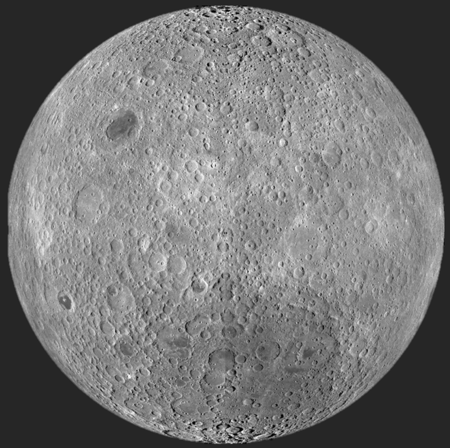
Lunar Communication and Navigation Architecture
NASA Viewpoint

Space Communications and Navigation (SCaN)
Space Operations Mission Directorate
NASA Headquarters
February 24, 2022

Evolution Toward a Desired Future State for the Lunar Communication and Navigation Architecture

Some Key Points:

- The consideration of needs, as described here, primarily focuses on driving requirements for anticipated NASA missions, but the future state of the architecture should take the expected growth in lunar activity by all nations and commercial entities into account, especially those who might participate in a cooperative lunar network.
- A cooperative lunar network for communications and navigation ("Lunanet") is envisioned to support the needs of multiple international partner governments and associated commercial partners and vendors. The cooperative lunar network would be enabled by a common set of interoperability standards and a coordinated operations concept for multiple service providers and mission users.
- This outline is intended to support discussions toward a common understanding of the evolving lunar network and to facilitate potential agreements on partner roles and responsibilities.
- There needs to be a balance between anticipating needs and providing services and capabilities with adequate lead time, redundancy, and margin for growth, while not creating an oversupply of services or establishing capabilities earlier than they can be used. Likewise, coordination is needed to avoid an oversupply of service providers or unproductive competition among providers.
- Careful consideration is needed to balance the benefits of the economy of scale for a small number of service providers versus the benefits of a diverse range of providers with those benefits being a more open, evolvable architecture, dissimilar redundancy, and competitive pricing.

CONTINUED

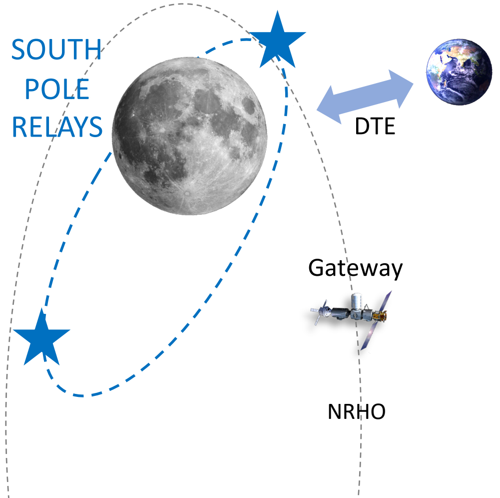
Evolution Toward a Desired Future State for the Lunar Communication and Navigation Architecture

Some Key Points: CONTINUED

- The architecture implementation described here is not intended to be prescriptive but to indicate a means to achieve the required services. Other implementations that would meet the same intent should be considered.
- NASA's preference is to acquire the communications and navigation capabilities needed through commercial contracts and international agreements rather than through direct NASA development and operation of assets.
- For individual satellites, there needs to be a balance between long operational lifetime and the benefits of more frequent replenishment, including the ability to incorporate new technology and capabilities.
- End of life planning for lunar satellites (either disposal in place, into other orbits or trajectories, or deorbit) is especially important. Satellites descending from lunar orbit naturally or intentionally will impact the surface at orbital velocity and fully intact, since there is no atmosphere to decelerate or disintegrate them.
- Development of communications and navigation assets for long term use on the lunar surface will require a multi-disciplinary engineering design effort to ensure survival and operation through the extreme temperature ranges of the lunar day-night cycle and the extended periods of darkness during lunar night.
- The description that follows is divided into an Initial Phase, a Growth Phase, and a Desired Future State. The transitions between phases are expected to be gradual and the Desired Future State is not an "end state" but a reference point toward which the architecture can evolve and from which it may continue to grow.

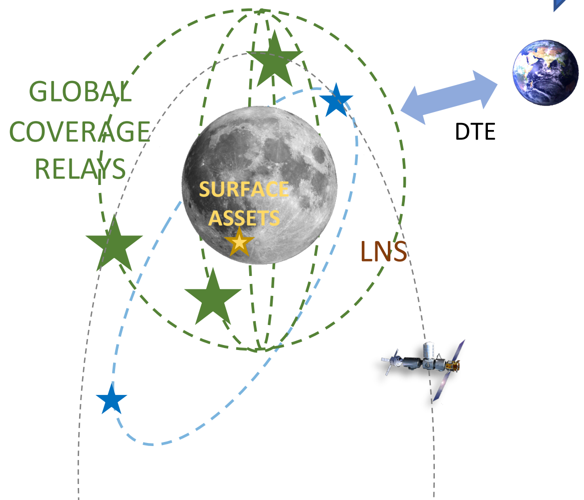
Overview of Architecture Evolution

Initial Phase: By 2024-2025



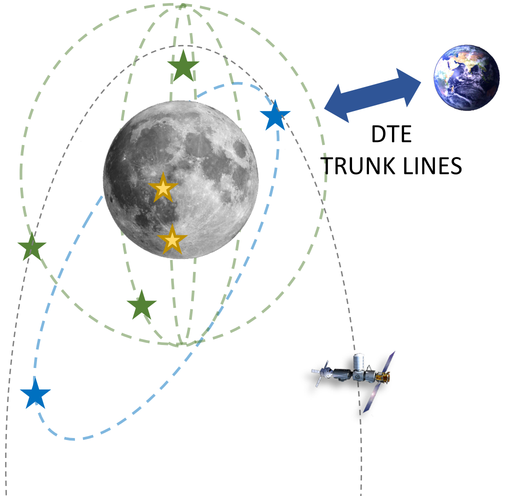
- *DTE service for Near Side, lunar orbiters and surface missions*
- *Intensive relay service for South Pole and a selected area of the Far Side*
- *Initial PNT service and lunar surface networks*
- *LunaNet interoperability established from the beginning*

Growth Phase: 2026-2030



- *Continued DTE service for Near Side*
- *Expanded relay service for South Pole and multiple Far Side regions*
- *Limited relay service for other globally-dispersed locations and orbiters*
- *Lunar Navigation Service for PNT*
- *Surface networking*
- *Introduction of optical links*

Desired Future State: 2030 + Beyond

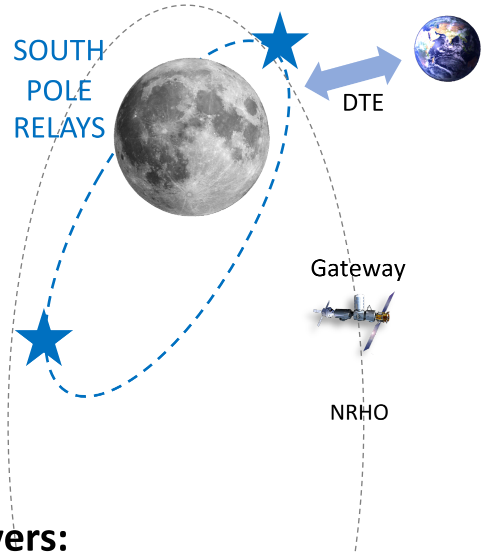


- *Satellite constellations with multiple operators functioning as cooperative set of networks*
- *Intensive coverage of specific regions and regular coverage of all regions*
- *Optical trunk line links*
- *Surface network assets in multiple locations*

The implementation described is not intended to be prescriptive but to indicate a means to achieve the required services. Other implementations that would meet the same intent should be considered.

Initial Phase Architecture

Initial Phase: By 2024-2025



Mission Drivers:

- Multiple spacecraft, orbiting and landed, requiring DTE service
- Far-side robotic users and human exploration at the South Pole
- High-rate services up to 50 Mbps return and 10 Mbps forward
- PNT knowledge for landed spacecraft to within 100 meters

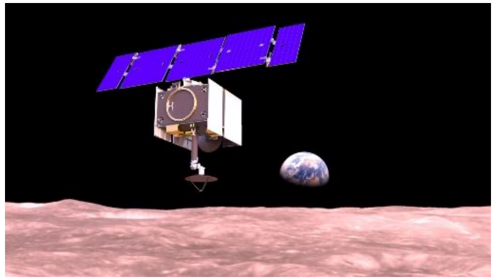
Implementation:

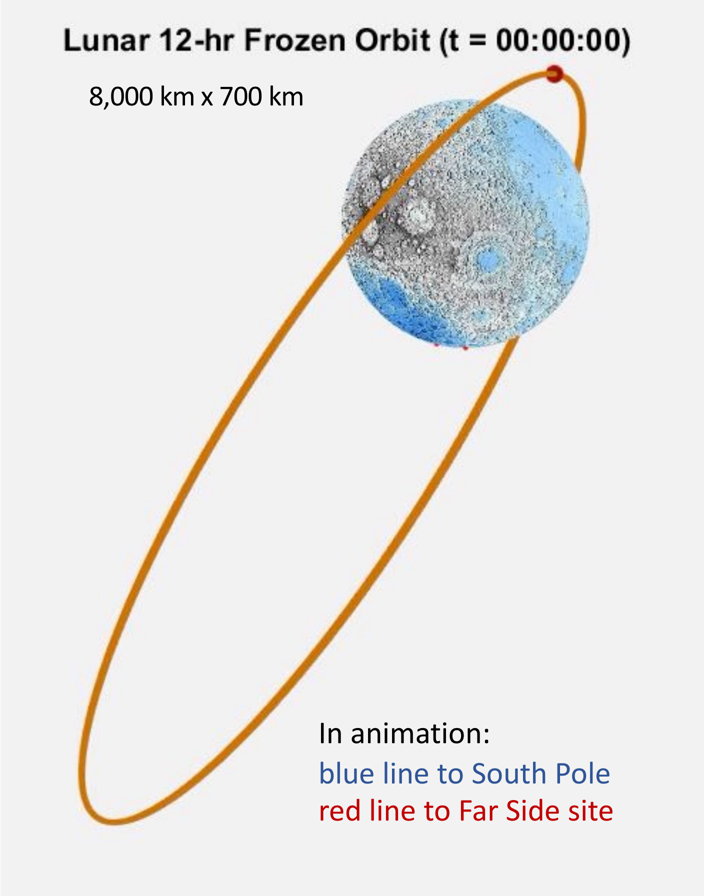
- **LEGS** assets supplemented by DSN when necessary for DTE service needs
- **One relay satellite by 2024** in an elliptical orbit to provide service to the South Pole and a portion of the Far Side.
- **Second relay satellite by 2025** with comparable capabilities, in a similar orbit, but 180-degrees out of phase, to provide more continuous service.
- As possible, additional relay satellites added for greater capacity and redundancy.
- Relay satellite systems comply with established **interoperability standards**
- **PNT service** from relay satellites to include, as a minimum, range and range rate service as part of communications link and incorporation of Earth-orbit-based GNSS reception and precise on-board time reference for position knowledge
- As possible, relay satellites should incorporate capabilities for direct links between lunar users and **intersatellite links** between relay satellites.
- **Gateway** and ESA **Lunar Pathfinder** may also contribute to relay capabilities.

Initial Relay Concept

For the initial architecture, coverage of South Pole and southern region of the Far Side is needed

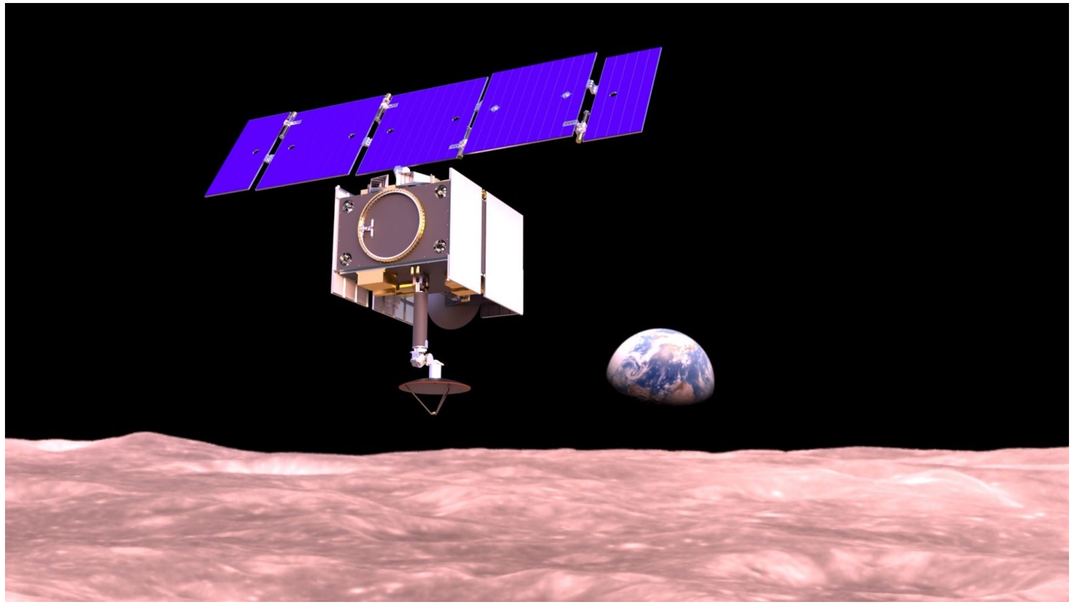
- There is a family of elliptical orbits that require minimal orbit maintenance and provide long dwell times over the South Pole
  - A single relay satellite in a 12-hour elliptical orbit can provide 8 to 9 hours of coverage of South Pole and Schrodinger Basin (Far Side reference site) in each orbit - yielding about 75% coverage time
  - With only two properly phased relays in this type of orbit, South Pole coverage could be continuous, independent of Gateway.
- Small spacecraft – as low as 150-300 kg could be adequate for the service needed. These could be delivered as rideshare payloads.
- Relays would link to Earth ground stations – assuming 18-meter class antennas.
- Gateway, when present, will provide substantial relay service to HLS missions
- ESA Lunar Pathfinder may provide service to NASA robotic science missions.
- Over time, more satellites can be added in order to augment redundancy, increase capacity for more users, and expand to global coverage.


Reference Relay Concept



Relay Satellite Reference Design Overview

- ESPA Grande Class Small Satellite
  - Volume allocation 42” x 46” x 52”
  - Wet Mass <500 kg
  - Power ~ 600 W
- Mission Lifetime 5 years.
- 12-Hr Elliptical Frozen Orbit, apolune at Lunar South Pole.
- Provides high data rate communications (Ka-Band) for Proximity and DTE links.
- Provides low-rate communications for proximity links (S-Band) and for DTE communications (X-Band).
- Includes position, navigation, and timing support to users through accurate relay ephemeris knowledge, structured signals, and associated messages.
- Provides coverage during HLS descent/ascent.
- Designed to support users sized from CubeSats to human spacecraft.



Relay PNT Reference Signal Source

Measurement Type	Systematic	Noise (1-s)
Pseudorange (PR)	< 0.65 m	< 0.32 m @10 sec
1-way Forward Doppler	(identify per frequency reference)	< 0.16 mm/s @10 sec
Coherent Ranging (2-Way) *	< 0.65 m	< 0.22 m @10 sec
Coherent Doppler (2-Way) *	n/a (expect none)	< 0.11 mm/s @10 sec
*Represented as one-way		

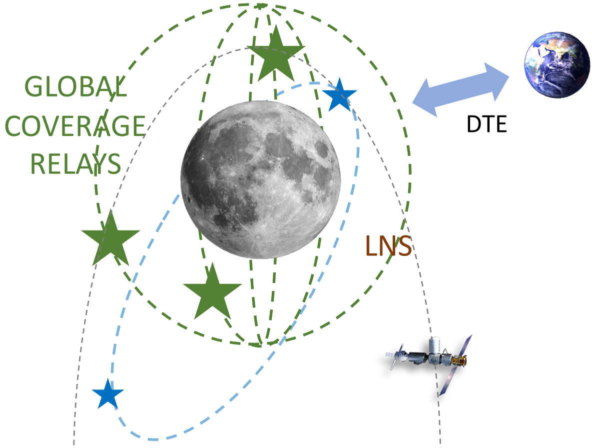
Link	Band	Forward Link Frequency	Return Link Frequency
Lunar Relay to Lunar System (Proximity Link)	S-Band	2025 - 2110 MHz	2200 - 2290 MHz
	Ka-Band	23.15 - 23.55 GHz	27.0 - 27.5 GHz
Earth to Lunar Relay (Direct-to-Earth Link)	X-Band	7190 - 7235 MHz	8450 - 8500 MHz
	Ka-Band	22.55 - 23.15 GHz	25.5 - 27.0 GHz

Note: 2.5 GHz frequency has since been identified with the Augmented Forward Service (**AFS**) PNT signal

Parameter	User Data Rate
Relay Return High Data-Rate	25-50 Mbps
Relay Forward High Data-Rate	1-10 Mbps
Relay Return Low Data-Rate	36 Kbps
Relay Forward Low Data-Rate	36 Kbps

Growth Phase Architecture

Growth Phase: 2026-2030



Mission Drivers:

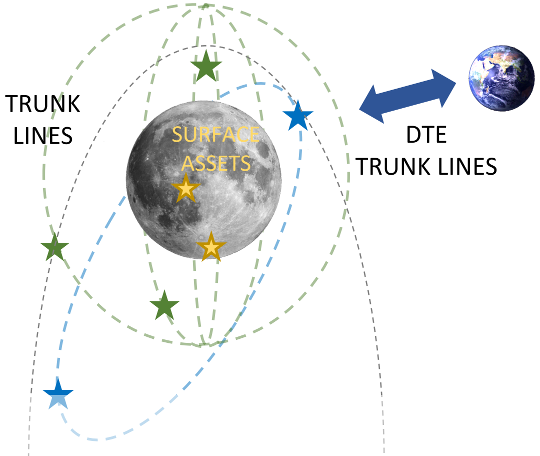
- Growth in assets and missions – multiple surface elements (e.g., LTV) and operations continue even when crew are not present
- Data rate growth to 150 Mbps and greater, and lower latency services for real-time telerobotic operations
- Growth in mobility operations – distance and durations
- More diversity in mission location across a range of far side and polar regions with longer durations
- Science missions and EVA crew will require very precise position information and on-demand location service
- Lunar orbiting spacecraft demand is likely to increase substantially, including many small satellites

Implementation:

- Maintain relay service in elliptical orbit over South Pole with **addition and/or replenishment of satellites**, as needed. Capacity of individual relay satellites or combined capacity of multiple satellites increase.
- Establish **3GPP/5G surface communications and navigation** assets to maintain contact between surface elements and between mobile elements and orbiting relays or Earth.
- Add relay satellites to provide **globally-distributed coverage**.
- DTE service needs will peak as lunar relay satellites and surface relays will **aggregate data and provide trunk lines to Earth**.
- Coherent **Optical links** might be introduced: 1) for trunk lines between lunar relays and Earth stations, 2) for intersatellite links between relays, and 3) between lunar relays and lunar users.
- Comprehensive PNT services with the introduction of "**Lunar Navigation Service**" (LNS) comparable to the Earth-based GNSS.
- Additional ground station capacity via commercial service contracts and international partner contributions.

Desired Future State Architecture

Desired Future State: 2030 + Beyond



Mission Drivers:

- Sustained Basecamp operations with high data rate communication between multiple lunar surface elements and Earth
- High data rate comm between lunar elements (without Earth)
- HSF missions to more diverse regions, including the Far Side
- Increase in the duration, complexity, and diversity (multiple nations, commercial) of human and robotic missions and an increase in their mobility
- Resource prospecting and industrial utilization activities become a significant service user
- Situational awareness needed for surface and orbiting elements

Implementation:

- Earth ground stations will remain important for some DTE services; coherent **optical trunk links** essential for high bandwidth
- **Data aggregation and local lunar traffic** enable a large increase in the overall communications capacity without requiring a proportional increase in Earth ground stations.
- Autonomous PNT capabilities with reduced reliance on Earth including **"Lunar Navigation Service"** providing 4+ signal visibility to the entire surface and low Lunar orbit
- Sharing of information among all orbiting users and service providers will enable continuous and comprehensive **situational awareness**
- Relay constellation will be scaled based on user demand, global coverage, sustainment, replenishment, and life cycle management of assets

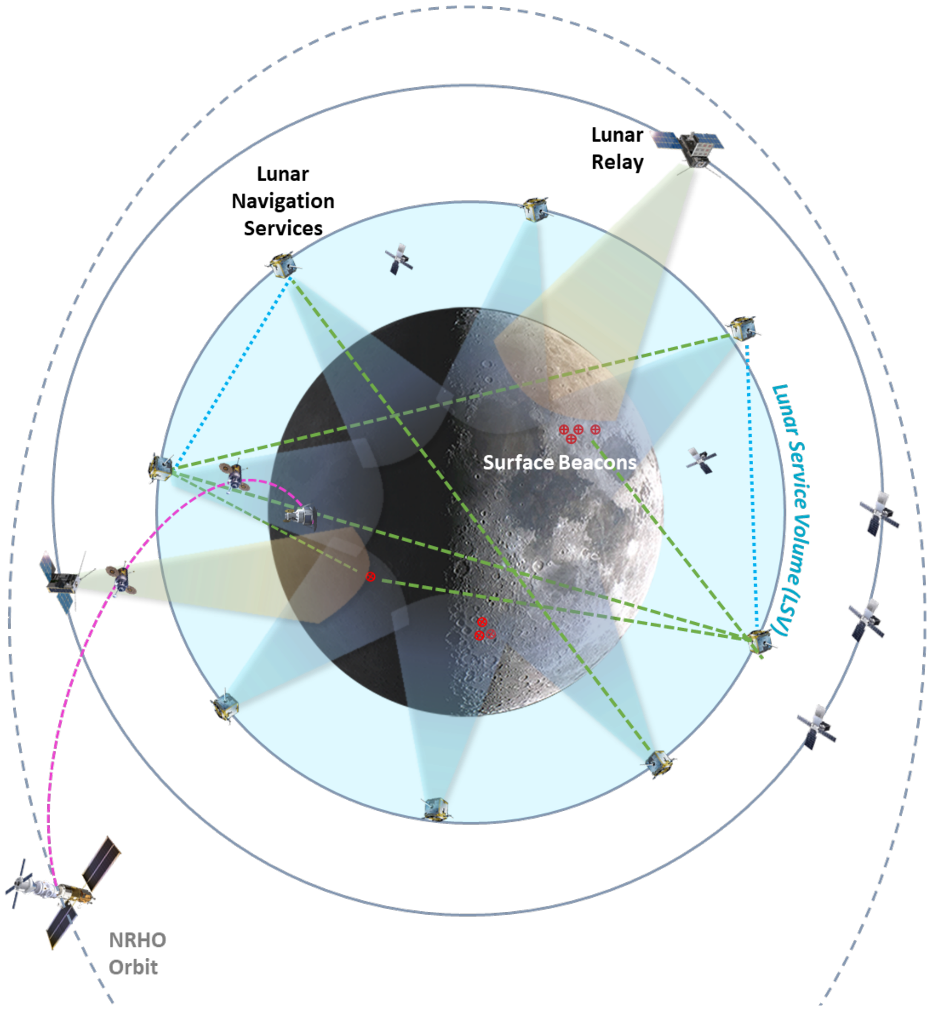
Lunar Navigation Services (LNS)

What and Why:

- Lunar Navigation Services (LNS) defines a Lunar Service Volume (LSV)
- Terrestrial GPS/GNSS analog shows significant benefits of broadcast metric tracking signals
- Addresses navigation and time needs to surface and orbital users
  - Overcomes link proliferation issues to support metric data
  - Reduces DTE ground system burden
- Enables transition to network service-based communications
- Enables both network and mission autonomy

Execution

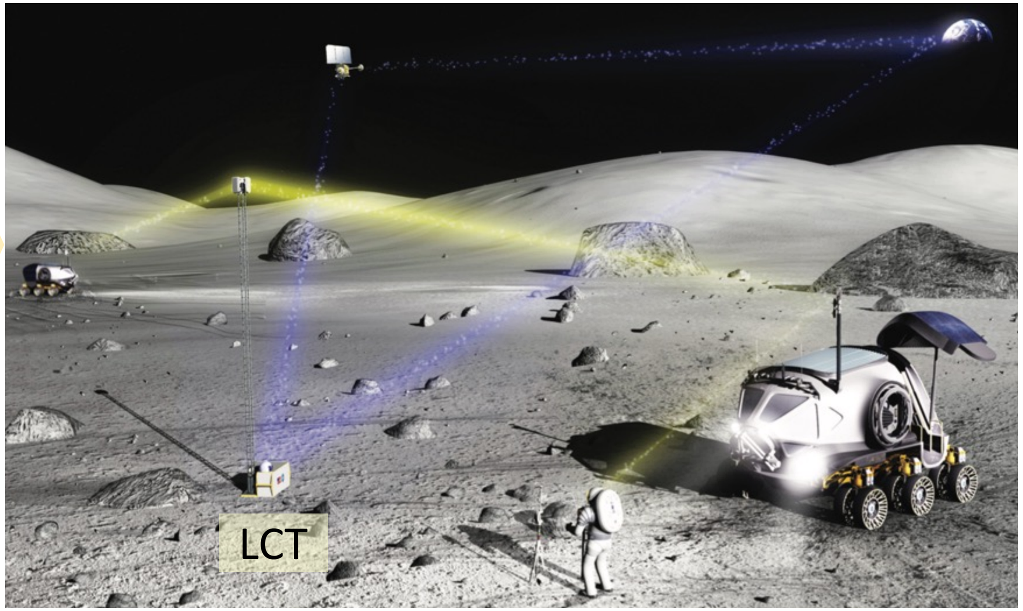
- Technology is mature and well understood
- Connects to science via support of definition and maintenance of lunar reference frame(s) and time scales
- Leverages
  - Weak-signal GPS/GNSS (NC3m) at Moon provides traceability to UTC
  - Deep Space Atomic Clock (DSAC) for long-term clock stability
- LunaNet defines messages and outlines signal structure(s) to ensure interoperability
- Excellent topic for OGA collaboration

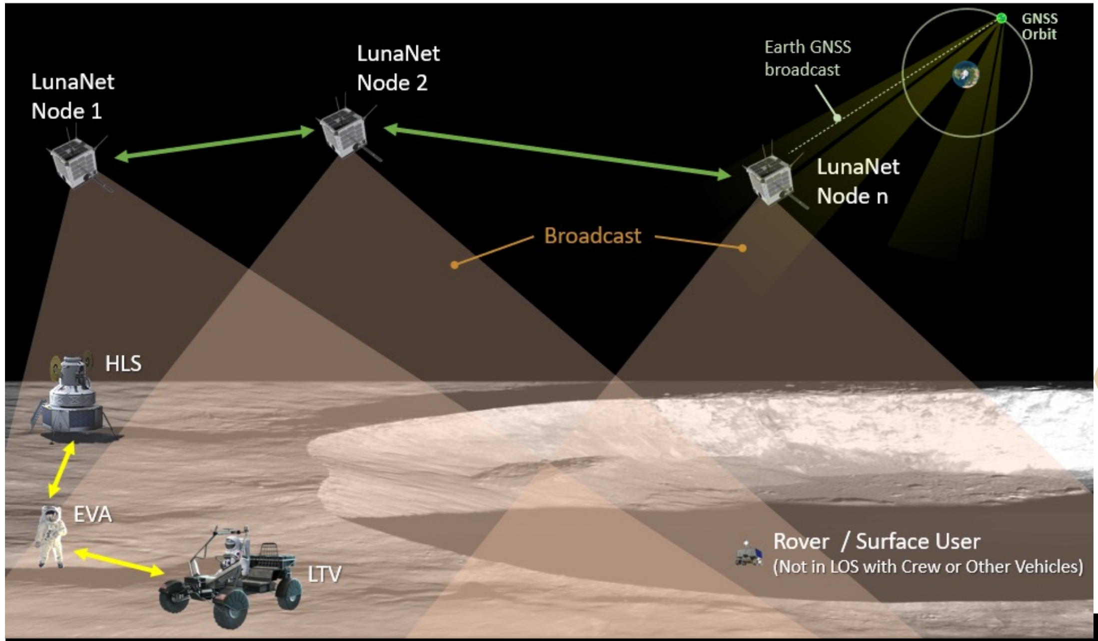


Lunar Surface Communications & Navigation

Surface Communication & Networking

- Point-to-point links between surface systems & Lunar Communication Terminal (LCT) that multiplexes & demultiplexes among users and links to overhead relays
- Initial capability limited to specific sites, e.g., Outpost
  - IP and DTN network protocols supported
  - UHF, WiFi and 4G/5G options being evaluated; Nokia 4G demo on CLPS
  - LCT may be relocatable so crew can move it to work sites
- Future capability adds enhanced services and increases assets to improve coverage and resilience





Surface navigation

- Range & bearing to users extracted from surface links
- Overhead relays broadcast RNSS navigation signal that user equipment processes like GPS to determine position & velocity
  - Weak signal GPS receiver demonstration on CLPS
  - Initial broadcast capability limited to 1-2 relays requiring long user integration time
  - Full constellation enables instant position calculation & adds optical PNT
- Augmented by science aids to get sub-cm accuracy at sites of geologic interest

Legend

Blue links = Ka-band
Yellow links = S-band, WiFi or 5G (trade in work)
Orange = Navigation broadcast (2.5GHz)
Green links: Crosslinks for PNT Calibration

3GPP/5G Surface Wireless Network

What and Why:

- 3GPP/5G cellular technology will provide a robust lunar surface communications and navigation infrastructure that is incrementally scalable to enable long-term exploration and industrial needs
- Essential to address surface and orbital link proliferation
- Enables direct surface/local communication and aggregates data for transition to backhaul
- Enables efficient routing of data

Execution

- Build on intermediate investments
- Continue to leverage LunaNet for interoperability
- Surface data aggregation with RF and/or optical links to relay
- Enable base-to-base connectivity
  - 5G base stations plus several central hubs
  - Connected via fiber optics, microwave links, optical links
- Augment PNT support
  - User derived data channels from local 5G network
  - Augmented by LunaNet network broadcast data
  - Potential direct relay support via Non-Terrestrial Network (NTN) features

Coherent 5+ Gbps Optical Links

What and Why:

- Operational optical communications between the Earth and Moon (coherent, multi-gigabit) supports high bandwidth needs of robust exploration, science, and industrial activity
- Enable robust, scalable, cost-effective lunar communication services to support long-term science, exploration, and industrial needs with reduced user SWaP burden
- Availability of optical links for data aggregation increased network capability and relieves spectrum pressure

Execution:

- 1 m class operational optical ground station w/adaptive optics
  - Low-Cost Optical Terminals replicate capability for commercial infusion and dedicated site utility
  - Geographically diverse, minimum 3 locations around the Earth
  - Augment with 2 to 3 additional ground stations per longitude to provide high availability
- Complete prototype (TRL 6) of a system-agnostic, low-SWaP, commercially sourced, 5+ Gbps optical modem combined with MASCoT (optical terminal) for relay payload system by FY25
- LunaNet compatibility with high-speed DTN support
- Continue collaboration with international partners for optical link cross support

NASA