National Aeronautics and Space Administration

LunaNet Concept of Operations and Architecture

Preliminary Summary for the
NASA Lunar Communications Relay and Navigation Services
Request for Information

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1 Introduction

Many countries are now cooperating in a vast effort to expand the sphere of human presence to the Moon and beyond. In the next decade, scores of missions will be launched to orbit or land on the Moon and begin to establish a sustained presence there. Lunar missions planned in 2020 and beyond will benefit from a flexible architecture to provide a phased approach for essential communications, Position, Navigation, and Timing (PNT), information, and other services. Collectively, these will be referred to as Communication and PNT (CPNT) services. The phased approach recognizes that initial capabilities, capacity, and coverage to support a small number of robotic spacecraft will expand within the decade to meet the rapidly growing needs of the Human Exploration campaign, experience increasing quantity and sophistication of science missions, and demonstrate technologies focused on developing emerging lunar capabilities.

A flexible and open architecture that can adapt to dynamic mission needs is achieved by a network-of-networks using a Service-Oriented Architecture (SOA), with space assets treated as nodes in a network topology where the fundamental purpose is to provide services to cislunar spacecraft and space systems. Nodes are compatible with each other in the architecture even when provided by different organizations. These networks will be owned and operated by different government space agencies and commercial vendors, both domestic and international. To provide effective services, this heterogeneous mix of assets requires strict adherence to a robust set of protocol standards and interfaces. This document will define the concepts and architecture for the Lunar Network, known as LunaNet, and provide the framework needed for any cooperating organization to become a LunaNet Service Provider (LNSP) or a LunaNet Service User.

1.1 Purpose

The purpose of this document is to define the LunaNet concept of operations (ConOps) and architecture as a common set of standards and interfaces that will provide phased CPNT support for a heterogeneous set of space assets provided by a variety of LNSPs. These assets may be operated by a broad range of participants: government and commercial organizations, academic entities, and others. By providing a description of potential user needs and corresponding LunaNet services, this document identifies where and how service providers can be integrated, providing for continued growth, expansion, and evolution as new capabilities, standards, and technologies emerge. Broad coordination of the proposed interfaces enables future tiered services and capabilities.

1.2 Scope

This document defines the concept of operations and architecture of LunaNet for an Internet-like architecture, known as LunaNet, which will support lunar missions – national and international, governmental and commercial – beginning in 2020. LunaNet will address communications, PNT, and other services for the following types of cislunar systems: lunar science orbiters, lunar exploration orbiters, lunar surface mobile and stationary systems, Moon and Earth orbiters that provide relay and PNT service to lunar systems, lunar ascent and descent vehicles, and associated Earth ground stations and control centers. LunaNet will provide these services from the service providers (networks) to the service users (missions). The architecture permits a wide variety of paths for data to space systems and between space systems and Earth systems including, for example, direct links from lunar surface and orbiting vehicles to Earth, links from lunar surface and orbiting vehicles relayed to Earth, links between lunar surface systems, and other permutations such as multi-hop end-to-end paths.

The advanced concepts of LunaNet will require a common set of standards and interfaces in support of interoperability and compatibility between service providers and service users. Currently these standards are based on previous work from the multi-national Artemis Program, Interagency Operations Advisory Group (IOAG) and the Consultative Committee for Space Data Systems (CCSDS). LunaNet will employ a diverse set of Radio Frequency (RF) and optical bands of the spectrum, taking advantage of existing international radio regulations. Increasingly, the LunaNet architecture will employ commercial standards (or adaptations for the space environment) such as cellular telephony standards by the 3rd Generation Partnership Project (3GPP) and the Institute of Electrical and Electronic Engineers (IEEE) 802.11™ Wireless Local Area Network (WLAN) standards family, known as WiFi™, and the DVB-S2X family of standards.

2 Overview and Terminology

2.1 LunaNet Overview

LunaNet is envisioned as a network defined by a framework of frequency bands, communication and PNT protocols, and interfaces to support an open, scalable, interoperable network-of-networks for missions to use in cislunar space. This framework can be introduced from the beginning of robotic lunar mission operations and expanded as new spacecraft and missions come online. LunaNet is established using existing ground networks such as those operated by the National Aeronautics and Space Administration (NASA), European Space Agency (ESA), Japanese Aerospace Exploration Agency (JAXA) as well as commercial networks. Figure 1 shows the initial space assets created for LunaNet using existing ground networks that provide services to lunar missions and form the initial operational LunaNet.

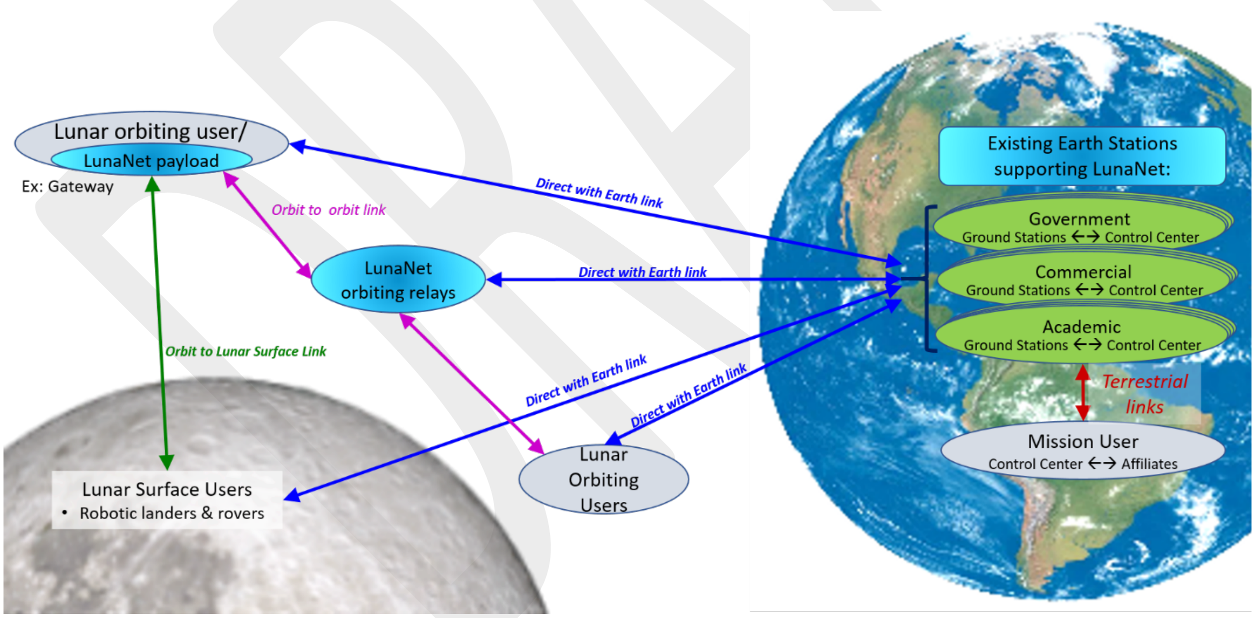


Figure 1. Early LunaNet Architecture – new LunaNet Assets Using Existing Ground Networks

Each organization that operates a network providing lunar CPNT services is called a *LunaNet Service Provider* (LNSP). Each LNSP decides which standard services to offer via their network, which is referred to as a *LunaNet System* (LNS). Offered services must comply with this LunaNet Architecture and ConOps Document to achieve interoperability. Each LNSP establishes agreements with other LNSPs for internetworking in compliance with this document and the LNSP Internetworking Standard. Figure 2 shows the two publicly exposed interfaces – User Services and LNSP Internetworking – that create LunaNet. Missions that use LunaNet services are *Service Users*.

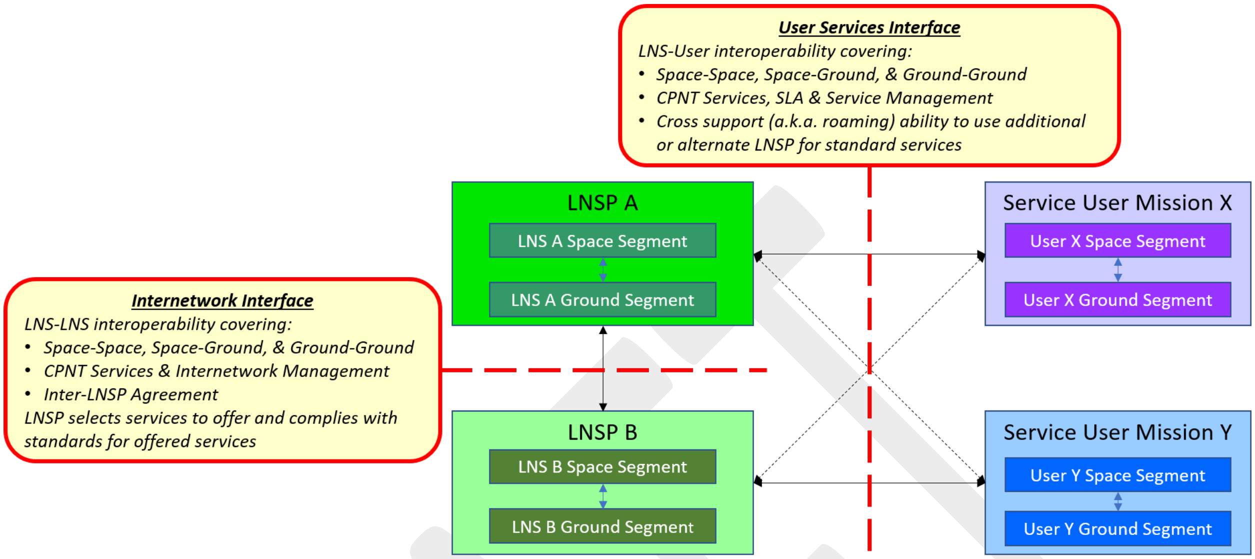


Figure 2. LunaNet is Created by LNSPs, Operating LNSs that Provide Standard User Services

Figure 3 shows that LunaNet has, for each LNSP, a ground segment on Earth (e.g., ground stations and network control centers) and a space segment that could comprise assets in Earth orbit (relays that may serve lunar users as well as other missions), in lunar orbit (dedicated relays and relay payloads on user mission spacecraft), and/or on the lunar surface (e.g., base station terminals and local network nodes). In addition to relay capabilities within the network, point to point capabilities are enabled and services can be provided by any element. For example, an element in lunar orbit can provide PNT services to other users, enabling user autonomous navigation. The individual links allow for data transfer between any two elements (nodes) in the network, with the relays acting as data routers and PNT references. LunaNet elements can also provide services directly to each other, allowing for coordinated operations and mission support. LunaNet nodes providing PNT services will make use of onboard sensor systems to maintain their own onboard state knowledge to high accuracy. This can include synchronization with other Earth-based services (such as Global Navigation Satellite Systems or GNSS), astronomical sources (such as X-ray Navigation), or optical navigation. These nodes operate within the architecture to anchor other elements’ timing and location information, supporting PNT independent of Earth-based assets and enabling the network to be autonomous and robust.

LunaNet consists of multiple LNSs provided by different organizations (LNSPs) providing services to many user missions. Some spacecraft can be both “users” and “providers”; for example, a LunaNet relay payload can be included on a robotic science spacecraft. Therefore, LunaNet is intentionally agnostic with respect to ownership and is equally applicable to any ownership model.

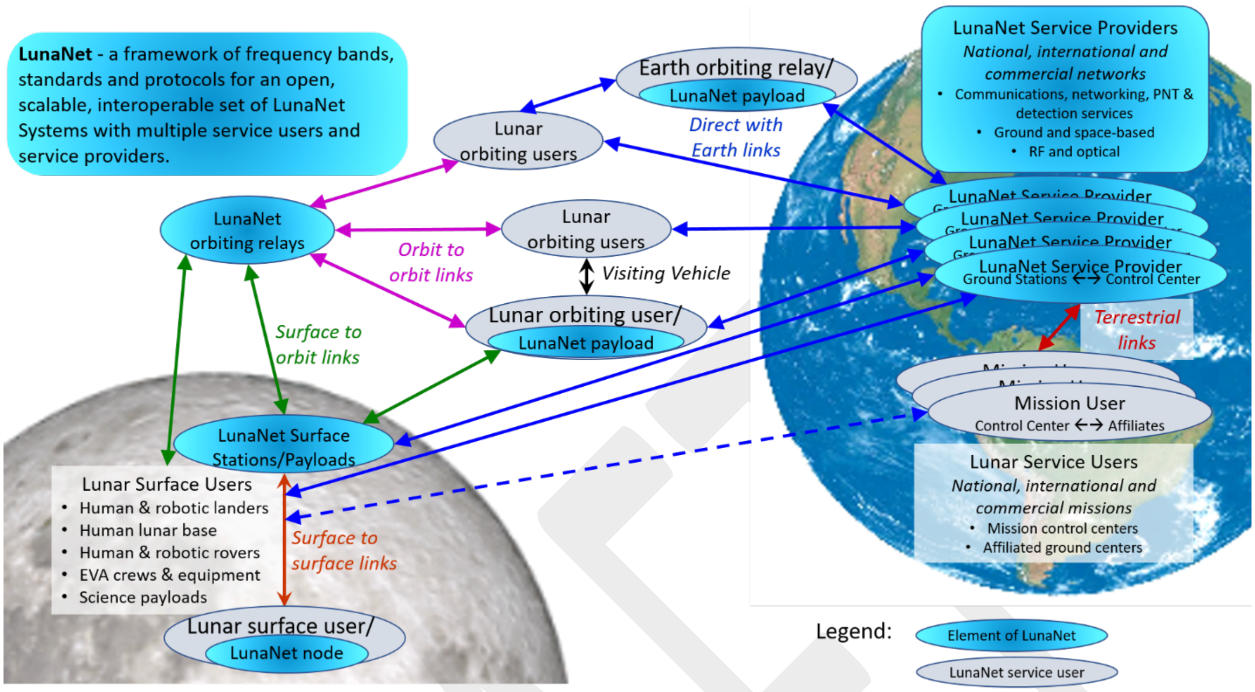


Figure 3. LunaNet Architecture Overview

LunaNet will provide CPNT services to users in all mission phases including: Cruise to the Moon, lunar orbit, descent, landing, fixed and mobile surface operations, launch, and cruise to the Earth.

- Cruise to and from the Moon: The Cruise phase may last days to months depending on a spacecraft's propulsion system. During this phase, the user spacecraft may transition from using services provided by Earth networks to a combination of Earth networks and LunaNet.
- Lunar orbit: During this phase, user spacecraft may transition to various orbits (e.g., initial orbit phasing to the primary mission orbit). The user may take advantage of any combination of Earth networks and LunaNet, utilizing LunaNet services for an entire orbit or for just a portion, such as when the user is on the far side of the Moon.
    - Visiting Vehicle: A special case occurs when one vehicle performs Rendezvous, Proximity Operations, and Docking (RPOD) (and subsequent undocking) with another vehicle. During the far rendezvous stage, both vehicles may use any combination of Earth networks and LunaNet to track their position via PNT services and exchange data on their health and status. During the close rendezvous stage, the vehicles switch to more precise short-range means of tracking range, range-rate, and attitude.
- Descent, landing, and ascent: LunaNet services, as well as Earth network services, may be essential for the critical phase of descent and landing. Command and telemetry are essential for the Mission Operations Center (MOC) to monitor a spacecraft's progress. LunaNet PNT services support accurate user Guidance, Navigation and Control (GN&C) procedures following the planned trajectory to/from prepared or unprepared landing sites.
- Fixed and mobile surface operations: LunaNet surface nodes combine with LunaNet orbiting relays to provide coverage to users throughout their surface operations. Surface nodes act to *multiplex* transmissions from and *demultiplex* transmissions to a variety of surface elements, enabling efficient use of limited bandwidth on the trunk links to Earth and on demand access for surface users.

LunaNet is similar to the terrestrial Internet in several ways:

- Network Organization: LunaNet is characterized by a set of *nodes* and *links* arranged in a physical and logical network topology. *Physical topology* is the placement and connection of the various components of a network (e.g., asset location and cable installation or antenna field of view), while logical topology illustrates how data flows within a network (e.g., across a grid of connected nodes). Nodes provide services to users (*edge nodes*) or support data transmission to other LunaNet nodes (*internal nodes*). Links connect nodes by *wired* or *wireless* means of transmission. Transmission occurs over the radio frequency (RF) and optical portions of the electromagnetic spectrum. Links are also designed to allow for inter-asset PNT observations, enabling time synchronization, disciplining, and orbit estimation through onboard processing.
- Open Architecture: LunaNet operates using an *open architecture* based on publicly available information. Specifications and protocols are public and intended to allow for modification and evolution. LunaNet is composed of a community of *Service Providers* and *Service Users* who voluntarily agree to abide by a set of standards and conventions that enable cooperation. Service Providers are organizations that operate network(s) to provide CPNT services to a set of entities that use those services to meet their objectives. Service Users are organizations that operate spacecraft or space elements with associated terrestrial capabilities and require CPNT services to operate their systems. LunaNet relies on standards and conventions to achieve *interoperability* among Service Providers and Service Users. As a result, no one organization owns LunaNet. The LunaNet community includes government, commercial and academic entities; it could eventually include individuals as well.
- Unlimited Scalability: LunaNet services can be provided to a nearly unlimited number of users since additional service providers, assets, frequency reuse, and frequency bands can be added over time to increase aggregate bandwidth.
- Ease of Evolution: LunaNet provides the ability to demonstrate new technologies as well as to conduct engineering tests of pre-operational capabilities simultaneously with provision of operational services. Once tested, these new technologies can transition readily into operational use.

LunaNet differs from the Internet in several key characteristics. It therefore offers advantages that the Internet cannot. LunaNet is:

- "Born Secure": The Internet was originally designed without regard to security because no one anticipated malicious activities to deny, degrade, disrupt, or destroy communications. While the Internet has evolved to become more secure over the past several decades, the cost of network security is high – and still rising – while the scope of malicious activities has continued to outpace and out-innovate attempts to contain them. From the outset, LunaNet has been designed to leverage everything known today about network security: including Confidentiality, Integrity, and Availability (CIA), secure communication and networking protocols, encryption, and other features. Future LunaNet technologies with security advantages include optical communications.
- Highly mobile and intermittently connected: The Internet was conceived for fixed installations of computers, message processors, and wired connections. Wireless technologies have extended the Internet, adding new topologies such as mesh networks and mobile connectivity to systems moving at relatively slow speeds (e.g., cars to aircraft). LunaNet is designed for space systems moving at orbital speeds. Satellites can come into view of potentially connecting systems, and move in and out of view within minutes, requiring rapid establishment and disestablishment of connections. LunaNet defines services to enable inter-asset awareness and synchronization of time with other networks. This shared knowledge is needed to allow for cross-element operational coordination and to enable accurate element-to-element operations (such as pointing maneuvers used to acquire and track

communication signals). By providing common understanding of where physical elements are at a given time, the network can smartly coordinate and distribute information.

- Interoperable and capable of incorporating special system functionality: The Global Positioning System (GPS) was conceived as a military capability to disseminate time and position information to military systems around the world. It evolved into a joint civil-military system whose capabilities have been incorporated into a vast number of Internet applications, cellular telephones, and other systems as well as spawning development of international GNSS. LunaNet will similarly provide PNT services as core capabilities to enable operations around and on the Moon. Sharing of navigation information between users and services allows for autonomous navigation and precise timing for coordination and delivery of vital commercial services and military capabilities. LunaNet incorporates these PNT capabilities directly avoiding the need for a separate "lunar positioning system".

The need for *interoperability* becomes apparent from several perspectives:

- Interoperability allows each Service User spacecraft or space element can take advantage of *roaming* – using whichever Service Provider's asset is in view – offering higher overall availability, dissimilar redundancy for high reliability, and multiple paths to/from Earth for higher capacity and coverage.
- Interoperability can result in cost savings. Each Service User spacecraft only needs to develop or procure communication subsystems that work with the interoperable services provided by all Service Providers, allowing use of off-the-shelf equipment, reducing hardware and software development costs and offering competitive procurement of operational services.
- Each Service Provider can offer services to the entire cislunar market. As the cislunar market grows, so does the Service Provider's business opportunity. Government agencies may choose to partner with emerging commercial Service Providers that are capable of being technologically agile and cost effective.
- Interoperability enables more effective aggregate use of fixed spectrum resources by allowing Service Users to "share" spectrum. Using LNS assets designed to support a large number of users will promote high spectrum efficiency.

Basic categories of LunaNet CPNT services include networking, PNT, and detection and information as shown in Figure 4. Networking services are based on Internet Protocol (IP) or Delay/Disruption Tolerant Networking (DTN) Bundle Protocol (BP). Use of BP allows networking services to function between any two nodes anywhere in the LunaNet, while IP will only allow for end-to-end data delivery within certain regions and operational conditions. Data link layer services are supported but network layer services are preferred. PNT services provide tracking, ranging, and timing to support user orbit or position determination and trajectory management. Detection and Information Services disseminate data from authenticated sources to subscribing users (including notifications and detection of events).

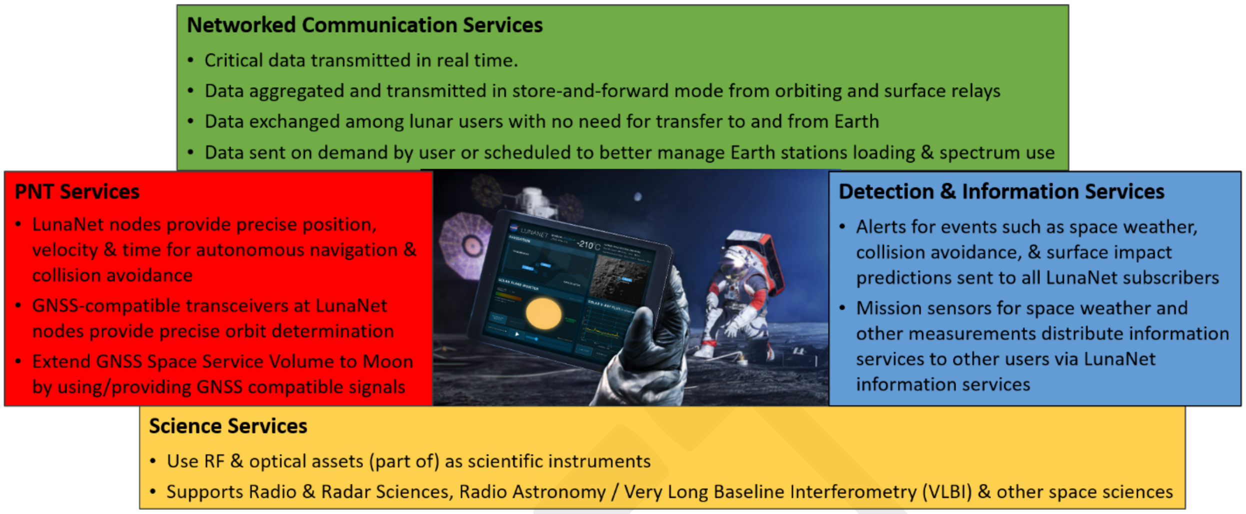


Figure 4. Categories of LunaNet Services

The implementation of the LunaNet infrastructure can take many forms, with a combination of Earth ground stations, lunar relays, lunar orbiting assets, and surface elements serving as nodes in the network-of-networks topology. Relay and PNT services could be provided by communication and navigation payloads hosted on other spacecraft, SmallSats, larger relay satellites, and lunar surface elements.

LunaNet is the first instance of a *planetary network* – a network-of-networks designed to provide the communications, networking, PNT, and information ecosystem for an entire celestial body. Figure 5 depicts the strategy of developing a flexible network architecture at the scale of a planet or Moon adaptable to any celestial body to reduce development and operation costs for both users and service providers. At this level, links between nodes and networks can be simplified to two types:

- User-to-network *proximity links* (space-space and space-ground/surface) provide standardized services & design for users of planetary networks; and
- Network-to-network *trunk links* are internal network space-ground connections for long distance “back haul”.

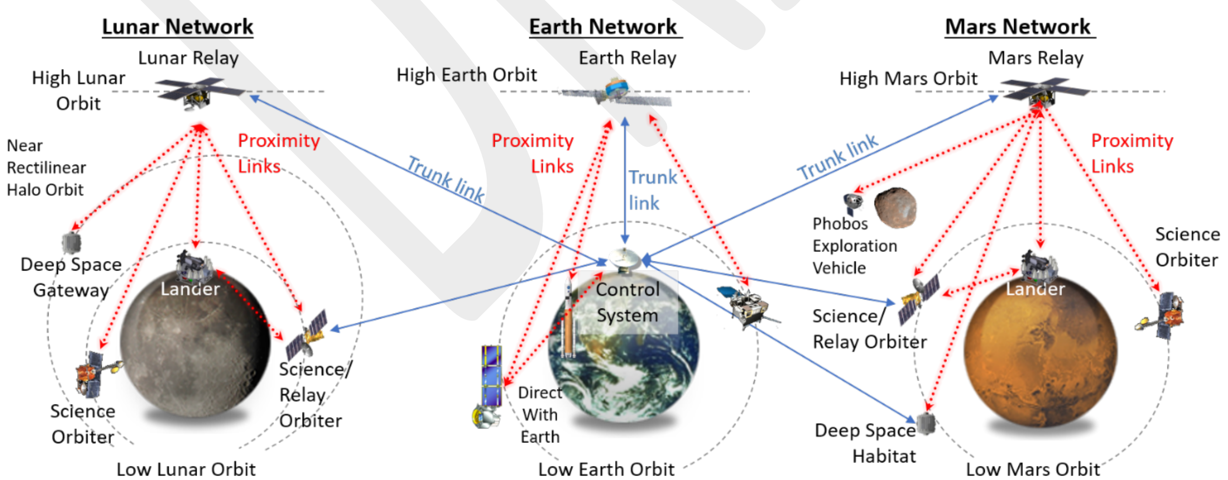


Figure 5. Planetary Networks: LunaNet Sets the Precedent for MarsNet

Trunk links are not exclusively limited to network-to-network interfaces; historically, deep space communications has been between a ground network on Earth and the user spacecraft. Similarly, proximity links can occur directly between users, such as the Visiting Vehicle link shown in Figure 3. Defining the class of proximity links highlights the benefits of multiplexing through network relays to minimize the power needed by users to communicate while networks shoulder the greater burden of the long trunk links. This same principle, driven by physics and economics, is present in all terrestrial networks. The Earth Network exists in a loose sense today, having evolved into a network-of-networks without unification as an organizing concept. The planetary network concept can be applied to Mars and may one day offer even greater advantages there due to the communications time delay.

LunaNet will be implemented in a series of incremental phases driven by major phases of human exploration and scientific discovery missions:

- 1^{st} Phase: Now-2024 – early robotic missions and crewed missions leading to the return of humans to the Moon. Initial LunaNet capability will become operational. At least one lunar relay will be launched to enable far-side robotic landers and science missions and support the southern polar site.
- 2^{nd} Phase: 2024-2028 – expansion of scientific capabilities and establishment of a sustainable human presence. The number of surface sites and missions will increase. LunaNet services and capacity will expand as more service providers join.
- 3^{rd} Phase: Beyond 2028 – sustained scientific and human lunar capabilities. The cislunar region will be used to conduct Mars analog missions to prepare for eventual human missions to Mars. LunaNet will continue to expand capacity and coverage as required to meet mission needs and will act as an analog for the Mars Network, MarsNet.

LunaNet can begin with limited capability but can scale up to eventually provide full surface coverage and continuous availability. Benefits to users can be characterized by the basic categories of surface locations (near side, far side, and polar) as shown in Table 1.

Table 1. Benefits to Missions Vary with Surface Location

Location: / User Benefits	Near Side	Far Side	Polar Remote Site	Polar Base Site
Feasibility	Enhancing: mission can return more data for given Size, Weight and Power (SWaP) compared to Direct With Earth (DWE) service	Enabling: unable to perform mission without far side relay	Enhancing: mission can return more data for given SWaP compared to intermittent DWE service	Enhancing: mission can return more data for given SWaP compared to intermittent DWE service
User Burden – Communications	User link distance is reduced from 400,000 km to ~10,000 km (orbiting relay) or < 10 km (surface node) reducing SWaP compared to DWE	Low SWaP to close links with orbiting relays	User link distance is reduced from 400,000 km to ~10,000 km (orbiting relay) or < 10 km (surface node) reducing SWaP compared to DWE	User link distance is reduced from 400,000 km to ~10,000 km (orbiting relay) or < 10 km (surface node) reducing SWaP compared to DWE
User Burden – PNT	• More precise knowledge of time and position enhance scientific measurements, and enable increased spacecraft autonomy and relaxed requirements for ground-based tracking			

Location: / User Benefits	Near Side	Far Side	Polar Remote Site	Polar Base Site
	• Alternate infrastructure based approach to precision landing and navigation within cislunar space, reduces burden on Earth assets and staffing, enabling more complex missions and operations			
Autonomy	Lunar infrastructure enables missions to reduce dependence on limited Earth infrastructure			

2.2 Terminology

Relevant terms are defined below.

Term	Definition
Abort	This phase is initiated automatically or by crew (visiting or target) for the visiting vehicle to perform a separation sequence (thruster firing), which places the visiting vehicle on a safe trajectory departing from the target.
Absolute navigation	The set of information that describes absolute position, velocity, attitude, and angular rate of a space vehicle measured by ground operation or onboard measurement with respect to a reference coordinate system.
CPNT	Communications, Position, Navigation, and Timing; when used in the context of services provided by an LNSP it refers to the complete set of communication, networking, PNT, detection, science and other LunaNet services offered by an LNS.
Confidentiality, Integrity, and Availability (CIA)	Confidentiality (privacy) ensures that sensitive information is accessed only by an authorized person and denied for those not authorized. Integrity involves maintaining the consistency, accuracy, and trustworthiness of data and ensures that data cannot be altered by unauthorized people. Availability ensures that the network is functioning and that information can be sent to those who need it. Security objectives extend this to include availability despite malicious actions.
Critical event	This phase is initiated automatically or by crew (visiting or target) for the visiting vehicle for an event associated with a spacecraft or space element whose success is essential to mission success. An example is a separation sequence (thruster firing), which places the visiting vehicle on a safe trajectory departing from the target.
Demultiplex	Separates one combined signal or data stream received over a shared medium into multiple individual signals or data streams to share a scarce resource such as limited bandwidth over a fixed frequency band or limited network resources such as antennas.
Departure	For visiting vehicle release and departure, this phase commences upon physical separation from the target vehicle. This phase is complete when the visiting vehicle is confirmed to be departing on a trajectory that is operationally safe and the visiting vehicle is outside the Approach Sphere.
Disadvantaged user	The class of Service Users that has very low power and small size limiting the Effective Isotropic Radiated Power (EIRP) and gain on their communications subsystem. Examples include CubeSats and EVA suits.
Docking	This event is defined as the docking mechanism contact, capture, and hard-mate.
Edge nodes	Network nodes that connect to user nodes and provide services to users.
Ephemeris	A vector of information that defines the position and trajectory of a celestial body or man-made satellite.

Term	Definition
Far Rendezvous	This phase brings the visiting vehicle closer to the target vehicle, while still protecting the ability to passively abort the approach on a trajectory that is operationally safe. Space-to-space communications have been confirmed and the visiting vehicle has transitioned to relative navigation.
Internal nodes	Network nodes that connect to other LNS nodes and support data transmission among those nodes.
Interoperability	The ability to exchange and understand information between entities that agree on: a) the syntax used to format (encode) the information; b) the semantic meaning (content) that represents the information or references the contextual meaning; c) the means of exchanging the information; d) the means of reconciling temporal differences in the entities' syntax, semantics, means of information exchange, and context; and e) the context in which the information exchange occurs.
Link	The wired or wireless means of transmission over the radio frequency (RF) and optical portions of the electromagnetic spectrum that connect nodes.
LunaNet	The network-of-networks provided by the complete set of LunaNet Service Providers.
LunaNet Service Provider (LNSP)	An organization that operates a network providing lunar CPNT services; a member of the LunaNet network-of-networks.
LunaNet System (LNS)	Any network operated by an LNSP that provides LunaNet services to service users; a member of the LunaNet network-of-networks.
Multiplex	Combines multiple signals or data streams into one signal or data stream over a shared medium to share a scarce resource, such as limited bandwidth over a fixed frequency band or limited network resources (such as antennas).
Navigation	(N in PNT) Given current understanding of where a node is and its desired state, calculations of maneuvers (either onboard or from ground) to correct any trajectory dispersions and/or to direct the node towards a specific end state. Can also refer to techniques for integration of individual one-dimensional measurements into a full state.
Node	An asset of an LNS that provides services to users (*edge node*), an LNS node that transmits data to other LNS nodes (*internal nodes*), or a user asset that receives services from an LNS node.
Open architecture	Composed of a community of *service providers* and *users* who abide by a set of standards and conventions that enable transmission and reception of CPNT services.
Planetary network	A network-of-networks designed to provide the communications, networking, PNT, and information for an entire celestial body; LunaNet is an instance of a planetary network.
Positioning	(P in PNT) Techniques and methods to determine a node's location (position and velocity) at a given time. This includes methods for measuring range, range-rate, and bearing to other elements (nodes, planetary bodies, stars).
Proximity link	Links between LNS nodes, or between an LNS node and a user node, that are separated by a distance short enough to support real-time protocols (such as acknowledgements without timing out, pointing, and adaptive optics); typically used for space-to-space or space-to-surface/ground links around a single celestial body.

Term	Definition
Proximity Operations (Prox Ops)	This phase encompasses multiple phases: final approach, fly-around, and undocking and departure. This is used to cover all maneuvers performed within the Approach Sphere.
Quality of Service (QoS)	The ability to provide different priorities to different applications, users, or data flows, or to guarantee a certain level of performance to a data flow; refers to traffic prioritization and resource reservation control mechanisms in addition to achieved service quality.
Ranging	Methods and techniques for measuring the distance between two assets across a physical link.
Relative navigation	The set of information that describes relative position, velocity, attitude, and angular rate of a visiting vehicle with respect to the target vehicle.
Rendezvous	This phase begins when the visiting vehicle is confirmed to be in an orbit established in cislunar space relative to the target vehicle and ends at the start of docking/berthing operations.
Roaming	The ability for users to accept services from more than one service provider due to interoperability.
Security vulnerability	A weakness which can be exploited by an attacker to perform unauthorized actions within a computer system or network.
Service	Provision of data transport by a service provider over RF and optical links that provide communications, PNT, information, and other data between user elements, such as space-to-ground or space-to-space elements.
Service provider	Organization that operates network(s) to provide communications, networking, navigation, and other CPNT services to a Service User; generic term that includes LNSP.
Service User	Mission that requests and receives services from a Service Provider.
State	A space vehicle's 3-dimensional position and velocity at a specified time.
State	In the context of PNT, state refers to the vector of information that defines the current Position, Velocity, and Time (PVT) of a node or space element.
Timing	(T in PNT) Approaches to correcting and transferring the current epoch reference time across nodes within the network. Ways to maintain a common time scale and epoch across the network. Services are required to distribute, synchronize, and manage time both relative to the central body and with regard to an absolute reference system.
Tracking	Operational mode where a host node tracks a user's state over time to generate measurements used to determine absolute position and velocity in space.
Trunk link	Links between LNS nodes, or between an LNS node and a user node, that are separated by a distance long enough to preclude effective use of proximity link protocols; typically used for space-to-space or space-to-surface/ground links between celestial bodies.
Undocking	This event is defined as the physical separation of two docked vehicles.
User	Organization that operates spacecraft or space elements with associated terrestrial capabilities and requires communication, networking, PNT information, and other services to operate its systems; a person who is part of a user mission organization who requests or receives data transport or who uses PNT or detection services.

3 LunaNet Concept of Operations

3.1 General Operations Concept

In contrast to traditional link-centric operations, the LunaNet architecture is based on interconnected network nodes and will create a network-of-networks similar to the terrestrial Internet extending between the Earth and the Moon. With the increase in human and robotic exploration at the Moon, it is not feasible for each asset to have its own direct-to-Earth communications link, and LunaNet mitigates this. Space-based users, surface assets, or lunar orbiters can utilize LunaNet's network nodes as access points, analogous in functionality to terrestrial Wi-Fi routers and cellular towers. If the user has connectivity to the network, and the network has adequate capacity to meet the user's operational requirements, the Service User does not need to be concerned about how many relays or hops there are between the Service User and the Service User's data destination.

LunaNet services will be provided by multiple providers, including NASA, commercial, and international partners. The primary LNSP selected by a Service User has responsibility for handling the operational complexity associated with routing data traffic between user source and destination nodes, though parts of the end-to-end paths will be provided by other LNSPs. Standard services should be available from any LNS consistent with Figure 2. The interfaces and methods for obtaining those services may be different between LNSPs though the service interfaces should be as standardized as possible to increase the accessibility of services for users.

Each LNSP will be responsible for the management and control of their LNS. An LNSP will provide services and interfaces with Service Users, as well as with other LNSPs. A LunaNet user will receive services from particular access point(s), but the data may travel through multiple LNS networks before reaching its destination. An individual user will work with a single primary LNSP for mission planning and ongoing operations and scheduling; and that LNSP will make the arrangements, agreements, and schedules in order to allow the user to receive services outside of its primary LNS. The primary LNSP has responsibility for handling the operational complexity associated with routing data traffic between user source and destination nodes, though part of the end-to-end path may require services from other LNSP(s). In some cases, a user may choose or be required to work with a second LNSP for services, but this situation adds operational burden on the user.

Some user mission events such as orbit insertion, docking, and landing, are deemed critical to mission success. LNSPs may be required by Service Users to provide enhanced support during critical events. For the duration of the event, this may include guaranteed availability of specific links, added redundancy (including support from other LNSPs), and higher staffing for rapid response to off-nominal conditions.

3.2 Services

Each LunaNet node will be capable of providing a combination of standard service types (Figure 6): Communications, PNT, Detection and Information, and Science. The degree to which each node provides each service type may vary. For example, it is possible for some nodes to provide only networking or only PNT services. The performance levels of each node may vary as well.

- Communications Services (Com): Data transfer services capable of moving addressable and routable data units between nodes in a single link or over a multi-node, end-to-end path via communications or networking services.
- Position, Navigation, and Timing Services (PNT): Services for position and velocity determination, and time synchronization and dissemination. This includes search and rescue location services.

- Detection and Information Services (Det): Services providing detection of events in order to generate timely alerts for human and asset safety and protection. These services publish other beneficial information to users as well.
- Science (Sci): Services that use the RF and/or optical capabilities of the node as a science instrument or part of an instrument.

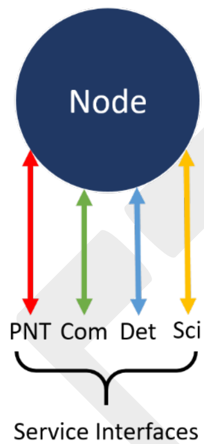


Figure 6. A LunaNet Node Combining the Standard Service Types

3.2.1 Service Attributes

The attributes of the LunaNet services are determined by the aggregation of all the attributes of the node performing the specific services. For example, the coverage of a single relay may be only one third of the lunar surface, but an infrastructure with three relays would have 100% lunar surface coverage. Key service attributes are defined in Table 2 below.

Error! Bookmark not defined.*Table 2. Key Service Attributes*

Attribute Name	Definition
Coverage	The physical location or region where CPNT services may be available.
User Capacity	The total number of users that can be supported.
LunaNet Data Capacity	The maximum combined data volume that can be supported for all users. Each LNS has a data capacity. LunaNet's data capacity is the combined data volume over all LNSs at any point in time.
Availability	The percent of time a service is available to a user.
Maximum Data Loss	Maximum allowable (not to exceed) amount of data loss guaranteed by an LNSP for a specific offered QoS.
Latency	Maximum time required to deliver user data.
Delay Tolerance	Based on the memory capacity of LunaNet assets and amount of user traffic, the amount of delay that an LNS can accept while meeting offered QoS.
Data Rate	Measure of the amount of data transferred over a short period of time, e.g., per second.
Data Volume	Quantity of data transferred over a longer period of time, e.g., per day.
Cross Support Completeness	The extent to which interoperable CPNT services are offered by LNSPs across LunaNet.

Attribute Name	Definition
Expandability	The extent of an LNSP's ability to expand capacity, coverage, and number of concurrent users and to infuse new technologies into their LNS.
Version Transparency	The extent of the ability of CPNT service protocols to support multiple versions and backward compatibility.
PNT Precision	Degree to which repeated (or reproducible) measurements under unchanged conditions show the same results of a position, navigation, or time measurement, i.e., to what fidelity a PNT measurement can be made. PNT precision may be limited by noise on the observation.
PNT Accuracy	Proximity of integrated results to the true value of a state. How well an estimated state (integration of multiple individual measurements) matches to the true state of the user (i.e., an accurate time solution).
Detection Sensitivity	Minimum detectable level.
Detection Timeliness	Speed at which a detection can be made.
Probability of Detection	The probability of correctly detecting an event.
Probability of False Alarm	The probability of incorrectly declaring an event.
Disadvantaged User Support	The extent to which an LNS provides sufficient power and gain to provide CPNT services to disadvantaged users.

3.2.2 Networked Communication Services

A LunaNet node providing Com services will enable networked communications across multiple space-based assets. With LunaNet capabilities, a rover on the Moon can communicate with an orbiter in space and so on, creating an end-to-end path for data.

Like networks on Earth, the user will not have to have knowledge of the underlying link topology or DTN functionality. If assets are built with standard operating protocols, the assets and nodes can interact as part of the larger architecture. Figure 7 is intentionally simple to indicate that this fundamental architecture is independent of any specific implementation concerning space platforms, frequency bands, protocols, or node providers. Well-defined standards enable this simple architecture to become the scalable, highly functional architecture experienced with the terrestrial Internet. Each node is required to be interoperable with any other node to which it will be directly connected. Networking standards are then required to allow the multi-node path(s) between two endpoints.

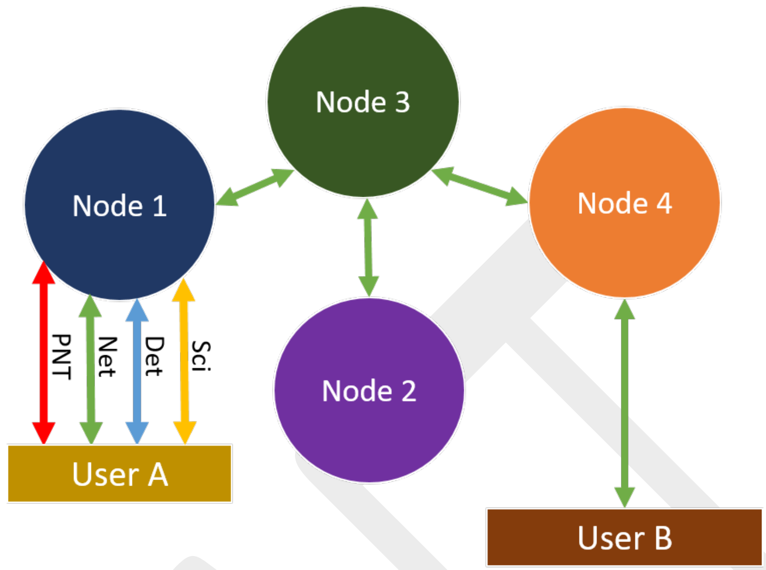


Figure 7. User A Receives Services through Node 1 and Communicates with User B through LunaNet

The architecture will aggregate links, funneling different sources of data to come together to one point to get combined into a single stream of data, as appropriate, to more efficiently use available links and to minimize the total number of links required.

If each node is capable of interoperating with its immediate neighbor and relaying data at the necessary link or network layer, the LunaNet architecture can be assembled through multiple infrastructure systems. The use of standard interoperable protocols for the necessary network layer functions is essential to allow the exchange of data across multiple hops or links.

Though portions of LunaNet will be able to use Internet Protocol (IP) using *packets* for internetworking, the DTN Bundle Protocol (BP) will be the network layer protocol that provides end-to-end connectivity across the full LunaNet using *bundles*. Adjacent nodes must only be interoperable down to the physical layer in order to transfer DTN bundles over their immediate links. Therefore, not all nodes need to be fully interoperable to be part of the LunaNet infrastructure. For example, a lunar surface-to-relay link could be based on commercial standards that are not part of the current IOAG standards. As long as those links can carry bundles or tunnel other framing[1], they may still be an integral part of the network. A relay would then insert the bundles into a fully IOAG-compatible trunk link back to Earth. The consequence for the use of the different lower layer standards may be increased complexity of user communication systems or the inability to use certain access points. The benefit, however, may be a lower-cost path to build out part of the infrastructure.

3.2.2.1 Link Layer Services

A user may receive link layer services only, that is the transfer of data frames. However, this service does not allow for any routing or storage at any intermediate nodes. A series of nodes may be connected by a series of link services to produce an end-to-end circuit between source and destination. This may be necessary in a case when the user communications are not interoperable above the link layer due to encryption or other factors. Some intermediate nodes may switch or forward data at the link or lower

[1] Data frames package protocol data units such as packets and bundles for use by their respective transmission protocols at the data link layer.

layer to minimize onboard processing requirements for supporting very high data rates such as trunk links.

3.2.2.2 Network Layer Services

The fundamental communications services will be networking services, based on the use of the DTN Bundle Protocol (BP). BP provides end-to-end networking functionality based on the bundle as the network data unit. Any node that is to provide network layer services must include a DTN bundle agent. The DTN bundle agent will be capable of storing bundles when individual links are unavailable and forwarding bundles when they become available (i.e., an active connection). It will also be capable of inserting and removing the bundles from the lower layers as required to communicate over its immediate links. Note that some nodes in the lunar or Earth systems may perform IP routing but IP is not guaranteed to be able to provide full end-to-end data delivery to all nodes in the larger LunaNet. There may be some regions able to use IP to connect all nodes within that region; for example, over proximity links. In those cases, bundles will be carried over IP packets to travel through that region or to reach an endpoint in that region.

Figure 8 illustrates a BP-based application communicating between a lunar surface rover and a Science Operations Center on Earth. The end-to-end networking is provided by BP, while portions of the path incorporate IP to connect two adjacent bundle nodes of a particular bundle hop or "bop."

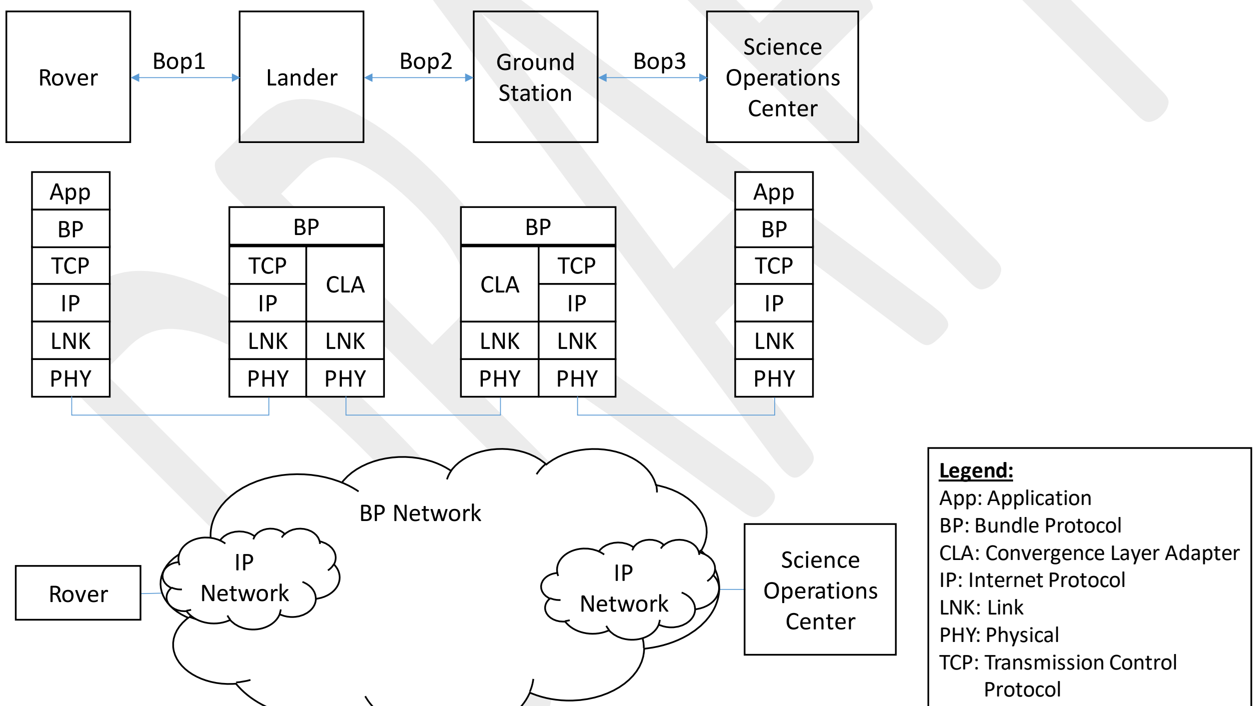


Figure 8. Typical Protocol Stacks on the Communications Path from a Rover to its Operations Center

The provision of networking services implies that the provider network is able to maintain and update routing information such that intermediate nodes are able to determine how to move the data towards the destination or put the data into storage until the right link becomes available.

Networking services introduce the potential for network *security vulnerabilities* like those experienced in the terrestrial Internet and must be addressed. The security objectives of Confidentiality, Integrity, and Availability (CIA) will be applied to all data carried across LunaNet. This will be achieved by a security architecture incorporating a layered security approach, including bundle layer security for DTN networking.

3.2.2.3 PNT Message and Coordination Services

Several standards exist to cover mechanisms for transferring tracking measurements, states, and timing references within the LunaNet framework. Existing CCSDS standards allow for robust mechanisms for supporting this function. To support PNT services, all nodes within LunaNet maintain onboard knowledge of their current location (ephemeris) and time and provide information on their projected state (i.e., any planned maneuvers), as well as information regarding their onboard uncertainty. With integration of PNT navigation observables within the LunaNet architecture, additional information is needed to close the loop with the spacecraft and enable autonomous processing and state estimation. Estimates focus on knowledge of the vehicle's state referenced to where it is traveling (whether fixed or in orbit). The precision of this knowledge directly limits the accuracy of the state estimation. As such, primary nodes within LunaNet maintain high accuracy state knowledge provided by either Earth-based tracking or autonomous observations to some other reference (e.g., optical navigation processing an image of an object with a known state to determine knowledge of the vehicle's state). An alternate use case is for the various Service Users in the network (spacecraft, fixed surface nodes, or rovers) to share their state with each other. This is needed for situational awareness and planning for communication passes or coordinated maneuvering (e.g., for docking or collision avoidance). The following sections will describe these cases in detail, explain the need for data, and outline potential implementations within the LunaNet framework.

Several formats have been used extensively in terrestrial and space networks that could be used to enable this. A key differentiator will be the location of the assets. For example, broadcast knowledge needed for a fixed surface asset will be less complex than for an element in a three-body orbit. As assets are integrated into LunaNet, it is important to identify and standardize the data formats shared between users. Several types of ephemeris transfer mechanisms are intended to be included within the network and support user scenarios. As such, this data is expected to be available on request within LunaNet nodes and maintained at central relay locations for distribution.

For Earth users, one typical format is in the form of Two Line Element (TLE) files. For terrestrial networks, this information is collected from independent, ground-based observations. As LunaNet grows, similar capabilities will be included to support coordinated orbital tracking and ephemeris distribution. While this method will work well at lower altitudes and in low eccentricity orbits around the Moon, operation at or near Lagrange points in the Earth-Moon system will require additional products to enable accurate state propagation. Similarly, high eccentricity orbits will require additional data fields to support long-term propagation and tracking. An increase in fidelity of shared ephemeris includes additional data to enable better longer-term state estimation. An example of this is the Receiver Independent Exchange (RINEX) format used in Global Positioning System (GPS) Broadcast Ephemeris. This data set also includes ground-determined data to inform state propagation and orbital element changes over time due to disturbances such as solar pressure or atmospheric drag (which is not a factor for lunar orbits). Similarly, this format also includes information about a satellite's clock errors (such as bias and drift rates) to enable onboard corrections to any navigation observations. Additional formats also include uncertainty information on PVT to better support inter-node positioning and can be tied to a node's real-time state estimate for processing in navigation algorithms.

For detailed long-term propagation, Chebyshev polynomials (provided within SPICE [**S**pacecraft ephemeris; **P**lanet, satellite, comet, or asteroid ephemerides; **I**nstrument information; **C**-matrix orientation information; **E**vents information] kernels) can be used to provide long-term high accuracy models of well-tracked planetary and celestial bodies. This data is generated using ground observations and high precision orbital propagation models with complex dynamics and perturbation models. This provides an accurate solution for longer term propagation at the cost of additional data being transmitted and more complex software onboard to compute state locations. With frequent updates and tracking, these files are intended to be regularly updated and provide overlapping coverage to reduce any errors induced by transitioning between polynomials during flight.

In order to enable active coordination between users, navigation broadcast services provide the mechanization of sharing this data. Ephemeris of all assets within the network will be collected and accessible via LunaNet messaging and data services. Throughout the network, central databases and application layers allow users to query ephemeris updates on specific other nodes. An example application would be a lunar surface user requesting the latest high precision ephemeris of an orbiting relay for operations planning. An inverse use-case is an application layer to enable nodes to update node-specific state data in the central database due to a recent tracking pass or onboard update. In this way, surface-based services can provide Orbit Determination (OD) solutions to a user.

In addition to supporting query-type response for state knowledge, LunaNet services also enable real-time state broadcasts. Individual nodes within LunaNet transmit state data at a low rate to enable situational awareness among assets. A GNSS satellite broadcasting its current state is a terrestrial example of this. Another example is Automatic Dependent Surveillance-Broadcast (ADS-B) services or MAPS packets, both of which represent active methods of real-time broadcasting of onboard state knowledge. This knowledge is needed for real-time processing of positioning observations such as range or range-rate into an onboard solution. These services are focused on enabling real-time awareness and sharing of state knowledge between nodes to enable coordinated activities. A summary of these and other potential navigation data of interest that are of use to individual elements is given in Table 3.

*Table 3**Error! Bookmark not defined.Error! Bookmark not defined.**. Navigation Data Message Types and Use Cases*

Navigation Data Message Type	Use Case
Ephemeris Information	Long time frame coordination of node's planned orbits and locations to enable link analysis, path planning, and navigation. Additionally, can be updates to planetary or stellar catalog information.
Current Position, Velocity, and Time with Uncertainty of the Host LNS Node	Used in processing relative navigation measurements such as range, range-rate, or bearing to correct an onboard absolute position. Used to support near-real-time situational awareness.
Current Attitude (Pointing)	Combined with position information, can be used to enable high accuracy pointing between two nodes to enable high bandwidth links.
Planned or Active Maneuvers	Used for situational awareness to avoid collisions between users.
Raw Observables	Containing unmodified measurements of relative states between two elements, this message provides the information back to the user for processing and integration into positioning and timing algorithms.
Current Position, Velocity and Time (with Uncertainty) of a Service User	When a node performs positioning for a service user, this message provides the user's current state, to use in onboard operations.

3.2.3 PNT Services

To support coordinated activity and autonomous operations in cislunar space, for missions operating on approach to lunar orbit, in lunar orbit, or across the lunar surface, distributed PNT services are needed to provide onboard knowledge of a vehicle's or satellite's current location and globally referenced time. This information has broad applications to pass information between elements in the LunaNet networks (both ground and orbital assets) and navigation throughout the Earth and cislunar regime. One example of this is a spacecraft planning to point a high gain antenna towards another asset for a pre-planned communication pass. By using LunaNet PNT services, a User's Mission Operations Center (MOC) or an autonomous User Spacecraft can previously plan when to point, where to point, when to enable onboard radio, when to begin and end transmission, and how to maintain pointing during the pass. This enhanced knowledge enables high accuracy pointing, maximizing received power and enabling increased bandwidth throughout the network. Additionally, with high accuracy and stability on timing, higher data rates can be enabled and the efficiency of the individual spacecraft can be improved, enabling greater coordination and planning across the architecture. Having an external method for updating a space system's state knowledge ("state" referring to a 3-dimensional position and velocity at a specified time), can allow the system to autonomously operate in areas such as cognitive communications or perform coordinated activities with other systems. Specific applications can include onboard planning of orbital change maneuvers, descent operations, or autonomous surface exploration.

Having local services in cislunar space also reduces demand on Earth ground-based assets by pushing the tracking capability out into the space-based portion of the architecture. Traditionally, for absolute positioning, OD has been provided by tracking services enabled within the Earth-based communication and navigation network. This involves taking long observations of spacecraft radiometric characteristics (such as coding phase change or Doppler shift) and processing with ground-operated OD algorithms to develop an updated state for mission planners. As the ground infrastructure is expected to support more operational assets simultaneously, less time is allowed per spacecraft. Some ways to address this include multi-user simultaneous operations on a single antenna or expanding the number of assets. LunaNet includes this PNT capability in the local planetary networks to create autonomous capabilities for selected celestial bodies throughout the solar system. This section describes the proposed PNT services, their implementation, and integration with vehicle operations.

The LunaNet PNT services can be characterized in terms of what function is being supported. Due to each element in the architecture providing some measure of cross-vehicle support, individual elements may act in multiple modes, for example, as a relay, ground station, or a mobile user (whether constrained to surface operations or not). In terms of navigation these functions break down as shown in Table 4, Table 5, and Table 6. Each of these functions is broken down into more detail in the following sections with details on planned implementation and interfaces.

Table 4. Description of Positioning Services

Function	Description
Generate ranging observable	Generation of time-synchronized ranging code.
Operate as turn-around relay	Enables two-way ranging between two elements using a known code where transmission source also performs measurement.
Identify and measure range to transmitting assets	Measure code phase and time of reception to produce a range estimate between two assets.
Measure Doppler frequency of received signal	Measurement of Doppler (received frequency vs. expected frequency) provides information on relative velocity between two assets along the line of sight.

Function	Description
Provide measurements via telemetry	Where two-way measurements are used, the transmission sources need to provide the measurements of relative range and range-rate to the receiving vehicle via standard telemetry.
Measure onboard position using *in situ* measurements	Use of additional onboard systems, such as optical navigation or low-signal GNSS, to determine an autonomous state estimate.

Table 5. Description of Navigation Services

Function	Description
Process multiple measurements into an integrated Position, Velocity, and Time (PVT) solution	Use of estimation algorithms to integrate multiple single-dimensional independent measurements to provide an estimated PVT state, both as an onboard and external service.
Transmit integrated PVT state to user	For external tracking scenarios, provide estimated PVT state to user/relay for onboard/autonomous operations .
Transmit vehicle ephemeris for use in measurement processing	For onboard state estimation, provide current PVT state of reference station to allow for processing and integration of low-dimensional measurement.

Table 6. Description of Timing Services

Function	Description
Maintain a stable onboard time reference	Usage of high stability onboard oscillators or external measurements to maintain a stable time-base.
Provide a coarse time synchronization capability	Broadcast of current time scale in a two- or one-way transmission to allow for updated onboard estimates of current global time.
Provide a fine time synchronization capability	Use of a specific ranging and broadcast code within signals to allow for high-accuracy disciplining of clocks within the network.

LunaNet PNT services also build on the foundational architecture developed and designed for Earth-centric operations such as a proposed terrestrial Space Mobile Network that takes advantage of concepts developed for and tested on the Tracking and Data Relay Satellite System (TDRSS) Augmentation Service for Satellites (TASS)[Error! Reference source not found.]. This approach provides a terrestrial analog to a lunar-focused implementation. This architecture takes advantage of well-known and highly accurate reference satellite (TDRSS) location and timing to provide in-space reference signals for PNT user needs. While this service was designed to support in-space users, it is highly applicable to ground users as well. The following sections describe the foundational services to enable PNT, with many parallels to the TASS approach as part of LunaNet. Tracking and positioning services are focused on the mechanization and approaches for relative state measurements between nodes, as part of the network infrastructure. Additionally, these services enable onboard navigation to support autonomous operations using individual measurements integrated with other potential onboard sensors to capture an absolute state. Timing services enable accurate knowledge, at the nodes, of when the measurements occurred and allow for integration and processing into an absolute state, in addition to relative tracking between nodes.

3.2.3.1 Tracking and Positioning Services

To determine one's location in space, measurements are needed to some known reference(s). These measurement types can be generalized into several fundamental properties: range to a known location, velocity relative to some point, or bearing to some object. Modern navigation systems can be simplified down to these observables. For positioning within a 3-dimensional space, three unique measurements are needed at a minimum. Additional simultaneous observations can help to reduce error or estimate other system errors. For example, for an instantaneous GPS position fix, ranges are needed to four satellites. The fourth measurement is needed to remove any user-side clock biases that affect the actual measurements. Additionally, given information about the dynamics of the system, such as in orbit about the Moon or Earth, filtering algorithms can be used to integrate time-separated one-dimensional observations. For example, for a satellite passing overhead, observations of range or range-rate between the ground station and the spacecraft can be processed together to perform an estimated state of the spacecraft's position and velocity. As such, the base tracking observables within LunaNet consist of bearing angles between nodes, range between nodes, and range-rate between nodes. This is important for LunaNet which will not have a large GPS-like constellation to provide instantaneous fixes.

These measurables can either be directly observed by a specific node or provided by an external reference. For radiometric (and in the future, optimetric) systems, two-way ranging is a baseline approach to tracking a node. In this architecture, a tone with a known frequency is transmitted from a navigation host to a node, which then sends that same signal back to the host. The host then compares the tone received to the one generated to determine the distance between two elements (measuring time of flight). Two-way ranging thus involves a signal traveling from a host to a node and back. The resulting observations can be provided to the user as range measurements for inflight processing. An example of this would be in proximity operations where relative positions are of key interest. In an alternate (navigation service) approach, the measurements are collected over a period of time and processed to estimate the position and velocity of the user, which is then transmitted. A similar approach to this tracking is called one-way ranging, in which the user has sufficient information to recreate the original tone at the host. An example of this is in GNSS systems such as GPS. This provides on-host measurement processing but requires additional onboard timing accuracy and processing capability for generation and correlation of the received versus expected signals. LunaNet tracking services support both types of ranging observations, allowing users to select based on their onboard capability and navigation requirements.

An alternate approach supported by LunaNet is Doppler Tracking between nodes. This observable of the transmitted signal gives insight to the relative motion between the two. The frequency shift can be correlated to a range-rate and utilized in OD routines (either on the host or node) to update the user's current state. This accuracy of this measurement is dependent on the stability of the transmitting node. For example, in a radio signal, an unstable oscillator results in a noisy transmission frequency that limits the node's ability to measure a stable Doppler shift, due to relative motion. Relay nodes within LunaNet are designed to have stable time and frequency generation to support improved use of this tracking signal. Similarly, this tracking data can be collected onboard the user from a node or captured at a node based on the user's signal and then either provided to the user or utilized in onboard OD routines.

The above two approaches to ground-based tracking are used extensively to support space vehicle navigation. For example, these services are considered standard within DSN and NEN. Similarly, they serve as an integral part of tracking nodes within the LunaNet architecture. Several experiments have been performed to show the promise of expanding these services within the overall CPNT architecture. Both methods – ranging directly to a TDRSS satellite (inter-node two way ranging) and pass-through ranging from a ground station with TDRSS as an intermediary – have been demonstrated and are in use in Low Earth Orbit (LEO) through systems such as TDRSS-relative navigation. Missions to the International Space Station (ISS), cislunar orbital platforms such as Gateway, and Human Lander System (HLS) elements all use two-way ranging to support relative navigation between target and chaser vehicles. Studies have been performed utilizing this same capability to support Entry, Descent, and

Landing (EDL) scenarios to improve landing accuracy on Mars. Two-way ranging functionality will expand to all elements within LunaNet to enable inter-asset relative and absolute navigation.

The remaining key observable is bearing angle to a known reference. In an onboard tracking application, this requires knowledge of the user's state at the time of observation, while in a navigation solution, the location of the host node is known and angles to the user provide an estimate of the user's state. This observation can be captured in multiple ways. For high accuracy ground stations, one approach is Delta Differential One-way Ranging (Delta-DOR) which uses well-known angular positions of high energy galactic sources in the sky to serve as anchors to help observe a broadcasting user's location in the sky. This approach can result in a high precision angular measurement, with multiples of these observations being used to solve for a user's state. Other approaches can use optical observation from an onboard camera for near-field relative navigation (OpNav) or radar observations for longer-range operations.

Lastly, surface users will require additional tracking services enabling direction finding to a known reference. For example, emergency tracking scenarios enable these elements to understand direction to and range to a reference point. This is primarily enabled through radio direction finding techniques for scenarios with limited ground infrastructure. As the infrastructure grows (through the use of portable relays, for example), more advanced techniques can be performed based on inter-relay ranging and power signal observation to aid in surface navigation. These services form the basis of LunaNet surface navigation services. They are intended to support location navigation needs and be portable, as well as support extended lunar exploration.

As the number of operating users within LunaNet begins to expand, and infrastructure is established to support new user scenarios, these tracking capabilities will provide extended coverage and support. Initial implementations focus on the use of LunaNet ground stations to provide tracking observables and integrated state solutions. As elements are deployed in lunar orbit and to the lunar surface, this tracking capability will be included to enable enhanced observation geometry, accuracy, and availability. Lunar surface elements will provide tracking capability for extended EVAs and provide direction-finding support to surface users. Future deployments may include dedicated lunar tracking stations in cislunar space to provide local tracking services to multiple users and serve as a high accuracy, well defined reference.

3.2.3.2 Time and Time Dissemination

As identified in the previous section, the potential navigation observables must be integrated together in order to provide an estimate of a spacecraft's position and velocity state. Part of this processing requires knowledge of the PNT asset's location at the time of the observation to process the data onboard. When processing this data, errors in time between two elements will feed into errors in position and velocity estimates. As such, the position and timing are inexorably linked for absolute ranging. Even for relative navigation, any timing errors will show up as system latencies, but due to the typically lower relative velocities, these errors have a smaller effect. Similarly, performing a time transfer between two elements requires a measurement of the light travel time between them. As such, any errors in state on either asset will cause timing synchronization errors between the spacecraft. For the traditional ground-based OD approach, extremely accurate clocks are used to timestamp the observed measurements and high-fidelity dynamics models are used to capture the light travel time (potentially with relativistic corrections) with the OD solution. With this knowledge, and timestamps of digital data received from the spacecraft with its onboard clock, spacecraft timers can be correlated to absolute time.

LunaNet proposes an autonomous capability to enable time transfer within the communication network and between any participating members. For assets within proximity link range, with low system latency and small light travel times, this can be as simple as applying a broadcast time to update onboard time for a coarse time update. Finer resolution can be provided using an approach like the network layer service Network Time Protocol (NTP) that uses call-and-response timestamps between assets to measure the time of flight delay at the host site to apply the broadcast time with a correction to account for the signal travel time. This can enable high fidelity synchronized time across the network (accurate to an order of microseconds). Similarly, ground testing can help to identify system internal latencies to provide better timing updates.

LunaNet nodes will utilize one of two types of timing subsystems to ensure accuracy – a high stability onboard oscillator (such as an Ultra Stable Oscillator or an atomic clock) or synchronization of onboard time with Earth-based master clocks. Examples of both can be found in GPS. Each GPS satellite contains an ensemble of high stability rubidium clocks for maintaining short time period accuracy and frequency updates, while GPS satellite tracking with ground assets is used to maintain estimates of their clock bias and drift, relative to feed, throughout the network for improved PNT services.

Two are included as independent time services within LunaNet: *coarse* measurement and *fine* measurement. Time comparisons between two nodes can provide a coarse understanding of time on the milli- or micro-second level. LunaNet, however, supports increased-accuracy time transfer services provided in this way: A high stability clock reference broadcasts signals at a fixed, well-established rate, with an objective of 10 nanosecond accuracy which is equal to GPS. This repeatable information on a broadcast signal helps to further discipline clocks across the architecture. The primary limitation to this service will be the correlation with onboard state knowledge to account for any Doppler effects. Optical PNT capabilities within LunaNet are anticipated in the future. Optical PNT functionality will push fine timing accuracy to the sub-nanosecond level with the operational benefits of reducing propellant usage and enabling unprecedented accuracy on numerous scientific experiments.

3.2.3.3 Navigation Applications within LunaNet

LunaNet's PNT services and capabilities support a variety of operational scenarios. For this section, navigation is referred to as the ability to guide or direct a spacecraft from one point to another. This function is enabled by the previous two services (timekeeping and positioning) that enable high fidelity knowledge of a vehicle's state and the current global time. Without these services, navigation capabilities are vastly limited in capability, e.g., ground-based pre-planned maneuver design. With the expansion of these services, additional capabilities are enabled throughout the network.

3.2.3.3.1 Human Missions Aided by LunaNet

For human-operated craft using LunaNet services, these tracking and timekeeping services can help mission planners define maneuvers to maintain planned operations. This knowledge is needed for orbit maneuver design, for example, transferring between lunar orbits or during descent operations down to the lunar surface. For current descent applications, the accuracy of lander knowledge prior to powered descent drives onboard sensor requirements. Navigation services provided by LunaNet enable future landers to maintain a high accuracy onboard state estimate, enabling robust and efficient mission scenarios. Without embedded navigation services, vehicles must rely on a combination of Earth-based tracking (placing a burden on constrained ground network capacity) and multiple autonomous sensors to provide lunar-relative observations onboard. The availability and usage of these services will help to reduce the need for extensive and expensive lander sensor suites allowing the mission to enhance landed mass and mission value.

3.2.3.3.2 Autonomous spacecraft aided by LunaNet

LunaNet navigation services also enable a jump in onboard autonomy for a variety of spacecraft platforms. By providing accurate state estimates and accurate timing knowledge, a user can track to a high degree of precision operational requirements versus mission requirements. For example, operating in a Near Rectilinear Halo Orbit (NRHO) requires regular maneuvers to counteract disturbance forces on the vehicle and maintain orbit stability. LunaNet services support the spacecraft estimating long-term orbital dispersions and being able to optimize maneuvers, reducing propellant usage.

3.2.3.3.3 Fully autonomous spacecraft

Fully autonomous spacecraft (i.e., spacecraft using no Earth-based network or external LunaNet support) can operate within the LunaNet service domain and help to provide independent references. A spacecraft utilizing navigation techniques, such as X-ray Navigation or autonomous optical navigation,[Error! Reference source not found.] could maintain its own state and time to a high precision. These types of nodes can help to anchor local PNT services on the far side of the moon, where only limited coverage may be available. With onboard positioning techniques, these nodes can provide LunaNet services in navigation, such as OD and state estimation, to other users.

3.2.4 Detection and Information Services

The atmosphere around Earth usually protects humans and space assets from harsh solar particles coming off the Sun during a solar flare. However, because of the lack of protective atmosphere at the Moon, there is an increased chance of solar storms impacting our astronauts, satellites, and systems. It is imperative for the safety of our people and assets that they receive advanced warning of these incoming particles from solar eruptions. The LunaNet services will enable dissemination of space weather data and event alerts from instruments (e.g., on heliophysics missions) that will constantly monitor the Sun for any increase in solar activity that could result in a solar eruption. This data will be sent through the LunaNet architecture as part of the Detection and Information (DET) services. With this constant monitoring, the architecture could warn astronauts exploring the lunar surface of an incoming event and advise them to seek shelter without the delay of routing the alert through mission control on Earth. It could be used by robotic missions to autonomously shut down experiments, shed the power load, and prepare to ride out the storm.

There are four key measurements of interest that are required to understand crew radiation exposure and guide crew action in future deep space missions.

1. Solar X-ray detection indicating that a major eruption has taken place. This arrives at light speed about eight minutes after onset.
2. Any predictive information about a possible associated Solar Energetic Particle (SEP) / Energetic Neutral Atom (ENA) event.
3. In-situ observation of the onset and progress of the SEP event (Figure 9). Protons and heavier ions >10 Million electron Volts (MeV) that can penetrate a spacesuit or habitat are the primary concern. The requirement for deploying a protective crew storm shelter is ~30 minutes from the event onset. Consequently, information on timescales of tens of minutes is relevant for crew space weather mitigation actions.
4. When SEP flux decreases sufficiently, an "all clear" event can be sent to notify crewmembers that they can emerge from shelter.

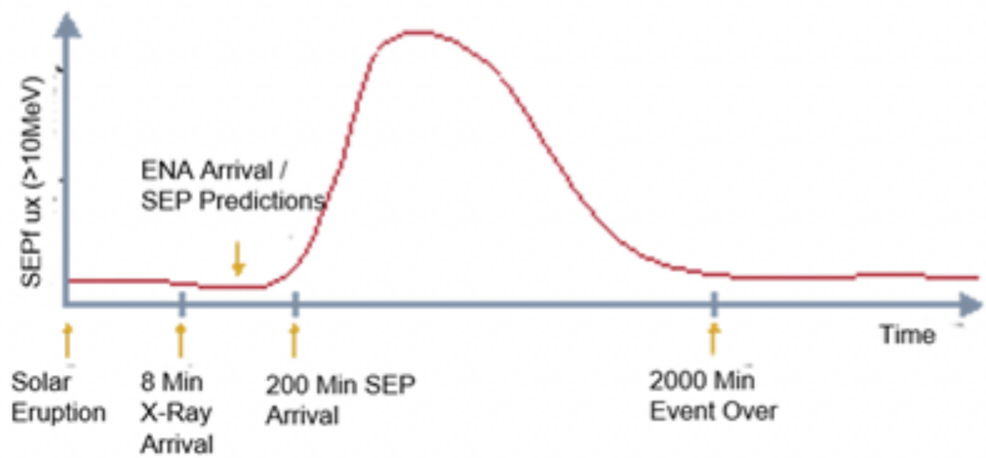


Figure 9. Event Timeline to which the Crew Onboard a Deep Space Vehicle Must Respond

Supporting the timeline in Figure 9 requires a suite of space weather observations that include solar soft X- rays and energetic charged particles. Importantly, these types of measurements also have significant national space weather dimension in terms of supporting National Oceanic and Atmospheric Administration (NOAA) space weather observation requirements and preventing damage to national and international systems such as power and communication utilities.

In addition to the heliophysics observations described here, other science observations may be identified as vital streaming information and notification services to support user safety and operations.

3.2.5 Science Services

It is possible that some LunaNet assets may be able to support direct science objectives through use of their available radio or optical links and telemetry. Some opportunities for science services only require the LunaNet space equipment to operate in a special mode within the capabilities of the communication and PNT subsystem. In such a case, services would be scheduled to support radio science investigations. The DSN, for example, supports Radio Science services, Radio Astronomy / Very Long Baseline Interferometry (VLBI) services, and Radar Science services, or the data and meta-data generated by these services. LunaNet assets could be designed to deliver measurements of the spacecraft downlink signal from open-loop receivers for use in radio science. This service could also be used to support mission critical events such as EDL or spacecraft emergency search.

Other opportunities may occur only if the LunaNet space equipment is designed to act as a multi-function device, e.g., for both communications and radar. This would require the LunaNet antenna and equipment string to also be designed *as a science instrument* (or at least as one end of an instrument). In the transmit process, the equipment may use more power and send pulses (with associated shaping or timing) instead of coding or modulating. On receiving, the equipment does not decode, demodulate, or filter out noise; it saves the entire spectral result; that is, it saves exactly what a communications device would filter out. Science services are specific to specially designed nodes and do not provide interoperable services over the network.

3.3 Service Management

Service Management, as a LunaNet function, will be conducted collaboratively by the LunaNet Service Providers and the Service Users to plan for services, track the service execution, and account for instances of services provided by LunaNet assets. The services to be managed encompass those provided at each network (and their network assets) as well as the "end-to-end" services across the set of Earth networks and LunaNet relay surface networks. Therefore, LunaNet service management will exist at two levels – at the individual LNSP level and the global end-to-end LunaNet level.

3.3.1 Strategic Planning

To create a long-range plan for LunaNet, a Strategic Planning process will be conducted to assess and project the overall network capacity and the ability to meet aggregate user needs. The anticipated cislunar CPNT market and all potential future user missions will be analyzed and their collective resource demands on communications and navigation will be modeled. This is likely to be done by each LNSP independently, followed by a process for coordination among the set of LNSPs, perhaps through an industry association. The extent of this coordination may differ among government, commercial, and academic LNSPs. For example, government agencies are likely to disclose their planned missions with adequate lead time to plan for evolution of network capabilities. Commercial LNSPs are not likely to share their private market analysis; however, this may be accomplished by a commercial market analysis procured by an industry association.

To ensure the development of high-fidelity mission models, it is expected that certain mission information, such as key mission timelines and trajectory, and relevant communication parameters at the link and network layers (e.g., frequency bands, symbol rates, contact hours, and data paths), will be provided by the user missions. The supplier model will encompass not only Earth networks as they are at present but also cislunar communication assets such as LNS relay satellites and surface stations. Coordination among LNSPs (e.g., incremental evolution plans for each Service Provider) will be needed but is part of the LunaNet governance question that is undefined.

3.3.2 Service Planning

Service Planning includes activities such as: negotiating service agreements with user missions; planning and allocating communication and navigation resources based on requirements; performing link analyses, coverage analyses, and loading analyses; and assessing the impact of proposed commitments. These activities will lead to the generation, approval, and maintenance of Service Level Agreements (SLA) for the commitment of LNSP service provision to Service User missions. Significantly different from the traditional approach commonly applied by present network Service Providers, the LunaNet service planning is characterized by a few salient features:

1. End-to-end service planning: The link analysis, coverage analysis, and loading analysis for LNSP support to an individual Service User will be conducted by taking into account all the service-providing assets on the end-to-end communication paths, including those of other cooperating LNSPs if required (e.g., for sufficient coverage). Each analysis can no longer be conducted for each service-providing asset independent of that for the other assets. Instead, the conjoint analysis approach will be taken with the primary LNSP identifying shortfalls in its capability and requesting cross-support from a second LNSP.
2. Integrated service provision trades: Trades for LunaNet service provision, given the available options for end-to-end paths, will be performed in an integrated fashion for each Service User mission to reach the optimal solution.
3. Federated or Integrated SLA for commitment process: For a Service User that requires services from communication assets of multiple LNSs, the commitment process will lead to the generation of federated SLAs. This is for accommodating terms and conditions that may vary with providers, e.g., cost and liability. For cases where all supporting assets are managed by the same agency/company, an integrated approach to SLA development will be employed.

3.3.3 Service Provision Management

To manage the service provision by the LNS(s), due to the broad scope of and diversity of providers within the LunaNet, it is imperative to establish a system for the automated tracking of service instances throughout their life cycle; i.e., from the creation of service requests (scheduled or user initiated) to the execution of service instances and the final delivery of service data to the Service User's designated destinations. Across the LunaNet, occurrences of anomalous conditions/events in service provision will be automatically reported and tracked for resolution. Outages of any communications link, detection of security breaches, and downtime of network assets due to maintenance that will affect the committed service provision will be resolved with users. At the end of the service life cycle, post-service reporting of results, in the form of service accountability and performance summary, will take place (see Section 3.4.3).

3.4 Service Acquisition

Initially, the LNSP will immediately provide scheduled services consistent with the service delivery methods used in legacy systems. However, the goal by Phase 2 will be to include on-demand services via onboard relays / nodes, which will lead to UIS capabilities made available to all users.

3.4.1 Requesting Service

3.4.1.1 Scheduled Service

A single scheduling interface will be established for users to schedule their LunaNet services via their chosen LNSP. Users will define their *Service User profile* – a combination of their requirements, preferences, flexibility, and LNSP-specific parameters defined in their SLA – to their LNSP to aid in partially or fully automating the scheduling process. This interface will be able to schedule access times for all assets directly operated by an LNSP and may be able to also schedule access through other LNSPs on behalf of a user. This scheduling will be done with a forecasting period of days to weeks that may vary by LNSP but may be adjusted up to minutes of an available time. Scheduling will be priority or QoS-based, as established through SLAs.

3.4.1.2 On Demand Service

Some services may be available "on demand", meaning that the service is available at any time a user wants them. For example, a return link path may be available on demand, if there is guaranteed to always be a receiver in view and "listening" for a user's transmissions. An on-demand forward service may be provided through broadcast channels that provide a continuous opportunity for communications to user spacecraft. On-demand service may be requested by the user spacecraft as well as by the User MOC.

To implement on-demand services, an LNS must perform *dynamic bandwidth allocation* and assure *end-to-end connectivity*. Note that "end-to-end connectivity" in a DTN network does not require all links along the end-to-end path to be connected contemporaneously. Dynamic bandwidth allocation reserves network capacity in real-time in response to the user's service request while meeting the user's requested QoS. End-to-end connectivity requires that a path must exist within the network between the source and destination(s) of the data being transported. In terrestrial networks, network nodes are permanently wired and the probability of end-to-end connectivity is very high. In space networks, connectivity is wireless and depends on Line of Sight (LOS) between nodes, which constantly changes due to the orbits of network nodes or user nodes; consequently, end-to-end connectivity may be frequently interrupted. Path routing algorithms search for alternate connections. If an LNSP has cooperative agreements with other LNSPs, paths may be discovered by using the combined topologies of two or more LNSs. DTN network layer service assures end-to-end delivery of data in spite of gaps in end-to-end connectivity but may not meet the user's requested QoS, particularly latency.

3.4.1.3 User Initiated Service (UIS)

UIS allows a user to request a service from the network through any available communications path with that user, e.g., from the User MOC or spacecraft. For example, an on-demand channel may be used to request a higher rate service that will be provided soon after that request and possibly through a different asset.

UIS automates current processes for space communications service acquisition using a request-response design pattern, with the service request generated by the user. The data contents of the request message may vary based on user mission compatibility constraints, degree of platform autonomy, or other considerations. However, a key distinction from current service acquisition processes is that a UIS request may be service-oriented as opposed to link resource-specific. For example, a user may specify a request to "Deliver 25 gigabytes of data from the mission platform to the science operations center within two hours," or "Get as much data as possible off my space platform as soon as possible [to avoid overwriting the on-board data storage], and deliver it to the science operations center within six hours." Requests specified in these terms allow the provider network – which may be government, academic, or commercial resources operating as a federated network – the flexibility to optimize allocation of the request across the set of link and network resources that best satisfy the user mission service and link parameter constraints.

A key architectural principle for realizing service-oriented requests in terrestrial networks involves the separation of concerns pertaining to network signaling and control data flows (which enable autonomous monitoring and control of resources) from those of the user data flows (which traverse the paths orchestrated by the signaling and control processes). UIS is an emerging class of space communications service acquisition processes implemented through signaling and control protocols.

Users with existing service on any data channel may use it to simultaneously initiate a UIS process to acquire additional service in the future. UIS protocol facilitates the exchange of a user's request and the confirmation of provisioning of resources.

The UIS protocol will communicate between the user and the network using specified network control messages and formats. If an LNSP is unable to satisfy a user request for on-demand service, the service request protocol may allow conversion of the request to UIS service, e.g., on a "next available asset" basis.

3.4.2 Providing Service

The highly automated LNS will manage all necessary activities to set up, provide, and tear down services without any involvement of user systems. Any required time for these activities will be factored into the scheduling and availability of the assets and must be taken into account in SLAs. There will also be time required to accommodate engineering support and calibration activities.

3.4.3 Service Accounting

LunaNet service accounting can be measured both by access time and by data volume transported through the end-to-end network. This would allow for verification of network performance to service level agreement levels and also provide data for billing purposes. The LNSP will provide accounting data for both services directly provided to users and services provided to support other LNSPs. LNSPs will need to record services provided to each user, noting satisfaction of service (or issues). For each billing period, the LNSP will convert the user's service record into a billing statement and deliver it to the user for payment. Accounting and billing functions are not addressed in this architecture document but recognition of them must be factored into the technical architecture. Billing for services rendered is not limited to commercial LNSPs. For example, the U.S. government is legally required to charge for reimbursable services depending on the SLA. Academic LNSPs could also charge for services.

3.5 Use Cases / Scenarios

3.5.1 Mission Phase Scenarios

3.5.1.1 Cruise to/from Moon

The earliest mission phase that LunaNet will support is cruise to cislunar space. Typically, this would involve a ground station on Earth providing communications to and radiometric tracking of the user. These PNT updates are typically processed on the ground and fed into mission design practices to support maneuver planning and operations support. When closer to the Moon, additional and possibly higher performance services may be available from lunar orbit or lunar surface access points.

Initial LunaNet capabilities will enable the spacecraft to track navigation measurements and perform autonomous navigation, integrating the observables onboard to determine a complete solution. Additionally, as nodes are placed into lunar orbit or on the surface, the user can also utilize these references for state determination. These navigation aids greatly improve state knowledge as the vehicle is on final approach to insertion into its desired lunar orbit – as the onboard state is better known, the vehicle can better perform insertion maneuvers, reducing propellant needs and efficiently entering the target orbit. By using local LunaNet assets, the user is more agile and responsive to actual in-flight conditions, minimizing the latency from external tracking references.

3.5.1.2 Lunar orbit

Local LunaNet reference nodes, both on the surface and in orbit, can support in-orbit operations of various vehicles. Providing local PNT services can enable rapid onboard state estimation. This support is needed for vehicles transferring into or changing phasing within their orbits. An example use case could be a vehicle transitioning from a high-altitude halo orbit down to a lower lunar orbit in preparation for descent. Similarly, improved state knowledge allows the vehicle to better perform onboard maneuvers and efficiently use onboard propellant. Cislunar PNT services enable a path to future fully autonomous operations by providing the accuracy of onboard state necessary to perform closed loop guidance, eliminating reliance on ground-planned maneuvering.

Lunar orbiting users will receive CPNT services directly from LunaNet Earth ground station access points during the initial LunaNet implementation phase. As the LunaNet implementation is built up and the number of missions increase, lunar relay and lunar surface access points will become available to aggregate user data flows to minimize the number of links to Earth required and to also facilitate routing of data within the lunar region.

3.5.1.3 Rendezvous, Proximity Operations and Docking-Undocking (RPOD-U)

With the on-orbit assembly of multi-element stations (Gateway) and logistical support of vehicles in lunar orbit (Gateway and HLS), LunaNet services provide lines of communication between elements operating in close proximity. As part of the RPOD-U process, a pre-planned corridor is used for flight maneuvering and approach. The process includes multiple stops and checkouts for safety and mission assurance prior to final approach and docking. CPNT services are used between the cooperating vehicles and their MOCs to coordinate activities. For example, Gateway gives a go-ahead for a final approach and docking of Orion. During this process, the two elements share their navigation data as well, in order to track each other within the planned approach corridor and identify any off-nominal behavior and respond accordingly. These LunaNet services will be used to enable safe operations and, eventually, autonomous docking and undocking in lunar orbits. RPOD-U operations will be treated as critical events. During far field approach, the two elements share their navigation data and track a bearing between them until they reach the near field, where high fidelity docking sensors come online. As the operational elements continue to mature, future applications of RPOD-U include vehicle or station inspection, refueling activities, and formation flying, e.g., for a distributed interferometer network of satellites around a Lagrange point to maintain a tight constellation. Details of RPOD-U operations between a target (passive vehicle) and chase or visiting (active) vehicle are defined in the following documents:

- International Rendezvous System Interoperability Standards (IRSIS): This standard defines operational phases for RPOD-U, including off-nominal cases, for visiting vehicles and the target. It defines operational regions and zones, approach and departure corridors, decision points for safe stepwise approach and departure, time distribution, inter-vehicle telemetry (time stamp, health status, approach/departure mode, and absolute and relative navigation data), crew interaction, RF range and range-rate, and secondary state determination system (SSDS) for independent sensor cross-check against the primary navigation performance. The CPNT capabilities used to support RPOD-U operations are part of LunaNet, except for the SSDS which is a rendezvous sensor (e.g., radar) that provides precise attitude/position/velocity information when the two vehicles are less than 1 km apart. Figure 10 describes the concept of a visiting vehicle approaching the target from the right, beginning with completion of the transfer phase when the visiting vehicle is inserted into the same general orbit as the target. The visiting vehicle then approaches the target tangentially with respect to the Rendezvous Sphere. A decision must be made to proceed to the next step of tangentially approaching the Approach Sphere. Another decision is required to proceed to tangentially approaching the Keep Out Sphere, before final approach and docking with the target at the center of the Keep Out Sphere can occur.
- International Communication System Interoperability Standards (ICSIS): This document defines the CPNT characteristics over the short range, space-to-space interface between a visiting vehicle and a target vehicle, for data exchange and radiometric tracking. Inter-vehicle telemetry is detailed to include commands, audio, imagery, time stamp, vehicle attitude/position/velocity, health status, and approach/departure mode. This link is compatible with the Orion space-to-space link used during Orion RPOD-U with Gateway. As the visiting vehicle, Orion generates, modulates, and transmits the ranging channel that Gateway receives and coherently turns around. Orion receives, demodulates, and processes the range channel and carrier to make the range and range rate measurements.

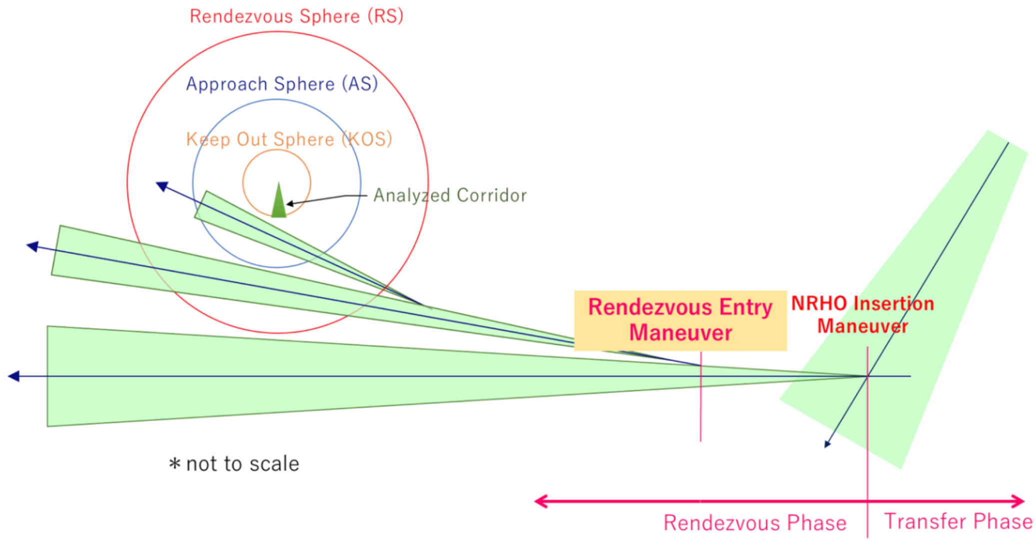


Figure 10. Notional Concept of RPOD Zones and Corridors [source: IRSIS]

3.5.1.4 Descent to surface

Currently, lunar descent vehicles are heavily dependent on complex onboard sensors systems to maintain accurate state knowledge during descent. These sensor suites typically include Terrain-Relative Navigation sensors, radar altimeters, and velocimeters. These are needed to provide state updates during descent operations to enable high precision landing accuracy. Concepts for a lunar base will require repeatable high landing accuracy with an error less than 100 meters and eventually, less than 10 meters.[2] This need is due to the growth of navigation errors caused by inertial drift of the state estimate from the final external update provided prior to powered descent initiation. LunaNet assets can aid descent navigation by providing positioning information during these critical maneuvers, allowing for enhanced accuracy and reducing the requirements on other autonomous sensors. This implementation has analogs to the terrestrial domain: as GPS receivers become smaller and lighter, they could be integrated into a diverse set of vehicle applications, and reduce the reliance on complex, high-accuracy sensors for tracking inertial states, providing the same or greater capability at lower cost and weight. During descent, LunaNet assets placed on the surface near or around the landing site, or passing overhead, provide relative measurements of range and range rate along with high-fidelity truth data of the transmitting node, allowing the lander to integrate the measurement and track its state to high accuracy. For lunar landers, having this infrastructure capability can help to reduce the need for complex onboard sensor suites and instead rely on LunaNet to enable more efficient operations with equivalent accuracy at reduced risk.

Lunar descent phase services will be supported as critical events. This would include the availability of redundant paths for communications.

[2] In 1969, Apollo 11 overshot its intended landing site by several kilometers due to rudimentary understanding of the uneven lunar gravity field. A few months later, Apollo 12 landed ~180 meters from its target, Surveyor 3, due to rapid improvements in understanding, modeling, and analysis.

3.5.1.5 Surface

In addition to CPNT services in orbit, LunaNet provides additional capability for surface users to aid in crewed exploration, robotic, and autonomous operations. These nodes can be included as dedicated elements or payloads on LNS host platforms and be placed across the lunar landscape as part of a growing infrastructure. These services provide real-time support for local operations, not limited by coordinating passes with satellites or Earth-based ground stations. Using radiometric tracking techniques, such as radio direction finding, it is possible to triangulate a user's position within the network, and similar terrestrial approaches can be implemented. This enables a rollout of PNT capability within planned communication network rollouts.

The LunaNet nodes can also be mobile and can be included in surface vehicles or rovers to provide an anchor point for other local users. The overall architecture can be referenced from the mobile vehicle to a global frame and coordinate system for local operations. For example, a base station mounted on a rover can use existing PNT services to determine its absolute surface location and then further act as a host for local exploration. This allows for the use of local power and potentially higher precision systems such as Ultra-Wide Band tracking or surface-based pseudolites to reduce the Size, Weight, and Power (SWaP) requirements on local users. This can support astronauts operating in EVA. It could also support a coordinated group of autonomous rovers performing *in situ* fabrication or resource collection. For lunar geological research, this enables samples to be accurately tagged with their site location to establish the geological context. As operations begin in areas that may not have coverage with orbital assets (i.e., within caves or lava tubes), these mobile relays can be used to support navigation into areas with limited or no line of sight to the sky. This also supports critical operations at any time of lunar day, independent of the availability of overhead assets, by acting as a local node.

3.5.1.5.1 Base station and vicinity – fixed & mobile

At the lunar South Pole's base station where multiple missions will land, assemble infrastructure, and explore the surrounding region, a surface wireless network will be deployed to interconnect fixed and mobile surface users. This surface network will likely be an IP networked leveraging terrestrial wireless networking technology. Use of DTN BP is still recommended for applications that will be exchanging data with other LunaNet users that are not guaranteed to be available over the local IP network. The DTN bundles will provide for the end-to-end routing of data as a network overlay when the IP network is available. LNS surface assets will communicate with LNS orbiting relays to extend the surface network to allow interconnectivity between surface users that are beyond line of sight with each other. Lunar surface locations with line of sight to Earth will also be able to connect to LunaNet directly with Earth or through local lunar access points that provide trunk link connectivity to Earth.

PNT services, using a combination of LunaNet surface and orbiting capabilities, will provide accurate position and tracking of surface users. If one system needs assistance, the mobile system can be vectored to the incapacitated system on the shortest path by a mapping application that knows the location of all equipment.

Lunar surface users on the far side of the Moon will have LNSP orbiting relays providing LunaNet access. Use of BP for end-to-end network connectivity will allow networking between the far side and Earth, even when a relay does not have visibility of both the surface user and Earth. This will be provided through DTN store-and-forward capability built into the BP protocol, so there will be extra latency for data delivery. As the density of LunaNet infrastructure increases (e.g., as more relays decrease the time between overhead passes), the latency in delivering data will decrease.

3.5.1.6 Ascent from surface

For vehicles returning from the lunar surface, LunaNet nodes can play a critical role in enhancing onboard PNT for ensuring proper operations and meeting orbital insertion requirements. Historically, ascent vehicles have focused on inertial-only systems that navigate using dead reckoning. The proliferation of LunaNet elements – including those in proximity to the launch site or passing overhead – can provide real-time navigation observations to be integrated into the onboard vehicle's solution, improving its state knowledge. This supports increased performance of operations and more efficient usage of fuel and onboard resources. Similarly, as the vehicle enters into a lunar cruise in preparation for traversing to another orbit or a return to Earth, LunaNet PNT sources provide PNT support, enabling a maintenance of positioning and timing knowledge for the user. With this information on board, the vehicle can perform autonomous maneuver planning to optimize its trajectory to a given mission. Similarly, broadcast vehicle ephemeris enables the vehicle to include conjunction analysis to schedule operations and to identify any potential risks.

Lunar ascent phase services will be supported as critical events. This would include the availability of redundant paths for communications.

3.5.2 PNT Scenarios

LunaNet provides an evolving architecture to support PNT services during cruise phase and in cislunar space. The initial implementation of LunaNet services mirrors existing operational modes.

3.5.2.1 Earth ground station tracking

The model shown in Figure 11 utilizes a two-way link between ground nodes on Earth and the user spacecraft directly. In this scenario, the ground node provides the navigation observable (typical two-way ranging or Delta DOR-type observations), integrates the tracking data, and provides an updated state to the spacecraft providing full PNT services through ground-based processing. As LunaNet services are implemented, part of this process can be moved onboard the service user vehicle by providing tracking measurements to the spacecraft for processing and integration with onboard solutions. Specifically, this data can be integrated with other onboard navigation sensors, such as optical navigation relative to the Moon, either through feature identification or celestial navigation techniques.

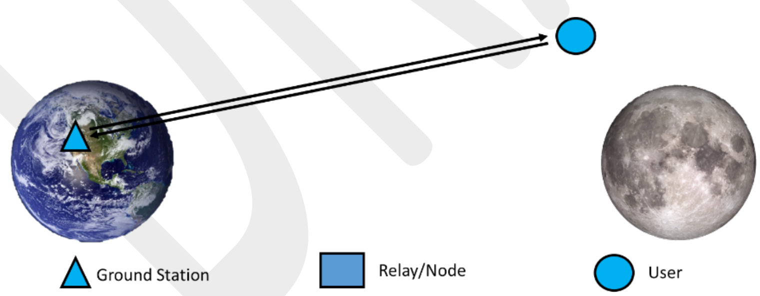


Figure 11. Tracking a User from a Ground Station

3.5.2.2 Tracking via LunaNet Relay

As the LunaNet architecture expands, additional cislunar relays will be introduced that can support local operations independent of Earth-based ground stations. Figure 12 shows an example of this user scenario. With a LunaNet node in cislunar space, the user can take advantage of CPNT services to reduce its need for terrestrial ground stations. In this scenario, the node's state (PVT) is regularly tracked using ground-based observations or other onboard navigation systems to maintain a high accuracy solution.

This node then generates the navigation observables for local user needs. For example, in this scenario, the LunaNet node provides the signals used for relative ranging, and also broadcasts information relating to its current state. The service user can then either measure its state relative to the node or can process the measurements collected by the node (whether these are two-way or one-way ranging observations).

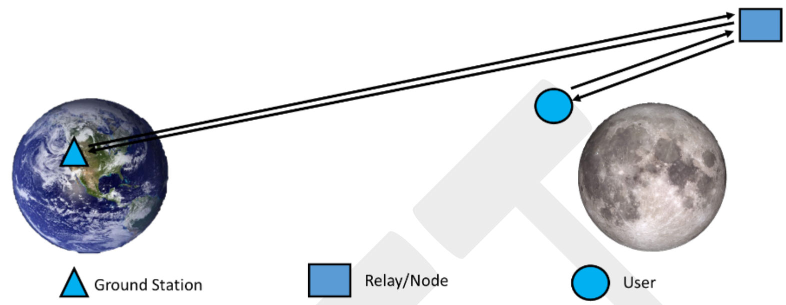


Figure 12. Tracking a User via a Lunar Orbiting Relay

As additional nodes are introduced into the network, either in orbit or in space, the architecture can evolve as seen in Figure 13. At this point, the user can take advantage of the space-distributed nature of the architecture to collect navigation measurements from multiple sources, enabling greater accuracy. As this architecture continues to expand, the vehicle will be able to observe a real-time 3-dimensional fix without needing to perform OD, making the architecture functionally similar to GNSS. Additionally, as the number of elements expands, individual spacecraft can operate as users or nodes, based on the link and role. For example, a user on the surface can also act as a navigation aid for other users, both on the surface and in orbit.

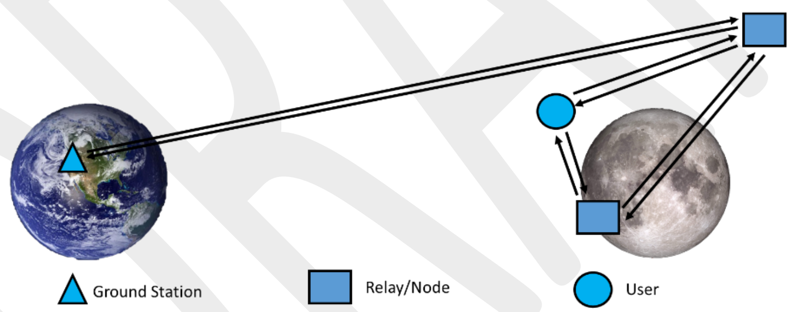


Figure 13. Tracking a User via Lunar Orbiting and Surface Relays

3.5.2.3 Maintenance of LunaNet relay accuracy

For many of the scenarios laid out, a cislunar relay (whether surface or orbital) node within LunaNet provides local PNT services to augment other operations (as laid out in the following sections) for missions, such as operations in lunar orbit, surface exploration, and ascent/descent-focused vehicle scenarios. To support high accuracy navigation and timing support, the relay's onboard state knowledge must be well synchronized to a global reference for other nodes to calculate an absolute state and time. LunaNet relays (and user nodes as well) take advantage of multiple levels of sensors and operations to maintain an accurate solution. These nodes take advantage of within-LunaNet radiometric navigation measurements as well as onboard autonomous systems combined with state estimation algorithms for flight operations. These individual functions of computing and tracking the onboard state are given in Section 3.2.3. An overview of LunaNet approaches to maintaining the relay's state are given in Figure 14.

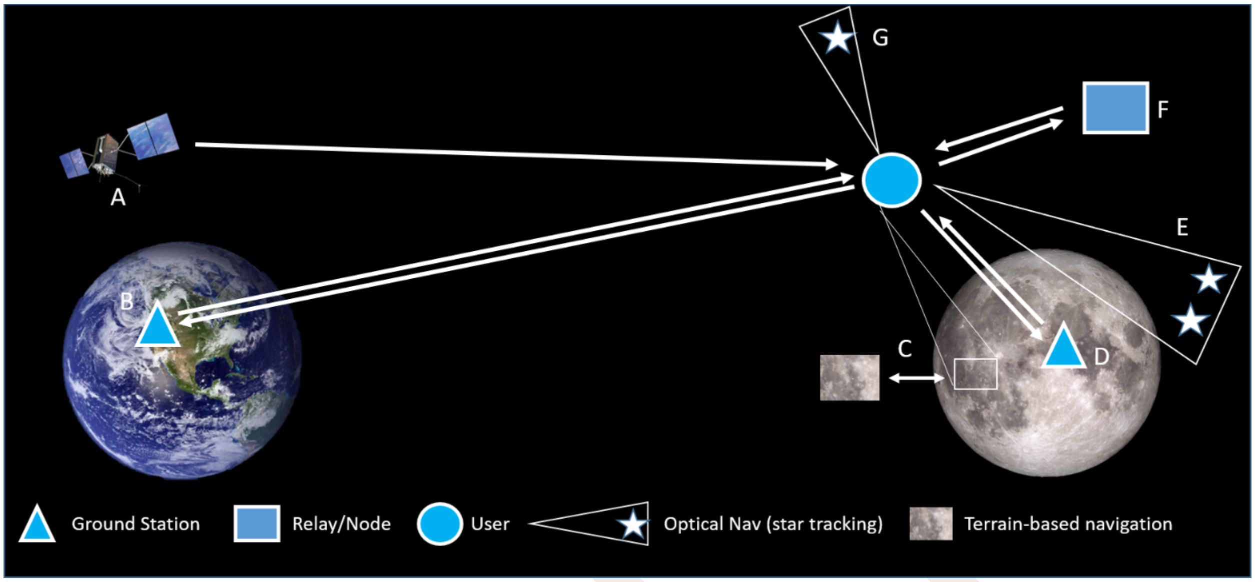


Figure 14. Maintaining LunaNet Tracking Accuracy via Multiple Data Types

Figure 14 shows several approaches for maintaining PNT knowledge among the users and nodes within LunaNet. Links B, F, and D utilize radiometric ranging between assets in the network, including ground stations and other nodes. The ground stations, by having high accuracy timekeeping references and well-defined truth locations, can be used to provide range, range-rate, and time transfer functions to maintain accuracy across the network. To release the burden on the network for these assets, other autonomous systems will be used as well and provide an avenue for future inclusion of new navigation techniques. These systems operate independently of LunaNet and act to provide external measurements of position and/or time. Spacecraft A represents the utilization of low-signal power GPS in use at lunar distances, as demonstrated operationally by the Magnetospheric Multiscale (MMS) mission. Studies have shown that the coupling of a high gain antenna and stable onboard oscillator can enable the relay to maintain its absolute state to within hundreds of meters in lunar orbit and provide high accuracy timing stability at the relay. This system can be used both for in-orbit nodes as well as surface nodes. Terrain-based navigation (C) can be used through surface feature identification and tracking to provide a high accuracy lunar position estimate. Lastly, E and G represent celestial-focused techniques and the use of techniques such as optical navigation and, eventually, X-ray pulsar-based navigation for providing an independent state estimate. These external sensors and measurements are used to tie the relay or user to absolute space and provide the accuracy needed for transferring state to other users.

3.5.3 Spacecraft Emergencies

Spacecraft Emergency Cross Support (SECS) is being defined by the Interagency Operations Advisory Group (IOAG) with the objective of identifying strategies that allow for both Service Users and Service Providers to streamline their responses during a spacecraft emergency. A spacecraft emergency is the anomalous state of the spacecraft in which its persistence will result in the loss of the spacecraft entirely, or the loss of any of the spacecraft's essential faculties (payload excluded). For human space flight missions, any external or internal conditions that could negatively affect the health and safety of the crewmembers are causes for a spacecraft emergency.

The SECS Standard Operating Process and Procedure (SOP) describes the services used during emergencies and preparation tactics for both Service Users and Service Providers to enable timely cross support when an emergency occurs. SECS is only related to establishing a Tracking, Telemetry, and Command (TT&C) link to the spacecraft for recovery operations and may require added engineering support negotiated with the LNSP.

The SOP applies to IOAG member agencies for SECS purposes, although the use cases may potentially be adopted by non-IOAG agencies in the future. This SOP defines the operational interfaces between the SECS Service User and Service Provider during emergency conditions under the following assumptions:

- Service User and Service Provider use standard forward and return data delivery and radiometric services compliant with IOAG Service Catalog #1 and the associated CCSDS standards.
- Service Provider ground stations have appropriate RF licenses to transmit on uplink frequencies that the Service User can receive. The Service User has appropriate RF licenses to transmit on downlink frequencies that the Service Provider can receive.
- Other detailed assumptions are specified in Reference 11.

During operations, if the Service User declares a spacecraft emergency, after exhausting normal recovery measures, the Service User requests support from the SECS Service Provider. The Service Provider employs standard forward and return data delivery and radiometric services to the agreed extent to support the Service User in recovering control of its spacecraft:

- Uplink engineering services:
    - Uplink Adjustment Service attempts to increase the probability of the spacecraft receiver locking on to the uplink signal transmitted from the ground station.
    - Local Radiation Service requests the Service Provider to radiate to the spacecraft despite the fact that there is no communications link to the Service User's MOC to facilitate clarification of the spacecraft condition.
    - Local Commanding Service requires the Service User to transfer details of Telecommand(s) (TC) to the Service Provider who then transmits the commands to the spacecraft.
    - Terminal Uplink Beamwidth Expansion expands the beamwidth (coverage) of an uplink signal by attaching a smaller antenna, e.g. horn antenna, to the tracking antenna and connecting it to the station transmitter. This type of event occurs typically during the Launch and Early Orbit Phase (LEOP) in which the spacecraft injection is flawed.
- Downlink engineering services:
    - Spacecraft Search Service applies to cases in which the spacecraft trajectory is different from its expected trajectory, causing the Service User's primary ground station to not point the antenna precisely in the spacecraft's direction. The Service User requests the Service Provider to search for the spacecraft's frequency from additional ground station(s).
    - Downlink Signal Analysis Service applies to cases in which the spacecraft downlink signal is received, but not correctly. Examples include the Service User's primary ground station not locking on to signal or not being able to demodulate or decode. The Service User requests the SECS Service Provider to attempt to receive spacecraft signals using ground stations.

4 Projected LunaNet Architecture

Conceptually, the LunaNet architecture embodies three types of networks: the lunar relay network, the lunar surface network, and the Earth network. In that sense, it is a lunar space internet which is architecturally similar to the terrestrial Internet. As in the case of multiple Earth networks, each of the other two network types – orbiting relays or surface networks – may itself operate as multiple networks across the cislunar regions.

4.1 LunaNet Service Architecture

Based on the various analyses previously conducted for assessing the needs of projected lunar missions, individually and collectively, it has been concluded that the LunaNet service architecture must have the following key characteristics:

1. *The communications capacity to service an unprecedented number of missions:* It is estimated that, just for the period between now and 2028, the LunaNet must have ample communications capacity to meet the demands of more than 30 missions. Approximately 60 space vehicles are planned by, or involve, 10 space agencies. An unknown number of commercial missions may be added to this.
2. *Cross-supportability* among the communications service providing systems "owned" by the various space agencies/commercial companies: As the aggregate demands on communications capacity increase, more missions will require cross-support by communication assets of other agencies. This leads to the concept of cooperative LNSPs.
3. *The inclusion of communications infrastructure to support lunar surface exploration:* Due to the trend toward more extensive exploration in lunar surface, the communications paradigm will depart from that featuring one-to-one (e.g., solely between a lander and a rover), point-to-point links – to that of a vicinity network involving multiple landed vehicles/platforms. The lunar surface network(s) will become an essential element of LunaNet.
4. *The inclusion of lunar relay orbiters to service missions with no, or low, Earth visibility*: Unlike the currently flying relays which are provided by science orbiters as a secondary capability, future lunar relay orbiters will largely be dedicated to providing CPNT service as a primary function. Moreover, they will be designed to provide services for inter-agency cross-support.
5. *The provision of service to support disadvantaged users:* There will be at least six CubeSat lunar missions (as the secondary payloads on Artemis-1) and two SmallSat missions. There will also be a set of CubeSat lunar missions associated with the Artemis-2 launch. The Space Launch System (SLS) is designed to accommodate up to 17 secondary payloads per mission. The Exploration EVA Mobility Unit (xEMU) spacesuit is another example of a system that must allocate minimal SWaP for communications. These low-cost missions and low communications capability systems collectively will drive LunaNet to offer low-cost solutions to CPNT services needed by small systems with little power and low gain. This forces LunaNet to accept the majority of the burden in closing links to this class of disadvantaged Service Users.
6. *The high reliability of service provision to crewed missions:* For crewed missions, there are a set of data types which are considered mission-critical because of their importance to astronauts' health and safety, as well as mission success. The services to deliver these data types (i.e., biomedical measurements, caution and warning, health and status, standard videos, training, situational awareness videos, family interaction, and recreational entertainment) must be fulfilled at a reliability higher than that for any ordinary robotic missions. The need to provide high bandwidth communications to astronauts also drives a 1000x increase in uplink data rates from tens of kbps for command uplink to tens of Mbps.
7. *The cost-effectiveness of providing CPNT service as a common utility:* Space communications and tracking have been provided since Sputnik, using expensive, largely government-owned systems driven by national security, prestige, and science goals with limited sensitivity to cost. Limited government budgets and increasing commercial capabilities drive the shift in LunaNet to much lower cost solutions for CPNT services while the increasing number of missions and services offer an increasing trend in market opportunities. LunaNet is based on establishing a set of Service Providers providing CPNT service as their business with competition driving technical innovation and cost reductions simultaneously.

8. *The* *<u>ability to accommodate</u>* *commercially "owned" service-providing assets:* A number of companies have set their sights on the Moon. As they are ramping up their plans to deliver relay satellites, surface assets, and Earth stations, the LunaNet architecture must be sufficiently agile to incorporate their service-providing systems.
9. *The* *<u>infusion of new communications and PNT technology</u>* *for the advancement of lunar exploration:* Chief examples of new technologies in the near term are optical communications and real-time positioning for lunar surface elements. As always, the infusion of any new technology will have some ramifications to end-to-end systems. That means the overall LunaNet architecture must be designed with sufficient <u>scalability</u> and <u>expandability</u> to accommodate future technology infusion.
10. *The* *<u>rate of expansion in capabilities</u>*[3] *demanded on some of the LNS systems:* Driven by some high-rate science missions (e.g., synthetic aperture radar and multi-spectral/hyper-spectral imagers) and human exploration (e.g., multi-channel high-definition video) and the low latency of certain mission critical data, the lunar communications will experience an unprecedented growth in capacity. In addition, there will be a rapidly rising number of low data-rate missions that collectively offer enormous capacity. To some LNSPs, this may increase their opportunities to provide a broader dynamic range of link capabilities. From the technical side, this drives modularity to allow additional capacity to be brought online rapidly; from the business side, this drives the ability to reduce the lead time for acquiring added capacity, e.g., shorter manufacturing and launch times.
11. *<u>Security protection</u>* *of the end-to-end lunar communications and PNT paths:* Security must be implemented as an integrated and inherent part of LunaNet. It must be done within the context of an open architecture that allows the entire LunaNet community to contribute to secure solutions while recognizing that vulnerabilities in the architecture will be visible to all, including those who would exploit those vulnerabilities.
12. *<u>Backward compatibility</u>* *with the existing communications infrastructure(s) resulting from decades of investment by space agencies:* To the degree possible, the LunaNet architecture must use the existing communications architecture (which is more Earth Network-centric and dominated by point-to-point, space-Earth links) as the basis and expand from it into an interplanetary internetworking architecture. As systems migrate towards the new era, infusing new capabilities and preserving existing capabilities/assets must be traded on an individual basis and designed to allow transparent support for earlier versions.

As stated in Section 2.1, LunaNet will be implemented in multiple phases to support human exploration and scientific discovery missions. Figure 15 depicts the LunaNet architecture that guides the Phase 1 development between now and ~2024. Key ingredients of the architecture for this phase are: the upgrades of Earth networks, the deployment of lunar relay orbiter(s) to form an initial lunar relay network, the incorporation of commercial communication assets in cislunar space and Earth, the emplacement of some limited lunar surface CPNT capabilities (likely via peer-to-peer mode only), and the integration of assets operated by participants in LunaNet development. The Phase 1 LunaNet also exhibits a rudimentary space internet architecture in which end-to-end communications at the network layer and above interconnect the diversely deployed heterogeneous communication assets. Basic architecture of this Solar System Internetwork (SSI) in defined in CCSDS Green Book 730.1-G-1.

[3] Defining capabilities in terms of gain (G/T) and EIRP for the *physical links* and capacity over end-to-end *network paths*

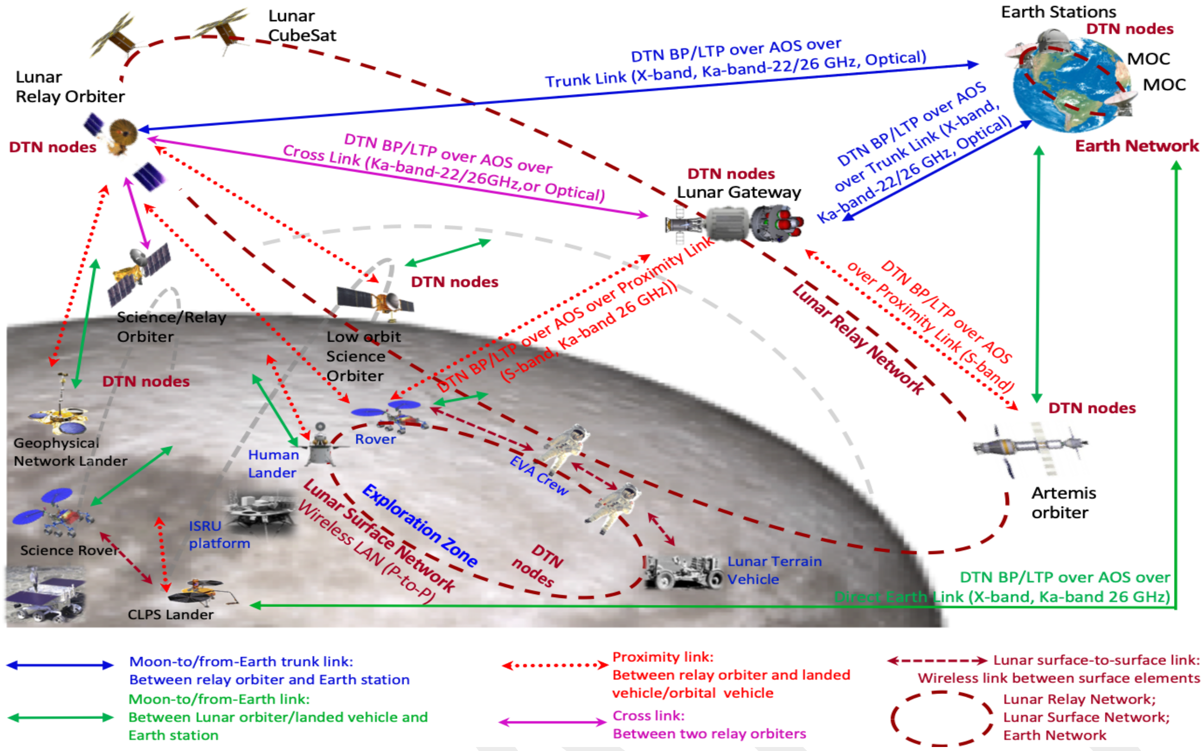


Figure 15. LunaNet Service Architecture – Development Phase 1

For Phase 2 development between 2024 and 2028, the targeted architecture is described in Figure 16. To support extensive human exploration and science investigations, the architecture will feature additional lunar relay orbiters, the lunar surface infrastructure, a significant number of commercial and international partners' assets, and introduction of optical CPNT capabilities. In addition, LunaNet will be expanded into a full space internet that interconnects the various elements of lunar relay network, lunar surface network, and Earth network. Emerging as a new element, the Network Management Element (NME), will become operational to coordinate management of LunaNet at the space-internet level, encompassing all LNSPs.

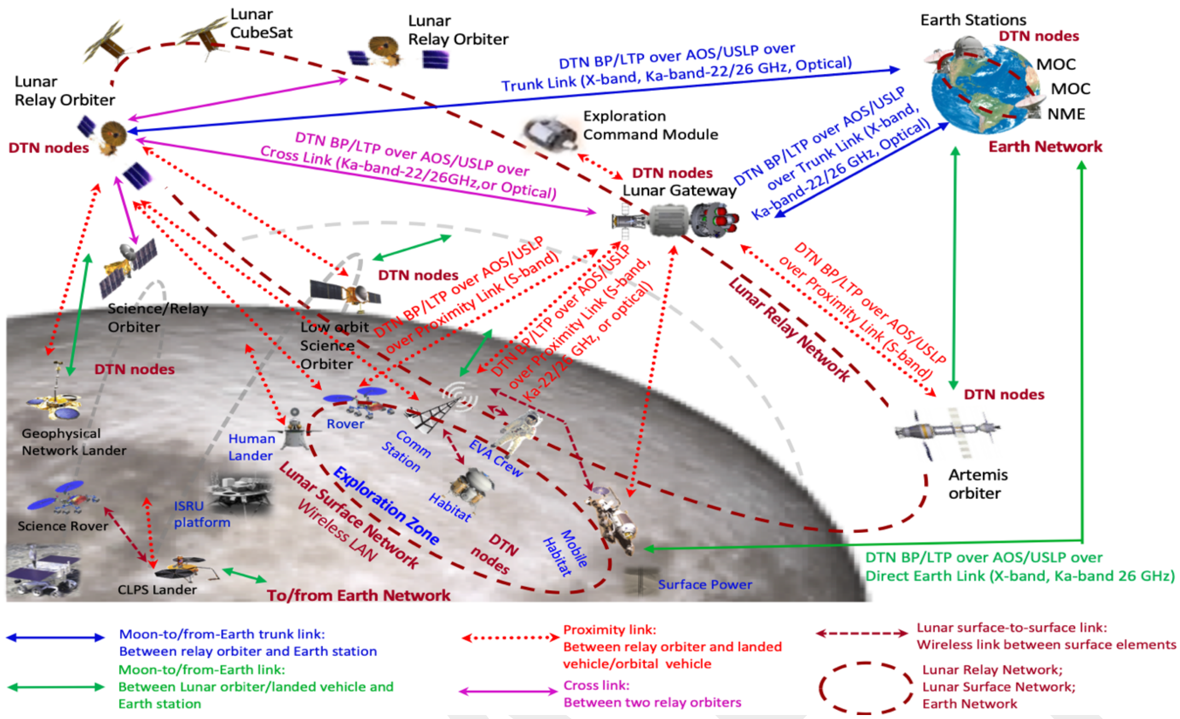


Figure 16. LunaNet Service Architecture – Development Phase 2

4.2 Spectrum

Radio frequency spectrum is needed for human and robotic missions from launch to operation in the lunar region through one or more services of CPNT networks in the LunaNet architecture. Mission requirements for radio spectrum include command, control and tracking of spacecraft from mission launch to completion, radio navigation services, collection of scientific/environmental information using a variety of sensors (active and passive), and communication with Earth facilities, either directly or through relay satellites/orbiters. International use of the radio frequency spectrum is regulated by the International Telecommunication Union (ITU), a specialized agency of the United Nations (UN) with responsibility for issues concerning information and communication technologies. The ITU Radio Regulations (RR) are treaty obligations, signed by approximately 193 countries, regarding utilization of radio frequencies both terrestrially and in space. Optical frequencies (e.g., the 1550 nm / 193 THz band to be used for LunaNet CPNT services) is not regulated but is selected for compatibility with terrestrial fiber optic systems and human eye safety related to lasers.

NASA uses spectrum across a broad array of frequency ranges (Figure 17). In general, specific frequency bands have relative advantages and disadvantages, and are chosen based on the characteristics needed to carry out a mission or provide a service. The lunar region is in the ITU's Near Earth region since the distance of the Moon from the Earth is less than two million kilometers.

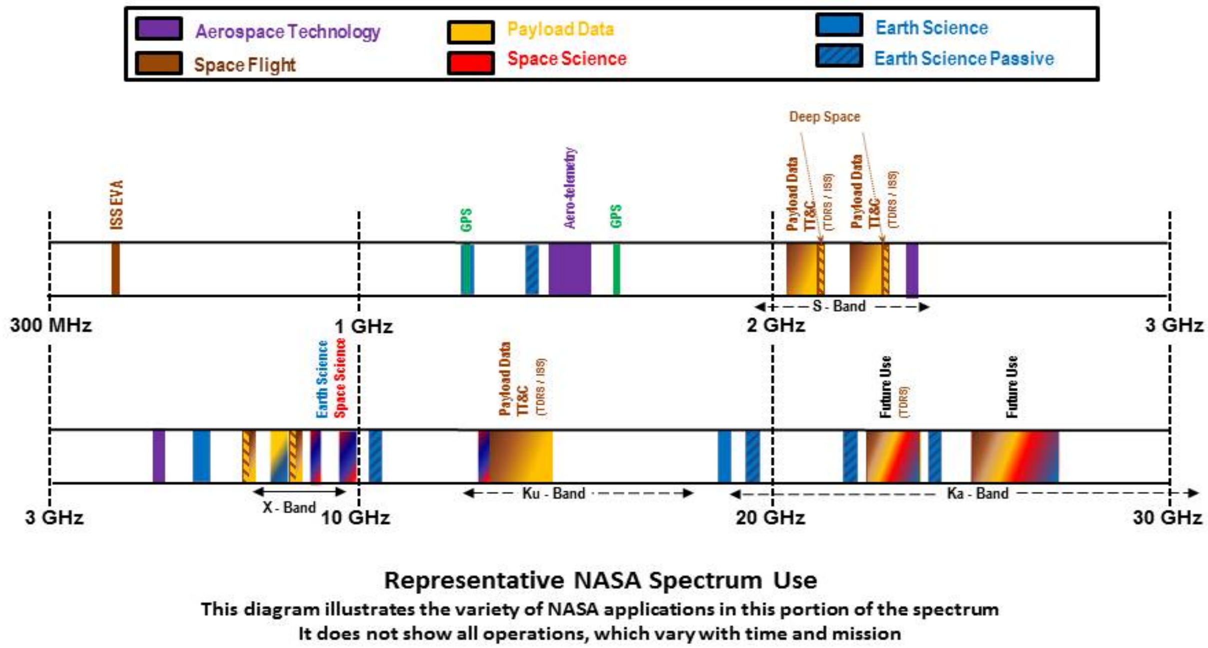


Figure 17. Lunar Frequency Bands

To facilitate the utilization of the LunaNet architecture, early and careful spectrum planning and frequency selection analysis is crucial to ensure maximum operational flexibility while minimizing operational restrictions. Analysis of mission-specific RF requirements, ConOps and available allocated spectrum in accordance with national/international frequency allocations and applicable technical standards is planned for each mission utilizing the LunaNet to ensure appropriate frequencies are chosen for each radiocommunication system. An operator is assigned a frequency or set of frequencies to provide services, and this assignment of frequencies is coordinated with other spectrum users in a way to avoid harmful interference among users. Spectrum authorization strategies have been developed to ensure proper radio spectrum use, facilitate reuse, and achieve spectrum efficiency.

The ITU Table of Frequency Allocations identifies by frequency band where services such as space research service (SRS), space operation service (SOS), Earth-Exploration Satellite Service (EESS) and Inter-Satellite Service (ISS) may operate. The subset of these frequency bands available for lunar region missions is shown in Table 7. Frequency bands allocated to SRS and ISS can be used for ranging applications as part of the telecommunication link operation. Additionally, Radio Navigation Satellite Service (RNSS) bands can be used to provide services to missions in the lunar region. Use of properly allocated frequency bands for the intended application with full compliance to technical standards is critical to provide assurance of operational protection under both national and international regulations. Use of frequency bands in a manner for which those bands were not allocated could result in operation on a non-interference basis (NIB), which means an LNSP or Service User mission accepts the risks that a mission may be forced to cease use of that frequency band when an interference to allocated/authorized users is identified.

Table 7. Lunar Spectrum Architecture with Constraints

Frequency Band	Link Types (Allocated Services[1])	Applicable Constraints[1, 2]
390-405 MHz	• Lunar Orbit (LO) to Lunar Surface (LS)	• LO to LS communications in this band will operate on a non-interference basis (NIB) to any allocated services • Shielded Zone of the Moon (SZM) consideration may apply. See Note 5.
410-420 MHz	• LS and LO EVA Communications and Wireless Network	• Power Flux Density (PFD) limits for protection of terrestrial fixed and mobile per ITU RR. No distance limitation. [Modified at WRC-15 based on Ref. **Error! Reference source not found.**] • See Note 3
435-450 MHz	• LS to LO • LS Communications & Wireless Network	• LS to LO communications in this band will operate on a NIB to any allocated services • SZM consideration may apply. See Note 5.
1614-1626.5 MHz	• LS to LO	• LS to LO communications in this band will operate on a NIB to any allocated services • SZM consideration may apply. See Note 5.
2025-2110 MHz	• Earth to LO (SRS Earth-to-space [E-s]) • Earth to LS (SRS E-s) • LO to LS (SOS space-to-space [s-s])	• For Non-Geostationary Orbit (NGSO) satellites, TT&C limited to science missions • s-s PSD per CCSDS recommendations to reduce potential Radio Frequency Interference (RFI) to E-s links • transmission masks when used in s-s direction with 2200-2290 MHz • Use for manned emergency comm (uplink or through Data Relay Satellites, DRS) • Maximum channel Bandwidth (BW) of 5 MHz • See Note 4
2200-2290 MHz	• LO to Earth (SRS space-to-Earth [s-E]) • LS to Earth (SRS s-E) • LS to LO (SOS s-s)	• For NGSO satellites, TT&C limited to science missions • s-s Power Spectral Density (PSD) per CCSDS recommendations to reduce potential RFI to s-E links • transmission masks based on necessary bandwidth and modulation • Maximum channel BW of 5 MHz • Protection of deep space operation per Ref. **Error! Reference source not found.**
2290-2300 MHz	• s-E or s-s	• Manned spacecraft emergency use, excluding 2293-2297 MHz (Ref. **Error! Reference source not found.** protection required within 2293-2297 MHz) • See Note 4
2400-2480 MHz	• LS Communications & Wireless Network	• Lunar surface communications and wireless networks in this band will operate on a NIB to any allocated services • SZM consideration may apply. See Note 5.

Frequency Band	Link Types (Allocated Services[1])	Applicable Constraints[1, 2]
2483.5-2500 MHz	• LO to LS	• LO to LS communications in this band will operate on a NIB to any allocated services • SZM consideration may apply. See Note 5.
7190-7235 MHz	• Earth to LO (SRS E-s) • Earth to LS (SRS E-s)	
8450-8500 MHz	• LO to Earth (SRS s-E) • LS to Earth (SRS s-E)	• Transmission masks based on necessary bandwidth and modulation • Maximum bandwidth of 10 MHz • Compliance with deep space protection criteria below 8450 MHz required
13.75-14 GHz	• LO to LO (SRS s-s)	• SRS secondary allocation
14.5-15.35 GHz	• LO to LO (SRS s-s)	• 14.8 – 15.35 GHz upgrade to primary SRS under study (World Radiocommunication Conference [WRC] Action Item [AI] 1.13 [WRC-23 AI 1.13])
22.55-23.15 GHz	• Earth to LO (SRS E-s) • Earth to LS (SRS E-s)	• Protection of Radio Astronomy Service (RAS) when making assignments in the frequency bands 22.81-22.86 GHz and 23.07-23.12 GHz
23.15-23.55 GHz	• LO to LS (ISS) • LO to LO (ISS)	• Protection of Earth exploration-satellite service (EESS) (passive) in the frequency band 23.6-24 GHz from International Mobile Telecommunications-2000 operating in the 24.25-25.25 GHz
25.25-25.60 GHz	• LS Communications & Wireless Network (Fixed or Mobile Service)	• Limited to this frequency range for sharing with DRS in the band 25.25-27.5 GHz
25.5-27.0 GHz	• LO to Earth (SRS s-E) • LS to Earth (SRS s-E)	• Limited to this frequency range for sharing with DRS in the band 25.25-27.5 GHz • Used for non-safety purposes (crew nor vehicle) • Geostationary Orbit (GSO) & NGSO EESS/SRS PFD limits for protection of lunar and Lagrange SRS missions • Consideration of Variable or Adaptive Coding and Modulation (VCM or ACM) when practical for High Data Rate (HDR) EESS/SRS s-E links • Consideration of high elevation tracking methods when practical for HDR EESS/SRS s-E links
27.0-27.5 GHz	• LS to LO (ISS) • LO to LO (ISS)	• Limited to this frequency range for sharing with DRS in the band 25.25-27.5 GHz
27.225-27.5 GHz	• LS Communications Y Wireless Network (Fixed or Mobile Service)	• Limited to this frequency range for sharing with DRS in the band 25.25-27.5 GHz

Frequency Band	Link Types (Allocated Services[1])	Applicable Constraints[1, 2]
37-38 GHz	• LO to Earth (SRS s-E) • LO to LO (NIB)	• Up to a maximum of 500 MHz bandwidth • 37-37.5 GHz be maintained available for implementation of s-E for manned and unmanned planetary missions and development of manned planetary missions in the lunar environment • Manned mission use of this frequency band has higher priority with protection over other uses • Deconflicted with L2 mission use of this band – L2 in 37.5-38 GHz • Coordinate with space Very Long Baseline Interferometry (VLBI) in this band
40.0-40.5 GHz	• Earth to LO (SRS E-s) • LO to LO (NIB)	• 40-40.5 GHz be maintained available for implementation of s-E for manned and unmanned planetary missions and development of manned planetary missions in the lunar environment • Manned mission use of this frequency band has higher priority with protection over other uses

Notes:

1. EESS – Earth Exploration-Satellite Service; ISS – Inter-Satellite Service; SOS – Space Operation Service; SRS – Space Research Service
2. ITU RR No. 5.149, In making assignments to stations of other services to which the bands:

13 360-13 410 kHz,	1660-1670 MHz,	22.21-22.5 GHz,	111.8-114.25 GHz,
25 550-25 670 kHz,	1718.8-1722.2 MHz,	22.81-22.86 GHz,	128.33-128.59 GHz,
37.5-38.25 MHz,	2655-2690 MHz,	23.07-23.12 GHz,	129.23-129.49 GHz,
73-74.6 MHz in Regions 1 and 3,	3260-3267 MHz,	31.2-31.3 GHz,	130-134 GHz,
150.05-153 MHz in Region 1,	3332-3339 MHz,	31.5-31.8 GHz in Regions 1 and 3,	136-148.5 GHz,
322-328.6 MHz,	3345.8-3352.5 MHz,	36.43-36.5 GHz,	151.5-158.5 GHz
406.1-410 MHz,	4825-4835 MHz,	42.5-43.5 GHz,	171.11-171.45 GHz,
608-614 MHz in Regions 1 and 3,	4950-4990 MHz,	48.94-49.04 GHz,	172.31-172.65 GHz,
1330-1400 MHz,	4990-5000 MHz,	76-86 GHz,	173.52-173.85 GHz,
1610.6-1613.8 MHz,	6650-6675.2 MHz,	92-94 GHz,	195.75-196.15 GHz,
	10.6-10.68 GHz,	94.1-100 GHz,	209-226 GHz,
	14.47-14.5 GHz,	102-109.5 GHz,	241-250 GHz,
	22.01-22.21 GHz,		252-275 GHz

are allocated, administrations are urged to take all practicable steps to protect the radio astronomy service from harmful interference. Emissions from spaceborne or airborne stations can be particularly serious sources of interference to the radio astronomy service (see Nos. 4.5 and 4.6 and Article 29). (WRC-07)

3. ITU RR No. 5.268: Use of the frequency band 410-420 MHz by the space research service is limited to space-to-space communication links with an orbiting, manned space vehicle. The power flux-density at the surface of the Earth produced by emissions from transmitting stations of the space research service (space-to-space) in the frequency band 410-420 MHz shall not exceed −153 dB(W/m²) for $0° \leq \delta \leq 5°$, $-153 + 0.077 (\delta - 5)$ dB(W/m²) for $5° \leq \delta \leq 70°$ and −148 dB(W/m²) for $70° \leq \delta \leq 90°$, where δ is the angle of arrival of the radio-frequency wave and the reference

bandwidth is 4 kHz. In this frequency band, stations of the space research service (space-to-space) shall not claim protection from, nor constrain the use and development of, stations of the fixed and mobile services. No. 4.10 does not apply. (WRC-15)

4. ITU-R SA. 1863: Supported the Recommendation that permitted use of deep space S-band for manned emergency communications. Applies to 2025-2110 MHz/2110-2120 MHz for commanding and 2290-2300 MHz for spacecraft transmission.
5. ITU-R RA.479-5: Protection of frequencies for radioastronomical measurements in the shielded zone of the Moon. Also, SFCG 23-5: Protection of future radio astronomy observatories in the shielded zone of the Moon.

In anticipation of multinational and commercial missions to the lunar region, the Space Frequency Coordination Group (SFCG) has developed a technical resolution on recommended frequency bands and their usage in the lunar region. While studies of additional frequency bands continue within the SFCG for applications in the lunar region, the baseline frequencies developed by the SFCG were endorsed in the International Communication System Interoperability Standards (ICSIS) for Artemis Partner missions to ensure end-to-end compatibility and interoperability between a Cislunar Space Platform, visiting vehicles, as well as lunar systems and Earth.

For TT&C operation from the lunar region missions with the Earth Network, the near Earth 8450-8500 MHz frequency band is recommended; this downlink frequency band is paired with the uplink frequency band from 7190-7235 MHz. For high data rate requirements from the lunar region missions directly through Earth ground stations, the near Earth frequency bands 25.5-27.0 GHz (space-to-Earth) and 22.55-23.15 GHz (Earth-to-space) are recommended. For direct crosslinks in the lunar region for rendezvous operation and between surface and orbital vehicles, frequency bands 2200-2290 MHz and 2025-2110 MHz are recommended to reduce the probability of unacceptable interference with LEO/GEO up and downlinks. For high data rate crosslinks, 23.15-23.55 GHz and 27.0-27.5 GHz frequency bands are recommended. Additional studies are in progress to determine additional frequency bands for extravehicular activities, surface rovers, and operation in the Shielded Zone of the Moon (SZM)[4]. Specific considerations, pertaining to protection of radio astronomy observation integrity, are required in the planning of allowed intentional radio frequency emissions by missions and by LunaNet elements when in view of the *S*ZM.

4.3 LunaNet Elements

While the LunaNet architecture defines the external interfaces of an LNS, the internal architecture is the responsibility of each LNSP. This section describes, but does not specify that internal LNS architecture as a reference concept, to ensure clarity in understanding functions, capabilities, distributed performance over an LNS, and issues that arise among LNSPs during discussions. This section should be viewed as an informative reference architecture that may be implemented differently by each LNSP.

4.3.1 Lunar Relay Network Element

Within the LunaNet, a lunar relay network is comprised of one or more lunar relay orbiters, each of which provides communications and/or PNT services with Service User space vehicles or elements, in

[4]Definition of the SZM: "The … invisible portion of the Moon's surface is that which lies more than 23.2° beyond the mean limb of the Moon as seen from the centre of the Earth. The SZM consists of the shielded area of the Moon's surface together with an adjacent volume which is shielded from interference originating within a distance of 100000 km from the centre of the Earth (Article 22, RR No. 22.22.1)."

orbit or on the surface, over proximity links. When such relay interfaces provide network layer services, the relay orbiter(s) and the user nodes together form a relay network. The relay orbiter, in this context, can be a dedicated relay satellite or the relay function of the communications subsystem of a spacecraft acting as a LunaNet node as shown in Figure 16.

Since the orbits of relay satellites or constellations are the choice of the service providers based on their respective business cases, given the principle of LunaNet's open architecture, the eventual existence of a variety of orbits is quite possible. For purposes of illustrating an example lunar relay network, Figure 18 depicts a satellite constellation that provides global lunar coverage and is characterized by a combination of circular orbits and elliptical orbits, including:

- a 12-hour frozen elliptical orbit with its line of apsides librating over the North Pole;
- a 12-hour frozen elliptical orbit with its line of apsides librating over the South Pole; and,
- a 12-hour circular elliptical orbit around the equator.

Initial partial coverage can commence with a single relay orbiter. For the minimal full coverage scenario, the constellation would include:

- Two relay orbiters phased 180° apart on the 12-hour frozen elliptical orbit with its line of apsides liberating over the North Pole, plus
- Two relay orbiters phased 180° apart on the 12-hour frozen elliptical orbit with its line of apsides liberating over the South Pole, plus
- One relay orbiter on the 12-hour circular orbit around the equator.

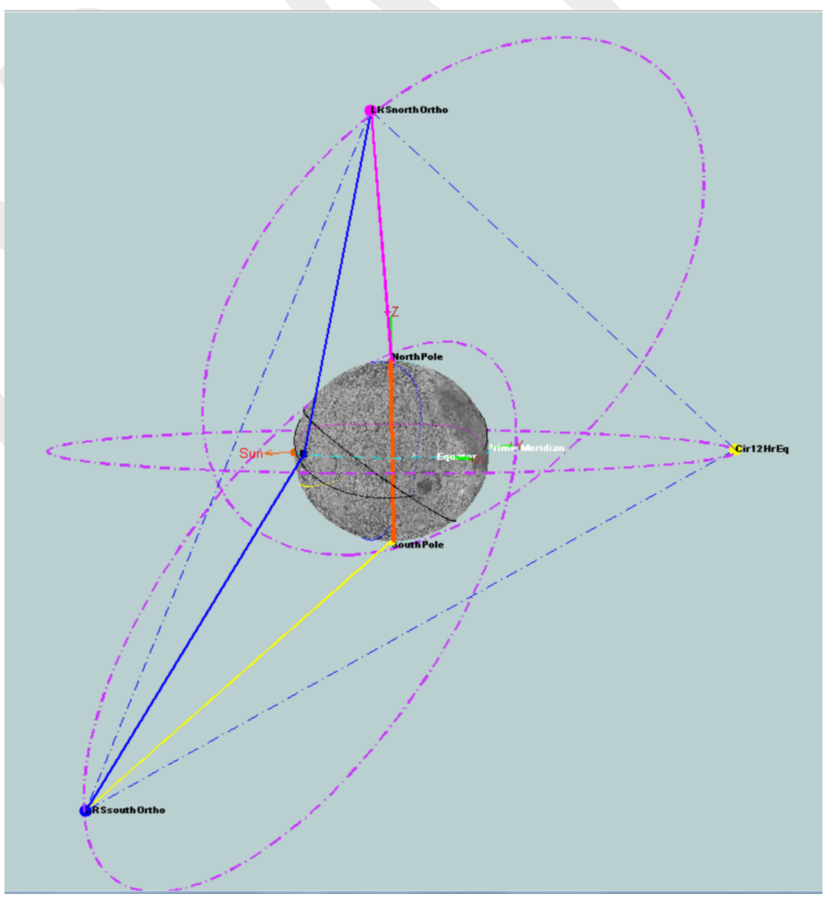


Figure 18. Lunar Relay Network – Example Constellation Orbits

The advantages of this constellation are:

- The pair of relays librating over the South Pole offer continuous coverage of the south polar region.
- The pair of relays librating over the North Pole offer continuous coverage of the north polar region.
- The relay in the circular equatorial orbit offers good but not complete coverage of the far side.
- This constellation is scalable – launch one relay to meet initial needs and add relays as the number of missions and demand for capacity increase. Additional relays can be introduced within each orbit to meet increasing demand. For example, the polar frozen orbit can be increased to three (or more) relays by decreasing the phasing separation, e.g., from 180° to 120°.
- The constellation can be built up incrementally and in any order as dictated by mission needs, e.g., S. Pole first, Equator, and finally N. Pole.
- The constellation offers good and relatively even coverage at different latitudes.
- Long contact duration: 5 – 7 hours per orbit.
- Large total contact time per day (17.6 – 19.4 hours).
- Short gap time (1.4 – 5.8 hours).

The downside, however, is that it requires launching multiple satellites into several different orbits.

4.3.2 Lunar Surface Network Element

It is expected that, during the human exploration era, with the deployment of multiple vehicles, platforms, and/or facilities, all clustered in a region of the South Pole for conducting exploration activities, more persistent surface-to-surface communications infrastructure will be built to support the various sample return missions, the series of commercial small lander missions, and the initial crewed surface exploration, including any potential robotic precursor missions. All these will lead to the establishment of the lunar surface network(s).

The following is a list of potential surface elements:

- Geophysical station
- Small science landers (CLPS)
- Robotic survey rover
- Radio telescope
- Surface CPNT station
- Crewed rover (unpressurized and pressurized)
- Solar physics telescope
- Medium-sized science landers
- Robotic exploration rover
- Communications tower with landing beacon
- Crew-deployed science experiments
- Crewed landers (descent & ascent modules)

Within an exploration zone or human outpost, a wireless LAN (WLAN), RF and/or optical, is proposed for the lunar surface network as in Figure 16. It is a local area network that facilitates vicinity wireless communications between the various landed elements (including an astronaut's hand-held/body-mounted devices, in the case of crewed missions). It also gives the mobile elements, e.g., the rovers and the EVA astronauts, the ability to move around within the area and still be connected to the network. Through a local gateway or hub, it interfaces with the lunar relay network via proximity links and with the Earth network via trunk links.

A typical lunar surface network will include two key entities:

- Network communications terminal – At the edge of the LunaNet surface network is the network terminal node, a physical entity which ends a telecommunication/optical link and is the point at which a Service User signal enters and/or leaves a network. It serves multiple Service Users via a multiplexer/demultiplexer device. This node may provide PNT services such as range, range-rate, and bearing angle. Depending on further selection of surface standards, e.g., IEEE 802.11 or 4G/5G cellular, sub-terminals may be used to support mesh networking with the ability to triangulate service users within the local area to provide precise position and elevation.

- Network management controller – The network management controller, in the form of software or firmware, orchestrates network functions for a LunaNet surface network. The network controller:
  - Maintains an inventory of devices in the network and monitors their operational status;
  - Executes automated device operations such as configuration set-up and updates;
  - Executes automated network initialization;
  - Detects and responds to network anomalies;
  - Stores user traffic temporarily until network connectivity is restored;
  - Performs network-wide traffic analysis and maintains relevant performance statistics;
  - Manages local PNT services for surface users; and
  - Provides local network management interfaces with Earth network management.

4.3.3 Earth Network Element

The LunaNet also includes a set of Earth-based network assets that provide CPNT services to relevant lunar missions as well as connecting each LNSP's lunar relay orbiters/payloads, and surface elements to their Earth-based Network Operations Center (NOC). Operating together, they form a global network to provide 24x7 coverage for lunar exploration.

4.3.3.1 NASA's Earth network element

NASA's Earth network element includes:

- Ground stations including: NASA's DSN 34m stations and Lunar Exploration Ground Stations (LEGS) 18m stations, DSN affiliate stations such as Morehead State University's (MSU) 21m station and the Sardinia 64m station.
- Network operations: DSN's Deep Space Operations Center at JPL.

4.3.3.2 International Earth network elements

International agencies that support lunar missions include:

- ESA's European Space Tracking network (ESTRACK) with its European Space Operations Centre in Darmstadt, Germany and its 35m deep space antennas at New Norcia, Australia, Cebreros, Spain, and Malargüe, Argentina;
- JAXA's Ground Network (GN) including the 64m antenna at the Usuda Deep Space Center, Nagano and the 54m Ground Station for Deep Space Exploration and Telecommunication (GREAT);
- ISRO's Indian DSN (IDSN) facility located near Bangalore and has 11m, 18m and 32m antennas. The 18m antenna was mainly built for the Chandrayaan lunar mission.
- KARI's Korea Deep Space Antenna (KDSA) (under development to support the Korea Pathfinder Lunar Orbiter, KPLO);
- CNSA: China's Queqiao L2 relay provides support to China's Chang'e missions.

4.3.3.3 Commercial Earth network elements

Commercial service is provided by stations such as Swedish Space Corporation's (SSC) South Point 13m and Dongara 13m stations with their SSC's Network Management Centers (NMC) located in Kiruna, Sweden, Horsham, PA, and Chantilly, VA. Several commercial entities have declared intentions to provide service to lunar missions including Goonhilly Earth Station with 32m, 30m, and 18m antennas, and the networks owned by SpaceX and Amazon Web Services (AWS). The Irish National Space Centre Limited has a 32m antenna at Elfordstown Earthstation near Midleton, County Cork. These may become part of LunaNet.

4.3.4 Network Management Element (NME)

In addition to a variety of communication assets, ground-based and cislunar space-based, the LunaNet includes a network management element in each LNS that performs the service management and network control functions for the LunaNet at the space internet level. Analogous to the terrestrial Internet, the LunaNet network management element embodies a collection of policies, rules, standard operating procedures (SOP), and network monitor and control capabilities provided by all Internet Service Providers for an enormous variety of networks using certain standard network management protocols. For each of the above, cybersecurity-related capabilities are an inherent aspect of the system.

Key functions of the NME are as follows:

- Coordinate the Service Management functions for missions requiring services from multiple communication assets owned or operated by other LNSPs;
- Ensure each LunaNet node meets the regulatory standards and complies with applicable laws and regulations of each relevant country;
- Monitor the status of LNS assets, at the LunaNet node level, and the aggregate behavior of an LNSP's portion of the LunaNet;
- Identify network faults and suggest recovery actions with coordination across LNSPs to resolve internetwork issues;
- Perform Configuration Management by each LNSP to ensure that across the LunaNet the network configuration is as desired. CM also includes the DTN-related items such as source/destination addressing, routing paths, and QoS assignments.
- Analyze LNSP network performance based on traffic data collected to detect performance bottlenecks, generate past/present performance summary statistics, and analyze trends.
- Coordinate cybersecurity actions and practices taken by all LNSPs and identify security risks based on data gathered from the participating LNSPs.

4.4 Security Architecture

Security mechanisms are viewed as an inherent element of the Lunar CPNT architecture. Explicitly shown in Figure 24 for Interface Type 6, authentication or encryption must be applied at one of the following two layers:

- Network Layer security – applied either within the DTN stack using Bundle Security Protocol (BSP)**Error! Reference source not found.**/Streamlined Bundle Security Protocol (SBSP) or within an IP stack using Internet Protocol Security (IPsec).
- Space Data Link Layer security - applied to the data link contents using Space Data Link Security (SDLS) protocol. The SDLS defines a security header and trailer for applying authentication and encryption. The frame headers are protected but left in the clear.

Application Layer security may be applied to the data by user applications for providing security services in addition to any such services provided at network layer or space data link layer.

It is recommended that the following general security policy be adopted by lunar missions and service-providing systems:

- All Lunar missions, regardless of robotic science, or human crewed missions, should use the SBSP or SDLS using Advanced Encryption Standard-Galois Counter Mode (AES-GCM) in authentication mode, at a minimum, for all links in all directions.

- All crewed or human exploration missions should use the AES-GCM in Encryption, or Authenticated Encryption mode with 256-bit (or larger) keys, for all links in all directions.
- All robotic science missions should use the AES-GCM in Encryption, or Authenticated Encryption mode with 256-bit keys, for all links in forward direction.
- Adopt the CCSDS SDLS Protocol – Extended Procedures as standard practices for key management.

4.5 Cross Support Services at the Space Data Link Layer

A key ingredient of the LunaNet architecture described in this section is the space internetworking capability enabled by the DTN protocol suite. The cross-support to lunar missions by Earth communication assets, owned by the space agencies and commercial service providers, will be through the Bundle Protocol, with the transfer of DTN bundles between each user's Mission Operations Center (MOC) and the service-providing asset, e.g., a ground station. One may rush to conclude that the current cross-support transfer services, based on the SLE/Cross Support Transfer Services (CSTS) standards and used by almost all agencies, will become irrelevant and obsolete. However, our past experience in operating many spacecraft has shown that monitoring and controlling any spacecraft through the rudimentary level of the communication system is essential from time to time. That means a cross-supported mission must be able to conduct the following scenarios by directly "poking" into the space data link layer without or bypassing the DTN layers:

- Link performance analysis, anomaly detection and isolation, troubleshooting
- Special configuration and control: bootstrapping flight computer and hardware commanding
- Spacecraft emergency and contingency modes
- Certain mission critical events
- Space vehicles and ground systems that lack DTN functionality

Therefore, out of necessity, the provision of cross-support services at the space data link layer by Earth communication assets will persist into the DTN era, although only in some limited scenarios.

4.6 Cislunar Link Types in LunaNet

Inherent in LunaNet are the cislunar links which can be categorized into five major link types, i.e., the direct with Earth (DWE) link, trunk link, proximity link, cross link, and lunar surface link. The LunaNet architecture, based on the key characteristics of these links, individually and collectively, at the physical and data link layers has the following salient features:

1) X-band DWE and trunk links for TT&C:

Departing from the practice by many past near-Earth missions, which relied on S-band predominantly, the DWE and trunk links will employ X-band as the preferred frequency band for the purpose of tracking, telemetry, and command (TT&C). While S-band is not prohibited, individual and collective space agencies are experiencing significant contention for the limited bandwidth when aggregated over their mission sets. Thus, X-band is the preferred frequency band for LNS trunk links to Earth.

2) Ka-band for high-rate DWE and trunk links:

Given the projected data rates for human lunar exploration in the post-2023 era, the existence of some high-rate DWE and trunk links based on the 22/26 GHz Ka-bands will become a key feature of the lunar communications architecture for this era. For the first time, the 22 GHz Ka-band will be used for space exploration. The infusion of Ka-band will also alleviate the potential predominant use of near Earth X-band bandwidth by high-rate missions and constrain the X-band to use for low-rate TT&C purposes.

3) Forward Error Correction (FEC) Code – LDPC Coding for all link types and directionality:

LunaNet will employ the Low-Density Parity Check (LDPC) code as the primary FEC code for all types of links in all directions (forward, return, and crosslinks). This is a major departure from the concatenated Reed-Solomon/convolution codes which have been used for several decades by many missions. Equally noteworthy is the use of LDPC code for forward links – a significant advancement from the conventional BCH code driven by the need to support much higher forward data rates for human missions.

4) Space Data Link Protocol for all links:

The convergence of communications protocols at space data link layer to a single protocol, regardless of link types and link directionality, is another feature of the LunaNet architecture. The Advanced Orbiting System (AOS) standard or the Unified Space Link Protocol (USLP), not both, is expected to be the choice. Departing from the practice of past missions, the multiplicity of space data link protocols (i.e., the TM protocol for downlink, the TC protocol for uplink, the Proximity-1 for proximity link, and the AOS for missions requiring high-rate links), will converge to either the AOS or USLP only. The AOS/USLP can be operated independent of link directionality (unlink TM and TC) and link rates (supportable to all rate regimes, RF and optical, unlike TM, TC, and Proximity-1 protocols). Clearly, this approach has the benefits of enhanced interoperability, reduced implementation cost, and reduced operational complexity for communications. [*Note: Throughout this document, each occurrence of the "USLP/AOS" or "USLP, AOS" is to mean either the USLP or AOS, not both.*]

5) Optical communications:

The LunaNet architecture includes a provision of optical communication capability in its Phase 2 architecture, i.e., ~2028 target architecture. Through the IOAG effort, the High Photon Efficiency (HPE) standards have been chosen over the other two approaches – the High Data Rate (HDR) and the Optical On-Off Keying (O3K). HPE is chosen for all optical links primarily to avoid any extra implementation cost due to multiple approaches. The solution based on the HPE standard meets the data rate requirements for all lunar links, i.e., the proximity links, cross links, and Earth-Moon links. HPE is based on using the 1550 nm wavelength family, which is also preferred for human safety and mission assurance reasons due to eye safety. The 1550 nm wavelength has been approved by the Federal Aviation Administration (FAA) in the United States with approval by the International Civil Aviation Organization (ICAO) in the process.

6) PNT Capability

As part of provisioning PNT services throughout LunaNet, expanded usage of CCSDS PN ranging codes are intended for S-band and X-band in one- and two-way ranging between elements across the architecture. By making these signals available and defining added navigation data messages for transfer of state and timing information as part of LunaNet, individual space elements can act as hosts for LNS payloads or service users in either scenario, providing reference signals or having the onboard capability to perform range measurements.

Based on these driving reasons for frequency band selection in the spectrum architecture, the following sections describe characteristics of the architecture for the major types of cislunar links.

4.6.1 Direct with Earth (DWE) Link

The DWE links include the forward link, i.e., from Earth station to cislunar spacecraft/platform/vehicle (in lunar orbit or on lunar surface) and the return link, i.e., from cislunar spacecraft/platform/vehicle (in lunar orbit or lunar surface) to Earth station.

The DWE links are broken into the TT&C link, the High Rate Links (RF and Optical), and the Contingency Communications link. The standards selected for these links maximize interoperability and compatibility with the different ground networks/stations (including NASA, other space agencies, and commercial service providers). These standards and protocols are consistent with the recommendations stated in the IOAG Lunar Communications Architecture Report. Table 8 gives a summary of the frequency bands, modulation schemes, coding capabilities, and space data link protocols for the DWE link. The standards that define the link characteristics are defined in Table 12 in Section 4.8.

The DWE link is used for sending:

1. Commands, configuration updates, guidance, navigation, and control (GN&C) state information, file uploads, audio, video, etc., over the forward link; and
2. Health and status data, engineering/science/payload data, file downloads, audio, video, etc., over the return link.

Table 8. Summary of LunaNet Direct with Earth (DWE) Links and Trunk Links

Source/Destination	Frequency Bands	Modulation	Coding	Space Data Link Protocol
DWE link/Trunk link (Earth station to cislunar orbiter or surface vehicle)	RF – low rate: 7190-7235 MHz	*Nominal:*		
		Option 1: PCM/PM/bi-phase-L (residual carrier); Option 2: GMSK with PN	LDPC; BCH (for low uplink rate missions only)	AOS, USLP; TC (for low uplink rate missions only)
		Spacecraft special event/emergency/contingency:		
		PCM/PSK/PM (subcarrier)	Option 1- BCH; Option 2 – LDPC	AOS, USLP
	RF – high rate: 22.55-23.15 GHz	Filtered OQPSK/GMSK (suppressed carrier)	LDPC	AOS, USLP
	Optical: 1550 nm	PPM	SCPPM	AOS, USLP
DWE link/Trunk link (cislunar orbiter or surface vehicle to Earth station)	RF – low rate: 8450-8500 MHz	*Nominal:*		
		Option 1: PCM/PM/bi-phase-L (residual carrier); Option 2: GMSK with PN	LDPC	AOS, USLP TM (for low downlink rate missions only)
		Spacecraft special event/emergency/contingency:		
		PCM/PSK/PM (subcarrier)	Option 1 – Concatenated Convolutional/ Reed-Solomon); Option 2 – LDPC	AOS, USLP
	RF – high-rate: 25.5-27.0 GHz	Filtered OQPSK/ GMSK (suppressed carrier)	LDPC	AOS, USLP
	Optical: 1550 nm	PPM	SCPPM	AOS, USLP

4.6.2 Trunk Link

The trunk link is a special type of the DWE link. It is the link between a lunar relay orbiter and Earth station. The trunk links include both forward and return links. The trunk link is used by a relay orbiter/payload to convey those data types, as identified above for the DWE link, for its cislunar users. In addition, certain data items specific to the relay orbiter are transferred over the trunk link.

The frequency bands, modulation schemes, coding capabilities, and space data link protocols for the trunk link are summarized in Table 8.

4.6.3 Proximity Link

The proximity link is the link between a relay satellite and its user spacecraft/platform/vehicle (in lunar orbit or on the lunar surface). Relay service users can be orbital spacecraft, descent/ascent vehicles, landers, rovers, communication stations/towers on the surface, human habitats, *In Situ* Resource Utilization platforms or facilities, and, potentially, astronauts equipped with portable or EVA suit-based communication devices. The proximity links include both the forward link, i.e., from relay satellite to user spacecraft/platform/vehicle and return link, i.e., from user spacecraft/platform/vehicle to the relay satellite.

The proximity link will be used by the relay satellite to communicate with users and, in conjunction with the trunk link, will be used to relay data between the Earth and end users. In addition, it could be used to “teleoperate” surface robotic elements. The proximity link, one or more relay satellites, and the user elements, can be interconnected via a network protocol to form the backbone of a lunar relay network.

Table 9 gives a summary on the frequency bands, modulation schemes, coding capabilities, and space data link protocols for the proximity link.

Table 9. Summary of LunaNet Proximity Links

Source/Destination	Frequency Bands	Modulation	Coding	Space Data Link Protocol
Proximity Link (lunar surface or user orbiter to Relay)	RF – low rate: 2200-2290 MHz; RF- Low Rate: 435-450 MHz (only for Moon’s near-side)	Option 1: PCM/PM/bi-phase-L; (residual carrier) Option 2: CDMA	LDPC; Convolutional Code (for low rate missions only)	AOS, USLP; Proximity -1 (for low rate missions only)
	RF- high rate: 23.15 – 23.55 GHz	Filtered OQPSK/ GMSK (suppressed carrier)	LDPC	AOS, USLP
	Optical: 1550 nm	PPM	SCPPM	AOS, USLP
Proximity Link (lunar surface or user orbiter to Relay)	RF – low rate: 2200-2290 MHz; RF- Low Rate 435-450 MHz (only for Moon’s near-side)	Option 1: PCM/PM/bi-phase-L (residual carrier); Option 2: CDMA	LDPC; Convolutional Code (for low rate missions only)	AOS, USLP; Proximity -1 (for low rate missions only)
	RF – high rate: 22.55-23.15 GHz	Filtered OQPSK/GMSK (suppressed carrier)	LDPC	AOS, USLP
	Optical: 1550 nm	PPM	SCPPM	AOS, USLP

4.6.4 Cross Link

The cross link is the link between two relay satellites, including two satellites by the same LNS or two satellites by different LNSs. The relay satellites in this context could be any of the two types, i.e., the lunar orbiters dedicated to providing relay services and the science/exploration orbiters, e.g., the Lunar Gateway, with relay capability as a secondary payload. The cross link, therefore, is essential to the formation of a lunar relay constellation. Table 10 gives a summary on the frequency bands, modulation schemes, coding capabilities, and space data link protocols for the cross link.

Table 10. A Summary of LunaNet Cross Links

Source/Destination	Frequency Bands	Modulation	Coding	Space Data Link Protocol
Cross Link (Relay orbiter to relay orbiter)	23.15-23.55 GHz 27.0-27.5 GHz	Filtered OQPSK/GMSK (suppressed carrier)	LDPC	AOS, USLP
	Optical: 1550 nm	PPM	SCPPM	AOS, USLP

4.6.5 Surface Link

The surface link is the link physically located between service users on the lunar surface to facilitate the communications between surface elements. From the LunaNet service perspective, such a surface-to-surface link will exist between the communications station (or base station and communications tower) and its user vehicle/platform/facility. Table 11 gives a summary of the frequency bands, modulation schemes, coding capabilities, and space data link protocols for the surface link.

Table 11. A Summary of LunaNet Surface Links

Source/Destination	Frequency Bands	Modulation	Coding	Space Data Link Protocol
Lunar Surface to Lunar Surface	2.4-2.48 GHz	IEEE 802.11	IEEE 802.11	IEEE 802.11

4.7 External Interfaces

The interfaces between LunaNet and cislunar user missions are depicted in protocol stacks with respect to different End-to-End Interface Types. In all interface types, the green boxes represent elements of user missions. Since the LunaNet is viewed as a system of service providing systems/assets, the external systems which it will interface with can further be categorized into user elements in cislunar space (i.e., cislunar spacecraft/platform/vehicle in lunar orbit or on lunar surface) and those in Earth (e.g., a mission operations system and a mission ground system such as a science data center). A salient feature of the interfaces across LunaNet is that its network-based architecture permits end-to-end transfer of network data units, e.g., the DTN bundles, while only adjacent nodes require lower layer interoperability. That means between any two end nodes across two or more networks, e.g., a lunar surface network and a relay network (and/or an Earth network); only compliance with the same networking protocol stack is required. That also means one of the two nodes joining two heterogeneous networks must possess dual-interface capability at lower layers to function as the gateway. Furthermore, within the LunaNet, any communication asset that would interface with multiple sources/destinations and/or route data via multiple alternate paths should serve as a LunaNet node, i.e., being networking capable. “Tunneling” with each source/destination is discouraged.[31], while only adjacent nodes require lower layer interoperability. That means between any two end nodes across two or more networks, e.g., a Lunar surface network and a relay network (and/or an Earth network), only compliance with the same networking protocol stack is required. That also means one of the two nodes joining two heterogeneous networks must possess dual-interface capability at lower layers to function as the gateway. Furthermore, within the LunaNet, any communication asset that would interface with multiple sources/destinations and/or route data via multiple alternate paths should serve as a LunaNet node, i.e., being networking capable. “Tunneling” with each source/destination is discouraged.

4.7.1 Interface Types

4.7.1.1 End-to-End Interface Type 1: Preferred approach for future missions including high-rate missions

For all future lunar missions, including high-rate missions, end-to-end communications feature the DTN Bundle Protocol (BP) for end-to-end data transfer and routing, the Unified Space Link Protocol (USLP) / Advanced Orbiting System (AOS) Protocol for all space links, and the provision of relay services. Figure 19 shows the protocol stack for Type 1 interfaces.

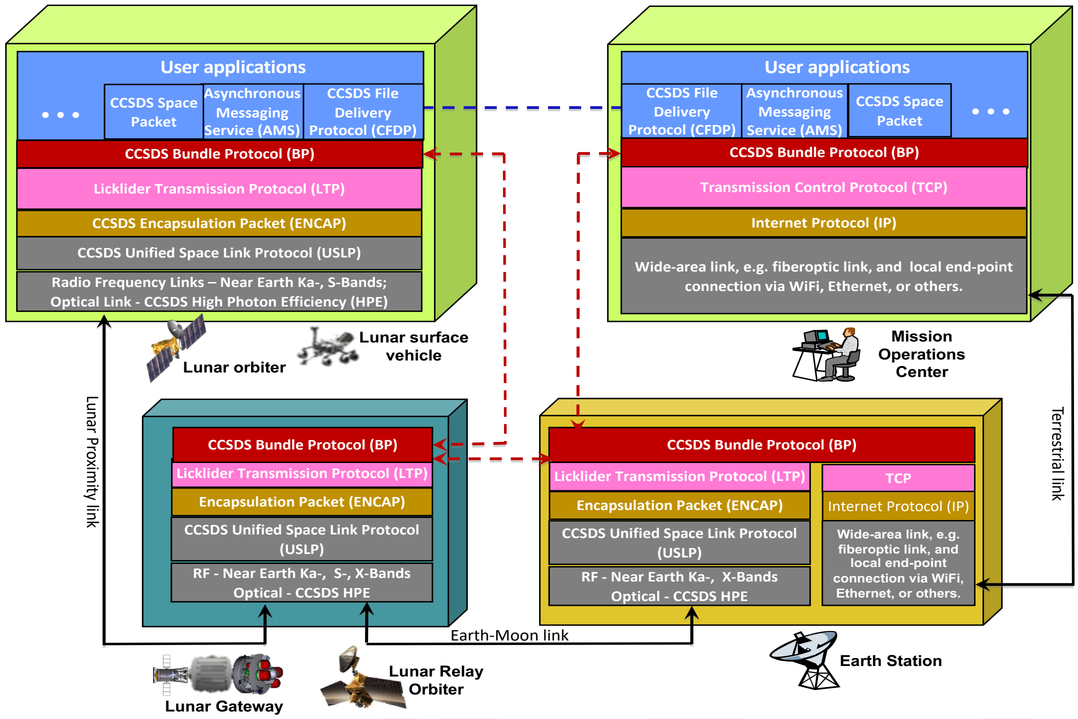


Figure 19. End-To-End Interface Type 1 Protocol Stack

4.7.1.2 End-to-End Interface Type 2: Acceptable approach for legacy-compatible, low-rate missions

Similar to Interface Type 1, this is only specifically for some low-rate missions that prefer to make use of the current space link protocols. Figure 20 shows the protocol stack for Type 2 interfaces.

A couple of points must be noted here:

- The UHF-band for proximity link is shown in the protocol stack along with S-band. This, however, is restricted to situations where proximity link communications take place in the near side of the Moon. For surface vehicles, for instance, located at the far side of the Moon, any UHF communications would violate the regulation for radio-quiet zone.
- Interface Type 2 does not apply to Gateway as it employs only USLP (or AOS) at space data link layer for all links in all directions.

4.7.1.3 End-to-End Interface Type 3: Preferred approach for future missions including high-rate missions

Similar to Interface Type 1, this is for all future lunar missions including high-rate missions; the only difference being no relay is involved in the communications path. Figure 21 shows the protocol stack for Type 3 interfaces.

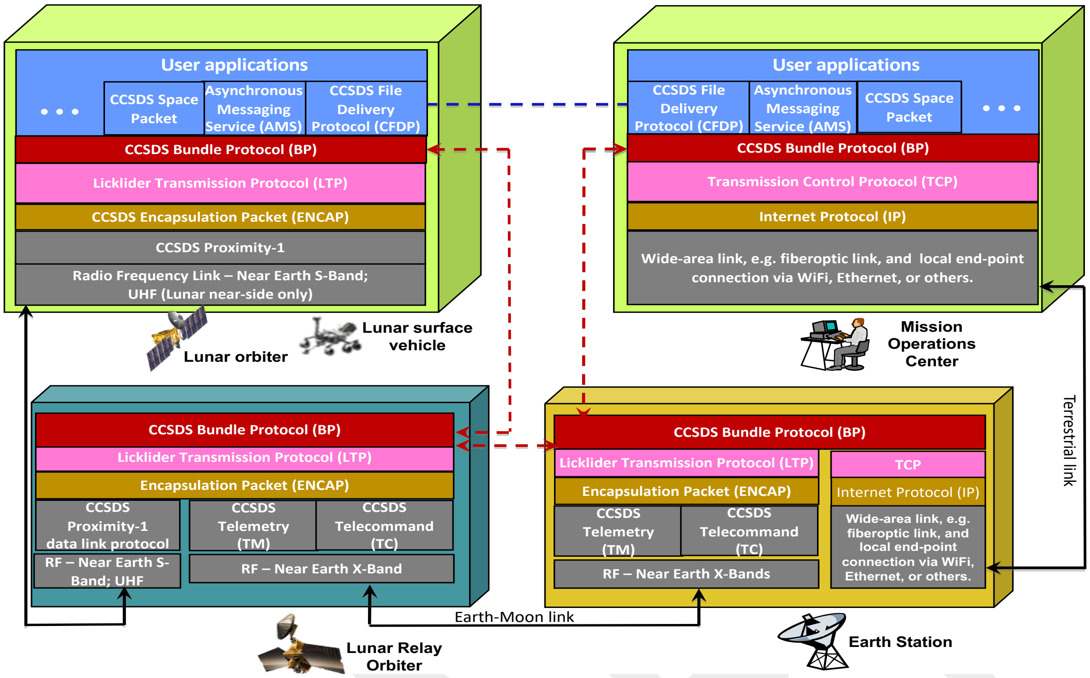


Figure 20. End-To-End Interface Type 2 Protocol Stack

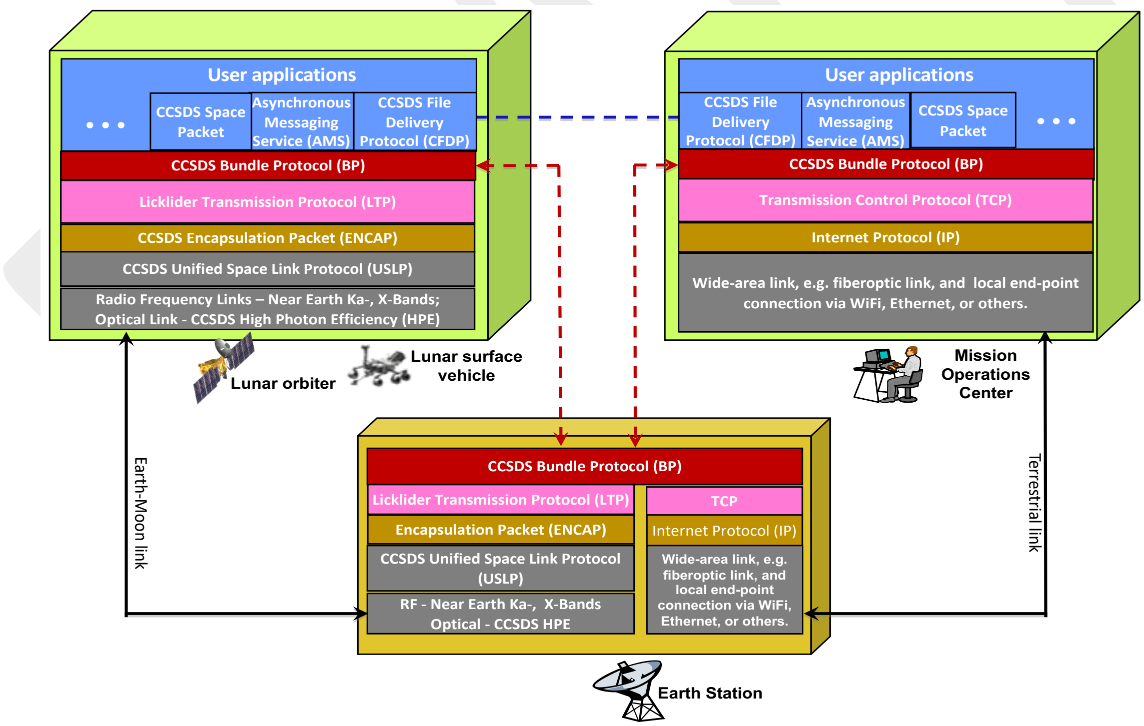


Figure 21. End-To-End Interface Type 3 Protocol Stack

4.7.1.4 End-to-End Interface Type 4: Acceptable approach for legacy-compatible, low-rate missions

Interface Type 4 is similar to Interface Type 2 except there is no relay involved in the communications path. Figure 22 shows the protocol stack for Type 4 interfaces.

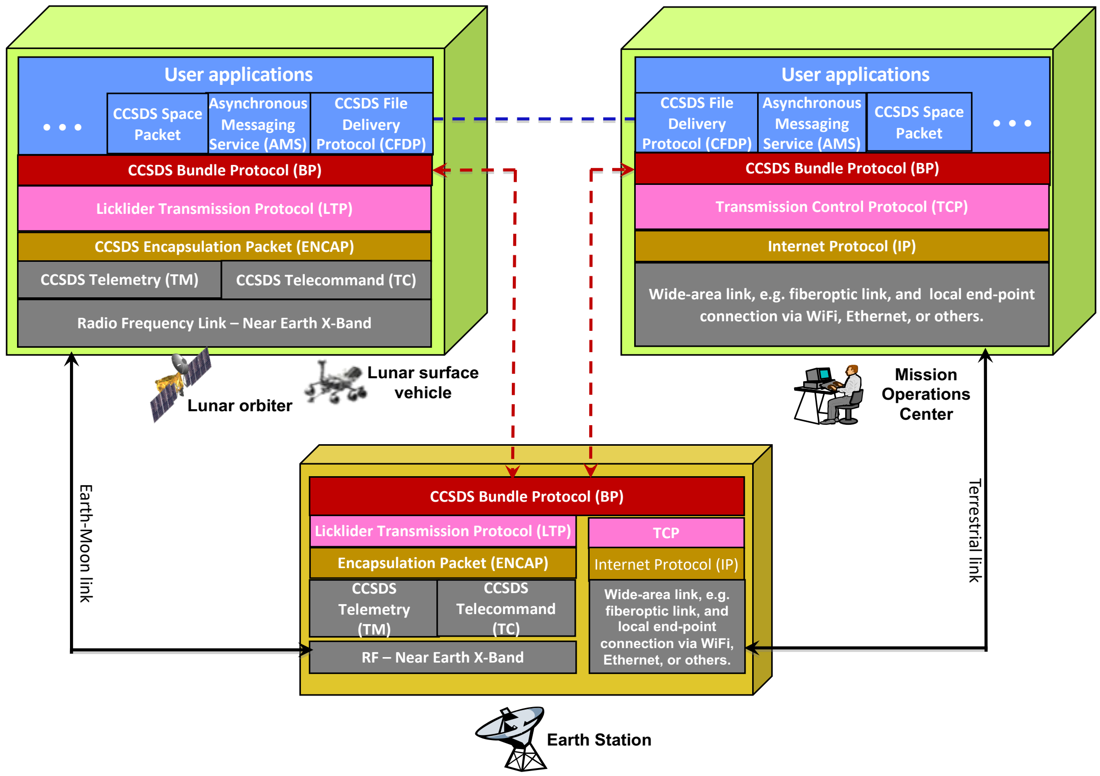


Figure 22. End-To-End Interface Type 4 Protocol Stack

4.7.1.5 End-To-End Interface Type 5: Preferred approach in the presence of lunar surface communications station

Interface Type 5 (Figure 23Figure 24) illustrates a representative case where multiple service-providing assets in cislunar space are involved in supporting user missions. Differing from Types 1 and 2, a surface communications station, in addition to the lunar relay orbiter, is present to serve as a gateway between the lunar surface network and lunar relay network. It communicates with all surface vehicles in the vicinity through the protocols unique to the surface network. For supporting any user surface vehicles demanding end-to-end interface with their respective end destinations/sources in Earth, it communicates with the relay orbiter via the protocols at physical, data link, and network layers defined for the relay proximity link. At the inter-networking layer for end-to-end routing and addressing, however, the DTN BP is the common means to ensure the coherent flow.

4.7.1.6 End-To-End Interface Type 6: Security interfaces

To illustrate the security approaches in the overall lunar communications architecture, the protocol stacks, as integrated with security mechanisms/protocols, for Interface Type 6 are shown in Figure 24.

Again, it is important to note that not all three layers (application, network, and data link layers) of the security mechanisms/protocol have to be implemented for a given mission or mission set. The protocol stack diagram shows them all merely for the purpose of depicting a viable, inclusive security architecture.

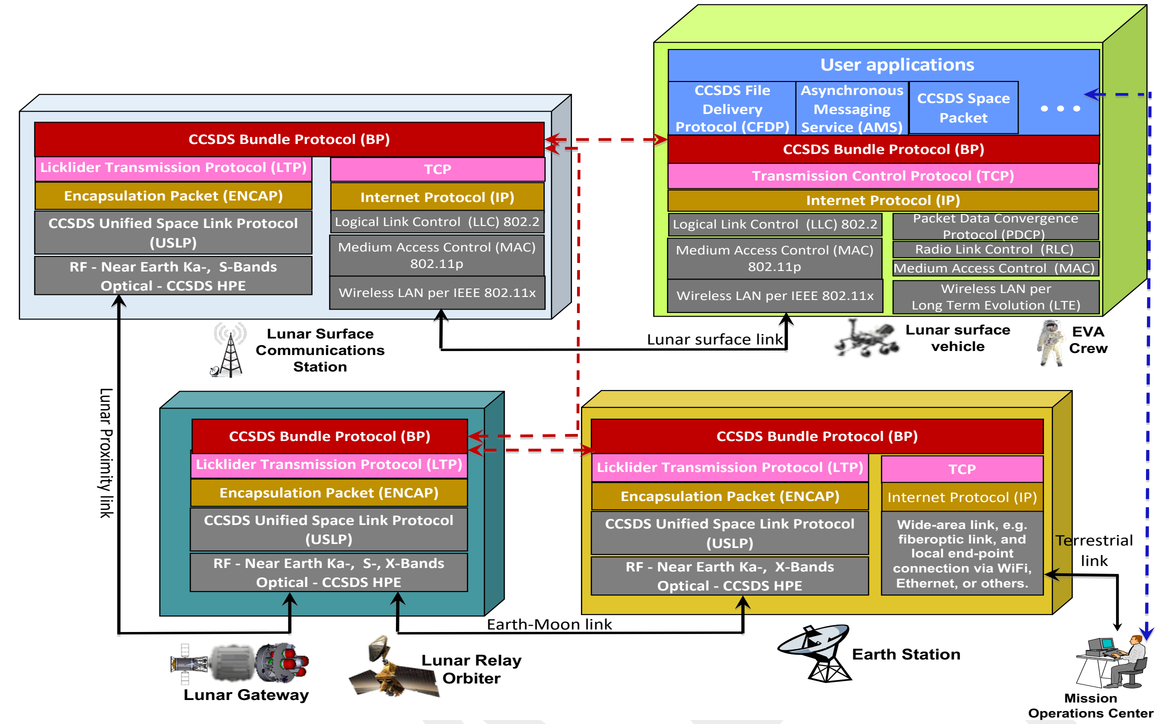


Figure 23. End-To-End Interface Type 5 Protocol Stack

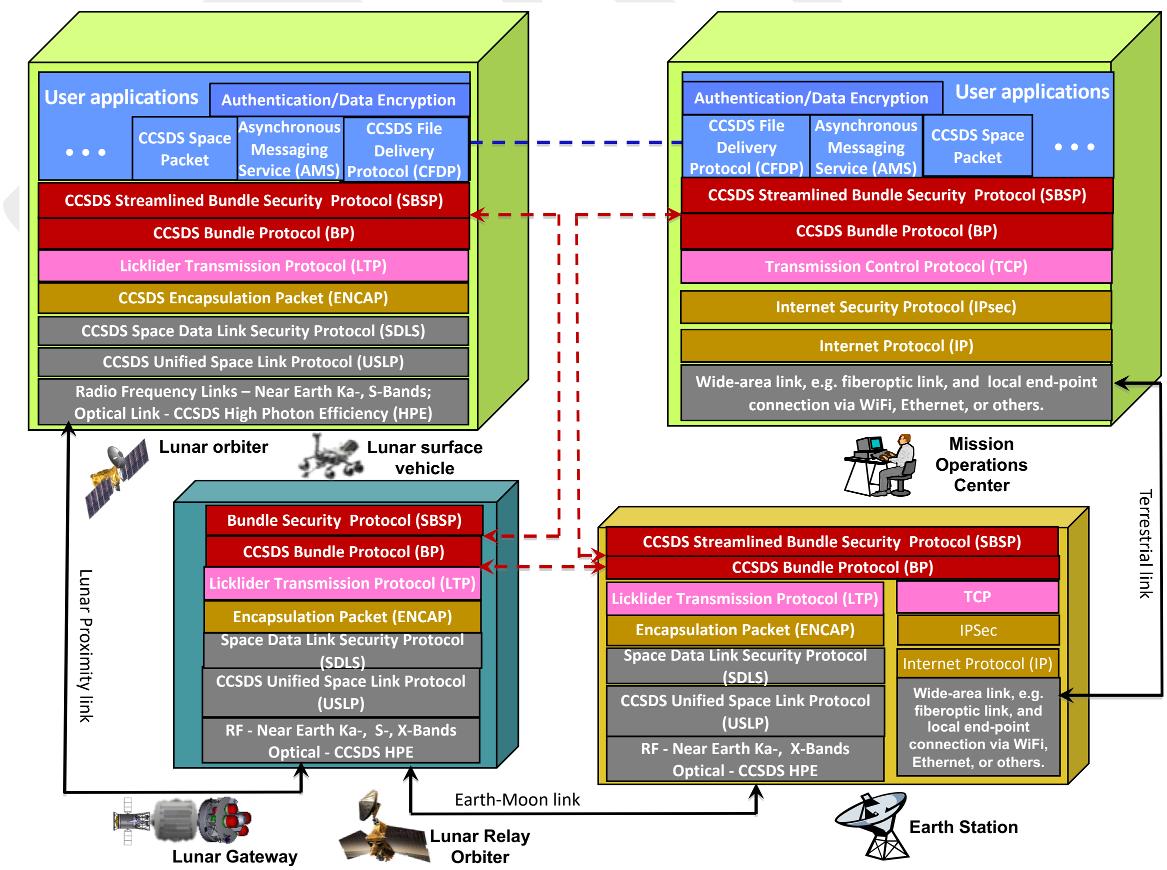


Figure 24. End-To-End Interface Type 6 Protocol Stack

4.7.1.7 End-to-End Interface Type 7: Lunar relay network intranet interfaces

For interfaces between the elements within a lunar relay network, the interface protocols (i.e., the typical intra-network protocol stack), is shown in Figure 25.

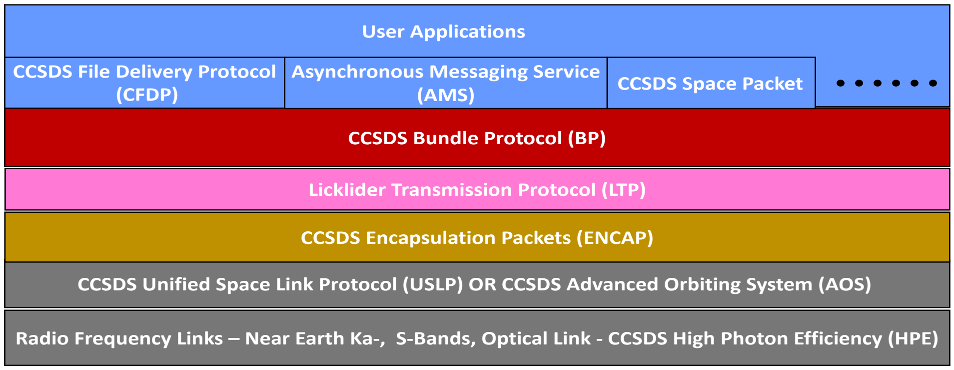
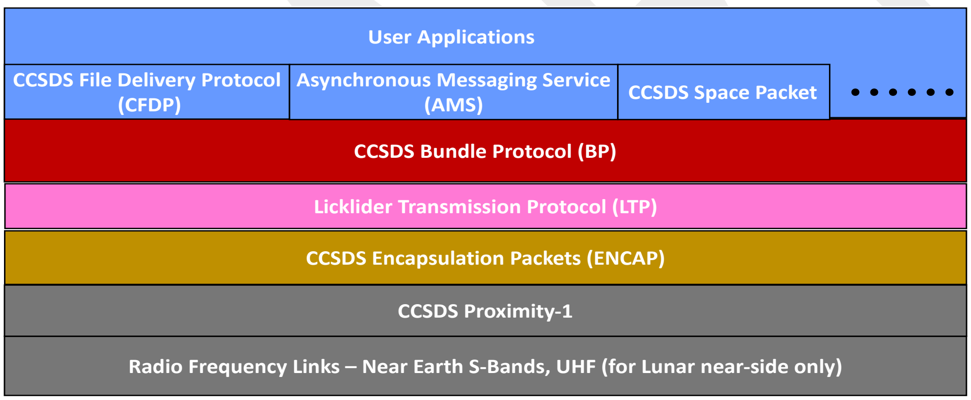


Figure 25. End-To-End Interface Type 7.1 Protocol Stack

A variation from the above is also proposed to accommodate some low-rate missions that prefer to make use of the current space link protocols (Figure 26).



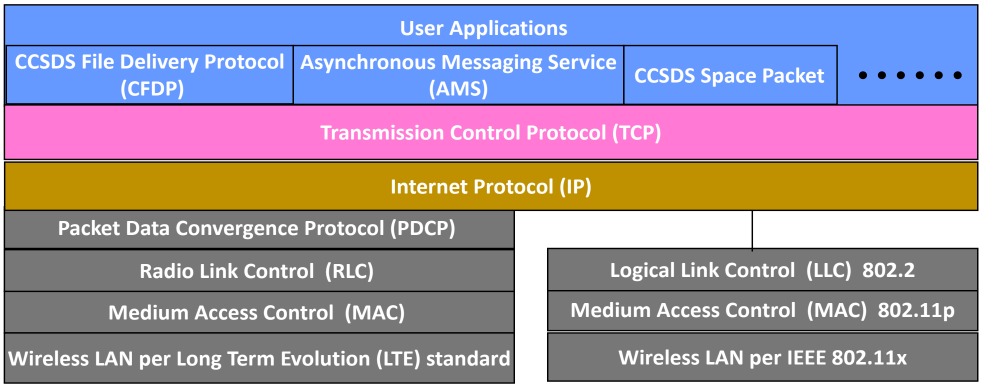
Note: Proximity-1 for data link layer is only for low-rate Lunar missions that require no interface with LOP-G.

Figure 26. End-To-End Interface Type 7.2 Protocol Stack

4.7.1.8 End-to-End Interface Type 8: Lunar surface intranet interfaces

Specific for the Lunar Surface Network, commercial solutions prevalently deployed for terrestrial internet and wireless LAN are encouraged. Nevertheless, to ensure a high degree of interoperability among communication capabilities resident at multiple surface vehicles, the protocol stack shown in Figure 27 is proposed.

All Interface Types using DTN protocol stacks include LTP; however, there is no need for LTP for missions that can tolerate certain data loss or for missions that use heavy enough coding at the lower layers and can accept unrecoverable data loss on the rare occasions when the coding is not strong enough. The downside of relying on the BP alone for retransmission is that the mechanism has no negative acknowledgments. Retransmission can only be triggered by the expiration of a timer prior to receipt of a positive acknowledgment.



Note: The wireless LAN for each Lunar surface network will be based on either LTE or IEEE 802.11x standard subject to selection by the respective commercial provider.

Figure 27. End-To-End Interface Type 8 Protocol Stack

4.7.1.9 End-to-End Interface Type 9: Radiometric tracking and navigation interfaces

To enable inter-asset relative positioning within LunaNet, individual nodes should support standard ranging codes as defined in documentation such as ICSIS and relevant CCSDS standards. For one-way ranging, the service provider shall also broadcast state ephemeris data adhering to LunaNet standards, including uncertainty on each element's position and timing. This can be met by Navigation Data Messages or other standards. This information is needed for the receiving node to process the observables into an absolute state update (PVT). For the purpose of two-way ranging, the user shall be capable of turning around the broadcast code at the pre-defined frequency for reception by the service provider. Upon reception, LNSP nodes shall be able to measure and provide range and range-rate observations, providing a timestamped estimated state (through onboard orbit estimation routines) or raw measurement sent back to the user for PNT integration. Conversely, when the service provider returns a ranging signal, it will also provide its state and uncertainty back to the user for processing the data.

For longer-rate operations between Earth and cislunar space, or from the Moon to Lagrange points, long codes similar to CCSDS are preferred due to the longer range supported, helping to limit issues with phase ambiguity. For near-field operations such as for RPOD and within cislunar space, shorter codes, such as those used in GNSS, are preferred due to their ease of signal identification and tracking. This will allow simplified onboard algorithms at less computational power and a quicker time to first fix.

LunaNet end-to-end services can be instantiated at three levels, based on the location of the service provider. Figure 28, Figure 29, and Figure 30 provide descriptions of these as Interface Types 9a, 9b, and 9c, respectively. Type 9a demonstrates how services implemented today fit within the LunaNet architecture. This approach represents a focus on Earth-centric providers performing PNT services using ground-based assets. For Earth-based tracking, state observables are captured on the ground with mission design and navigation activities being performed externally to the spacecraft. The final estimated state and any maneuvers, for example, are then telemetered back to the user for onboard processing and execution. Examples of this implementation approach are captured by infrastructure, facilities, and staff within NEN, DSN, and Estrack. The services provided by LunaNet are shown where the physical functions are performed. These figures begin to show the offloading of services and applications to the user sphere (for example, one-way ranging from Earth-based assets and position determination performed by the user internally).

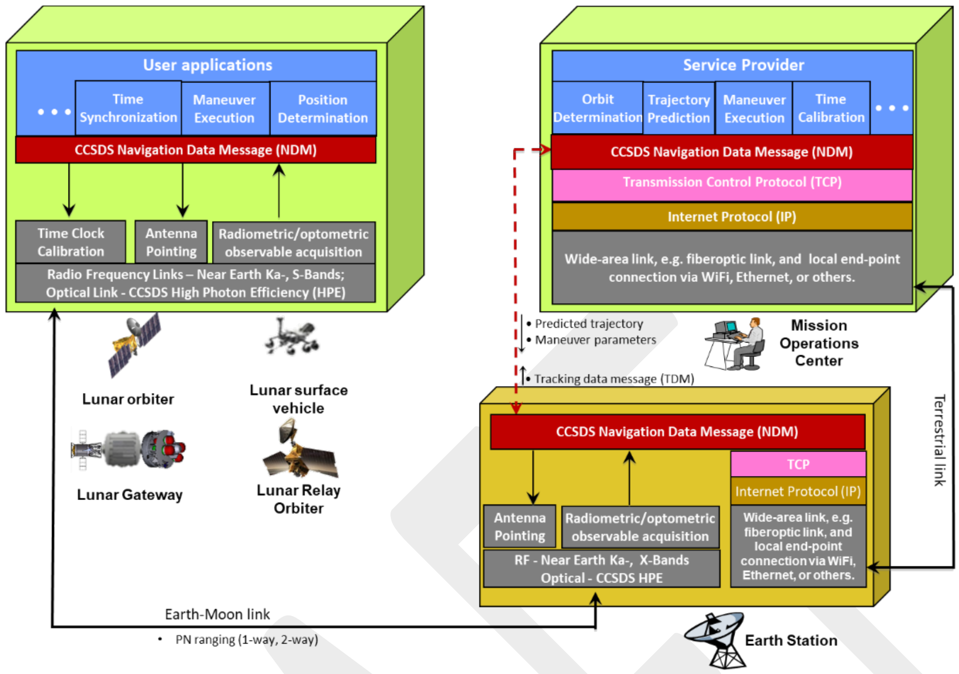


Figure 28. End-to-End Interface Type 9a: Radiometric Tracking and Navigation Protocol Stack Direct to Earth Service Approach

As lunar relay elements are introduced into the LunaNet architecture, the link slightly morphs, as shown in Figure 29, to include additional capabilities and services distributed throughout the network. The inclusion of local PNT references at the relay enables expanded operations within cislunar space. For example, a dedicated relay may be able to more regularly provide PNT observables and services to local users through the use of proximity links. In this type of end-to-end interface, the relay provides additional services that augment ground-based assets and operations. By acting as intermediary between existing infrastructures and the user, it allows for increased coverage and local operational support, while still interfacing with legacy services.

LunaNet also includes dedicated services distributed throughout cislunar space to enable autonomous operation and support, independent of Earth-based service providers. These types of services are described in the illustration of Interface Type 9c, shown in Figure 30, which focuses on links fully captured among lunar elements. Lunar elements could include surface stations as part of landed assets, orbital stations, and dedicated relays as potential nodes and providers. These systems have the capability to accurately maintain their PNT information through the use of onboard sensor systems and high-stability timing modules, and infrequent tracking and synchronization to Earth-based references. This onboard state knowledge accuracy enables them to provide services similar to that shown in Type 9a, provided by ground-based service providers. Type 9c captures a fully lunar-central architecture. Also included within this architecture are the standard interfaces and links back to mission controllers on Earth. The responsibility for transferring and coordination of data among elements across LunaNet is performed by the various supporting LNSPs, providing links back to the ground user for PNT coordination.

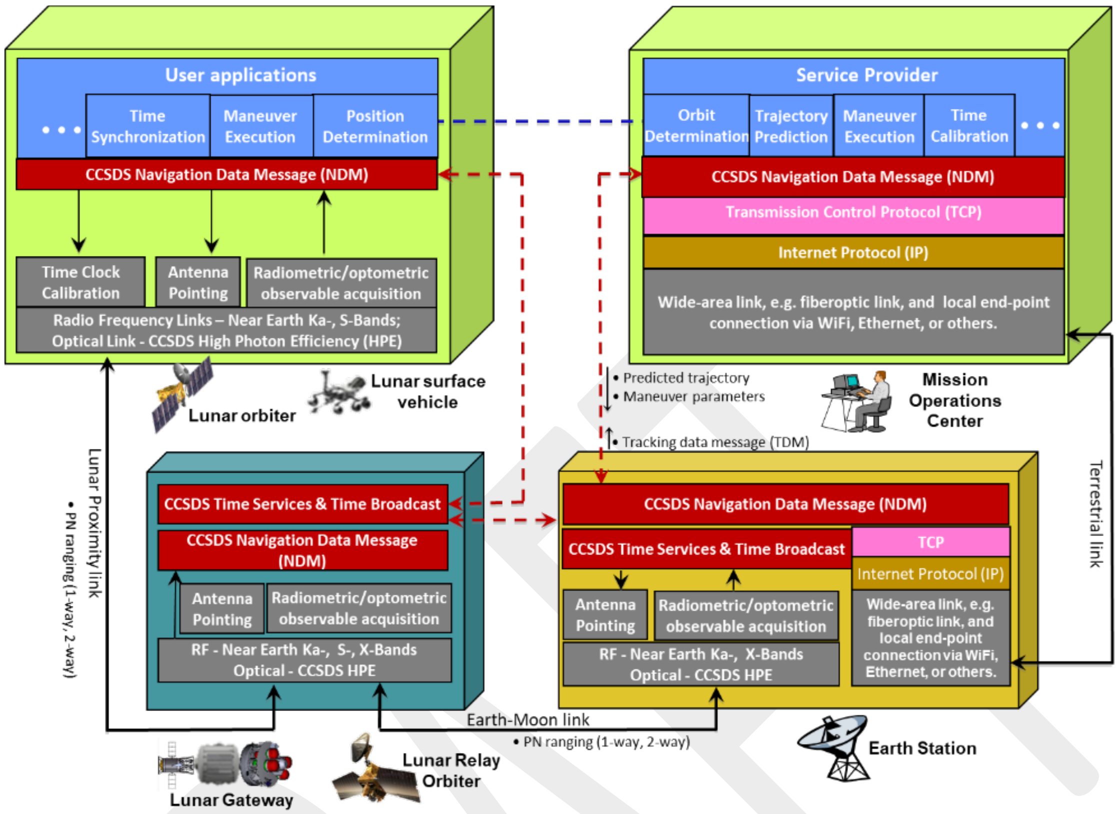


Figure 29. End-to-End Interface Type 9b: PNT Protocol Stack with Integrated Relay for Direct to Earth Service Approach

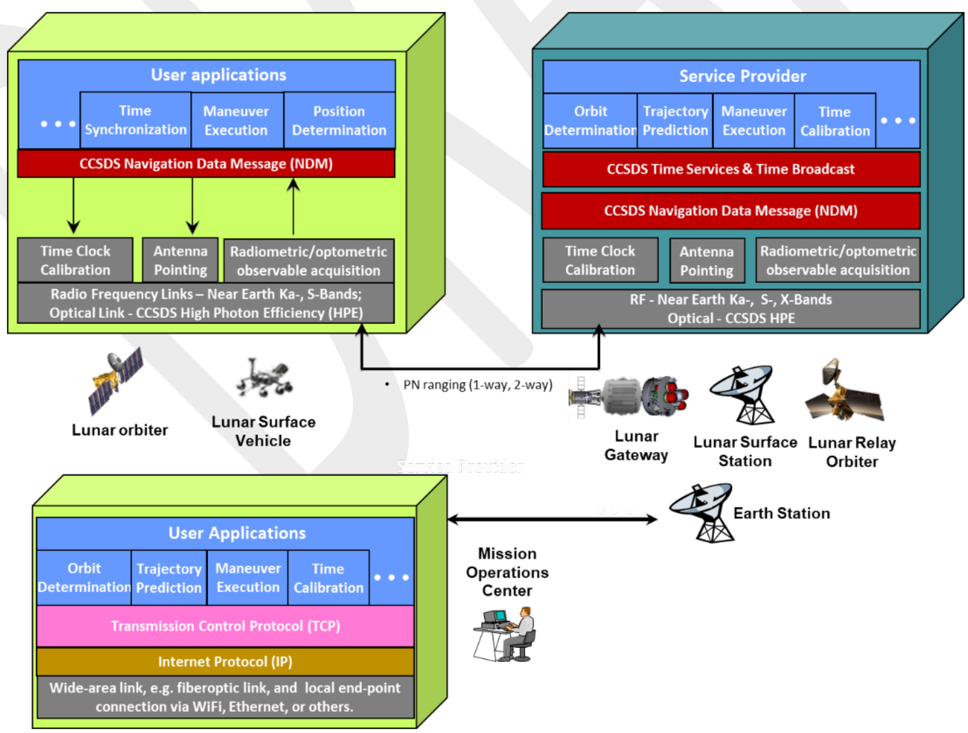


Figure 30. End-to-End Interface Type 9c: PNT Protocol Stack for Deployed Lunar Services

As LunaNet expands, it is expected that multiple types of links will be supported simultaneously. Through the use of common standards for data transmission and navigation observables, service providers can spread throughout the network and be able to plug and play into existing architecture. Additionally, individual users may have specific operational needs requiring a specific type of link. For example, during critical operations, a user may desire a Type 9A interface to allow for rapid assessment and coordination with ground operations support and mission planners. Similarly, a vehicle operating in a standby or non-critical mode may prefer to use a specific relay or service for infrequent PNT updates, based on its onboard capabilities. The intention of these interfaces is to allow users the flexibility and robustness to support a wide variety of mission scenarios, ensuring that adequate coverage is available to meet PNT needs. Additionally, with robust services, the user is able to develop a platform around available services and streamline design.

While the above scenarios provide descriptions of the service interfaces between LunaNet and the user, it is also beneficial to describe the system from the point of view of the user operating a node. Figure 31 provides a summary of how this is broken down between onboard systems, user-driven commanding, and LunaNet Services. The colors indicate whether a function is performed onboard the node, provided by LNS-provided services, or computed at the user level. The user level can be done either onboard or from a MOC, based on the degree of the node's autonomy and design. This diagram shows the primary functions, at the user level, for the node: processing navigation measurements (both generated at the node and from external users); interfacing with any node level hardware for both data acquisition and control; and developing and executing maneuvers. The split boxes indicate functions that can fit as either LunaNet-provided services or applications performed at the user level. Similarly, these user-driven functions can either be computed at the user level or onboard the node, providing pathways for increasing autonomy within the node. As mentioned previously, the intent of LunaNet-provided services is to provide the user with options and services, enabling the user to define a platform and balance the need and usage of onboard PNT capabilities versus that provided by LNSs.

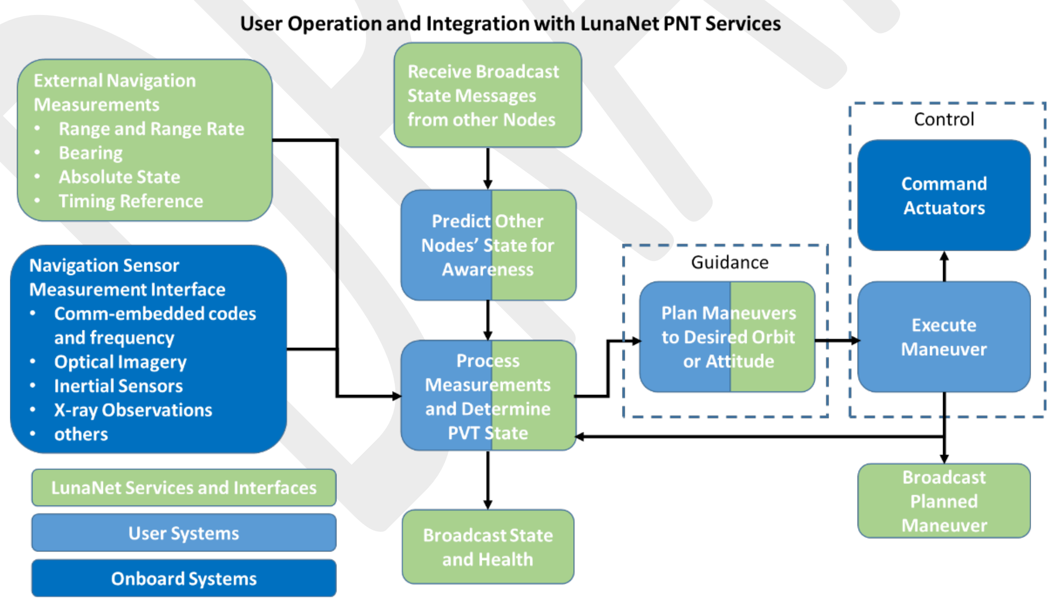


Figure 31. User Integration and Operation with LunaNet

4.7.2 LunaNet to Service User

As shown in Figure 16, LunaNet will interface with cislunar user elements via three types of service providing assets: the Lunar relay orbiters, the Earth stations, and the surface communication stations.

The protocol stacks, at the DTN BP layer and below, required for the point-to-point interfaces are illustrated in the diagrams for Interface Types 1 through 8.

For the end-to-end communications between any two user elements, multiple LunaNet service providing assets may be involved, as illustrated in Interface Types 1 and 2. They, along with the two user elements, will all function as DTN nodes. Data integrity and accountability exist at the end-to-end via the DTN BP and point-to-point interfaces between each pair of adjacent nodes.

4.7.3 LunaNet to LunaNet to Mission Operations Center/Mission Ground Systems

As shown in Interface Types 1 through 8, at lower layers a variety of interface capabilities are identified to accommodate multiple, heterogeneous communications medium/assets/networks available in the various mission ground system environments. For the interface between a MOC and an Earth station, the data transferred are the DTN bundles over the TCP/IP protocol via a terrestrial network. The MOC is, therefore, insensitive to the space data link protocols (e.g., AOS/USLP in Interface Types 1 and 3, and TC/TM in Interface Types 2 and 4) between the Earth stations and the destination spacecraft. In that sense, the Earth station essentially behaves as a MOC's gateway to the cislunar space. Data integrity and accountability exist at the end-to-end level via the DTN BP and point-to-point interfaces between each pair of adjacent nodes.

4.7.4 LunaNet to GNSS

GNSS systems play a prominent role in helping to anchor and provide autonomous PNT capability within the LunaNet framework. This is implemented both at the ground station and user/relay levels. For the ground station, GNSS systems, coupled with high stability oscillators, provide the precision timing and location needed when processing relative measurements of range, range-rate, or bearing angles into absolute positions in ground-based OD. Part of this process also implements the transfer of time as part of the ground processing approach. GNSS anchors and synchronizes the ground network to a common time for operations and time transfer among assets within LunaNet. Similarly, by anchoring the ground systems to GNSS-based time, global time cam be broadcast and updated throughout the network. For example, high fidelity OD and time transfers can allow nodes in cislunar space to remain tightly synchronized and maintain linkages to a common time. This is necessary not only for coordinate operations, but also for onboard processing of navigation measurements into an absolute state position.

A second interface between LunaNet and GNSS systems is through the use of low signal GNSS receivers hosted on lunar craft (both in orbit and on the surface). Integration of these sensor systems into the various nodes allows a direct tie back to global time independent of links back to Earth-based ground stations, enabling a secondary chain to same synchronization source. Similarly, this system, when coupled with onboard high-stability timing sources and state estimation algorithms, can provide the node with an absolute measurement of its current PVT. With this information, the node can act as a timing and navigation relay in cislunar space and provides the anchor to other local assets, helping to coordinate LunaNet.

Additionally, the use of GPS pseudolites is being pursued as another technique of providing inter-asset ranging and range-rate information. This path allows the usage of commercial receivers and pseudolite transmitters for integration into the LunaNet architecture to support PNT. As such, these elements must adhere to GNSS standards in terms of data formatting, rates, and broadcast ephemeris. With the introduction of these local GNSS-references into cislunar space, it is important that they operate on a non-interference basis with low signal level GNSS receivers tracking broadcasts from Earth orbit. This puts constraints on local resources in two ways: transmission power and PRN ID used. For example, lunar assets should avoid using PRN's that are in active usage in Earth space and focus on unused (or new) codes for identifying the specific satellites (which lists the various potential PRN codes that can be used). A secondary constraint is on transmission power. The local references should have the capability to support operations in low lunar orbit and NRHO orbits, but low enough power not to overpower terrestrial sources. This will require integration between low-signal noise users and pseudolite developers. Additional proposals may be available in the spectrum domain by placing the new signals apart from existing frequencies in use. An alternate approach to remove any potential overlaps would be to locally operate the system at a removed frequency band from terrestrial GNSS.

Lastly, the ephemeris data broadcast by any pseudolites will need to adhere to standards in terms of the standard broadcast messages in use by existing GNSS constellations to allow for inter-system operability. Coordinated updates will also be required to transfer properly Earth-centric, orbital-defined data into lunar-centered parameters. This will require identification of reference frame as well as potentially including additional parameters for elements operating within 3-body specific orbits, such as a halo orbit.

4.7.5 LNS-to-LNS within LunaNet

As shown in Figure 16, within the LunaNet, internal interfaces will exist between the three types of service-providing assets; i.e., the lunar relay orbiters, the Earth stations, and the surface communication stations. The types of links involved are: (a) the trunk link between a lunar relay orbiter and an Earth station, (b) the proximity link between a surface communications station and a lunar relay orbiter, (c) the cross-link between any two relay orbiters, (d) the DWE link between a lunar relay orbiter and an Earth station, and e) the terrestrial link for the Earth-based LunaNet elements, e.g., between an Earth network and the NME.

As illustrated in diagrams for Interface Types 1 through 6, the relevant point-to-point interfaces are provided via the protocol stack at the DTN BP layer and below.

4.8 Applicable Documents

The standards and documents cited in Section 4 and in Table 12. establish specifications, requirements, recommendations, and/or interface information relevant to LunaNet. Other standards will be added as LunaNet definition is completed in coordination with LNSPs. In most cases, the latest revision is used, unless otherwise stated. Click on the specific Number or Title to retrieve a document.

Table 12. List of Applicable Documents

Agency	Number	Title and Link	Version	Date
CCSDS	131.0-B-3	TM Synchronization and Channel Coding, Blue Book	Issue 3	Sep 2017
CCSDS	132.0-B-2	Space Data Link Protocol, Blue Book	Issue 2	Sep 2015
CCSDS	141.0-B-1	Optical Communications Physical Layer, Blue Book	Issue 1	Aug 2019
CCSDS	211.0-B-6	Proximity-1 Space Link Protocol—Data Link Layer, Blue Book	Issue 6	Jul 2020
CCSDS	211.1-B-4	Proximity-1 Space Link Protocol—Physical Layer, Blue Book	Issue 4	Dec 2013
CCSDS	211.2-B-3	Proximity-1 Space Link Protocol-- Coding and Synchronization Sublayer, Blue Book	Issue 3	Oct 2019
CCSDS	231.0-B-3	TC Synchronization and Channel Coding, Blue Book	Issue 3	Sep 2017

Agency	Number	Title and Link	Version	Date
CCSDS	232.0-B-3	TC Space Data Link Protocol, Blue Book	Issue 3	Sep 2015
CCSDS	352.0-B-2	CCSDS Cryptographic Algorithms, Blue Book	Issue 2	Aug 2019
CCSDS	355.0-B-1	Space Data Link Security Protocol, Blue Book	Issue 1	Sep 2015
CCSDS	355.1-B-1	Space Data Link Security Protocol – Extended Procedures	Issue 1	Feb 2020
CCSDS	401.0-B-30	Radio Frequency and Modulation Systems--Part 1: Earth Stations and Spacecraft, Blue Book	Issue 30	Feb 2020
CCSDS	414.1-B-2	Pseudo-Noise (PN) Ranging Systems. Blue Book	Issue 2	Feb 2014
CCSDS	415.1-B-1	Data Transmission and PN Ranging for 2 GHz CDMA Link via Data Relay Satellite. Blue Book	Issue 1	Feb 2011
CCSDS	500.0-G-4	Navigation Data Definitions and Conventions, Green Book	Issue 4	Nov 2019
CCSDS	502.0-B-2	Orbit Data Message, Blue Book	Issue 2	Nov 2009
CCSDS	503.0-B-2	Tracking Data Message, Blue Book	Issue 2	Jun 2020
CCSDS	504.0-B-1	Attitude Data Message, Blue Book	Issue 1	May 2008
CCSDS	508.0-B-1	Conjunction Data Message, Blue Book	Issue 1	Jun 2013
CCSDS	509.0-B-1	Pointing Request Message, Blue Book	Issue 1	Feb 2018
CCSDS	732.0-B-3	AOS Space Data Link Protocol, Blue Book	Issue 3	Sep 2015
CCSDS	732.1-B-1	Unified Space Data Link Protocol, Blue Book	Issue 1	Oct 2018
CCSDS	734.1-B-1	Licklider Transmission Protocol (LTP) for CCSDS, Blue Book	Issue 1	May 2015
CCSDS	734.5-B-1	Streamlined Bundle Security Protocol (SBSP) for CCSDS	Issue 1	In preparation
CCSDS	734.2-B-1	CCSDS Bundle Protocol Specification, Blue Book	Issue 1	Sep 2015
CCSDS	901.1-M-1	Space Communications Cross Support – Architecture Requirement Document, Magenta Book	Issue 1	May 2015
CCSDS	911.1-B-4	Space Link Extension – Return All Frames Service Specification, Blue Book	Issue 4	Aug 2016
CCSDS	911.2-B-3	Space Link Extension – Return Channel Frames Service Specification, Blue Book	Issue 3	Aug 2016
CCSDS	912.1-B-4	Space Link Extension – Forward CLTU Service Specification, Blue Book	Issue 4	Aug 2016
CCSDS	921.1-B-1	Cross Support Transfer Service – Specification Framework, Blue Book	Issue 1	Apr 2017
CCSDS	922.1-B-1	Cross Support Transfer Service – Monitor Data Service, Blue Book	Issue 1	Apr 2017

Agency	Number	Title and Link	Version	Date
CCSDS	922.2-B-1	Cross Support Transfer Service – Tracking Data Service	Issue 1	May 2020
GPS	IS-GPS-200J	NAVSTAR GPS Space Segment/ Navigation User Segment Interfaces		22 May 2018
IETF	RFC 6257	Bundle Security Protocol (BSP)		May 2011
ISO/IEC	7498-1:1994 (E)	Information technology -- Open Systems Interconnection -- Basic Reference Model: The Basic Model	Edition 1	Jun 1996
ISO/IEC	7498-2:1989	Information technology -- Open Systems Interconnection -- Basic Reference Model: Security Architecture	Edition 1	Feb 1996
ISO/IEC	7498-3:1997	Information technology -- Open Systems Interconnection -- Basic Reference Model: Naming and addressing	Edition 1	Apr 1997
ISO/IEC	7498-4:1989	Information technology -- Open Systems Interconnection -- Basic Reference Model: Management framework	Edition 1	Nov 1989
ITU-R	SA. 2271	Sharing conditions between space research service proximity operations links and fixed and mobile service links in the 410-420 MHz band		Sep 2013
ITU-R	SA. 1157	Protection criteria for deep-space research		Mar 2006
IEEE	802.11-2016	Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications	General: additional standards exist for specific version of 802.11	7 Dec 2016
NASA	HEOMD-003 Volume 2	International Communication System Interoperability Standards (ICSIS)	Revision A	Sep 2020
NASA	HEOMD-003 Volume 5	International Rendezvous System Interoperability Standards (IRSIS)	Baseline	Mar 2019
SFCG	RES 23-5	Protection of Future Radio Astronomy Observatories In The Shielded Zone Of The Moon		25 Sep 2003
SFCG	REC 32-2R2	Communication Frequency Allocations and Sharing in the Lunar Region		Aug 2019

Appendix A. Abbreviations and Acronyms

Acronym	Definition
AES	Advanced Exploration Systems
ATLO	Assembly, Test, and Launch Operations
AutoNav	Autonomous Navigation/Autonomous Optical Navigation
BP	Bundle Protocol
C&N	Communication and Navigation
CCSDS	Consultative Committee for Space Data Systems
CIA	Confidentiality, Integrity, and Availability
CLPS	Commercial Lunar Payload Services
ConOps	Concept of Operations
COOP	Continuity of Operations
CPNT	Communications, Position, Navigation, and Timing. When used in the context of services provided by an LNS, CPNT refers to the complete set of Communication, PNT, information, and other services.
CR	Contractor Report
DOR	Differential One-Way Ranging
DSN	Deep Space Network
DTN	Delay Tolerant Networks/Disruption Tolerant Networking
DWE	Direct with Earth
EDL	Entry, Descent, and Landing
EESS	Earth Exploration-Satellite Service
EIRP	Effective Isotropic Radiated Power
ENA	Energetic Neutral Atom
ESA	European Space Agency
ESD	Exploration Systems Development
ESTRACK /Estrack	European Space Tracking network
EVA	Extravehicular Activity
GN&C	Guidance, Navigation and Control
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GW	Gateway / NASA Gateway Program
HEO	Human Exploration and Operations
HLS	Human Landing System

Acronym	Definition
I-HAB	International Habitat
ICAN	Integrated Communications and Navigation
ICSIS	International Communication System Interoperability Standards
IEEE	Institute of Electrical and Electronic Engineers
IOAG	Interagency Operations Advisory Group
IPoC	Initial Point of Contact
ISS	Inter-Satellite Service
ISS	International Space Station
LunaNet	Lunar Network (see Terminology Table for additional definition)
ITU	International Telecommunications Union
JAXA	Japanese Aerospace Exploration Agency
LEGS	Lunar Exploration Ground Stations
LNSP	LunaNet Service Provider
MOC	Mission Operations Center
OD	Orbit Determination
OpNav	Operational/Navigational
OPoC	Operational Point of Contact
NOAA	National Oceanic and Atmospheric Administration
NASA	National Aeronautics and Space Administration
NEN	Near Earth Network
NTP	Network Time Protocol
PN	Pseudo-Random Noise/Pseudo Noise
PNT	Position, Navigation, and Timing
PVT	Position, Velocity, and Time
QoS	Quality of Service
RF	Radio Frequency
SECS	Spacecraft Emergency Cross Support
SEP	Solar Energetic Particle
SFCG	Space Frequency Coordination Group
SLA	Service Level Agreement / Service Level Agreement
SOA	Service-Oriented Architecture
SOP	Standard Operating Process/Procedure
SOS	Space Operation Service

Acronym	Definition
SRD	System Requirements Document
SRS	Space Research Service
SCaN	Space Communications and Navigation
SZM	Shielded Zone of the Moon
SWaP	Size, Weight and Power
TDRSS	Tracking and Data Relay Satellite System
TLE	Two-Line Element
TT&C/ TTC	Tracking, Telemetry, and Command
UIS	User Initiated Services
US SPACECOM	United States Space Command
VLBI	Very Long Baseline Interferometry
WLAN	Wireless Local Area Network

Appendix B. **References**

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