on one particular data source introduces risk to achieving mission objectives.
However, multiple data sources or data types deliver other challenges. Considerations such as weighting the respective data type and source in the navigation solution in accordance with the expected system noise and bias; accurate data modeling including appropriate partial derivatives of the state estimate according to observability; resolving discrepancies across disparate measurement types; and adequate application of fault detection and observation editing, each come into play to obtain a reliable navigation solution. Overall, appropriate attention to those considerations in fusing multiple data types and/or sources into the estimated state offers the resiliency needed for autonomous operations.

1.3 Autonomy

Several mission scenarios planned for Artemis require autonomous operations [1],[8] that rely on near real time navigation knowledge updates for success [9].

- Highly dynamic trajectories, such as orbit insertion, surface descent to landing and ascent, or rendezvous and proximity operations.
- Robotic or crewed surface traverses and operations that take place in extreme environments with limited communication or line-of-sight with an operations center that impede meeting timing constraints, for example from oxygen limits on extravehicular activity suits.
- Between the shorter duration early Artemis missions, NASA and its partners plan to land cargo and components for terrain mobility and a permanent Artemis Base Camp. [1] Telerobotic operation of surface vehicles will occur to prepare for crewed missions by deploying the landed cargo or accomplishing other logistics.

Many of these scenarios require navigation knowledge relative to another object in real time to operate autonomously and meet mission objectives. Autonomous operations require validated data sources, processing systems, and fault detection and correction/recovery to achieve real time navigation updates. Given the lack of existing infrastructure on the lunar surface, such as roads and power supply, the lighting constraints described above, and the unintuitive horizon on a smaller body than Earth [10], autonomous activities obligate missions to seek robust and ubiquitous solutions to empower the PVT knowledge needed for global freedom to operate at the Moon.

1.4 Timeliness

In parallel to the autonomous operations, the highly dynamic scenarios discussed above dictate timely updates to the navigation, guidance, and control, to either plan the next propulsive maneuver during a descent or ascent phase, to limit crew hours of operations by reducing dwell times in orbits to obtain a navigation update, or to avoid hazards during terminal landing sequence. With a growing number of objects in the lunar orbital environment, situational awareness becomes a critical capability and introduces another use case requiring near real time decisions on risk mitigation maneuvers. In-situ sensors such as accelerometers, gyros, or inertial measurement units (IMU) provide direct sensing of non-gravitational forces, but require calibration and drift removal. Today on Earth, IMUs are coupled with radionavigation sources Error: Reference source not found.[12] to enable closed-loop control on the navigation solution for safe guidance.

Crew traverses, robotic logistics preparation, and some sample location tagging and science investigations on the surface require accurate real time positioning. Often times, the navigation knowledge needed in these use cases is relative to a local grid or asset. By virtue of the science and exploration objectives sought, missions descending to and on the lunar surface will encounter stark lighting conditions, either in deeply shadowed regions or with the Sun at low elevation angles skimming the horizon undiffused by atmosphere. The variable, glaring, or lack of lighting restricts navigation efficacy based on camera imagery for terrain relative navigation. IMUs and celestial object navigation, useful
for orientation, limit the achievable localization solution accuracy.

2.5 Resource Constraints

As with any spaceflight mission, size, weight (or mass), and power (SWaP) limits apply to orbital and surface vehicles and crew. Consideration for carrying multiple unique sensors and the associated harnessing and computer processing must be balanced with the ability to achieve the required timely navigation or positioning accuracy. An integrated multi-functional sensor and processing suite capable of processing a fused set of data inputs such as an IMU, camera image processing, and radionavigation provides a sound and low SWaP solution for navigation. However, such a suite does not currently exist and achieving the technology readiness level for space qualification of an integrated sensor suite takes time. Similarly, the ramifications of implementing disparate, non-interoperable, or non-compatible systems with no unified orchestration of the observation sources and/or processing layer reduces reuse, leading to the potential increase in SWaP to manage different sources.

2.6 Security

Distribution of radionavigation signals come with vulnerabilities [13]. System design must account for both in-band and out-of-band interference, especially in suppressed carrier signals such as Global Navigation Satellite System (GNSS). While there is no ionospheric scintillation, the lunar environment is susceptible to space weather events capable of interfering with low power radio signals. In addition, unless embellished by a repeater, radionavigation signals from orbiters or surface elements are unavailable in confined, undersurface areas, such as lava tubes. Under any circumstance, a higher-powered signal acts as a jammer for the weaker radionavigation signals.

Lunar dust from surface activity may preclude reliable use of fiducials or reflective surfaces for near-field relative navigation. Electrically charged particles at the lunar terminator, driven by the solar wind plasma and ultraviolet radiation increase the lunar dust loft. Large topological features in the local area that create positive and negative charged surfaces amplify the dust loft effect and introduce an electric field on the surface that may impact science instruments or navigation systems [14],[15].

2.7 Standards

Contributions from many partnering entities are expected to field the infrastructure necessary for PNT at the Moon. To effectively employ a disaggregated approach to orbiting relay or surface radionavigation signals, to enable a plug and play system for vendor-specific sensors or software tools, and to distribute unifying reference system, time transfer, and cartographic product updates requires defined standards and interoperability among these specialized systems. This applies to all radio or optical signals; PNT and data exchange messages; sensor, software and processor interfaces; and reference system definitions. Strict adherence to standards and interface definitions for interoperability enables alignment among systems that provide PNT services or capabilities and expectations among the PNT user community at the Moon.

3. LunaNet Overview

LunaNet is envisioned as the central piece to the deployment of an infrastructure at the Moon which will help solve the navigation and communications challenges discussed in the previous section. LunaNet will be based on internationally agreed standards and protocols which ensure the infrastructure can grow with increasingly complex user needs. [2][16][17]

LunaNet does not represent a specific implementation of an architecture but rather a set of ground rules by which each provider or user of services can interface within that set framework. These users and providers of services include US and international governments, universities, and commercial partners. As an example, the NASA Lunar Communication Relay and Navigation System (LCRNS) [18][19] intends to provide navigation and communication services at the Moon with an architecture and implementation which may be different from the European Space Agency’s (ESA) Moonlight program [19][20]. However, users will be able to interface with and benefit from services from an amalgamation of both programs as they intend to be compliant with the LunaNet framework. In addition, the LunaNet framework includes standards for service provider-to-service provider interfaces as well as time and reference frames. These are crucial building stones to ensure that missions at the Moon have a common language by which they communicate information akin to the standards we now have on Earth.

There are currently four major types of LunaNet services identified: Networked Communication Services, Position, Navigation, & Timing Services (PNT), Detection and Information Services, and Science Services. Networked communication services will cover real-time transmission of critical data, store-and-forward data transmission and relay of data between surface users. PNT services, which are detailed in the next section, will include dedicated or broadcast one-way signals for pseudorange and Doppler usable for accurate in-situ navigation solutions. Detection and information services are envisioned to be dissemination of alerts such as space weather events, collision avoidance or surface impact predictions, and search and rescue support. Finally, science services enable precept
observations from LunaNet signals and dissemination and usage of sensor/instruments data across the architecture, as well distribution of scientific products such as solar terminator charging.

Fig. 4. Illustration of the various LunaNet services link. [credit NASA/GSFC]

These services will be provided via different types of links as shown in Fig. 4: user-network proximity links (space-to-space or space-to-lunar surface), network to Earth trunk links and within network crosslinks. While not planned in the early stages of the navigation and communication Moon infrastructure, the standards will be augmented to support in-situ user-initiated service request as well as optical links which are the next steps in further removing reliance on traditional Earth-based services.

3.1 LunaNet Services

As described above, historically and up to this date, methods in place to provide navigation to lunar missions involve the use of coherent radiometric links with Earth ground stations, that perform 2-way or 3-way Doppler and/or ranging measurements. While coherent measurements provide users with a method to obtain very accurate line-of-site observables, attaining a final navigation solution requires a combination of them from a variety of geometrical perspectives. As shown in Figure 5, adding lunar assets that provide additional observational geometry greatly improves upon the limited dilution of precision (DOP) offered by Earth-based stations. Therefore, LunaNet incorporates different options to support coherent Doppler and range measurements, in service of missions that continue to employ the coherent radiometric approach.

The straightforward option consists of performing 2-way Doppler and range measurements by LunaNet assets in analogous fashion to ground stations. A signal originating from a LunaNet source is coherently turned around by the user and returned to the source, where the incoming signal is compared to the transmitted. Ranging measurements utilize a specialized signal, with a non-spread-spectrum version based on Pseudorandom-Noise (PN) codes that reduce the power and spectrum available for data transmission. The spread-spectrum version requires a regenerative ranging transponder on the user end, with the benefit of allocating transmitted power and spectrum for data throughput.

2-way measurements employ dedicated links that do not occur simultaneously from each provider asset, tying up scarce provider network resources as depicted in Figure 6, and complicating scheduling and planning of services.

Fig. 6. One provider to one user dedicated link for 2-way metric tracking

Non-coherent 1-way measurements carried out by users have the potential of resolving the limitations imposed by dedicated coherent links, however present another set of challenges. Differences in frequency references between signal source and sink result in unresolved biases in the Doppler measurement. Likewise, time offsets between source and sink exhibit unresolved biases in the pseudorange measurements. Developments in flight-qualified, low SWaP stable frequency oscillators enable users to estimate biases over time, when presented with varying dynamics and observables from multiple signal sources.

Fig. 7. Multiple users serviced by a single lunar asset

LunaNet supports 1-way forward services by providing reference signals. These signals serve multiple users that are in the field of view, in a one-to-many approach as illustrated in Figure 7. While accommodating Doppler by offering signals with well-
known frequency characteristics may be straightforward, incorporating pseudorange-enabling signals begs for special considerations. The phase of the ranging signal at the source, related to specific time intervals, must be conveyed to the user for the computation of the pseudoranges. Typical ranging signal sequences utilized by Earth ground networks are not usually aligned with integer seconds to form a rational time base. These sequences are normally coherently related to the transmitted frequency. The complexity lies in the fact that each second is likely related to a different ranging signal phase, and it becomes a burden to inform the user efficiently. One option is to select discrete center frequencies which align the ranging patterns with integer time steps. As autonomous in-space navigation expands, Earth ground stations will need to evolve their methodologies to support 1-way forward reference signals.

Up to this point, the discussion focused only on dedicated signals in support of navigation, which results in observables separated in time (Figure 8, left), requiring navigation systems to obtain solutions by combining measurements over long periods. Ideally, a user would receive multiple reference signals simultaneously from geometrically diverse sources (Figure 8, right). When processed together, accurate and timely PVT estimates are derived, drastically reducing the need for extremely sophisticated frequency and timing reference sources on the user end.

Many Low Earth Orbit (LEO) missions are now utilizing GNSS-based navigation receivers onboard. GNSS services are intended to serve Earth users, with official service volume provisions for space-based radionavigation only for Earth orbits in space between 3,000 km and Geosynchronous Orbit (GEO) with altitudes of approximately 36,000 km [13]. However, by application of weak signal reception techniques, the MMS mission receives GPS signals for accurate navigation at 29.4 Earth Radii, half-way to the Moon, and serves as an empirical calibration for simulations at longer ranges. At lunar distances, GNSS signals are few and faint, requiring a large antenna and specialized equipment onboard; navigation solutions rely on sequential estimation over a period of time to compensate for the limited GNSS DOP when at the Moon. Even then, the resultant DOP limits PVT accuracy, and the GNSS signals suffer from occultation when blocked by the Moon.

The idea of directly transporting the GNSS solution by incorporating transmitters in the lunar environment comes to mind. However, interference in both directions, near-far signal strength problems, and frequency considerations for the Shielded Zone of the Moon call for a dedicated frequency for the application of lunar navigation services. In fact, the Space Frequency Coordination Group (SFCG) has allocated the band within 2483.5 MHz and 2500 MHz for radionavigation satellite services in the lunar environment [21].

LunaNet introduces the Lunar Augmented Navigation Service (LANS) that purposefully intends to promote significant GNSS technology reuse to allow for a more feasible implementation by industry and capitalize on the one-to-many/many-to-one features of GNSS (see Figure 9). The LANS is envisioned to provide standard PNT capabilities for the lunar environment, in addition to limited low-rate data message transmissions. Data dissemination via messages embedded in the LANS signals are tailored to meet the lunar environment needs. In particular, ephemeris products will be tied to the lunar reference frame and time system instead of the Earth reference frame and UTC. The augmentation for PNT comes from data messages needed to sustain operations in the evolving lunar environment, such as lunar orientation, and coordinate transformations, with additional features for common data needed to serve autonomous and safe operations at the Moon, such as conjunction messages.
Fig. 9. Lunar Augmentation Navigation Service (LANS) provides multiple simultaneous reference signals for PNT services [Courtesy ESA]

Other 1-way forward reference sources under consideration, but not directly part of LunaNet at this time, are signals simultaneously transmitted from different Earth locations. [22][23]. While the large DOP presented by Earth transmitters at lunar distances and their inaccessibility to the far side of the Moon are limiting factors, such sources may contribute to an overall solution when in combination with sources in orbit about the Moon. Some missions can use such services alone if their PVT requirements are coarse or they heavily constrain operations, such as filtering observations for extended periods of time, including onboard clocks with good long-term stability.

Additionally, LunaNet devises performing 1-way return (i.e., user-to-relay) measurements, including Doppler and pseudorange observables. As capabilities build and the number of relays increases, such measurements enable localization techniques such as Time Difference of Arrival (TDOA). A possible application for TDOA is Search and Rescue (SAR) localization. Such a process involves an orchestrated support from LunaNet elements, measuring a specific signal simultaneously in concert, and forwarding the observables to a centralized system for computation.

3.2 Messages

The lunar ecosystem warrants the development of a set of messages that enable communication and navigation services by LunaNet, allow lunar elements to exchange standard products, provide a channel for assets to alert and remain informed of current conditions or risks, and offer a means of unifying operations in the environment. Establishing common message formats and dissemination methods empowers providers and users to develop missions with decreased effort and time dedicated to establishing distinct interface configurations.

Generic messages that support LunaNet services address network access information, health and status, asset characteristics, link schedules for users, and user requests and acknowledgements. These messages resemble a service catalog and associated queries.

LunaNet PNT services are fulfilled not only by providing reference signals or measurements, but also by communicating indispensable information to/from users. PNT related messages include PVT of lunar assets, definitive or predictive orbital products, ranging signal data, time synchronization parameters, maneuver data, attitude data, PNT measurements, lunar reference system information, reference system conversions, and lunar Digital Elevation Maps.

Situational awareness is promoted by messages conveying alerts such as Space Weather events and possible asset conjunctions. LunaNet collects and disseminates these messages as required to assets in the relevant environments. The lunar SAR function is envisioned as a special instance, consisting of an initial SAR alert by the user, followed by acknowledgment and response messages conveyed through LunaNet assets.

LANS includes low data rate messages employed in enabling the PNT function, however is also utilized as a platform to disseminate information of the overall network, active alerts, SAR service, and other low data rate messages. While data throughput is expected to increase slightly from what is provided by current GNSS, large messages such as high-fidelity digital elevation maps are transferred via higher rate communication channels.

3.3 How LunaNet Aids in Overcoming Challenges

In-situ navigation for a sustained duration at a central body necessitates clear and unified understanding of that body’s reference frame and time system. In the same manner by which GPS directly ascribes to and distributes the canonical World Geodetic Survey (WGS-84) and Universal Time Coordinated (UTC), LunaNet PNT services become distributors of the Lunar Reference Frame (LRF) and Lunar Time. Surface realization points consisting of precision clocks and surveyable instrumentation such as laser retroreflectors and structured radio frequency signals serve to tie the LunaNet constellation to the LRF and synchronize to Lunar Time via two-way satellite time transfer. Constellation synchronization occurs via crosslinks between LunaNet orbital nodes for both relative navigation observables and node-to-node time transfer and synchronization. The comprehensive synchronized Lunar network of surface realization assets and orbital nodes to distribute a common reference system enables accurate navigation relevant to an inertial body frame and time system.
The disaggregated set of orbital nodes providing PNT services provides a one-to-many and many-to-one scenario for navigation of the receiving user. The combination of these different provider assets mitigates reliance on any one PNT service provider. Offering PNT services via the LANS as well as via Peer-to-Peer (P2P) signals further distributes the dependence on one particular measurement source, which is a necessary feature for autonomous navigation as it allows for fault detection through comparative measures. While not an exclusive source for navigation observations, LunaNet offers a core PNT service with ubiquitously present LANS for an always-available service that occurs independent of lighting conditions. The specified accuracy and availability of LANS, identified by a Signal-In-Space-Error and Service Volume, serves as a backbone for in-situ navigation in the lunar frame. Observables from LANS can be readily fused with optical (image-based) navigation or other observables, such as range from surface cell signals or high-rate optical communication links, or IMU data. Through proper weighting in the estimation process, the fused set of direct or differenced observations supplies both absolute and relative position, velocity, and time knowledge in lunar orbit and on the lunar surface through dynamics periods such as descent, landing, and surface rover operations that require timely updates. Even though the round-trip-light-time (RTLT) between the Earth and Moon is less than three seconds, the areas of interest for planned Artemis campaigns lack line of sight to Earth, and must rely on lunar-centric capability for autonomous navigation. In turn, Earth-independent operations at the Moon enables preparation for future human missions to Mars, where RTLTs up to 45 minutes induce restrictions for Earth-based commanding, especially when engaging in regular real-time dynamic exploration activities. The design for LunaNet with both LANS and P2P signals offering PNT observables, enables the timely position and velocity updates needed for autonomous operations, especially when coupled with direct sensing of accelerations through an IMU. LunaNet’s orbital nodes’ proximity to the Moon allows for signal power and data exchange rates tailored for users in the lunar environment. In turn, the proximity of LunaNet to the end user reduces the SWaP burden on the users’ receiver and processing system compared to a system needed to receive or transmit data from/to Earth-based networks or PNT provider systems. In a similar way that GPS receivers fit into a smartphone form factor for terrestrial users, the concept translates readily to a user terminal for real time PVT knowledge for human traverses on the Moon via LunaNet, albeit at an increased SWaP for radiation tolerance. As seen in Table 1, this represents a significant savings compared to a GNSS weak signal receive and antenna system and a terrestrial communications uplink receive and antenna system. Table 1. Notional User Terminal Size, Mass, and Power (SWaP)

<table>
<thead>
<tr>
<th>Element</th>
<th>Size (cm³)</th>
<th>Mass (kg)</th>
<th>Power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low SWaP LANS Receiver for Surface User</td>
<td>10 x 10 x 4.5</td>
<td>0.5</td>
<td>4.0</td>
</tr>
<tr>
<td>USO</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S-Band Omni Antenna</td>
<td>4.8 x 4.8 x 1.5</td>
<td>0.06</td>
<td>&lt; 0.11</td>
</tr>
<tr>
<td>Total LANS Receiver</td>
<td>484.6</td>
<td>0.56</td>
<td>4.11</td>
</tr>
<tr>
<td>GNSS Receiver</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GNSS Radio with Processor and USO</td>
<td>10.5 x 11 x 9.5</td>
<td>2</td>
<td>50.0</td>
</tr>
<tr>
<td>LNA</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GNSS Antenna Array with S-Band Radio and LNA</td>
<td>43 x 43 x 2</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Total GNSS Receiver</td>
<td>4,795.3</td>
<td>4.0</td>
<td>50.5</td>
</tr>
</tbody>
</table>

Source: Based on commercially available products, notional only.

Secure signals and services provide an underlying philosophy of the LunaNet framework. Considerations include measures for authentication and jamming protection. As conceived, LunaNet relies heavily on interoperability definitions to facilitate a collection of providers for the services envisioned at the Moon and thereby streamline the user burden for receiving and processing those amalgamated signals. Use of the collective to constitute a complete system necessitates perhaps even greater interoperability and data sharing than currently employed in terrestrial GNSS. The LunaNet Interoperability Specification [17] and the associated Applicable Documents provide standards to define these interoperable services. While LunaNet aims to provide an internet-like user experience coupled with the benefits of terrestrial GNSS, the non-terrestrial nature of LunaNet introduces long-term remote operations and orbital dynamics that drives to a broad and deep level of standardization. Time Management, data exchange via Messages, specific signal structures for PNT and data exchange, data routing and network protocols, as well as the Lunar Reference System each require documented standards. The LunaNet Interoperability Specification set of documents continue to evolve to optimize the green field of operations at the Moon.

4. Path Forward
In planning for the deployment and operations of a lunar infrastructure at the Moon which supports in-situ accurate navigation around the Moon and on the lunar surface, much work is needed to ensure its success within the LunaNet open framework.
This infrastructure is essential to all missions heading toward the Moon and beyond and is a steppingstone in enabling human exploration and science advancement (see Figure 10). Consequently, it will involve international collaboration and inter-agencies coordination. This section outlines the many areas of collaboration being worked and the inter-dependencies.

Fig. 10. Overview of various lunar PNT infrastructure components and their intended users.

**Lunar Reference Frame and Timing Definition**

Time is a critical component of any navigation solution and establishing an in-situ lunar time reference such as is available on Earth allows for accurate time knowledge and synchronization of any architecture at the Moon and mitigating errors associated with relativistic effect estimation. To do so, one could deploy a network of very stable clocks on the Moon’s surface and define a Lunar Master Clock through an in-situ voting and estimation process. Defining the resultant lunar time relationship to UTC enables knowledge with respect to an Earth time system. Time knowledge directly impacts navigation, and differences in application of time introduce navigation errors. As an example, a one nanosecond time error contributes to 0.3 m in position error.

In addition, if these clocks were coupled with sensor/instrumentation which allowed their accurate surveying on the Moon’s surface via retroreflector and/or fiducial and measurement of the local gravity and lunar orientation, they would then provide a very accurate definition of Lunar Time, Lunar Reference Frame and associated lunar properties. These accurate time/surface anchor points equipped with an RF transponder could then transfer time to lunar assets as well as transmit their known position for use in an onboard navigation solution on the surface or in orbit about the Moon.

NASA and its partners are studying concepts and deployment for initial lunar realization reference(s) to initiate such an infrastructure. There are many challenges to overcome, including designing a unit which would be capable of surviving lunar night. This effort overlaps with the reference frame and timing standards Applicable Documents in the LunaNet Interoperability Specification [17].

4.1 Lunar Surface Infrastructure

Fig. 11 illustrates surface assets beyond the ones discussed previously in support of time and reference systems. These modules can also be an essential part of the overall navigation architecture. They could retransmit a signal from an astronaut’s suit or another nearby surface user to a LunaNet-based orbiting network or could be used as a calibrated source to certify on-boarding new LunaNet service providers. In addition, they could generate a navigation signal on the surface to be used for localized navigation. The overall concept of operations for such surface assets is in development and may take various implementation paths as technologies are studied and deployed at the Moon. For example, Third Generation Partnership Project surface network is currently under investigation to evaluate its applicability and usefulness at the Moon, including provisioning of navigation-quality signals. A first demonstration of Fourth Generation Long-term Evolution (4G/LTE) is planned for late 2022. [4].

Fig. 11. Surface-to-Surface Communication and Navigation Illustration.

4.2 LunaNet Interoperability Specification

LunaNet relies on signal standards for both communication and navigation. Efforts have started laying out the path forward in defining adequate navigation signals including spectrum allocation, signal modulation and coding, and their associated data rate for each considered services [17].

The main signal for navigation is the Augmented Forward Signal (AFS) under the LANS as shown in Figure 12. Combining the signal specified as PFS5 with the messages (MSG in figure) forms the AFS. When multiple LunaNet Service Provider, noted as LNSP in the figure, provide AFS, it becomes the LANS.
Performance factors such as data rate, tracking jitter, emitted out of band interference, data/pilot channel interference, as well as how much leverage of/overlap with current Earth standards are being considered as performance evaluation metrics. Once the AFS signal is agreed upon, similar spectrum, channelization, modulation, and coding analyses will be conducted on dedicated peer-to-peer signals, return signal such as the ones needed for Search-And-Rescue, as well crosslinks between service providers. It is critical that spectrum allocations agreements are done as early as possible for all the LunaNet signals to ensure that these signals can exist in the future in an already limited spectrum environment without crippling interference. The latest version of the signal definitions will be captured in the LunaNet and User Signal Structure Definition Document [17].

Another very important aspect of the interoperability specification is the message definition, not only of the format and content but also the associated update rate, transmission cadence, and expected accuracy and latency as those parameters levy requirements on the service providers. An initial set of messages has been identified for navigation services, and the effort continues to establish the details and associated analysis/testing for validation. These message definitions will be captured in the LunaNet Detailed Message Definition Document [17].

### 4.3 LunaNet Concept of Operations

Each major program/project such as LCRNS and Moonlight are developing concepts of operations within their organization and within the framework of LunaNet. Work is underway on the LunaNet-based architecture concept of operations for scheduling, prioritizing, and managing services across the multiple providers and users of each program/project. This will necessitate coordination between international agencies and industrial partners to ensure availability of the full aggregate of services.

### 4.4 LunaNet Architecture, Constellation Design, and Topology

The ultimate topology of the architecture will be driven by the deployment of the selected service types and orbits as well as crosslink abilities among the various LunaNet providers and associated programs. Consequently, there is a large effort underway to identify collaborations and synergy between the intended participants to ensure that the architecture topology can support viable time synchronization/data distribution across assets, which minimizes Earth reliance, as well as the coordinated constellation geometry essential to navigation solutions.

### 4.5 LunaNet User Terminals

In parallel with the interoperable signal being defined, user terminals capable of using these navigation signals need to be developed and tested. Besides processing the LunaNet signals from multiple providers into navigation measurements, they must do so in-situ and fuse other types of navigation observables to derive their own PNT solution. Current GNSS receiver techniques and packaging must be applied to RF modems for multiple LunaNet PNT signals to be simultaneously accurately received. Localization algorithms need to be studied to identify optimal sensor fusion across many different types of observables, especially in the initial operational capability period with limited orbital and surface assets deployed and the planned use of IMUs and imagery. This is especially relevant to the surface user as its predicted position will not be governed by astrodynamics modeling, but rather follow an unpredictable motion.

### 4.6 LunaNet Earth Assets

As equally critical to the LunaNet architecture are the Earth assets used to route command, telemetry, and data to and from the Lunar Architecture. While an in-situ architecture with onboard navigation will remove a large portion of the Earth reliance for navigation signals or data routing, there are still needs for communication with Earth for provider assets basic health and safety checks, upload of software upgrades, exchange of architecture data (not carried over crosslinks), and recovery from unforeseen faults. However, the current DSN network is very much oversubscribed. Network upgrades to support the expected load are currently underway within NASA at the DSN and new sites referred to as Lunar Exploration Ground Site (LEGS) [25].

### 5. Conclusion

As we further our exploration of the Moon and beyond, we need to incrementally build a lasting and
evolvable architecture to provide basic support to sustained human presence on the lunar surface and in the lunar environment. This infrastructure, just like on Earth, requires positioning, navigation and timing as a critical resource for humans’ and robotic assets’ health and safety. This paper provides an overview of the PNT challenges addressed by using an interoperable LunaNet framework, the current standards developed, and the work ahead for NASA and its partners in deploying such an architecture at the Moon.

As we once again prepare to step on the Moon’s surface, the PNT architecture lays out part of the foundation to enable sustaining human presence beyond Earth and advancing our understanding of the universe.

6. Acknowledgements

The authors thank the NASA Johnson Space Center (JSC) Virtual Reality team for the representative illumination scenario simulation shown in this paper. The Space Communications and Navigation program sponsors the LunaNet effort within NASA.

7. References


13
submitted for peer review to NAVIGATION (Journal of The Institute of Navigation).


