NASA's Lunar Communications and Navigation Architecture

white paper

2023 Moon to Mars Architecture

I. Introduction

NASA's Artemis missions will return humanity to the Moon, establishing a long-term presence there and opening more of the lunar surface to exploration than ever before. This rapid growth of lunar activity requires robust and resilient communications, navigation, and networking capabilities for crew safety, command and control of spacecraft, return of science data, and precise maneuvering of assets in space and on the lunar surface.

Within the Moon to Mars Architecture,[1] the Communications, Position, Navigation, and Timing (CPNT) sub-architecture details the specific CPNT systems, functions, and use cases required to meet the NASA's Moon to Mars Objectives throughout each segment of the architecture. The CPNT sub-architecture through the Human Lunar Return segment — approximately through Artemis V — is detailed here.

The architecture development effort utilizes an objectives-based approach that focuses on the ultimate goals of human exploration of the Moon, Mars, and beyond.[2] The three objectives most fundamental to the CPNT sub-architecture are:

- Develop a lunar surface, orbital, and Moon-to-Earth communications architecture that scales to support long-term science, exploration, and industrial needs.
- Develop a lunar position, navigation, and timing (PNT) architecture that also scales to support long term science, exploration, and industrial needs.
- Preserve and protect representative features of special interest, including the shielded zone of the Moon.

II. Lunar Communications Architecture

The CPNT sub-architecure enables communication and navigation on the lunar surface, in cislunar space, and with Earth. Use cases allocated to the CPNT sub-architecture include:

- Crew voice and data communications.
- Video for scientific data collection, public outreach, and crew safety.
- Science data transmissions across:
  - Direct-to-Earth communications.
  - Communications among surface assets, orbiting relays, and Gateway, NASA's lunar-orbitting space station.
  - Lunar surface-to-surface communications.

PNT use cases include providing position and timing of lunar samples, to crew navigating the surface, for landings and ascents, and to other cislunar assets. NASA will lead a distributed team of government, commercial, and international partners to implement the CPNT sub-architecture on Earth, in cislunar space, and on the lunar surface.

Cooperation among multiple service providers and users across government, industry, and international partners requires coordination and planning through established and new interface and operations standards. This will enable a long-term, scalable, and interoperable architecture that provides communications services across all the assets.

Beginning with the initial Human Lunar Return segment of the architecture, a variety of interface standards will enable interoperability. These include the LunaNet Interoperability Specification, the International Communication Systems Interoperability Standard, terrestrial wireless cellular standards, and other similar coordination with industry and international partners.[3,4,5]

LunaNet is an internationally coordinated framework for lunar interoperability, envisioned as a set of cooperating networks providing communications, navigation, and other services for users on and around the Moon. The LunaNet concept is based on a structure of mutually agreed-upon standards, protocols, and interface requirements that enable interoperability.

The International Communication Systems Interoperability Standard was developed to enable collaborative operations. These systems provide end-to-end compatibility and interoperability between a cislunar space platform, visiting spacecraft, lunar systems, and Earth.

Figure 1 illustrates the principal CPNT architecture during early exploration segments, including Human Lunar Return.[6] Ground stations from multiple providers offer connectivity direct to the lunar surface and to communications relays or assets in lunar orbit. Surface communications occur between crew and landing vehicles using a wireless network. Equipped surface assets communicate with Gateway and via orbital relays to Earth.

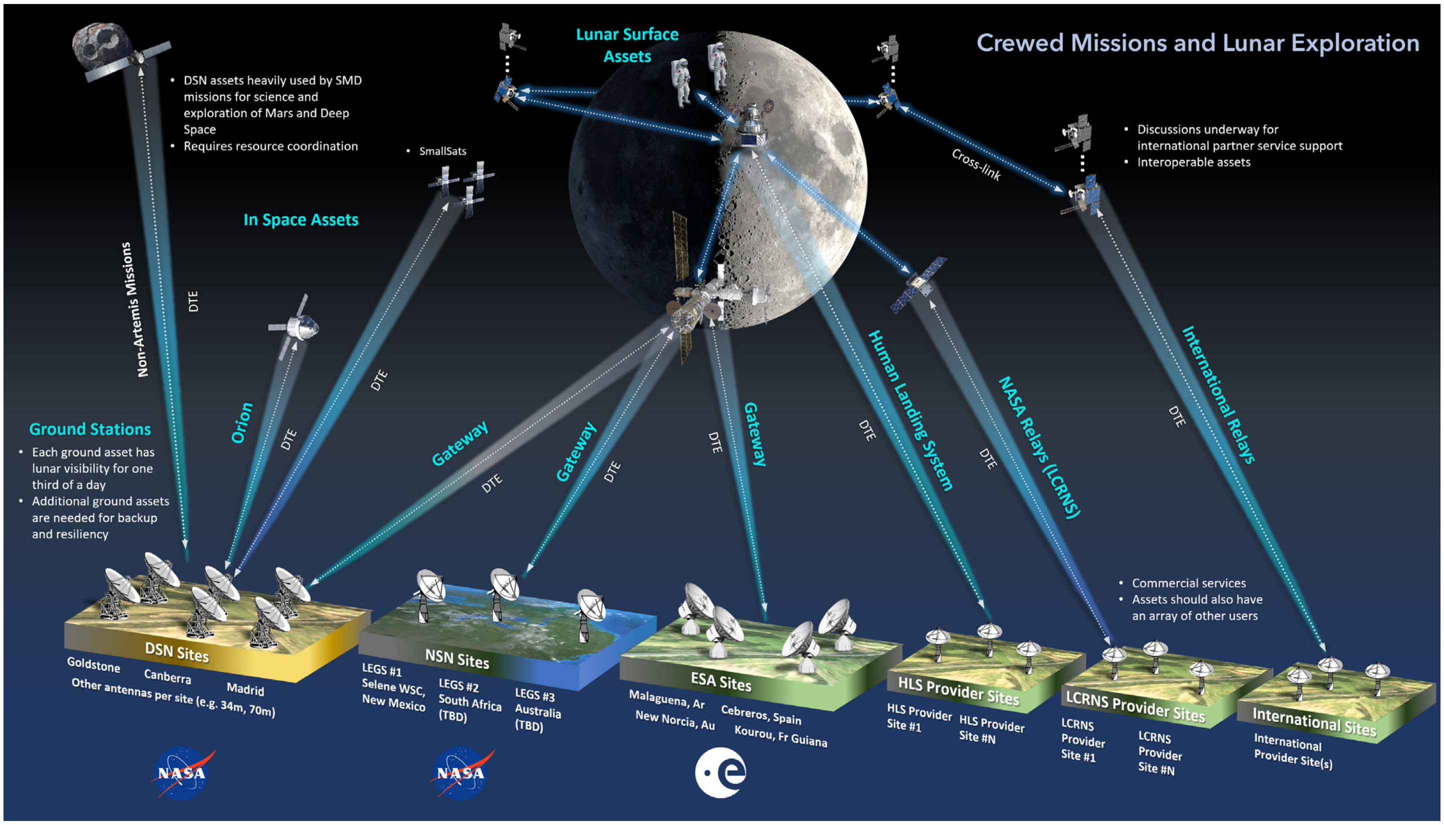


Figure 1. *The CPNT Architecture for Early Lunar Exploration*

A. Direct-to-Earth Communications

For users near the lunar South Pole, communications with Earth are complicated by the orbital geometry of the Earth-Moon system. The Moon's orbital inclination — the tilt of its orbit around Earth — and obliquity — the tilt of its rotational axis — cause Earth to be visible from the lunar South Pole for only about half of every sidereal month, the time it takes the Moon to orbit once around Earth (approximately 14 days). This will require deployment of orbiting relays to maintain continuous communications.

Furthermore, the topography of the polar regions is unlike the lunar maria, the large plains visited by the Apollo missions, or any region on Earth. For example, Shackleton Crater — a dominant feature of the lunar South Pole — is over two times deeper than the Grand Canyon. Nearby regions of interest are challenging for rovers and astronauts to traverse and safely navigate while maintaining reliable communications.

Additionally, when Earth is visible from the lunar South Pole, it is always seen near the Moon's horizon. The lunar terrain can also adversely affect communications signals traveling over it.[7]

Direct-to-Earth communications for Gateway and lunar missions will be supported by NASA's Deep Space Network facilities, NASA's Near Space Network's future Lunar Exploration Ground Systems, the European Space Agency's European Space Tracking (ESTRACK) network, and commercial ground assets. Together, these will provide near-continuous coverage to Gateway and the lunar South Pole when in Earth's view.

Projected communication needs beyond Human Lunar Return are expected to exceed the planned radio frequency communications capacity. Future optical communications capabilities, which use infrared lasers to provide higher data throughput, will accommodate the increased data volume at the Moon.

B. Orbiting Communication Relays

To close the gaps in direct-to-Earth communications, NASA is pursuing commercial satellite services to provide connectivity for missions on the lunar surface and in cislunar space. These providers will employ lunar-orbiting relay satellites with downlinks to commercial ground stations on Earth. Additionally, Gateway will provide communication links and limited PNT functions for surface and in-orbit users. International space agencies are also considering lunar communications relays, which may hold potential for collaboration.

The Lunar Communications Relay and Navigation Services project will provide consistent availability, visibility, and higher data rates for surface users. With multiple relays incrementally launched, the project can offer phased and incremental coverage of the South Pole region.[3] Early implementations will also offer preliminary PNT services as a stepping stone to a more robust, dedicated capability beyond the Human Lunar Return segment.

C. Surface Communications

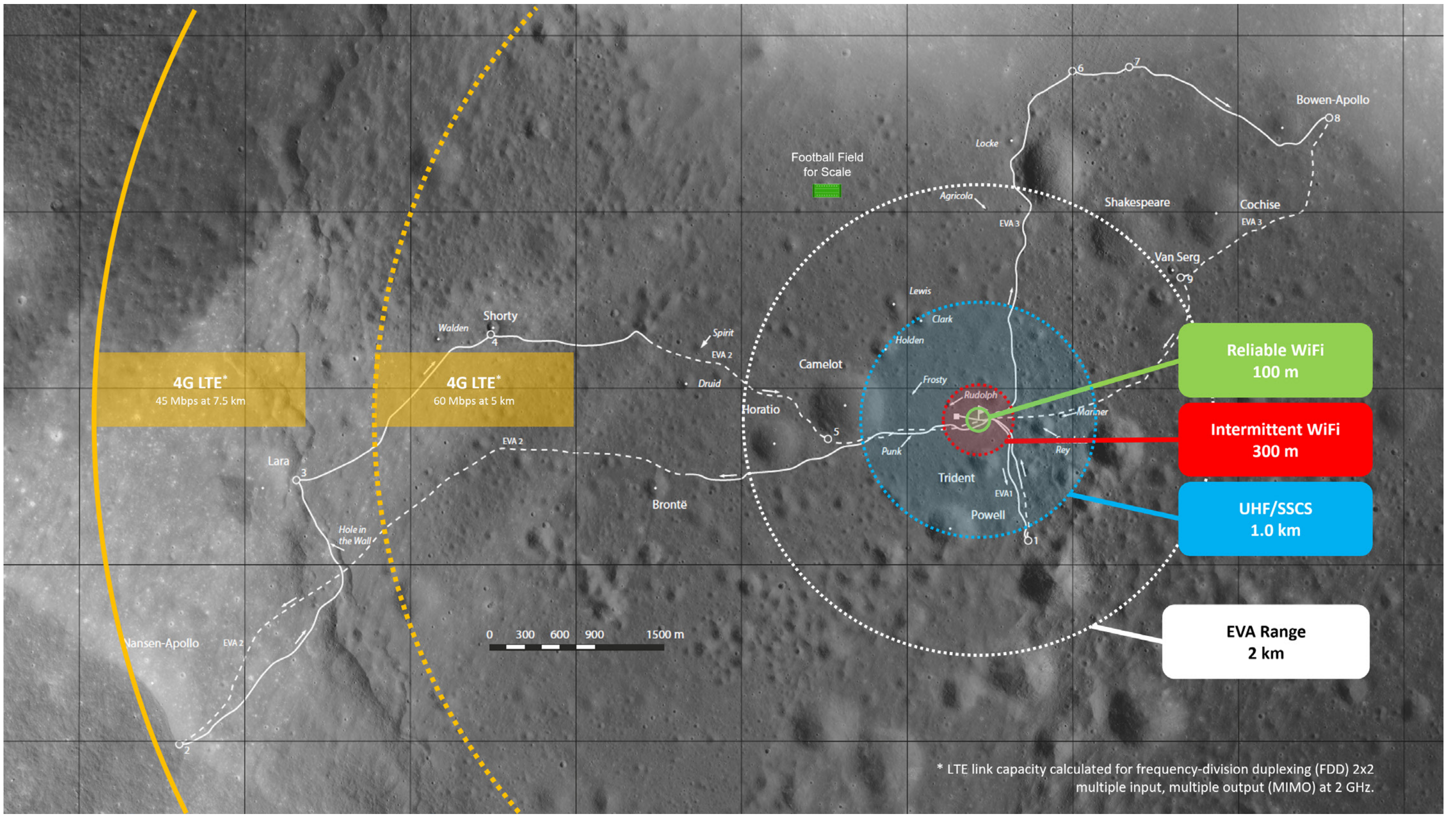
NASA is pursuing trade studies on different approaches to lunar surface networking to select implementations that best meet the exploration requirements. These potential approaches include:

- Adapting NASA's Space-to-Space Communication System — a two-way communications system designed to provide voice and telemetry data between the space shuttle orbiter, the International Space Station, and the Extra Vehicular Activity Mobility Unit — at ultra-high frequency for voice communications.
- Using Wi-Fi for close-proximity high-rate video communications.
- Leveraging terrestrial wireless cellular standards for scalable, longer range, high-throughput connectivity with PNT services.[8] Such a network could enhance exploration range and mobility and the aggregation of data between a variety of science users.

Figure 2 illustrates the anticipated excursion ranges (e.g., a 2km extravehicular activity range) with different surface networking implementations, compared to exploration distances of Apollo 17.[9] Specific communications range distances can extend beyond those illustrated in the figure with varying data throughput. These ranges will also vary by system design choices and other considerations.

The combination of proposed approaches should meet exploration requirements. Range needs will vary by mission, driven by exploration objectives, crew mobility capabilities, and landing site considerations and constraints, such as terrain, slope, and regolith displacement due to landing.

During the Human Lunar Return segment, initial CPNT infrastructure concepts, capability, and hardware elements will be demonstrated through technology demonstrations and initial operational support. The expansion to longer term, sustainable implementation of a lunar surface network will occur during subsequent segments, incorporating advancements and lessons learned from technology demonstrations.



* LTE link capacity calculated for frequency-division duplexing (FDD) 2x2 multiple input, multiple output (MIMO) at 2 GHz.

Figure 2. *A Comparison of Estimated Ranges for Several Surface Network Implementations, Plotted against the Longest Apollo-era Traverses with the Lunar Roving Vehicle during Apollo 17.*

III. Lunar Position, Navigation, and Timing Architecture

The lunar PNT architecture provides core functions to users on the Moon and in cislunar space. PNT capabilities allow lunar assets to know their current position, velocity, and time, and to navigate safely in lunar orbit and on the Moon's surface. Real-time, precise PNT services benefit the breadth of lunar users and scenarios, including orbiters, landers, surface exploration, and image and science collection. PNT needs vary from a Human Landing System accuracy requirement of within 100 meters of a planned landing site, surface position accuracy requirement of within 50 meters, and surface sample location marking accuracy requirement of within 10 meters.

There are a number of challenges associated with PNT on the lunar surface. Traditional methods of tracking by Earth networks will be difficult, if not impossible, during surface operations on the South Pole when users have limited or no line of sight to Earth. Use of GPS at the Moon is limited by the weakness of GPS signals at lunar distances, GPS satellite geometry, and occultation, where Earth blocks GPS signals from reaching the Moon. The variable lighting environment and challenging terrain conditions will make it difficult for the crew to use orienteering or camera-based approaches.

NASA's navigation architecture is comprised of both infrastructure and user capabilities. Infrastructure includes critical reference system components and radionavigation sources provided via communications and network assets. User-side capabilities include the onboard navigation systems that collect, process, and filter the data required to successfully navigate.

A. Infrastructure

Radio frequency (radiometric) sources are the most traditional means of navigation for spacecraft from near-Earth to deep space. At the Moon, these sources will include ground stations on Earth, satellites in orbit around Earth and the Moon, and assets on the lunar surface.

Earth-based Global Navigation Satellite System (GNSS) PNT services, like those provided by the U.S. Global Positioning System (GPS) constellation, can extend to the lunar regime in certain circumstances. These GNSS signals can aid the data diversity for resilient navigation when combined with traditional deep space signal tracking methods.

Communications relays in lunar orbit will provide cislunar and surface PNT services by broadcasting reference signals. One such approach, an augmented forward signal, combines navigation information with broadcast data messaging.

During the Human Lunar Return timeframe, NASA will roll out PNT capabilities across the early Artemis missions. This will begin with PNT provided by Earth-based tracking and surface elements, and expand to services provided by an initial relay satellite in luanr orbit. Subsequent to the Human Lunar Return segment, additional relay satellites could be supplied for a GNSS-like PNT capability that covers the global lunar service volume.

B. User Capabilities

In addition to using radiometric measurements from Earth, lunar orbit, and surface assets, lunar users will employ any number of other navigation data sources. These could include cameras and optical sensors, light detection and ranging (lidar) payloads, solar compasses, and inertial measurement units, which can use a combination of accelerometers, gyroscopes, and other tools to determine specific force, angular rate, and orientation.

During the Human Lunar Return phase, NASA will plan surface operations during well-illuminated conditions, allowing missions to rely largely on orienteering with use of maps, solar compass, and inertial measurement units. Additional sensors such as cameras or light beacons from a lunar lander will also be considered.

IV. Conclusion

The Moon to Mars CPNT sub-architecture defines the relevant functions necessary to achieve high availability, high throughput communications, and accurate PNT to enable the safe command and control of spacecraft, the return of science data, and precision maneuvering of assets. Together, these functions will enable the long-term goals laid out in NASA's Moon to Mars Objectives.

Through the Human Lunar Return segment, CPNT sub-architecture needs will be met through a combination of direct-to-Earth, space-based relay, surface-to-surface communications, navigation assets, and in-situ sensors. Deep Space Network facilities, upgraded to support additional Ka-band frequencies, and the Near Space Network's Lunar Exploration Ground Systems will provide near-continuous coverage of the lunar South Pole when in view from Earth and to Gateway. The European Space Agency's ESTRACK network will provide support for Gateway alongside potential commercial services from ground stations and lunar relay satellites, which could also support other cislunar and surface users.

Commercial and international partnerships will be key to developing a robust CPNT sub-architecture. During the Human Lunar Return segment, incremental improvements will facilitate more efficient network scheduling and utilization as a first step toward a more robust network management framework. These efforts are intended to meet the needs of near-term exploration and scale to support the increasing complexity of long-term lunar science and exploration.

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