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NASA's Lunar Communications Relay and Navigation Systems (LCRNS)

Jaime Esper[a]*, Gregory Heckler[b], Jonathan Verville[c], Grant Ryden[d]

[a] *NASA Goddard Space Flight Center*, *Jaime.Esper@nasa.gov*
[b] *NASA Headquarters*, gregory.w.heckler@nasa.gov
[c] *NASA Goddard Space Flight Center*, jonathan.p.verville@nasa.gov
[d] *NASA Goddard Space Flight Center*, grant.a.ryden@nasa.gov
* Corresponding Author

Abstract

In early 2020, NASA's Space Communication and Navigation (SCaN) program recognized the need for lunar orbiting relays to enable Artemis mission flexibility to land at the lunar South Pole or the lunar far side, in areas with limited or no direct Earth communication, and to reduce strain on NASA's ground systems especially the Deep Space Network (DSN). The lunar relays would not only improve the landing site availability but would also contribute to astronaut safety by providing communications and navigation services independent of Earth's line of sight. At the end of 2020, the NASA Goddard Space Flight Center (GSFC) created a concept design to evolve lunar relay capabilities and lay the foundation for the Lunar Communications Relay and Navigation Systems (LCRNS) project. Since its inception in April 2021, LCRNS has worked with SCaN's stakeholders, including the Moon-to-Mars and the Artemis program, to identify and represent NASA's requirements for communications and navigation in lunar orbit. The project's charter is to enable an interoperable commercial lunar communications and navigation orbiting service infrastructure that meets NASA's needs, represents a sustainable approach to long-term human and robotic exploration, and embodies an extensible solution for Moon –to –Mars missions. This paper will: (1) describe NASA's vision for LCRNS; (2) introduce the early concept for a lunar communications relay and navigation satellite, and the corresponding evolution of performance and interoperability requirements; (3) describe the important differences in communications approaches between LCRNS and NASA's existing Tracking and Data Relay Satellite System (TDRS); (4) explain how LCRNS plans to validate commercial services capabilities; and (5) introduce LCRNS Position, Navigation, and Timing Instrument (LPI).
Keywords: NASA, LCRNS, LunaNet, Communications, Navigation, Artemis

1. Introduction

The Space Communications and Navigation (SCaN) program at NASA is responsible for providing communications and networking services to missions by integrating government-owned infrastructure with the capabilities of commercial and academic partners. At the same time, SCaN is tasked with designing the future of network services. One of the most pressing areas of focus is cislunar space, where there is currently no existing communications, position, navigation, or timing infrastructure. However, the need for such infrastructure is clear. Reliable, continuous communications between Earth and lunar missions—especially from locations like the lunar South Pole or far side that are not directly visible from Earth—will be crucial for missions like Artemis operating on and around the Moon. Connectivity is essential not only for mission control but also for transmitting scientific data and ensuring crew safety.

In response to this critical gap, SCaN formed the Lunar Communications Relay and Navigation Systems (LCRNS) project. LCRNS is designed to exemplify key SCaN principles and align with broader shifts in both space policy and NASA's strategic direction. The first of these principles is to foster commercial space partnerships. National Space Policy emphasizes the government's responsibility to utilize commercial capabilities wherever possible to meet its needs. SCaN has embraced this directive, as demonstrated by its decision to end its reliance on the government's Tracking and Data Relay Satellite System (TDRSS) and investing in commercial space relay infrastructure as a long-term solution. Additionally, SCaN's industry partnerships, which began in the 1990s to support direct-to-Earth (DTE) communications, have continued to grow. As expanded services and providers are integrated into SCaN's service offerings, legacy DTE government assets will be phased out in favor of a flexible private framework. Lunar-capable ground assets and services are also being pursued, complementing government-owned, contractor-operated sites with purely commercial services. In alignment with this long-term vision, the LCRNS project was designed from the outset with the goal of partnering with commercial providers.

SCaN's second key principle is to advance interoperable communications, ensuring that robust services are provided to users while maximizing investments. Interoperability and cross-support among international civil space agencies—primarily achieved through civil space standards bodies—have long been foundational to space operations. In recent years, NASA and SCaN have worked to extend this framework into the commercial sector. This shift is highlighted in the maturation of the LunaNet Interoperability Specification (LNIS) [1], informed by feedback from industry stakeholders, and the integration of commercial standards like 3GPP into the lunar surface communications architecture. Furthermore, this approach to networking and interoperability in the cislunar domain will lay the groundwork for similar capabilities to be developed for Mars and other deep space missions in the future.

In short, the vision for LCRNS is to enable sustainable and advanced lunar exploration. Its significance lies in its ability to provide reliable communications and precise navigation, foster commercial collaboration, and promote interoperability, all of which are essential for the success of lunar and deep-space missions.

2. Enabling Sustainable and Advanced Lunar Exploration

In the vision for LCRNS to enable a sustainable and advanced lunar exploration, the projects' activity spans the duration of an incremental Initial Operating Capability (IOC) buildup in three stages named *Alpha*, *Bravo*, and *Charlie*. The IOC development includes verification and validation of NASA requirements, alongside collaborative technical exchanges with stakeholders. Once the incremental IOC buildup is complete and validated by the LCRNS project at the end of Stage Charlie, full operational commercial service is made accessible for NASA mission operations support through NASA's Near Space Network (NSN). As part of the Artemis program, LCRNS is expected to primarily support human spaceflight, though science missions will be able to access the service both within Artemis flights and dedicated lunar exploration missions. NASA is expected to be only one of many users of LCRNS services, and commercial providers may refer to those commercial services with their own nomenclature. Intuitive Machines (IM) of Houston, Texas, was competitively selected in 2024 through a NSN Services (NSNS) call for proposals to be the first commercial LCRNS service provider. IM's network of satellites and ground stations forms the Lunar Data Network (LDN), a commercial service the company will manage independently of NASA.

Global systems interoperability is an important tenet of NASA's LCRNS services. The European Space Agency (ESA) analog is called Moonlight. Japan's Aerospace Exploration Agency (JAXA) also plans to contribute the Lunar Navigation Satellite System (LNSS). LCRNS, Moonlight, and LNSS providers are expected to be interoperable, meaning their services to Artemis or other lunar systems are compatible in both communications and navigation support. The lunar network (a.k.a., LunaNet) is envisioned as a network of cooperating networks (e.g., a network of networks akin to the terrestrial Internet) upon which providers can deliver communications, position, navigation, and timing (PNT), and other services for users on and around the Moon. LunaNet is based on a framework of mutually agreed-upon standards, protocols, and interface specifications that enable interoperability. In other words, LunaNet is based on LNIS. Insofar as the three agencies have agreed to operate within LNIS standards, they are referred to as LunaNet Service Providers (LNSP). Note that commercial providers are free to offer other services not within LNIS bounds.

Key points about LCRNS' significance can be summarized in six bullets:

- *Reliable Communications*: LCRNS enables the deployment of a commercial network of communications relay satellites in lunar orbit, providing continuous and reliable communications between Earth and lunar missions, even in locations where the Moon is not directly visible from Earth.
- *Precise Navigation*: LCRNS provides position, navigation, and timing (PNT) services, which are essential for crewed missions, robotic missions, rovers, and infrastructure development on and around the Moon [2].
- *Support for Artemis Missions*: LCRNS is part of the Artemis program, which aims to return humans to the Moon and establish a sustained lunar presence. The relay services will support near-term objectives and future Artemis endeavours [3].
- *Commercial Collaboration*: NASA's approach to commercial services development fosters competition, economic growth, and access to new technology and innovation [4].
- *Incremental Deployment*: The relay services will be deployed and verified incrementally, starting with Artemis III, and will demonstrate full-range communications and navigation capabilities with subsequent Artemis missions. Nonetheless, the service may be fully operational at any point in the Artemis timeline, depending on schedule.

- *LunaNet Interoperability*: The LCRNS project follows LNIS, which aims to bring internet-like capabilities to the Moon, allowing all assets to exchange communications, navigation, and science information seamlessly.

Overall, the LCRNS project is crucial for enabling sustainable lunar exploration and paving the way for future missions to Mars.

3. Design Reference Mission Zero: Feasibility Study

At the end of 2020, GSFC undertook an effort to define basic requirements to constrain the design of a small satellite capable of providing high-speed communications and navigation support to Artemis and science missions. The concept was modest in scope but laid the foundation of two more iterations of the design, and the definition of more detailed requirements that would subsequently make it into NASA’s NSN Request for Proposals (RFP), specific to LCRNS lunar relays. The so-called geo-to-cislunar relay service included specifically Category 2.2, lunar relays. The Design Reference Mission Zero (DRM-0) is a concept feasibility study that involved a set of basic constraints geared to minimizing the overall cost of production. Additional iterations brought the concept to Phase A maturity level, through DRM-1 and DRM-2.

3.1 Design Reference Zero Lunar Relay Requirements

The objectives of the DRM-0 design were primarily geared toward meeting the high-rate communications needs of Artemis vehicles, while minimizing the cost of implementation. High data rates were required at the lunar proximity (via proximity links) and extended all the way to Earth (via trunk links). Different link types connect individual network nodes: proximity links, or forward and return links, connect users to the network and transfer data between them, while network-to-network trunk links establish connections between two network infrastructure nodes. These links may be between two spacecraft, a spacecraft and Earth, a spacecraft and the lunar surface, or between two lunar surface elements.

Figures 1 through 3 illustrate key communications link parameters. Figure 1 shows the acceptable frequency bands for each link type. Figure 2 shows a block diagram of the basic rate and frequency requirements in lunar proximity. Figure 3 shows the corresponding requirements for the direct-to-Earth (DTE) trunk links. Note that radiometric rate/range needs were considered optional at the time, given the initial focus on link-frame communications and reduced cost. DRM-0 relays are noted as D0R.

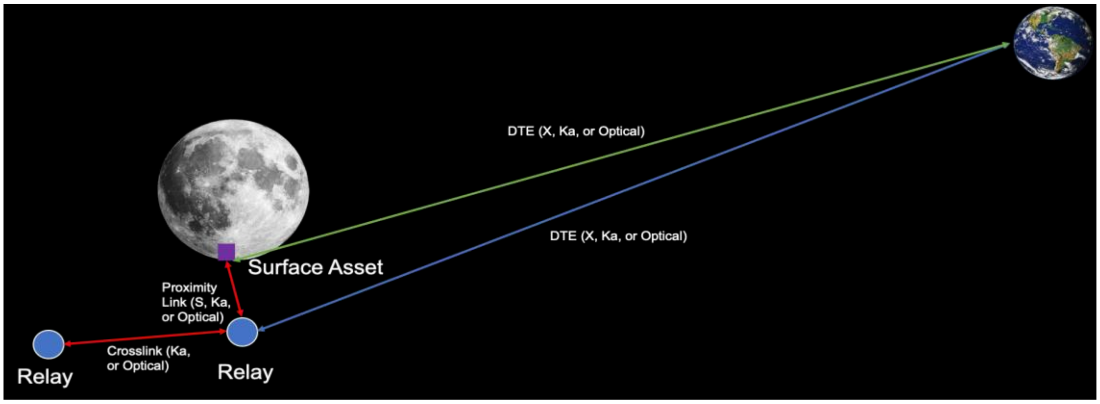


Fig. 1. Acceptable frequencies for proximity and trunk link types

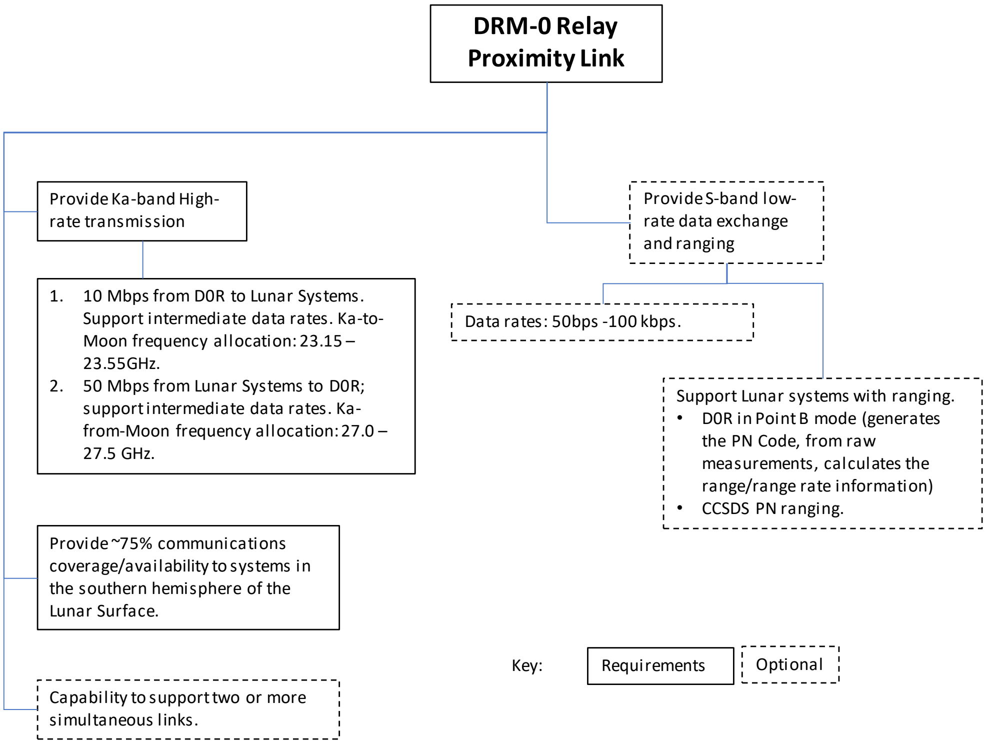


Fig. 2. DRM-0 requirements in lunar proximity

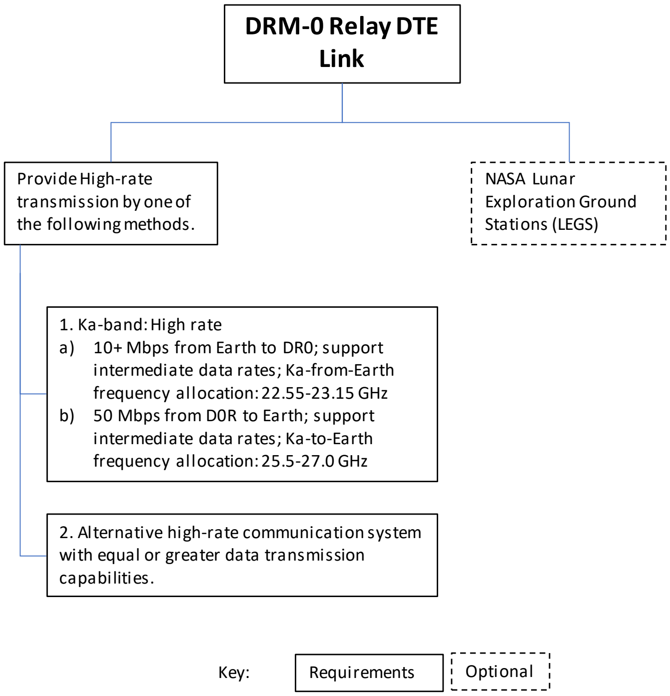
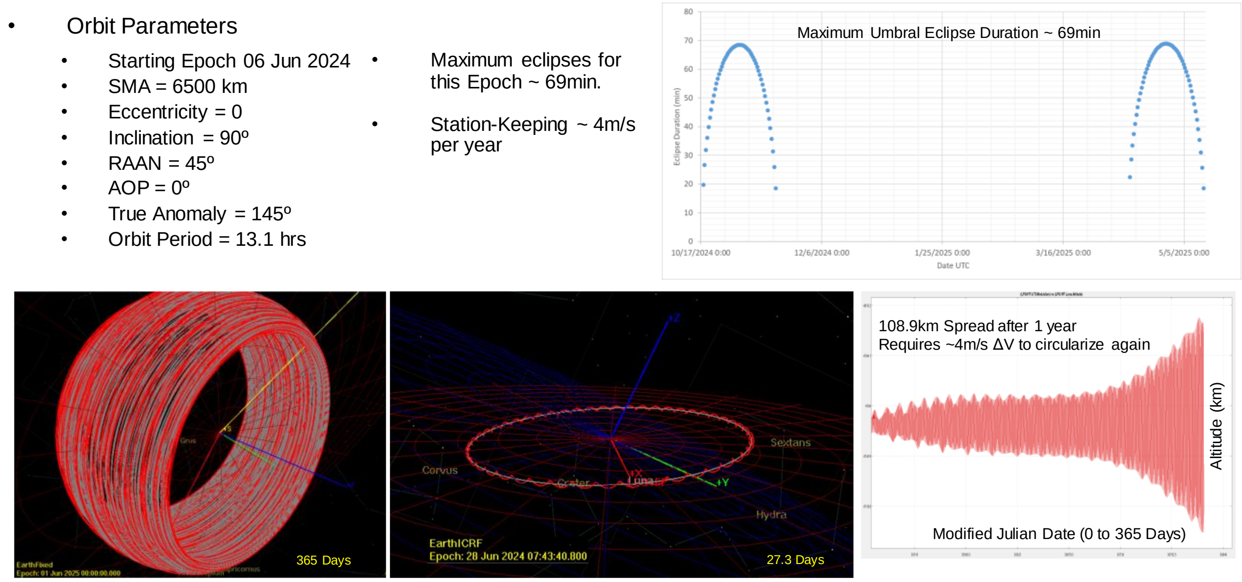


Fig. 3. DRM-0 requirements for Earth trunk links

Additional requirements included maximizing simultaneous communications coverage between Earth and the lunar surface to provide “real-time” relay, with 80% simultaneous coverage time to a lunar South Pole landing site. DRM-0 baselined 6,500 km radial polar orbits. In this configuration, a single spacecraft has a 41% coverage time of the lunar South Pole (324 min over a 784 min orbit period). Three spacecraft in a single orbital plane at 120° achieve 100% coverage time, thus meeting the coverage requirement.

These orbits are also very stable. Figure 4 shows a single orbit evolution over an Earth year. After a year, the orbit develops a 109 km altitude spread, requiring about 4 m/s ΔV to re-circularize.



- Orbit Parameters
  - Starting Epoch 06 Jun 2024
  - SMA = 6500 km
  - Eccentricity = 0
  - Inclination = 90º
  - RAAN = 45º
  - AOP = 0º
  - True Anomaly = 145º
  - Orbit Period = 13.1 hrs
- Maximum eclipses for this Epoch ~ 69min.
- Station-Keeping ~ 4m/s per year

Fig. 4. DRM-0 365-day orbit simulation for Epoch 2024

While there was no initial consideration of geometric dilution of precision (GDOP) to service a particular position and velocity accuracy on the surface of the Moon, navigation support was planned and included in the DRM-0 relay payload capability. Broadly speaking, navigation includes position and timing services enabling missions to determine position and velocity and maintaining time. The DRM-0 architecture for satellites operating in the lunar regime considered the following elements when defining the capabilities of the position, navigation, and timing (PNT) payload:

- A common stable time and frequency reference source with synchronized distribution across all elements.
- Radiometric measurements from each observable communications link.
- Observability of GNSS signals (or the creation of a native cislunar navigation satellite system).
- Angular measurements to define plane-of-sky.
- Imaging of nearby celestial body surface features.

Additional requirements/assumptions included: (1) providing sufficient onboard data storage to support store-and-forward communications, such as delay/disruption tolerant networking (DTN); (2) designing single-fault-tolerant spacecraft; (3) satisfying all operations requirements necessary to integrate with NASA lunar assets and, if applicable, NASA ground stations, such as modulation, coding, security, end-to-end network protocols, and DTN. This marked the point at which interoperability became an operational requirement to ensure all NASA assets and, by extension, commercial service vehicles could "speak the same language." (4) targeting an Evolved Secondary Payload Adapter (ESPA) class spacecraft; (5) choosing high-technology readiness level components; (6) providing a mission life of 8+ years, with fuel sized for ten years of operation starting from a near-rectilinear halo orbit (NRHO), power systems designed for a ten-year duration, and radiation-hardened/tolerant components to ensure longevity, incorporating single-string redundancy where possible. Additional assumptions included (7) carrying spacecraft to Gateway's NRHO orbit by other lunar-delivery vehicles to minimize onboard fuel; and (8) always defining the final operational orbit as 6,500km radial, circular, polar, with no plane change from delivery orbit.

3.2 DRM-0 Spacecraft Layout and Launch Vehicle

The resulting spacecraft design is illustrated in Figure 5, together with its accommodation in a Falcon 9 launch vehicle. As the design was geared toward ascertaining initial concept feasibility, the spacecraft's performance was necessarily modest, particularly in relation to coverage and PNT service support. The vehicle fit within a standard ESPA payload port capacity, provided consumables, including fuel, to last eight years or more in orbit (assuming a direct drop into its final orbit), and carried a dual-gimbal solar panel with a beginning-of-life capacity of 1.1kW.

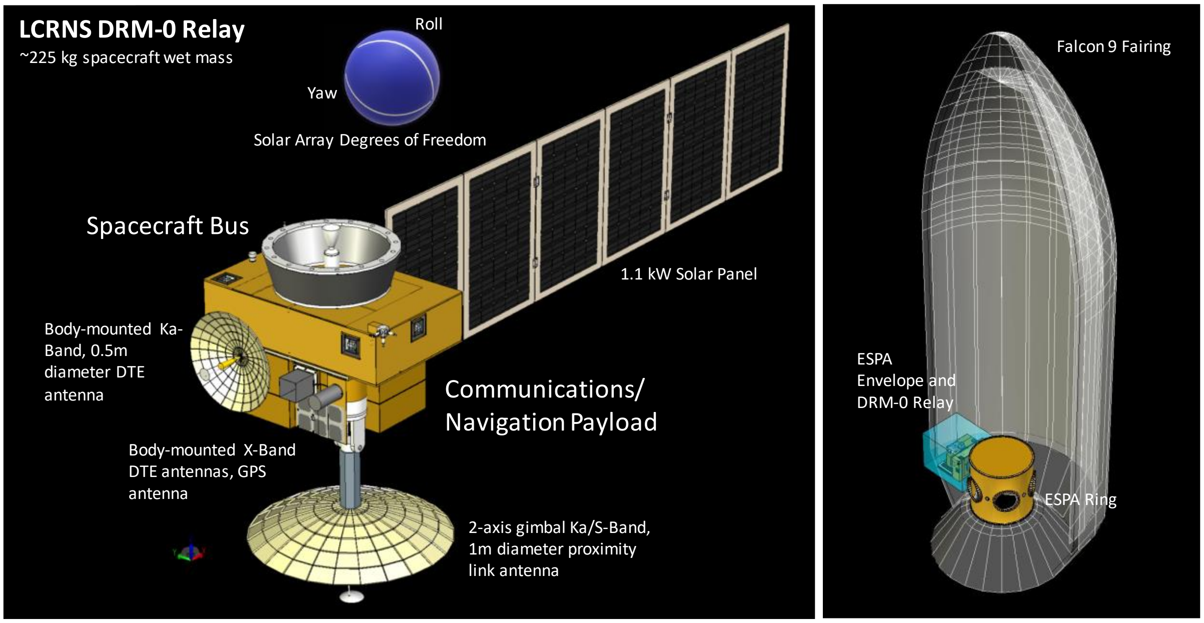


Fig. 5. DRM-0 Relay Spacecraft Layout and Launch Vehicle Accommodation

Although body mounted DTE antennas reduced spacecraft complexity, they complicated operational availability for a single vehicle. Figure 6 illustrates the spacecraft's attitude evolution over a lunar period. The spacecraft is normally Earth-pointed, with its nadir facing the Moon, while the S/Ka-band antenna gimbal covers additional locations within cislunar space. The body-mounted DTE X-Band, Ka-Band, and GPS antenna face Earth, while the solar panels must be rotated 180º twice per orbit, with yaw adjustments used to track the Sun. Even though orbital dynamics allowed 41% coverage of the lunar South Pole, these constraints reduced the actual service availability per vehicle.

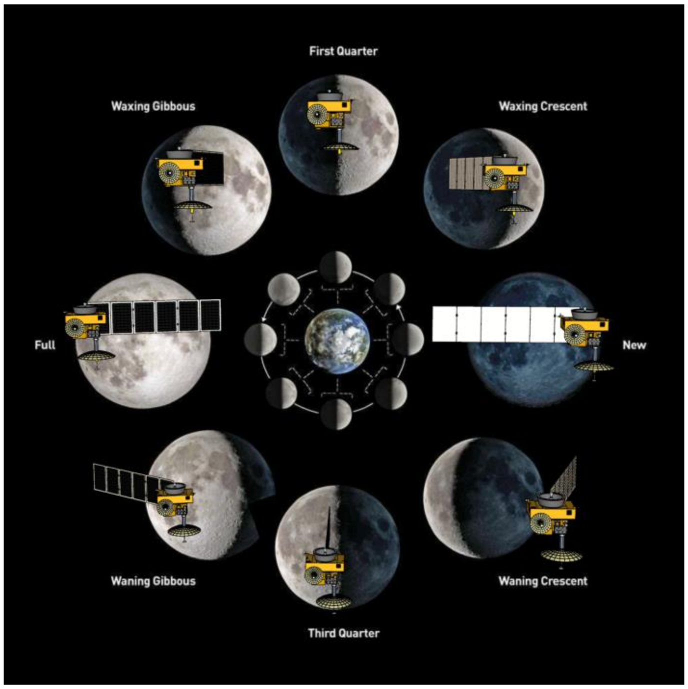


Fig. 6. DRM-0 Relay Spacecraft Attitude Over a Lunar Period

3.3 Design Evolution and LCRNS NSNS Requirements

The results of DRM-0 ultimately aligned with NASA’s SCaN program objectives to commercialize the near-Earth communications and navigation services for the agency. However, its maturity was not at a level that could levy feasible requirements for all agency needs. The LCRNS project undertook the extensive process of identifying requirements for NASA’s Moon-to-Mars, and particularly the Artemis program. Science Mission Directorate (SMD) requirements were found to be enveloped by Artemis needs at the time. The process took the project through two additional DRM exercises, leading to a preliminary design (NASA *Phase A*) maturity. The resulting document, LCRNS’ *Lunar Relay Services Requirements Document* (SRD), was released as a draft in early 2022. After public comment and DRM 2 fine-tuning, the final document (Revision B w/DCN 001) was released on December 2, 2022 [5]. Concurrently, LCRNS worked on interoperability specifications with ESA. After initial release for public comments in the middle of 2022, LCRNS published *LunaNet Interoperability Specification (LNIS V4)* on December 14, 2022. Both publications were added to the applicable document requirements for the NSNS RFP in April 2023 [6].

3.4 Lunar Relays Increase Operational Options and Improve Safety

With the full set of LCRNS requirements released, NASA is expecting to solve several critical operational impediments to achieve a sustained lunar presence and contribute to lunar commercialization. By providing communications and navigation capabilities, LCRNS’ commercial services will expand landing site availability and support astronaut safety throughout lunar transit and surface operations. Figure 7 shows the yearly average lunar communications coverage for lunar South Pole landing sites. Lower-bound (worst case) coverage assumes the human landing system arrives at Spudis Ridge Peak, and upper-bound coverage (best case) assumes landing at Mount Malapert Peak. The coverage data is based on a ten-year line-of-sight simulation using the Earth’s center. The simulation also assumes a constellation orbit choice that differs from DRM-0—the result of multiple iterations and refinements through DRM-2 and beyond to optimize coverage on the lunar South Pole. As Figure 7 shows, DTE communications dramatically limits landing site availability, with 43% best case and 17% worse case coverage availability. A single lunar relay improves the situation dramatically, with 80-86% coverage for worse-best case landing sites respectively, while adding two additional relays solves the communications restrictions and opens a range of options for exploration. The incremental build of capabilities from Stages Alpha, Bravo, and Charlie lead to an IOC that will provide 100% communications coverage and establish a GPS-like capability at the Moon, enabling unimpeded human and robotic traversal across the lunar surface.

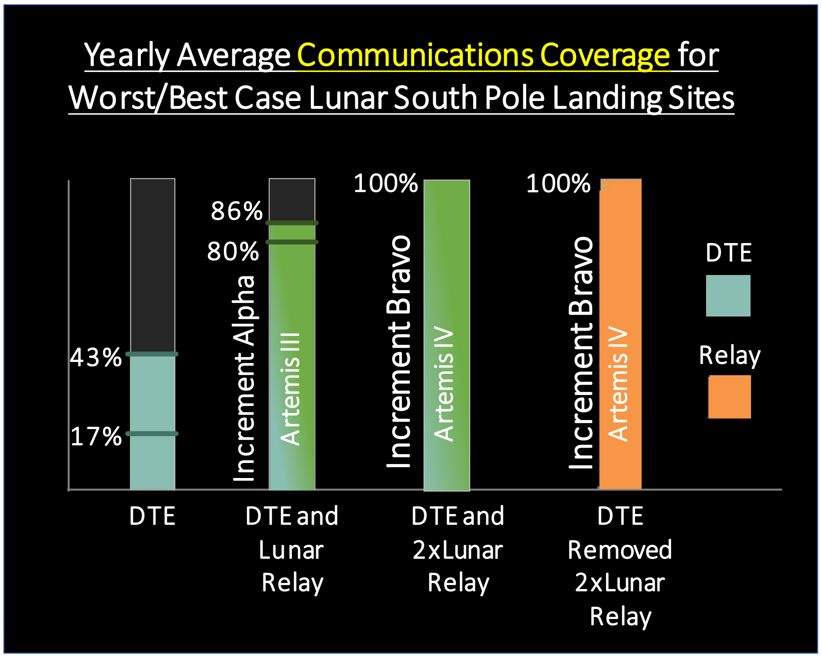


Fig. 7. Lunar Relays Enable Sustainable Lunar Exploration

4. LCRNS and NASA’s Existing Tracking and Data Relay Satellite System (TDRSS)

For several decades, NASA has supported numerous high-profile science missions (e.g. Hubble, EOS, etc.), human spaceflight, space launches, and more through its TDRSS constellation. However, the TDRSS design and system architecture predate the availability of sophisticated onboard processing systems and emerged at a time when networking technology was emerging terrestrially. For user services, TDRSS includes only analog processing onboard (e.g. up/down conversion, amplification, filtering), and most of the processing is within the ground segment (beamforming, modulation, coding, frame synchronization and processing, etc.). While TDRSS users can provide networking services within their own systems “over the top” of its relay satellite services, there is natively no routed data networking through TDRSS itself, only “bent pipe” services using analog radio frequency (RF), bitstreams, and frames. At deployment, TDRSS offered revolutionary relay capabilities; however, multiple major industry trends have advanced the state-of-the-art today.

In recent years, the advent of low Earth orbit (LEO) mega-constellations with hundreds or even thousands of satellites have driven industrial capabilities forward in many areas including:

- Affordable onboard physical and link layer processing, including software-defined radio systems.
- Onboard network layer routing/switching protocols and capabilities.
- Dynamic control of routing paths and end-to-end traffic management through feeder and user links.
- Intersatellite links (e.g. optical), including multi-vendor standards (SDA).
- Multi-user capabilities (including antennas, RF, and digital processing systems).

These advancements greatly improve the design space available for LCRNS vendors and the service capabilities that LCRNS can offer users.

Additionally, NASA and its partners have developed open standards for store-and-forward services like DTN, which enable relays to hold data during periods where there is no concurrent end-to-end path between a data source and destination. These new capabilities will support Artemis objectives, including communications, networking, and navigation for multiple simultaneous vehicles, habitats, suits, and other systems on the Moon’s surface and in lunar orbit. Standards-based approaches are critical, as the scale of U.S. and international activities call for multiple providers with redundant, compatible services.

Due to the distance between Earth and the Moon, the transmission latency acts as a driver to push onboard processing and storage capabilities into the relay systems for LCRNS. Historically, ground-based processing had been a strength of TDRSS, and space relay services could be upgraded and improved through ground segment modernization and replacement projects. In contrast, LCRNS services can be modified and extended through software updates to the relays themselves, leveraging software-defined radio and upper-layer processing.

Given the factors influencing the LCRNS requirements and design space, some key feature differences between classical TDRSS bent-pipe relay services and LCRNS are summarized in the table 1.

Table 1. Differences between TDRSS and LCRNS

Key Feature	**TDRSS**	**LCRNS**
Service Area	Primarily LEO and terrestrial	Lunar surface and orbits
Satellite bus	Large GEO platforms	Designed for launch and lunar transfer vehicles, and lunar orbit station-keeping, etc.
User data processing	Ground based modulation & coding	Onboard modulation & coding Onboard networking
Onboard switching	RF/analog domain between antennas	Digital bundle/packet routing based on user data
Routing	Purely schedule-driven	Data-driven
Trunk/Feeder Link multiplexing	Frequency division separation of user service signals	Network-based
Intersatellite links (within the constellation)	None	Present

Key Feature	**TDRSS**	**LCRNS**
Navigation	Tracking services based on user RF; data provided only on ground	Broadcast GPS-like signals, along with messaging; provided on-orbit to user spacecraft
Data services	Real-time only; physical layer	Real-time & store-and-forward; link-layer or networked (IP or DTN)
Standardization	Mixture of NASA-specific and CCSDS-standards	LunaNet Interoperability Specification (LNIS) including Consultative Committee for Space Data Systems (CCSDS) and Internet Engineering Task Force (IETF) networking standards

Altogether, the LCRNS service builds on NASA's historic experience with TDRSS, but massively departs in terms of the onboard capabilities and support for network data processing and storage onboard.

5. LCRNS Interoperability and Performance Validation Capability

LCRNS is working with industry to verify its communications and navigation services according to NASA and Artemis program requirements. For the incremental verification of service capabilities, LCRNS is developing an Interoperability and Performance Validation Capability (IPVC) that includes:

- *Interoperability and Performance Testbed (IPT)*: A hardware-in-the-loop testbed emulating a universal lunar-user terminal, allowing for verification by test of LCRNS lunar relay service performance and interoperability requirements [7].
- *LCRNS Government Analysis Tools (LGAT)*: A suite of software tools used for verification by analysis of LCRNS lunar relay service performance and interoperability requirements.

At its core, the IPT is a "universal user terminal" capable of verifying communications and navigation signals abiding by the LCRNS SRD and applicable sections of LNIS. Functionalities carried out by ancillary elements and accompanying software modules execute scripts and record results for real-time monitoring and/or later analyses. The IPT tests all LNSP segments, including space (data relay and navigation satellites in orbit around the Moon), and ground (ground stations and processing centers on Earth). However, LNSP intra-links are not tested, as the LNSP is fully responsible for their internal working elements. The tests are therefore executed at the interface of either segment. Figure 8 shows the basic elements of the IPT.

LGAT includes a suite of analysis tools meant to be executed in sequence, beginning with a radio frequency (RF) static analysis generating link budgets. Orbits introduce dynamic analyses, which are input into a set of PNT, data services, and DTN tools. Dynamic analyses account for constellation initialization and maintenance, check for Signal-in-Space Errors (SISE), examine coverage and scheduling parameters, analyze latency, and track DTN performance. Figure 9 shows the LGAT tools and execution process.

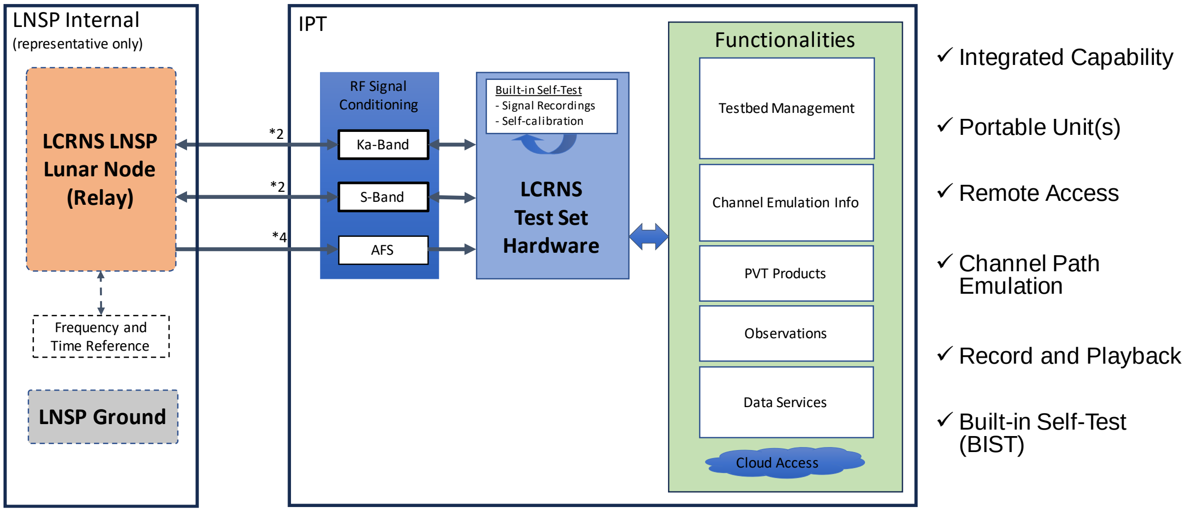


Fig. 8: IPT Block Diagram

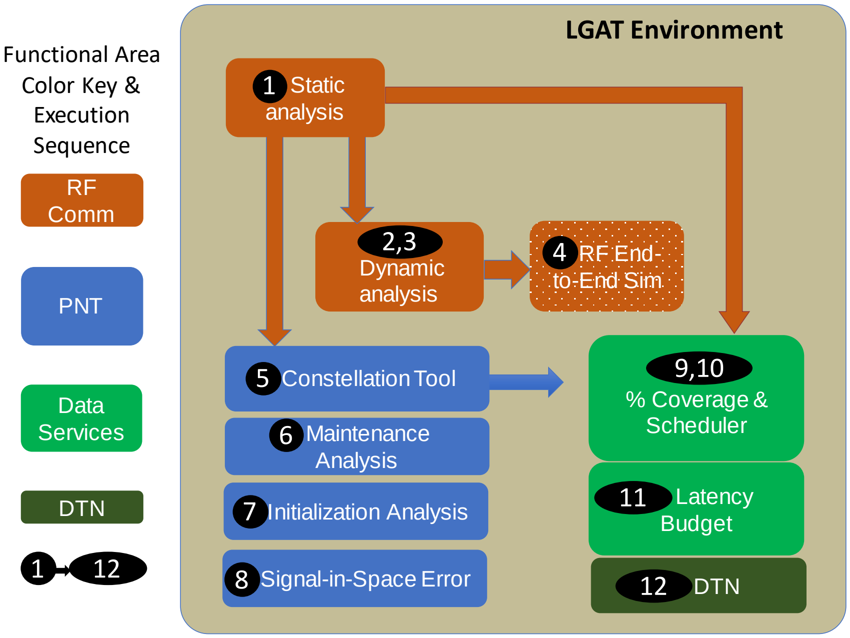


Fig. 9. LCRNS Government Analysis Tools (LGAT)

6. LCRNS Position, Navigation, and Timing Instrument (LPI) Summary

NASA’s Tracking and Data Relay Satellite System (TDRSS) anchors its PNT capabilities to an Earth-based infrastructure. The time references for the system are Caesium ground station clocks that are synchronized to UTC to high precision. TDRSS satellites act as “bent pipe” relays, rebroadcasting signals coherent with incoming signals only with a ratio offset. This eliminates the need for precision clocks onboard. The positional reference for the system is the phase center, or reference point, of the ground station antennas, which have surveyed locations in the Earth body frame to within centimeters. The TDRSS satellite’s positional information is only needed to resolve tone ranging ambiguities.

The *position* observables generated by the TDRSS’ tracking system function consist of a four-hop range measurement—Ground Station-to-TDRSS-to-User-to-TDRSS-to-Ground Station. A range *rate* (Doppler) observable can also be generated by TDRSS using a similar method. Given the known positions of the ground stations and TDRSS satellites, and the range and range-rate observables along with their time stamps, a user in orbit around the

Earth or within the operational range of TDRSS can perform its own orbit determination. A key element not resolved by TDRSS observables is the user's time.

Global Navigation Satellite System (GNSS), on the other hand, uses a one-way forward broadcast method. Satellites transmit timing signals, information regarding their orbits, and clock corrections. All satellites in a particular GNSS constellation operate on a common "system time." For instance, GPS time (GPST) equates to the system time for the GPS constellation and serves as a reference for all GPS satellites and user receivers. A user's GPS receiver tracks signals from four or more satellites simultaneously, while the receiver samples the tracking states at a specific moment. From these samples, the receiver extracts "pseudo-range" observables, which are approximate distances between the receiver and each satellite based on the time the signal took to travel from the satellite to the receiver. Using the pseudo-range measurements from multiple satellites, the receiver then solves for two key pieces of information: (1) the precise system time corresponding to the moment of measurement, and (2) the user's position in three-dimensional space. At least four satellites are needed to solve for the four unknowns: three position coordinates (x, y, z) and time. This process allows GNSS receivers to determine position and time with high accuracy through passive reception of satellite signals, without the need to transmit any information back to the satellites. The missing element in this description is, "how did the GNSS satellites know their positions and time as a function of a system time?" This information comes from observables generated by numerous surveyed monitoring stations, which are brought together and processed by a massive Kalman filter like the GPS Master Control Segment.

The cost of installing a monitoring station on Earth is negligible compared to the expense of placing one on the lunar surface. In the near term, PNT infrastructure around the Moon would need to piggyback on existing Earth-based PNT infrastructure (e.g. GPS constellation). The *LCRNS PNT Instrument* (LPI) was developed to do just that. It consists of a GPS receiver, a stable clock, and an onboard filter that estimates its position, velocity, and clock relationship to GPST. LPI will predict future positions, which then become the anchor for PNT observables generated by the LCRNS vehicle. These predicted states will be transformed into the Moon-PA (Principal Axis) body frame, fit into a broadcast message, and used for a one-way broadcast service called Augmented Forward Service (AFS). Akin to the GPS Earth-analog, when there are four or more AFS broadcasts sharing a common system time, a user AFS receiver can calculate its position and velocity at a given time. The Lunar Augmented Navigation Service (LANS), the lunar analog of GPS, requires at least four satellites in view of a user AFS receiver. LCRNS will also provide a Peer to Peer (P2P) navigation service, where the range and range-rate is measured from a two-leg signal LCRNS-to-User-to-LCRNS. These observables will provide the relay state, along with range and range-rate observables to the user receiver, so that it can in turn perform orbit determination (position, velocity, at a given time).

Looking to the future, when there are surveyed stations on the Moon, a satellite navigation system may be able to tie their constellation directly to the Moon without the crutch of terrestrial navigation systems. This will prepare a path for deploying similar systems around Mars. In the meantime, LPI offers a solution to deploying navigation services at the Moon.

7. Conclusion

It is pioneering forethought in areas not yet fully developed today, what creates the opportunities of tomorrow. NASA's efforts in experimental geostationary communications satellites directly led to the first launch of a commercial communications satellite, Intelsat 1 ("Early Bird") in 1965. The event had far-reaching consequences, leading to the global interconnected world of today. Through LCRNS, NASA is now seeding a new type of enterprise in the lunar domain, with commercial communications and navigation. Its significance lies in its ability to provide reliable communications and precise navigation, foster commercial collaboration, and promote interoperability, all of which are essential for the success of lunar and deep space missions. What will be the impact of this activity this time, can only be fully understood in retrospect.

8. Acknowledgements

The authors wish to thank the dedicated NASA team who have contributed to LCRNS' work throughout the Agency. Their persistence despite challenges continues to enable a world where humans will travel and work at the Moon and Mars, reaping untold benefits back on Earth.

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