National Aeronautics and Space Administration

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Moon to Mars Architecture

white paper

Communications and Navigation Needs for the Foundational Exploration Segment

Introduction

NASA's Moon to Mars Objectives[1] guide the agency to develop scalable communications and positioning, navigation, and timing (C&PNT) capabilities "to support long-term science, exploration, and industrial needs," "a continuous human presence, and a robust lunar economy." NASA's Moon to Mars Architecture[2] — documented in the agency's Architecture Definition Document[3] — outlines the agency's roadmap for realizing these capabilities to support exploration of the Moon, Mars, and beyond.

The architecture comprises segments of growing complexity as lunar exploration and user needs evolve. After the Human Lunar Return segment, where NASA lands astronauts on the Moon for the first time since the Apollo program, the Foundational Exploration segment expands operational capabilities to meet the increased user needs of longer mission durations, regional exploration of the lunar South Pole, and Mars-forward demonstrations of exploration systems and capabilities.

The architecture also comprises sub-architectures, tightly coupled groups of systems, services, and capabilities (e.g., transportation, mobility, habitation). The C&PNT sub-architecture consists of assets, elements, and service providers that enable data transmission and reception, determination of location and orientation, and precise time synchronization. C&PNT sub-architecture users comprise exploration assets utilizing shared C&PNT resources at Earth, in orbit, or on the surface of planetary bodies.

Robust C&PNT capabilities are critical to all aspects of human spaceflight, including ensuring astronaut safety and maximizing science and exploration data returns. This white paper offers key considerations for the evolution of the C&PNT sub-architecture as the NASA's Moon to Mars Architecture progresses from Human Lunar Return through the Foundational Exploration segment.

Key Challenges

During the Foundational Exploration segment, NASA will realize increasingly ambitious capabilities that empower new science and exploration returns. As the agency does so, exploration elements and assets (i.e., users) will increasingly rely on shared C&PNT sub-architecture infrastructure, capabilities, and services.

Segment users will include landing assets, mobility assets, habitats, long-term telerobotic science investigations, in-situ resource utilization payloads, Mars-forward technology demonstrations, and more. Missions in this segment will send crews to visit novel areas in the lunar South Pole region, emplace critical infrastructure, and more.

Each individual user will have specific needs for data transmission and reception, aggregation and processing, including between lunar assets and with controllers and investigators on Earth. Users will also require navigation and time data to land accurately, traverse the lunar surface, perform precision science, and more.

Lunar user electronics must operate across widely varying temperatures and in an extreme radiation environment. Users will need sufficient power to transmit and receive data long distance to Earth and antenna systems capable of tracking ground stations on Earth and relay satellites in lunar orbit. They will also need to consider and mitigate the effects of lunar regolith on signal propagation. Polar lighting conditions present a navigation challenge for both crewed and robotic missions, with long shadows and sharp contrast between dark and light regions.

Finally, the architecture needs to facilitate and sustain interoperability, ensuring that users and service providers can communicate with each other. It must also consider the extensibility and scalability of C&PNT systems to empower evolution through Foundational Exploration and into the Sustained Lunar Evolution segment.

To address these C&PNT challenges, NASA will need to advance new technologies, establish interoperability standards, and grow its understanding of the lunar environment. In parallel to these efforts, the agency and its partners will instantiate infrastructure that addresses user demand and minimizes user burden (e.g., by reducing power needed to access C&PNT services, enabling higher throughput, or offering more accurate position and timing data) while also optimizing network loading and performance.

See the 2023 white paper, "NASA's Lunar Communications and Navigation Architecture," for more detail.[4]

Architecture Considerations

During Human Lunar Return and for the early Foundational Exploration segment, the C&PNT sub-architecture will provide services for user communication direct with Earth or through lunar relays, and cis-lunar users to Earth or to surface users. On the surface, surface exploration elements (e.g., landing systems, rovers, habitats) will serve as C&PNT hubs for other lunar users (e.g., astronauts performing EVAs, surface science payloads). These elements aggregate the data from multiple surface elements and transmit it directly to terrestrial ground stations or through lunar relays. Certain hubs (e.g., Lunar Terrain Vehicle, Pressurized Rover) will have dual roles as network users and hubs.

As the architecture evolves through the mid and late phases of the Foundational Exploration segment, NASA will meet increased user demand and support extended mission durations through increased reliance on lunar relay links and data aggregation on the surface. For example, NASA could add surface relays to aggregate and relay data, much like a terrestrial cell tower or wireless hub. Such a surface asset could communicate direct with ground stations on Earth or through orbital relay elements already instantiated into the architecture (e.g., Lunar Communications Relay Navigations Systems).

The integrated C&PNT sub-architecture will be a lunar network comprising a variety of lunar surface and orbital assets operated by NASA, commercial partners, and international space agencies. It can scale up to support new exploration assets as they come online (or scale down as assets reach the ends of their operational mission.)

Below are some key architecture considerations for the evolution of the C&PNT sub-architecture through the Foundational Exploration segment, including **interoperability**, **user demand**, and **technology development** considerations.

Interoperability Considerations

Establishing a cohesive C&PNT sub-architecture depends on defining interface standards for all elements and assets. Adoption of common C&PNT standards by NASA and its partners will be essential to the success of cooperative exploration of the Moon and Mars.

Types of needed C&PNT standards include provider-side service interfaces, user-side interfaces, spectrum allocations, and networking protocols, as well as time and reference systems. These standards require coordination between NASA, other government agencies, international partners, and standards-setting bodies.

LunaNet is an internationally coordinated framework for an interoperable lunar network of networks. Envisioned as a set of cooperating networks, service providers can deliver communications, data transmission services and distribution of position, navigation, timing, and situational awareness information. The LunaNet Interoperability Specification comprises mutually agreed-upon standards and protocols that meet the needs of lunar exploration.[5]

The initial LunaNet Interoperability Specification includes a frequency plan for the lunar vicinity and surface. The frequency plan includes allocations for:

- Ka- and X-band connections with Earth
- Ka- and S-band connections between lunar relays and surface assets
- C- and S-band connections for lunar surface wireless networking

In addition to LunaNet, the International Communication System Interoperability Standard enables collaborative operations among international partner systems.[6] On the lunar surface, NASA plans to use Third Generation Partnership Project (3GPP)[7] cellular and 802.11 Wi-Fi[8] standards to best meet users' growing needs and enable communications between systems and services. For spectrum allocation, NASA works with the Space Frequency Coordination Group,[9] the Interagency Operations Advisory Group,[10] and others.

C&PNT standards are agreed to internationally but are often implemented by individual nations, so close coordination between partners is essential. NASA's Space Communications and Navigation program — in coordination with relevant stakeholders — represents the agency when negotiating many of these standards.

Individual Programs have latitude to broker C&PNT services for their vehicles to meet the requirements for human space flight. This offers architecture efficiencies and multiple options for brokering C&PNT services.

User Demand Considerations

As operations concepts mature into manifested missions, C&PNT requirements become clearer. User demand describes which services users will need from the C&PNT sub-architecture. While data volume will vary between missions and elements, user demand can describe the general capacity and characteristics of needed communications and navigation systems.

Basic C&PNT user demand characteristics include connectivity, coverage, capacity, and PNT Accuracy. See table one for simple descriptions of these characteristics.

Table One: *Basic C&PNT user demand characteristics. (NASA)*

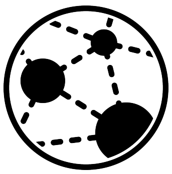
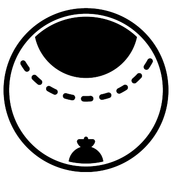
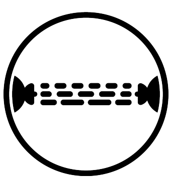
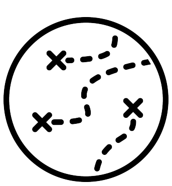
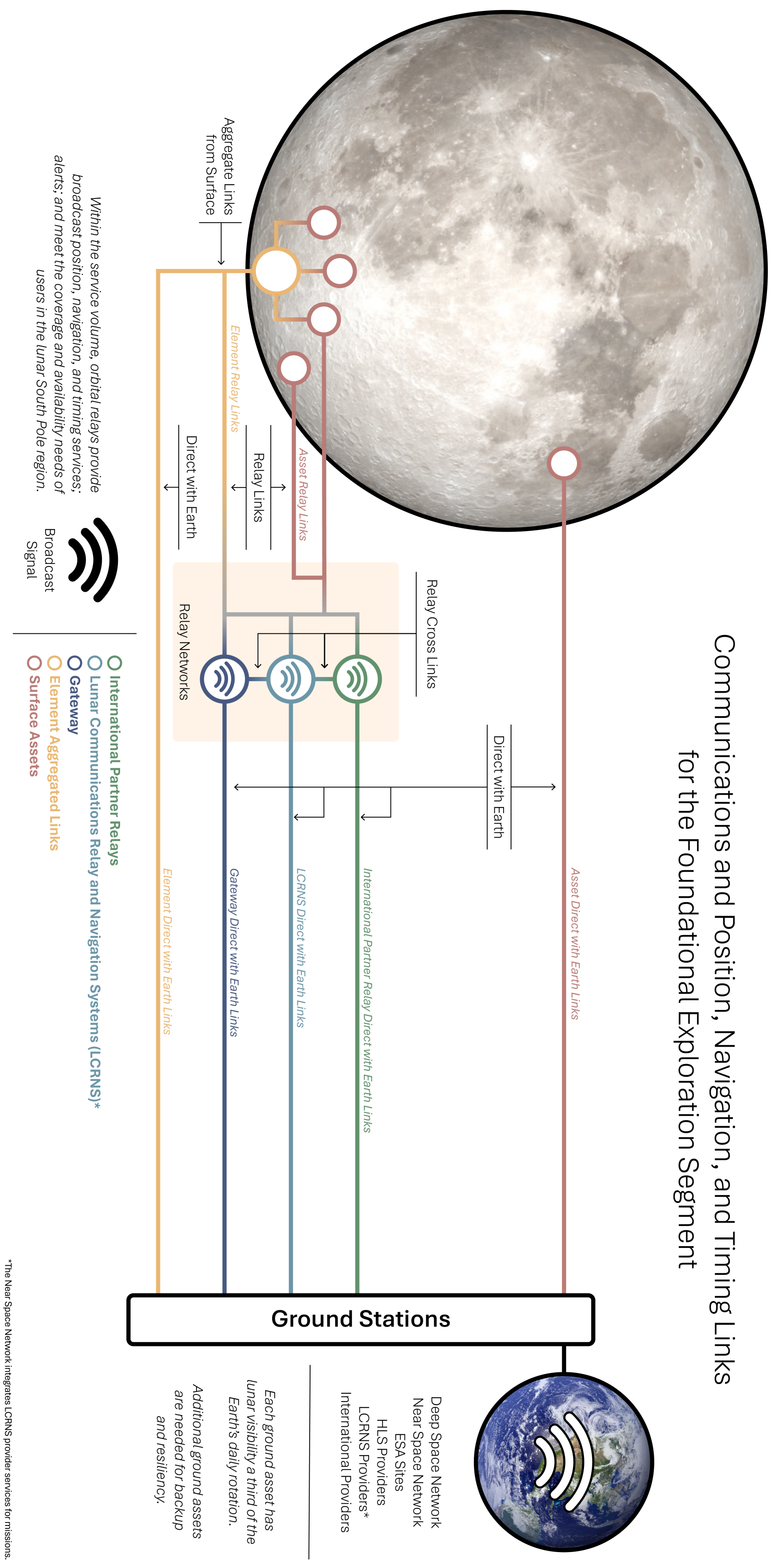
 **Connectivity**	The need to create links between host and destination and sustain the associated communications protocol such that data is successfully exchanged over the established links.
 **Coverage**	The need to provide an acceptable quality of service connectivity over a given region or volume, where users reside.
 **Capacity**	The need for sufficient data throughput across multiple simultaneous links, throughout operational mission phases.
 **PNT Accuracy**	The need for a time synchronization and navigation system to enable users to establish their selenographic position to a specified degree of accuracy.

Figure One: *Diagram illustrating the C&PNT sub-architecture for the Foundational Exploration segment. (NASA)*



Connectivity
User connectivity demand can be expressed as the number and types of links the C&PNT sub-architecture must support. Types of links include direct-with-Earth from the lunar surface, direct-with-Earth from lunar orbit, surface-to-surface, and surface-to-cislunar space (e.g., relay). The number of links will increase as NASA and its partners emplace more exploration systems on the lunar surface and crewed missions grow in duration and complexity.

The number of individual links could vary depending on the applications and missions. For example, crew spacesuits might link to their landing element. The system might aggregate voice communication, suit telemetry, multiple video streams (e.g., helmet camera, external handheld camera), and other instrument data onto a single link. Thus, one link between spacesuit and landing element could facilitate, for example, five unique data streams and/or service types, each with different data rates and priority.

Coverage
Maintaining user coverage includes providing C&PNT services wherever missions operate; in transit from and back to Earth, in cislunar space, and on the lunar surface, including the lunar far side. Earth visibility can be intermittent in the polar region due to orbital geometry and rugged topography, complicating both communications and navigation. Surface coverage accommodates the networking needs of surface elements emplaced across the lunar South Pole region.

There are many architectural drivers for the location and separation between exploration assets. These include areas of scientific interest, locations of landing vehicles, hazardous terrain features, and lunar lighting. Specific factors affecting separation include lunar blast ejecta from landing vehicles, long shadows that could impair solar array systems, and aggregation of elements in general vicinity of each other with multi-region mobility and operations.

User coverage demand can also refer to the total supported service volume. For example, as the Foundational Exploration segment progresses, lunar relay service support grows to include a greater portion of the lunar South Pole region and increasing orbital altitudes (see the Architecture Definition Document for more detail).[3]

Capacity
User demand for data transfer capacity is often expressed in terms of data volume per unit time, otherwise referred to as the instantaneous throughput rate. For example, a lunar lander might require a large data throughput to support video feeds, science payloads, vehicle telemetry, and other component systems. A rover with fewer payloads and telemetry sensors might only need half that data throughput.

Figure two shows how user demand is expected to grow in terms of data throughput over the Foundational Exploration segment through three segment phases (early, mid, and late). It shows how the total demand on the C&PNT sub-architecture increases as it onboards new users and crewed missions grow in complexity. Note also the expected change in variability or uncertainty of total throughput as missions refine and update their needs, and as new science missions are planned.

The illustration distinguishes priority users — those supporting crewed missions — as a portion of total demand. Since many high-rate data needs are associated with video feeds required by crew or crewed elements, priority throughput approaches that of total throughput (i.e., data needs are highest during crewed operations as opposed to uncrewed operations).

Figure three shows user demands in terms of the C&PNT needs of the sub-architectures. The graph shows how certain types of elements (e.g., habitation elements) have larger needs for C&PNT services. Certain types of activities might greatly increase the needs of a given sub-architecture (i.e., the addition of large-scale in-situ resource utilization demonstrations would greatly increase the C&PNT needs of the utilization systems sub-architecture.)

PNT Accuracy
Exploration and science user demands for navigation are generally in terms of navigation accuracy requirements and timeliness. For example, a vehicle may require a certain accuracy for landing, but astronauts collecting and logging samples may require accuracy beyond that. In general, accuracy requirements will evolve as NASA gains operational experience through the early Artemis missions and to support more ambitious and coordinated utilization objectives.

As the architecture progresses through the Foundational Exploration segment, accuracy requirements may become more stringent. For example, aggregation of exploration systems in a region or logistics deliveries near hazardous terrain might require more precise landings. To realize more precise positioning, C&PNT data must enable greater accuracy and timeliness. The C&PNT sub-architecture must support these needs by supplying positioning and timing data to exploration assets. These services, delivered by lunar orbiting relays or augmented by wireless surface network from surface elements must consider current and future accuracy needs and requirements.

At the 2025 Architecture Concept Review, NASA presented findings on real-time absolute navigation accuracy for the Foundational Exploration segment. To satisfy the Artemis mission needs and support early utilization activities (e.g., science, technology demonstrations), the C&PNT sub-architecture needs to offer a real-time absolute accuracy of 25-50 meters. While NASA needs 25-50-meter accuracy early in the Foundational Exploration segment, NASA has procured systems to realize 10-meter or better accuracy, which offers margin for future missions. As the architecture evolves to support increasingly ambitious activities (e.g., making simultaneous measurements at multiple locations on the lunar surface, multiple systems performing cooperative activities in close proximity), navigation accuracy requirements may shift accordingly.

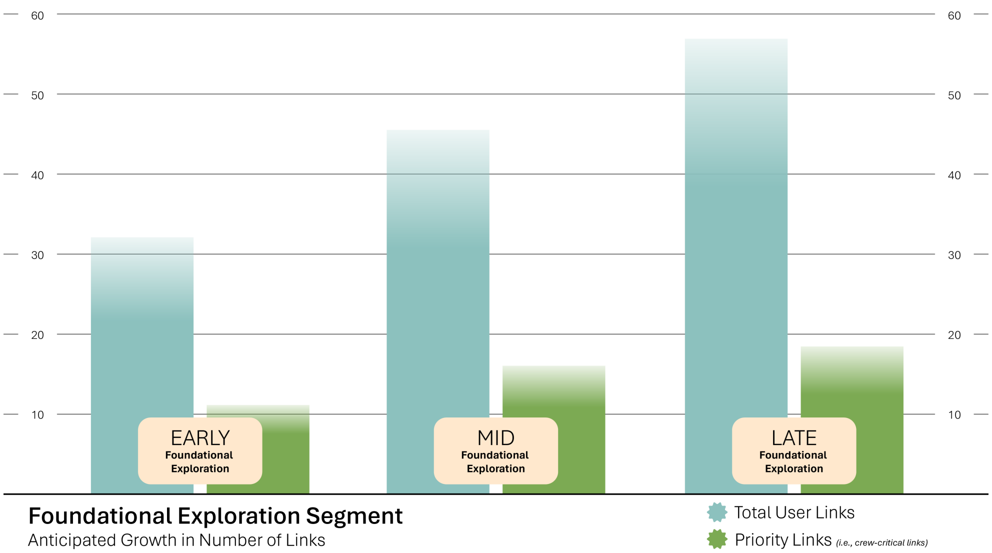


Figure One: *Graph illustrating notional number of links needed with Earth as the Foundational Exploration segment progresses through three phases. This graphic focuses on aggregate links from the surface, not total number of links routed through other assets on the surface (e.g., spacesuit links routed through landing systems). (NASA)*

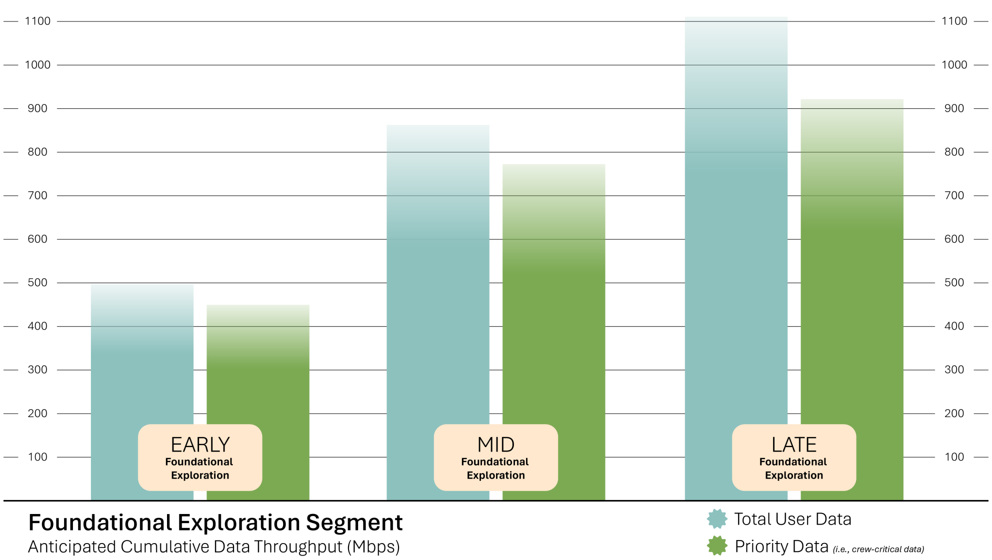


Figure Two: *Graph illustrating notional data throughput of lunar users as the architecture progresses through the Foundational Exploration segment. The confidence bars at the top indicate an expected range of throughput. (NASA)*

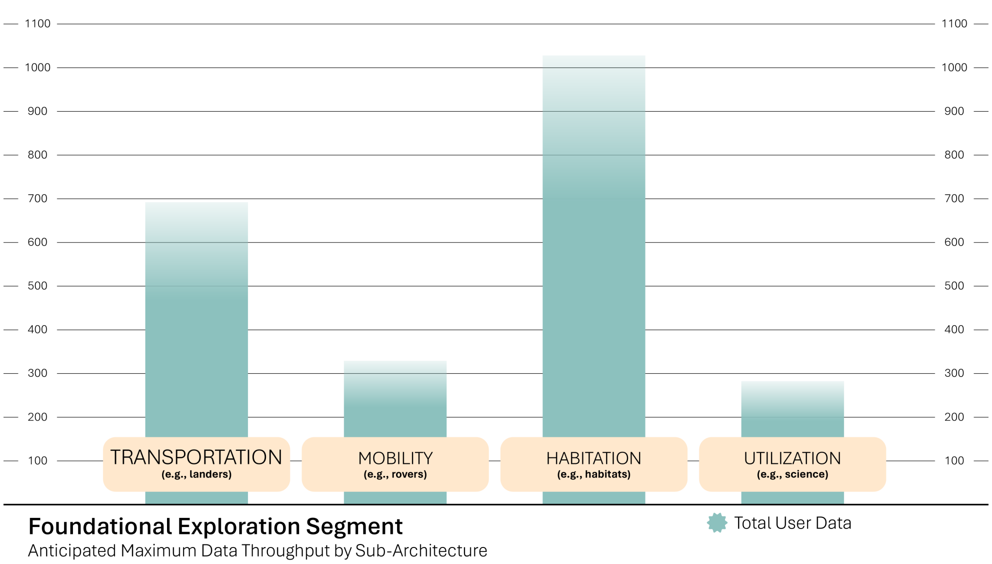


Figure Three: *Notional maximum data throughput of lunar users by sub-architecture during the Foundational Exploration segment. (NASA)*

Technology Development Considerations

As the architecture evolves, so will the technologies available to meet evolving mission needs. The C&PNT sub-architecture must consider integration of new capabilities to realize a flexible and efficient network robust to future needs.

To meet the challenges described in this paper, NASA will need new or advanced communications and navigation capabilities. Some of these are already captured in the architecture-driven technology gaps[11] in an appendix of the Architecture Definition Document[3] (e.g., Position, Navigation, and Timing (PNT) for In-Orbit and Surface Applications, High Rate Comm Across the Lunar Surface, and High-Rate Deep Space Comm), Others will arise as the architecture evolves.

Additionally, NASA will use lunar missions as opportunities to test technologies and operational paradigms that can enable the first human mission to Mars. A 2023 Moon to Mars Architecture white paper captures many of the C&PNT challenges NASA will face at Mars, many of which can be simulated or addressed at the Moon.[12]

NASA and its partners are already developing and demonstrating many C&PNT technologies that will enhance exploration capabilities. These include optical communications,[13] which can offer higher data rates using infrared lasers; delay/disruption tolerant networking,[14] which can offer internet-like protocols for space applications; autonomous network management, which can use artificial intelligence and machine learning to realize self-operating systems; deploying real time in situ radionavigation and timing services to the Moon; and more.

Conclusion

As NASA's Moon to Mars Architecture progresses from the Human Lunar Return segment through the Foundational Exploration segment, the C&PNT sub-architecture will evolve to support more ambitious exploration missions. This evolution requires thoughtful consideration of current and future needs.

Defining interoperability standards is essential to realizing a network of networks — one that can harmonize system operations between NASA, industry, and international partners. Analyzing the change over time in user demands will support development of a scalable network to support a growing number of exploration systems and users. Understanding technology gaps is critical for successful implementation of a network extensible to the future and prepare the agency for human missions to Mars.

NASA is actively conducting the analyses, developing technologies, and engaging in partnered actives needed to evolve a robust C&PNT sub-architecture that meets the needs described in this paper.

Key Takeaways

As NASA's Moon to Mars Architecture progresses into the Foundational Exploration segment, the Communications and Positioning, Navigation, and Timing sub-architecture must evolve and scale to support a growing number of users and increasingly ambitious crewed missions.

Interoperability is key to realizing a multi-partner network robust to the needs of all lunar users. NASA must work with commercial and international partners to establish and implement standards for service interfaces, spectrum allocations, networking protocols, and more.

The increase in user demand requires the Communications and Positioning, Navigation, and Timing sub-architecture to evolve to offer extended availability, greater throughput, improved accuracy, and enhanced services. User demand considerations include connectivity, coverage, capacity, and accuracy.

As the Foundational Exploration segment progresses, integrating new services and technologies like laser communications, delay-tolerant networking, and lunar-equivalent GPS could meet additional user needs, demonstrate new technologies, and prove Mars-forward capabilities.

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