LunaNet Position, Navigation, and Timing Services and Signals, Enabling the Future of Lunar Exploration

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# Biographies

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**Dr. Ventura-Traveset** is working at ESA since more than 30 years, having been involved in multiple space programs, covering

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Lunar Pathfinder and Moonlight. He is also the Executive Secretary of the ESA GNSS Scientific Advisory Committee.

# Abstract

The International Space Exploration Coordination Group established in 2018 the 3rd edition of the Global Exploration Roadmap (ISECG, 2018) that aims to achieve Mars human surface activities and identifies the exploration of the Moon as a critical intermediate step. A supplement covering updates on surface exploration scenarios was released in 2020 (ISECG, 2020). The Artemis Accords (NASA Artemis, 2020), first signed in October 2020, now includes over two dozen nations, in an agreement on the principles for best practices, including interoperability. In September 2022 the National Aeronautics and Space Administration (NASA) introduced the Moon to Mars Objectives highlighting recurring tenets of collaboration with international and industry partners and interoperability, along with infrastructure objectives for Position, Navigation, and Timing (PNT). The successful Artemis 1 mission paved the way to the ambitious plans to establish a sustainable human presence on the Moon. Just a few months after Artemis 1 launch (NASA, 2022), iSpace HAKUTO-R Mission1 (iSpace, 2022) launched, being the first-ever mission launched by a commercial launch service provider aiming to land on the lunar surface. The NASA Artemis program plans initial crewed landings and surface traverses in 2025, supported by the Lunar Gateway. Regular launches will follow to build the lunar systems for a sustained presence as presented in the Artemis Plan (NASA Artemis Plan, 2020), (NASA, 2022). NASA’s contracts with commercial providers through the Commercial Lunar Payload Services program (CLPS, (NASA, n.d.)) will deliver science and technology demonstration missions to the Moon starting in November 2023. The European Space Agency (ESA) Argonaut (ESA Argonaut, 2022) program plans to have recurrent missions to bring payloads to the lunar surface, supporting lunar exploration. These are just a few examples of planned missions that will target Earth’s natural satellite in the next decade, with forecasts of tens of missions per year (NSR, 2022), (Euroconsult, 2020). The large number of missions and the complexity of landing and operating are expected to demand a change of paradigm from the current Earth-based communication and navigation services, that may be combined with onboard sensors. In recent years, several agencies have proposed to deploy cislunar communication and navigation services to support lunar missions (NASA LCRNS, 2022), (ESA Moonlight, 2022), (JAXA, 2022)). All these proposals seek to deploy service-providing satellites in lunar orbit to ease the user missions’ operations. The PNT services objective is to support all types of lunar users (e.g.: orbiters, landers, ascent vehicles, surface crew, rovers, and deployed science payloads). At the same time, NASA and ESA initiated an effort to define a common framework to ensure interoperability among different service providers: the LunaNet framework. The LunaNet Interoperability Specification (NASA and ESA, 2023) covers communication, PNT, and auxiliary services, by establishing a common set of requirements to ensure interoperability. This conference contribution will present the LunaNet PNT services, focusing on the Lunar Augmented Navigation Service (LANS) that would be provided by a system that resembles the Global Navigation Satellite System (GNSS) concept on Earth: constellations of satellites broadcasting a radio navigation signal synchronized to a common reference clock, with augmentations to accommodate users’ needs in an environment away from Earth. This paper includes a description of the high-level LANS concept, and the basic principles defined to ensure interoperability. In addition, it will describe the common S-band PNT Augmented Forward Signal (AFS) and common messages to be adopted for compliance with the LunaNet framework, and the justification of the selected approach.

**1 INTRODUCTION**

The past years have marked the beginning of a new era for human solar system exploration, with plans underway for a sustainable human and robotic presence on the Moon. In the last 10 years, more than 10 missions have been launched to Earth’s natural satellite, and many more are foreseen to be launched in the next decade (NSR, 2022), (Euroconsult, 2020). The current approach that relies on Earth ground station networks will not be sustainable in the long term. The use of ground stations for communication and navigation services have shown its limitations in the recent past (Space.com, 2022) and, despite recent efforts by multiple agencies to increase the ground network capabilities, it is becoming evident that in-situ services will be paramount to support future lunar exploration. The extensive dissemination of internet, mobile wireless, cellular networks and GNSS on Earth is attributable to the ease of developing user terminals that are compatible with every network. Standardization processes have been and remain central to adoption of new technologies. Today’s Earth-based communication service providers unquestioningly adhere to the existing standards. Concurrently, the large success of GNSS can be attributed to the agreements to achieve interoperable signals. In addition, even if not formally required, GNSS service providers aim to align their system time to Coordinated Universal Time (UTC) and their reference frame to International Terrestrial Reference Frame (ITRF), which de facto implements interoperability. Following the terrestrial paradigm, ESA and NASA are collaborating on a concept aiming to ensure that future lunar communication and PNT services, provided by institutional or commercial entities, will be interoperable. The LunaNet Interoperability Specification (LNIS) (NASA and ESA, 2023) is the outcome of the work of the two agencies. The following text, extracted from (NASA and ESA, 2023) explains the scope of the document: “LunaNet is envisioned as a network of cooperating networks (network of networks, akin to the terrestrial Internet) upon which providers can deliver communications, navigation, and other services for users on and around the Moon. LunaNet is based on a framework of mutually agreed-upon standards, protocols, and interface specifications that enable interoperability. LunaNet is intended to allow many lunar mission users to engage the services of diverse commercial and government service providers in an open and evolvable architecture. This document specifies a set of standards for services so that users may design their systems with the expectation of interoperability with multiple providers and users. Any individual provider is not required to offer all services and interfaces in this document, but the aggregation of providers will have the interfaces and services described. It is also possible for providers to offer services and interfaces beyond what is described in this document. However, those services and interfaces will likely not be interoperable between service providers, thereby limiting the service options for a user on or around the Moon.”

The contribution in this paper focuses on the LunaNet PNT services, that align with the definition of interoperability in International Committee on GNSS (ICG) (International Commitee on Global Navigation Satellite Systems, 2018), which is suitable for the lunar environment “(interoperability is defined as) the ability of global and regional navigation satellite systems, and augmentations and the services they provide, to be used together to provide better capabilities at the user level than would be achieved by relying solely on the open signals of one system”.

The following sections describe the LunaNet PNT services. Section 2 focuses on the Lunar Augmented Navigation Service (LANS) that is provided by means of the Augmented Forward Signal (AFS). The proposed signal characteristics, navigation message frame structure, and message specifications will be covered in section 3. Section 4 provides the conclusions.

**2 LUNANET NAVIGATION SERVICES**

The PNT services in LunaNet can be grouped into two categories, as shown in FIGURE 1:

1. Point-to-Point (P2P, Dedicated Links): These services are to be provided by direct links between the user and the provider. A dedicated link can provide a reference signal for PNT observables with associated messages, and additional messages relevant to PNT. Alternatively, a signal that is not inherently designed to offer PNT observables (e.g.: a communication data relay link) may still be employed to transmit messages that support PNT. This group includes all the services that are not broadcast in 2483.5-2500 MegaHertz (MHz).
2. Lunar Augmented Navigation Service (LANS): This service is provided from multiple provider nodes to multiple users at the same time. The concept is similar to GNSS. The AFS broadcasts in the 2483.5-2500MHz band and the service is expected to transmit with relatively large field-of-view antennas to cover a significant portion of the service volume with the same signal. A collection of LunaNet Service Provider (LNSP) nodes will coordinate to achieve global lunar coverage by a minimum of four simultaneous nodes in view to a user in the service volume at any given time, creating LANS. Therefore, users employing omnidirectional or hemispherical antennas can receive signals from at least four LNSP nodes simultaneously. It should be noted that LANS can also be implemented over a select (local) lunar region (e.g., the South Pole), if the right number of vehicles (nodes) are in view at any given time.



FIGURE 1: PNT Services provided by multiple LNSP

In this publication we will focus on the LANS concept, but many of the aspects described apply to the other services as well.

Deriving the interoperability definition presented earlier for LANS results in the following 3 points, for which each service provider that claims to be LunaNet compliant (becoming a LNSP), must adhere:

1. Compliance to a common signal and message structure (Augmented Forward Signal, AFS).
2. Adoption of a common lunar reference system (including reference frame) and lunar time system.
3. Compliance to Signal In Space Error (SISE) requirements.

A collection of at least four LNSP nodes transmitting the AFS constitutes the LANS, which is illustrated in FIGURE 2.



FIGURE 2: LANS PNT concept provided by LunaNet nodes

The use of a common signal is expected to significantly ease the development of user terminals; section 3 provides further details. The definitions of common lunar reference system components (including related frames and geodetic system parameters) as well as a lunar time system are very important. On Earth each GNSS service provider implements its own reference frame (e.g. World Geodetic System-84 (WGS-84) or Geocentric Terrestrial Reference Frame (GTRF)) and its own time scale (e.g. Global Positioning System (GPS) time or Galileo System Time (GST)). Interoperability among GNSS service providers is only possible because all specific reference frames are aligned to the ITRF to within centimeter or decimeter level. For the timing aspects, the situation is more complicated, with each service provider furnishing synchronization to UTC. However, the accuracy is often not sufficient to achieve precise positioning; hence users tend to estimate the clock bias among different service providers, thereby increasing the number of parameters estimated within the navigation filter (an alternative approach specific to users of GPS and Galileo systems is to use the Galileo-to-GPS time offset, GGTO, removing the need to estimate the offset between the system clocks at the receiver level). This approach is feasible thanks to the large number of satellites visible on or near Earth, but likely will not be feasible on or near the Moon, where the number of satellites is expected to be small, at least at the beginning, and the cumulative assets from different LNSP work in concert to achieve service volume coverage with an adequate number of provider nodes. For this reason, LunaNet aims to specify common lunar reference system components and a common time system. Extensive work is ongoing on the subject, in cooperation with other international organizations. The outcome of this work will be subject of future publications.

The last element to guarantee compliance to the interoperability definition is the SISE. To ensure that using more than one LNSP offers benefits to the user, there is a need to guarantee a bound on the errors under control of a particular LNSP, which is the SISE. The SISE is defined as the instantaneous difference between the position, velocity, and time (PVT) of a LNSP node as broadcast by that node’s navigation message and the true satellite PVT, respectively expressed in the lunar reference system and the lunar time system standard. This definition is independent of the orbital characteristics of each LNSP satellite node and establishes an upper bound on the error experienced at the user level resulting from the projection of the SISE onto the user-to-LNSP satellite direction. This allows users to derive reliable PVT solutions at a dependable level when using LANS from different LNSP. The SISE consists of a combination of errors that are the responsibility of the LNSP, such as:

* LNSP ephemeris uncertainties or errors in the orbital products tendered to users, as represented in the lunar reference frame.
* LNSP timing errors due to time knowledge uncertainties, inaccurate clock correction information conveyed to users, or misalignments of time with the signal realization.
* Uncalibrated or unknown LNSP group delays due to code phase offsets, antenna phase offsets and variations, unaccounted transmit path delays and variations, code-to-code incoherency, code-to-carrier incoherency, etc.

The approach adopted in LunaNet is defined to achieve interoperability among LNSP contributing to the LANS concept. However, unlike GNSS systems on Earth which are controlled by governmental organizations, LunaNet is open to any private or governmental organization. In this context, it is important to allow sufficient flexibility to the LNSP to implement their own concepts.

The LNIS main document refers to the LunaNet Signal-In-Space Recommended Standard (LSIS), (ESA and NASA, 2023) for the detailed specifications of the PNT signals (extension to other signals to be considered in the future). The LSIS is intended as a recommended standard, applying a definition from Consultative Committee for Space Data Standards (CCSDS). The adoption of the standard by a Service Provider is voluntary; however, as mentioned earlier, a Service Provider that claims to be LunaNet compliant (becoming a LNSP) must conform to this recommended standard in all of its parts.

LunaNet may encompass systems of different characteristics, including dissimilar orbits, diverse Earth segments, etc. Thus, some aspects of specific LunaNet services might be implemented differently by various LNSP, without impacting the service interoperability. Therefore, it is important to define specifications to the right level, leaving flexibility to enable each LNSP to implement their specific concepts, without impacting core interoperability. For this reason, LSIS implements two categories of specifications, broadly defined as follows:

1. precise specifications are provided to avoid ambiguity, with no flexibility at the LNSP level;
2. general specifications are provided in order to guarantee interoperability yet allow flexibility for the LNSP to define a specific implementation.

Per number 2 above, general specifications left for definition by the LNSP are referred to as *LNSP flexibility*. Examples of LNSP flexibility are: the cadence of dissemination of data content, the update rate of the data, etc.

To develop an interoperable LunaNet compatible user terminal, the detailed definition of parameters covered by the LNSP flexibility must be known. Therefore, an LNSP-specific Signal in Space Interface Control Document (SISICD) will need to be generated and made available by the LNSP for dissemination to a specified distribution.

In summary, each LNSP that intends to be interoperable as defined in LNIS shall:

1. comply with the LSIS, and
2. generate and deliver a LNSP-specific SISICD that defines what is identified as LNSP flexibility in the LSIS, and
3. define, document, and deliver user algorithms and models required to process the data specified in the provider-specific SISICD, and
4. develop and deliver an example software implementation of the user processing, including test vectors.

The following section will address AFS specification details. It is important to note that at the time of writing of this paper, both LNIS and LSIS are published as drafts. ESA and NASA plan to collect feedback on the drafts and release the final document versions in the future. Some values in the draft documents are marked as To Be Confirmed (TBC) to allow for the solicited feedback.

**3 AUGMENTED FORWARD SIGNAL (AFS)**

The signal has been defined to reduce the user burden for using the service, thus following these principles:

1. to exploit, to the extent possible, the available bandwidth, as assigned by the Space Frequency Coordination Group (SFCG 23),
2. re-use GNSS concepts as much as possible, and
3. re-use CCSDS concepts as much as possible.

To ease adoption of LANS by the user, the specifications should allow re-use of existing technologies. GNSS is currently used in most Low Earth Orbit (LEO) missions, in many Geosynchronous Transfer Orbit (GTO) and Geosynchronous Earth Orbit (GEO) missions, and even by Highly Elliptical Earth Orbit (HEO) spacecraft at distances half-way to the Moon. Spaceborne GNSS receivers are commercially available from many manufacturers. At the same time, CCSDS standards document the basis of all communication and PNT-over-comm links between Earth-centric networks and spacecraft, and terrestrial file-based data exchange.

Justification for many of the specifications included in LSIS trace back to the principles mentioned above.

**3.1 Signal specification**

The AFS signal is transmitted at a fixed frequency and consists of two main components: one denoted as AFS-I that is spread by a ranging code and modulated by a data message; and the other denoted as AFS-Q that is spread by a ranging code without any data message, forming the pilot component. The signal frequency, bandwidth, and polarization are reported in TABLE 1. Details of each requirement at the signal level can be found in LSIS (ESA and NASA, 2023).

|  |  |
| --- | --- |
| Carrier frequency | 2492.028 MHz |
| Frequency band | From 2483.5 MHz to 2500 MHz |
| Polarization | Right-Hand Circularly Polarized (RHCP). |

TABLE 1: AFS signal frequency, bandwidth, and polarization

One of the most critical aspects of interoperability for a broadcast service such as LANS is the user’s received power. In GNSS (and in general on Earth), International Telecommunications Union (ITU) establishes rules for the maximum power density of each system, and significant effort over the last decades has ensured minimization of interference among different service providers. The same principle should be adopted in cislunar space. LNIS does not define the specific implementation of the different systems; instead, the specifications are defined at service level. This level of definition is required because it is not possible to know, a-priori, the LNSP orbits and thus the resulting distance between a LNSP node and a user. For this reason, the LSIS defines the maximum and minimum power level at the lunar geoid within the LNSP-defined service volume. In fact, LNIS defines the full LANS service volume (out to altitude of 200 km) as the minimum global lunar space volume in which LANS will be provided and performance must be met. However, an evolutionary approach is anticipated to build toward the full service volume, with an expected start over the South Pole of the Moon. These are notionally shown in FIGURE 3.

A picture containing circle

Description automatically generated

FIGURE 3: LANS Full Service Volume (left) and Notional LANS South Pole Service Volume (right)

In order to guarantee interoperability for situations in which service volumes from different LNSP do not completely overlap (e.g. one LNSP covers the full service volume and another only a South Pole volume), LSIS specifies the maximum power on the lunar geoid outside the service volume. The proposed values for the received power on the lunar geoid are provided in TABLE 2.

|  |  |  |  |
| --- | --- | --- | --- |
|  | **Within the LNSP-Specific Service Volume** | | **Outside the LNSP-Specific Service Volume** |
| **AFS Component** | **Received Minimum Power [dBW]** | **Received Maximum Power [dBW]** | **Received Maximum Power [dBW]** |
| I | -166 (TBC) | -153 (TBC) | -143 (TBC) |
| Q | -166 (TBC) | -153 (TBC) | -143 (TBC) |

TABLE 2: Received minimum and maximum power within and outside the LNSP-defined service volume

The modulations proposed for the AFS-I and AFS-Q are BPSK(1) and BPSK(5), respectively, with the signal components linearly multiplexed to obtain the transmitted signal. The signal PN code and data rate parameters are provided in TABLE 3, and FIGURE 5: shows the synchronization between the data and pilot signal components.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Component** | **Ranging code chip-rate [Mchip/s]** | **Symbol-rate [symbols/s]** | **Primary code period [ms]** | **Secondary code period [ms]** | **Code length [chips]** | |
| **Primary** | **Secondary** |
| I | 1.023 | 500 | 1 (TBC) | N/A | 1023 | N/A |
| Q | 5.115 | No data (pilot component) | 1 (TBC) | 20 (TBC) | 5115 | 20 (TBC) |

TABLE 3: AFS chip rates, symbol rate and code lengths

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Description automatically generated

FIGURE 4: Data and pilot channel code and data synchronization

The use of BPSK is expected to facilitate the adoption of AFS as it is identical to existing GNSS signals, namely GPS L1C/A and Galileo E6BC). The lengths of the primary and secondary codes are similarly aligned with existing GNSS signals.

The current structure of the pilot signal does not preclude the use of additional information provided in the pilot channel by means of overlay symbols on top of the pilot secondary code (e.g. one symbol every one secondary code period), as shown in FIGURE 5: . Examples of capabilities provided by an overlay code are: faster synchronization with the data frame, faster provision of health status, faster time dissemination, etc.

A black background with a black square

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FIGURE 5: Tiered codes generation with overlay code

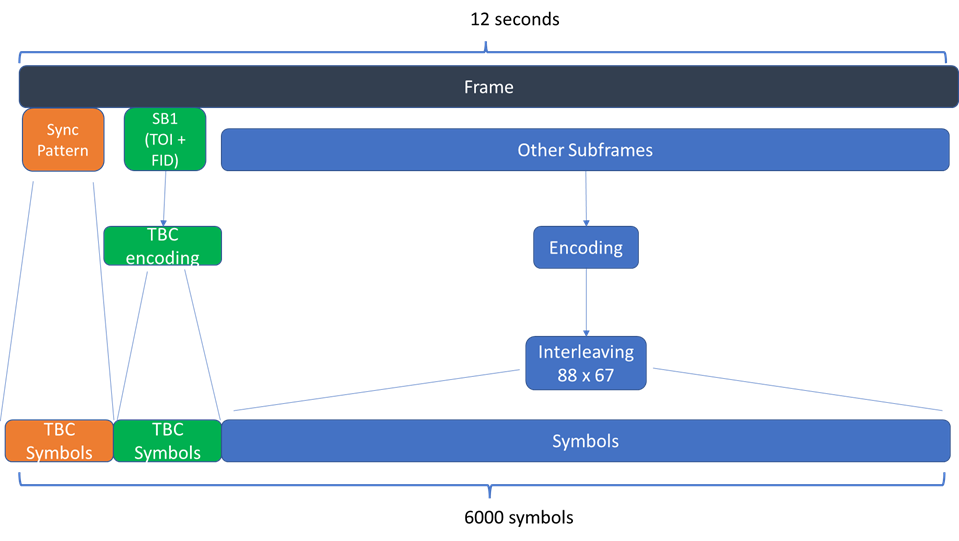
**3.2 Frame structure specification**

The message dissemination within the AFS-I channel needs to comply with the following high-level objectives:

* disseminate the mandatory messages for PNT (e.g. clock and ephemeris data, time, etc.)
* allow dissemination of the optional messages defined in LNIS (meaning that it is left to the LNSP whether the information is disseminated)
* allow dissemination of LNSP-specific information/data/messages that are not defined in LNIS

FIGURE 6 provides a visual representation of the message frame structure. A frame is composed of 6000 symbols, lasting 12 seconds. The first field of the frame is the synchronization pattern (SP), required to identify the beginning of the frame, hence the beginning of the subframes. The synchronization pattern is followed by the subframe 1 (SB1) that contains at least two fields:

Time of Interval and the FrameID, for which both bit values will be confirmed.



**FIGURE 6**: Generic frame structure

The FrameID (FID) field is used to define different types of frames and allows for implementation of different schemes, including:

* encoding of the “Other Subframes” that differs from SB1 (encoding of SB1 does not depend on the FID),
* alternate type and number of subframes. The characteristics of this last part of the frame is a function of the FID.

LSIS currently defines only the case for when FID equals zero, leaving the other options for future use. As shown in FIGURE 7, the FID equals to zero structure contains three other subframes:

* Subframe 2 (SB2) is always broadcast in every frame and its structure does not change.
* Subframe 3 (SB3) is a variable data frame that might contain different information. The specific information broadcast is identified by the subframe identifier.
* Subframe 4 (SB4) is a variable frame that, in addition to data for navigation, can potentially contain variable data supporting other services. The specific information broadcast is identified by the subframe identifier.

Note that the number of bits and the encoding rate are to be confirmed.

A screenshot of a computer screen

Description automatically generated with medium confidence

FIGURE 7: Frame structure of FrameID equal to zero (values are TBC)

SB2 contains mandatory data to be disseminated to support PNT services including clock and ephemeris data, week number, interval time of week, and health status. The subframe structure remains identical in every frame. On the contrary, SB3 and SB4 implement a variable structure function of the respective subframe identifiers. Both mandatory and optional messages are disseminated using SB3 and SB4.

The adoption of generic specifications gives the flexibility to implement dissemination schemes specific to the LNSP, as long as compliance to the LSIS is maintained. At the same time, a user terminal manufacturer has all the necessary information to build a LunaNet compliant user terminal, because the LNSP-specific SISICD is expected to only influence a reduced part of the software component within the user terminal. It is important to highlight that SB3 and SB4 allows dissemination of custom messages defined by the LNSP. TABLE 4 provides the allocation of the messages defined in LNIS to the subframes of the frame when FID equals zero.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **MSG ID** | **MSG Title** | **Category** | **SubFrame** | **Notes** |
| MSG-G1 | LunaNet Network Access Information | F | SB4 | periodic |
| MSG-G2 | Health and Safety | F | SB2 | periodic |
| MSG-G3 | MAntennaProperties | O | SB3 and/or SB4 | TBD |
| MSG-G4 | Sorbit Ephemeris & clock correction | F | SB2 | periodic |
| MSG-G5 | MOrbit Almanac | F | SB3 and/or SB4 | periodic |
| MSG-G8 | Time of transmission | F | SB2 and SB3 | periodic |
| MSG-G10 | Maneuver | O | SB3 and/or SB4 | Ad-hoc |
| MSG-G11 | SAttitude State/ Ephemeris | O | SB3 and/or SB4 | Ad-hoc |
| MSG-G14 | Conjunction | O | SB3 and/or SB4 | Ad-hoc |
| MSG-G15 | Maplet | O | SB4 | Ad-hoc |
| MSG-G17 | Ancillary info | O | SB4 | Ad-hoc |
| MSG-S19 | Acknowledge- of SAR - LvL1 | F | SB3 | Ad-hoc |
| MSG-S20 | Acknowledge- of SAR - LvL2 | F | SB3 | Ad-hoc |
| MSG-G22 | Acknowledge- of non-SAR MSG | O | SB4 | Ad-hoc |
| MSG-G23 | GNSS Augmentation | O | SB3 and/or SB4 | Ad-hoc |
| MSG-G24 | Detection Alert | O | SB3 | Ad-hoc |
| MSG-G25 | Science | C | SB4 | Ad-hoc |
| MSG-G27 | UIS Response | C | SB4 | Ad-hoc |
| MSG-G28 | User Schedule Notice | C | SB4 | Ad-hoc |
| MSG-G29 | FF Commands | C | SB4 | Ad-hoc |

**TABLE 4**: Message allocation to subframes. F = Fundamental, meaning it shall be broadcast by the LNSP; O = Optional, meaning it should be broadcast by the LNSP; and C = Comm, meaning it may be transmitted on AFS to facilitate LunaNet services.

**4 CONCLUSIONS**

As on Earth, a lunar PNT infrastructure, predicated on providing services, enables a vast array of capabilities for orbital and surface users. In alignment with the Artemis Accords (NASA Artemis, 2020) and NASA’s Moon to Mars Objectives (NASA, 2022), interoperability of those services is a keystone to an inclusive architecture for a vibrant lunar ecosystem that provides safe navigation for all actors involved. NASA and ESA jointly developed the LunaNet framework of interoperable standards as defined in the LNIS (NASA and ESA, 2023). The broadcast AFS and associated messages form the primary PNT service known as LANS, which is expected to evolve over time and across multiple different LNSP to cover the lunar global service volume out to 200 km. A collection of geographically diverse LNSP nodes transmitting AFS forms the LANS, that enables users within that volume to perform near real time estimates of their position, velocity, and time. Core tenets of LANS include aligning with existing PNT service provider concepts and application of interoperability, addressing specifications that guarantee interoperability, and allowing flexibility for a particular implementation by a LNSP. Of noteworthy significance for the Moon, the LNIS seeks to define the lunar reference system components and lunar time system common to all LNSP. This paper focused on the AFS parameters and top-level message frame and sub-frame definitions, as documented in the draft versions of LNIS (NASA and ESA, 2023) and LSIS (ESA and NASA, 2023) currently released for comment, and the rationale behind the specifications. Future papers intend to provide similar content for PNT services available via dedicated links and additional PNT services identified in the LNIS.

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