National Aeronautics and
Space Administration

LunaNet: The Lunar Internet for Space Communications, Position, Navigation, & Timing (CPNT)

Jim Schier, Chief Architect, Space Communications and Navigation Program

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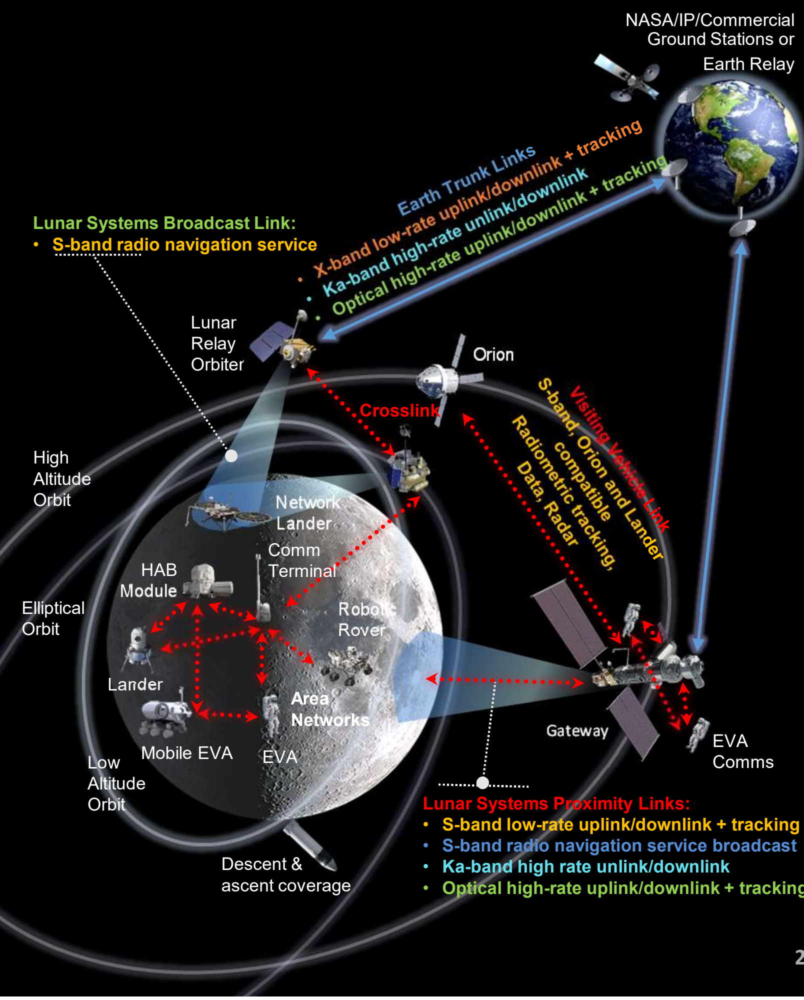
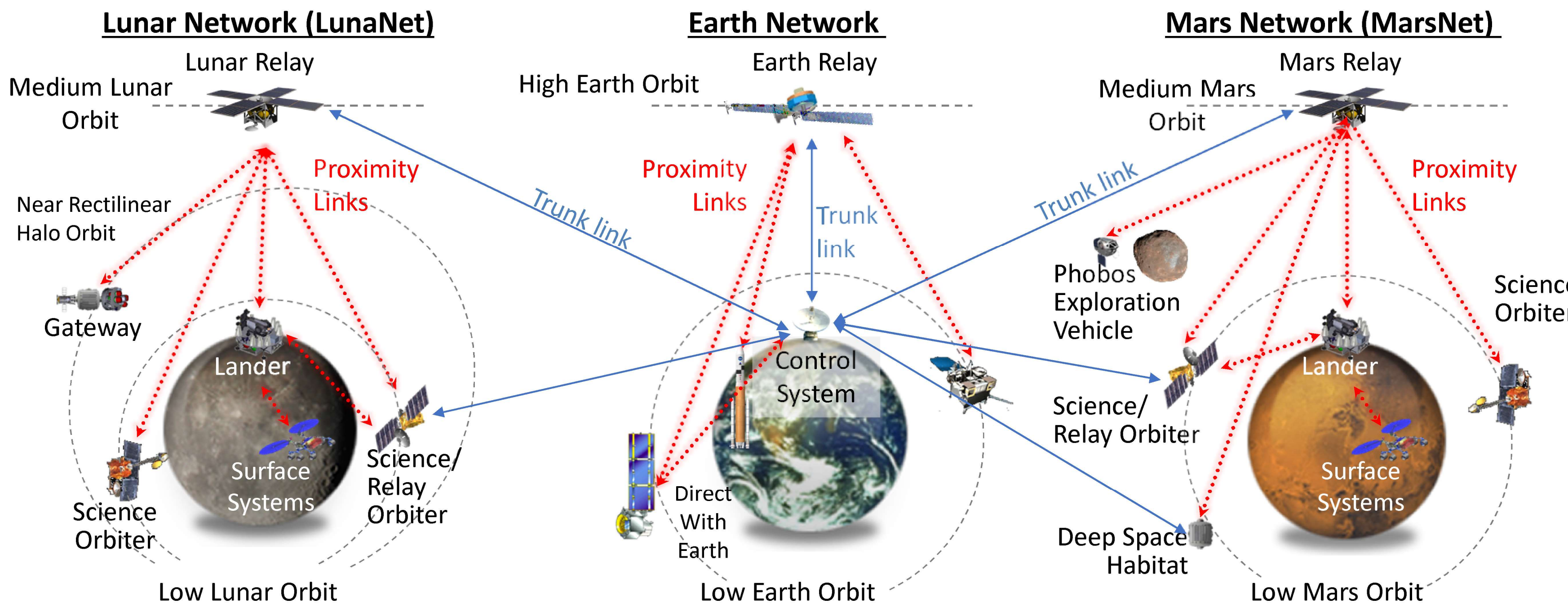
LunaNet, the Lunar Internet

- ***LunaNet is a set of cooperating networks providing interoperable communications and navigation services for users on and around the Moon.***
- ***Based on a framework of mutually agreed-upon standards, protocols, and interface requirements that enable interoperability.***
- ***Allows many lunar mission users to engage the services of diverse commercial and government service providers in an open and evolvable architecture.***
  - **Service-Oriented**: LunaNet services can include data transmission and distribution of position, navigation, timing (PNT), and situational awareness information.
  - **Scalable**: LunaNet can be introduced as part of the earliest missions and accommodate expansion as new users and service providers come online.
  - **Open**: LunaNet is based on open international standards like the Internet
  - **Resilient**: As LunaNet grows into many networks and users, it becomes steadily more resilient to individual failures and outages
  - **Secure**: LunaNet protects sensitive and proprietary data while preventing or rapidly recovering from cyber threats
  - **Extensible**: The LunaNet concept is applicable to any planetary body.



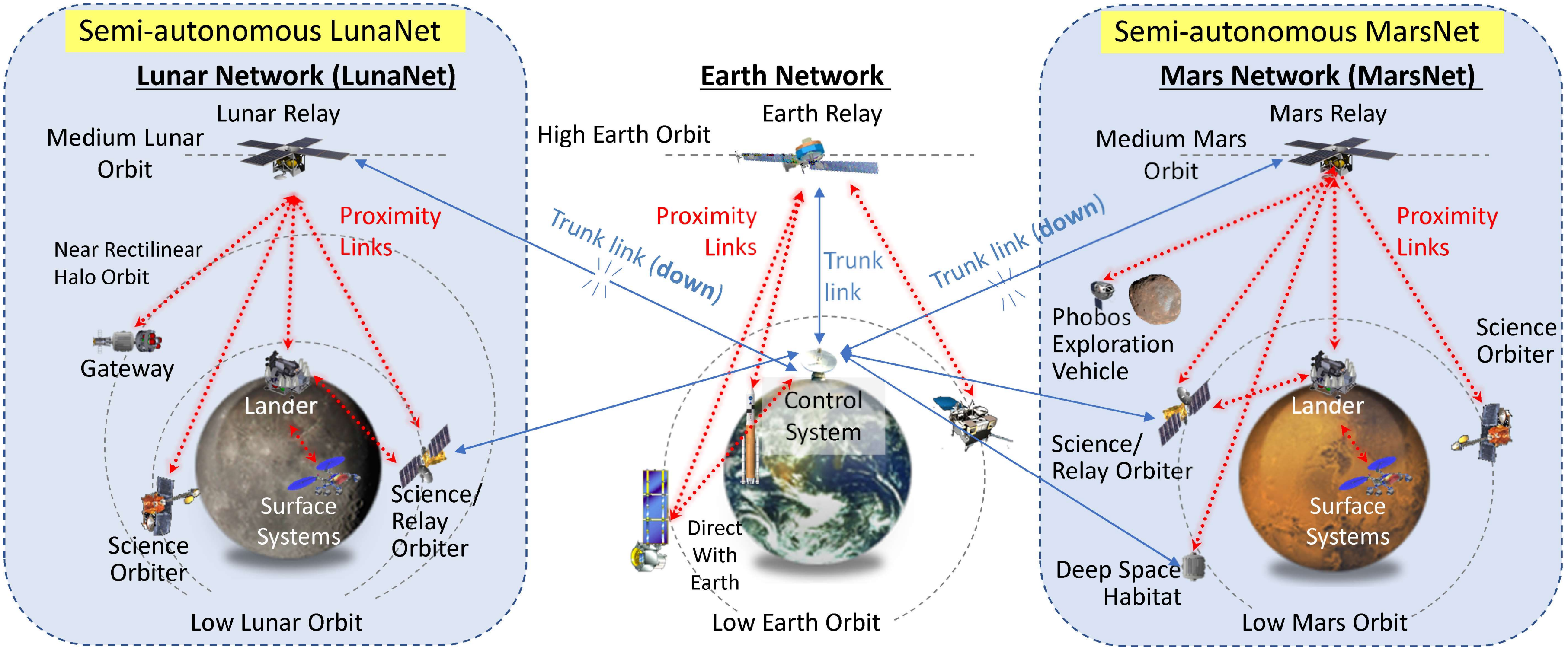
LunaNet and Planetary Networks

Planetary Networks: Earth, Moon and Mars - One Architecture



- **Strategy: Develop a flexible *planetary network* architecture adaptable to any celestial body to reduce development & operation cost**
- **User-network proximity links (space-space & space-ground/surface) provide standardized services & design for users of planetary networks**
- **Network-network Trunk links are internal network space-ground connections for long distance "back haul"**

LunaNet Autonomy Goal
Planetary Network Autonomy from Earth



- **Strategy: Develop *planetary network* architecture capable of temporary autonomous operations of the space segment**
- **Develop and test the autonomy strategy at the moon with LunaNet (Earth-Moon latency ~1.2 seconds)**
  - **Few latency requirements cannot be met**
  - **Proximity links continue when trunk links are lost**
  - **Autonomy "mode" can be turned off with little consequence**
  - **Nav broadcast service continues with slowly decreasing accuracy when GNSS links are lost**
- **Deploy operational autonomous MarsNet for future human exploration of Mars (Earth-Mars latency up to 22 minutes)**

Planetary Network Services

Networked Communication Services

- Critical data transmitted in real time.
- Data aggregated and transmitted in store-and-forward mode from orbiting and surface relays
- Data exchanged among lunar users with no need for transfer to and from Earth
- Data sent on demand by user or scheduled to better manage Earth stations loading & spectrum use

PNT Services

- Precise position, velocity & time for autonomous nav & collision avoidance
- Fusion of multiple data types including radiometrics, optimetrics, celestial nav, optical nav, terrain relative nav, & GNSS
- Broadcast service supplies time transfer and metric tracking to synchronize users

Detection & Information Services

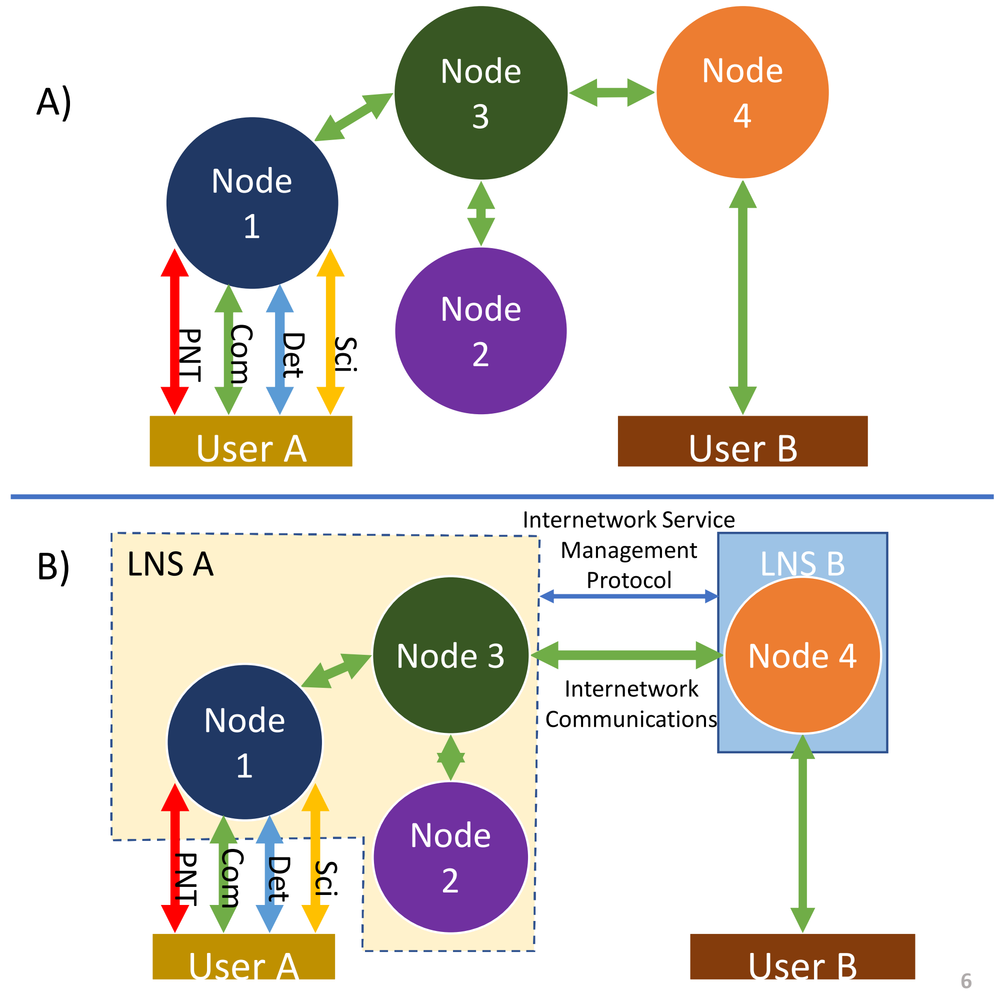
- Alerts for events such as space weather, collision avoidance, & surface impact predictions sent to all LunaNet subscribers
- Mission sensors for space weather and other measurements distribute information services to other users via LunaNet information services
- Search and Rescue (SAR) services

Science Services

- Use RF & optical assets as (part of) scientific instruments
- Supports Radio & Radar Sciences, Radio Astronomy / Very Long Baseline Interferometry (VLBI) & other space sciences

Networked Communication Services

- **Conventional link-layer services are still supported but LunaNet networks are built for network-layer service using packets (IP) or bundles (BP)**
- **A) Shows an end-to-end path between User A and User B via several LunaNet nodes**
- **B) Shows the nodes are part of different LunaNet Systems (LNS) operated by providers that interoperate to support that path**
  - **The LNSPs must have an agreed Internetwork Service Management Protocol in place based on the Internetwork Interface standard**

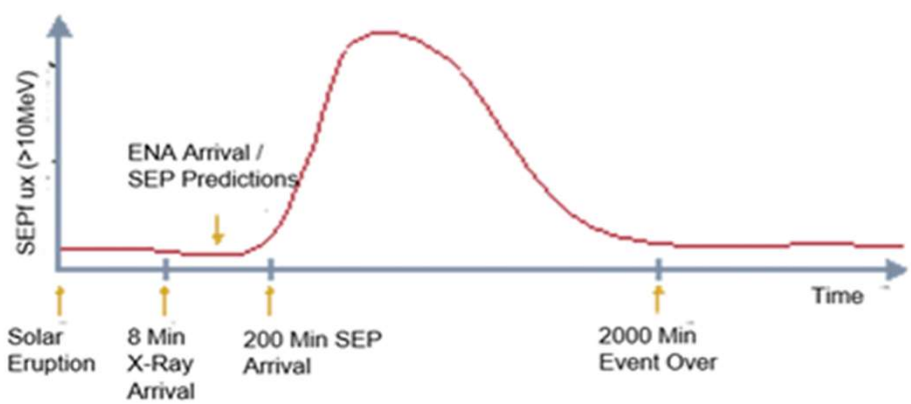


LunaNet PNT Services

	Service	Description
Positioning	Generate signal for range, Doppler, and time observable	Produces time-synchronized fixed frequency signal with known ranging code for enabling 1-way pseudorange, Doppler, and time by receiver; or 2-way as a relay.
	Provide measurements via telemetry message	Transmits the LunaNet-created measurements of 1- or 2-way range and Doppler to a receiving vehicle via standard message.
	Establish onboard navigation using *in situ* measurements	LunaNet estimates state using onboard sensors, such as optical navigation, weak-signal GNSS, accelerometer, IMU, or pseudorange and Doppler from communication links to autonomously determine state in flight software and disseminate via standard message.
Navigation	Transmit user's integrated position, velocity, & time (PVT) state to user	Communicates LunaNet's estimate of user's position, velocity, and time ("solve-fors") single-epoch state to another user or LunaNet node to support tracking scenarios. Enables autonomous onboard operations.
	Transmit LunaNet ephemeris for use in measurement processing	Provides spacecraft time series of position, velocity, and time ("solve-fors") states to user or LunaNet node to allow autonomous onboard processing of radiometric data for user estimate of state and network access.
Timing	Maintain a stable onboard time reference	Utilizes high-stability onboard oscillators/time source or external measurements to maintain a stable time-base.
	Provide a coarse time synchronization capability	Broadcasts current time scale in a two- or one-way transmission to update onboard estimates of current global time, e.g., network-layer service such as Network Time Protocol (NTP)
	Provide fine time synchronization capability	Uses time-synchronized fixed frequency signal with known ranging code on P2P, Broadcast, and Crosslink signals to permit high-accuracy disciplining of clocks within the network.

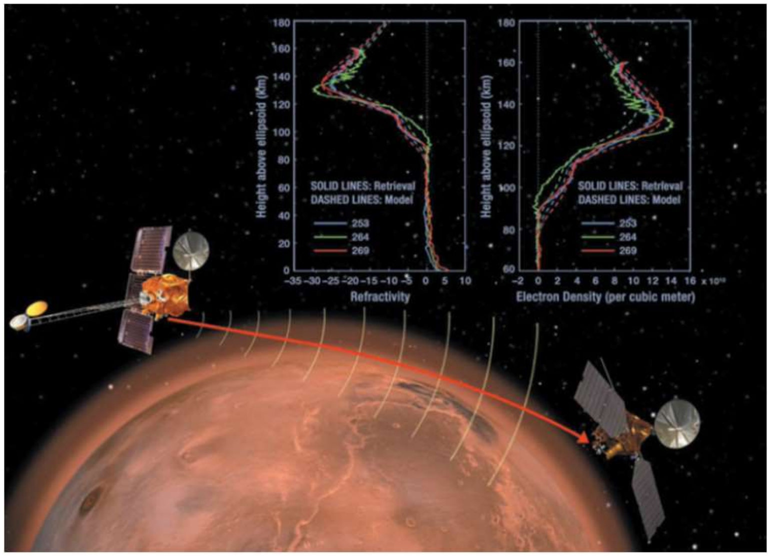
Detection and Information Services

- **In-space user 2 can subscribe to information stream published by user 1 for point-to-point or broadcast service. Example:**
  - **Space weather sensor located in S-E L1 monitors solar X-rays to sense Solar Energetic Particle (SEP) / Energetic Neutral Atom (ENA) events; broadcasts event & streams data on flux & particle energy**
  - **Crew receives event notice & data stream**
  - **Crew relocates to protective storm shelter within ~30 minutes of event onset**



Science Services

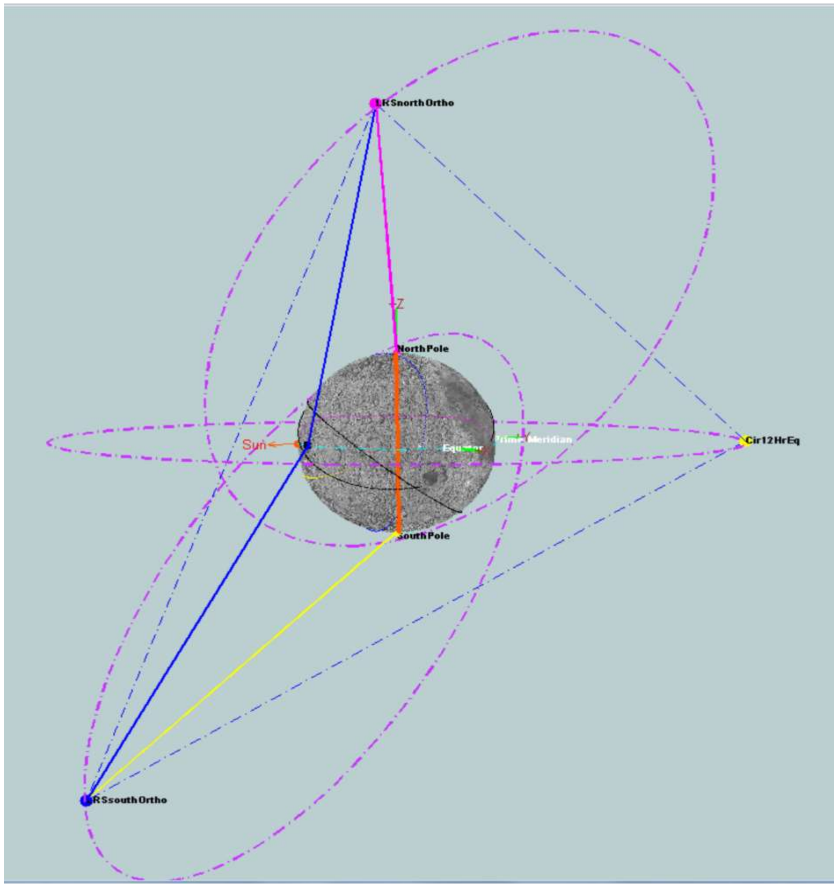
- **Proximity, crosslinks & trunk links can be used to conduct a variety of scientific investigations such as geodesy (e.g., rotational variations including precision & nutation) and atmospheric density and composition (e.g., Mars crosslinks and prox links to rovers; GPS experiments)**
  - **The DSN supports Radio Science, Radio Astronomy / Very Long Baseline Interferometry (VLBI), and Radar Science services**
- **Using these links to support science may impose additional requirements on link performance such as open-loop recording, higher accuracy time source, higher SNR than communication links, & capturing parameters not involved in CPNT services**
- **The incremental cost of improving performance of communications and/or PNT links to support science objectives may be worthwhile**
- **Hence, the LunaNet architecture allows for the potential to perform scientific experiments using LunaNet links**
  - **RF has been used to-date but optical measurements may be added**
- **This service schedules links between cooperating spacecraft (LunaNet-LunaNet or LunaNet-mission user) to capture signals of interest and transmit them to Earth**



First radio crosslink occultation experiments were conducted between Mars Odyssey & MRO in 2007 using the MRO Electra transceiver to acquire open-loop recording of UHF signal transmitted by Odyssey.

Expansion of Lunar Relay Network

- Each LunaNet Service Provider (LNSP) designs its own set of orbits
- Figure shows notional constellation characterized by a combination of circular orbits and elliptical orbits, including:
  - a 12-hour Elliptical Lunar Frozen (ELF) orbit with its line of apsides librating over the South Pole;
  - a 12-hour frozen elliptical orbit with its line of apsides librating over the North Pole; and,
  - a 12-hour circular elliptical orbit around the equator
- Initial partial coverage can commence with a single relay orbiter. To achieve full coverage, the minimal constellation would include:
  - Two relay orbiters phased 180° apart on the 12-hour northern ELF orbit → covers north polar region
  - Two relay orbiters phased 180° apart on the 12-hour southern ELF orbit → covers south polar region
  - One relay orbiter on the 12-hour circular orbit around the equator → good but not complete far side coverage
- Constellation can be built out in any order to meet changing mission needs
- Number of relays per orbit can be increased by reducing phasing angle, e.g., 2 relays at 180° to 3 relays at 120°
- Sufficiently rapid motion across the sky to assist surface users in determining their position using relay tracking service



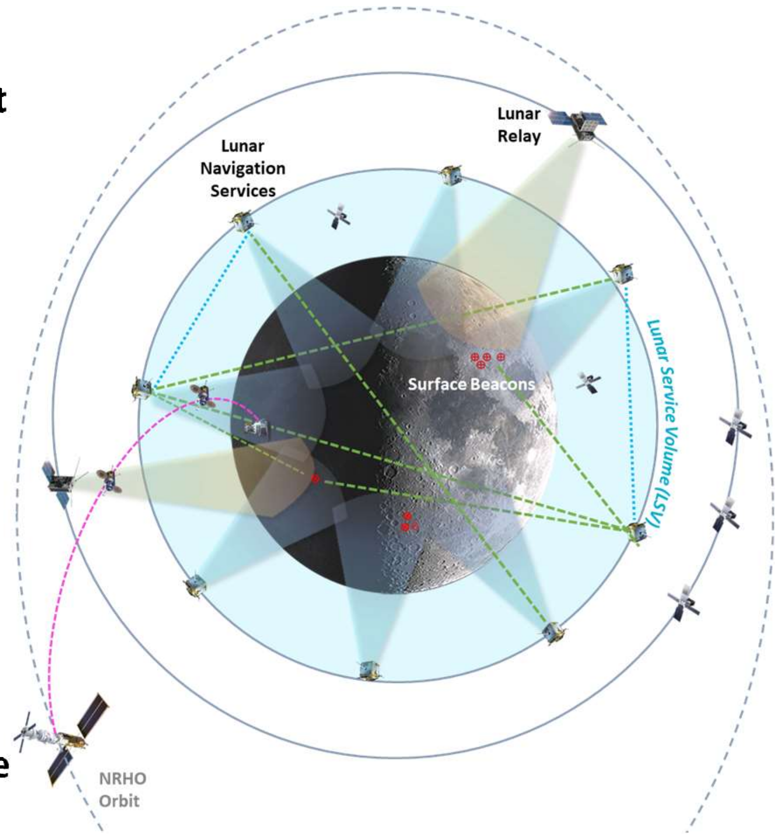
Lunar Augmented Navigation Service (LANS)

What and Why:

- LANS is defined by a lunar Service Volume (SV) that expands over time
- 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 Direct To Earth (DTE) ground system burden
- Enables transition to network service-based communications
- Enables both network and mission autonomy

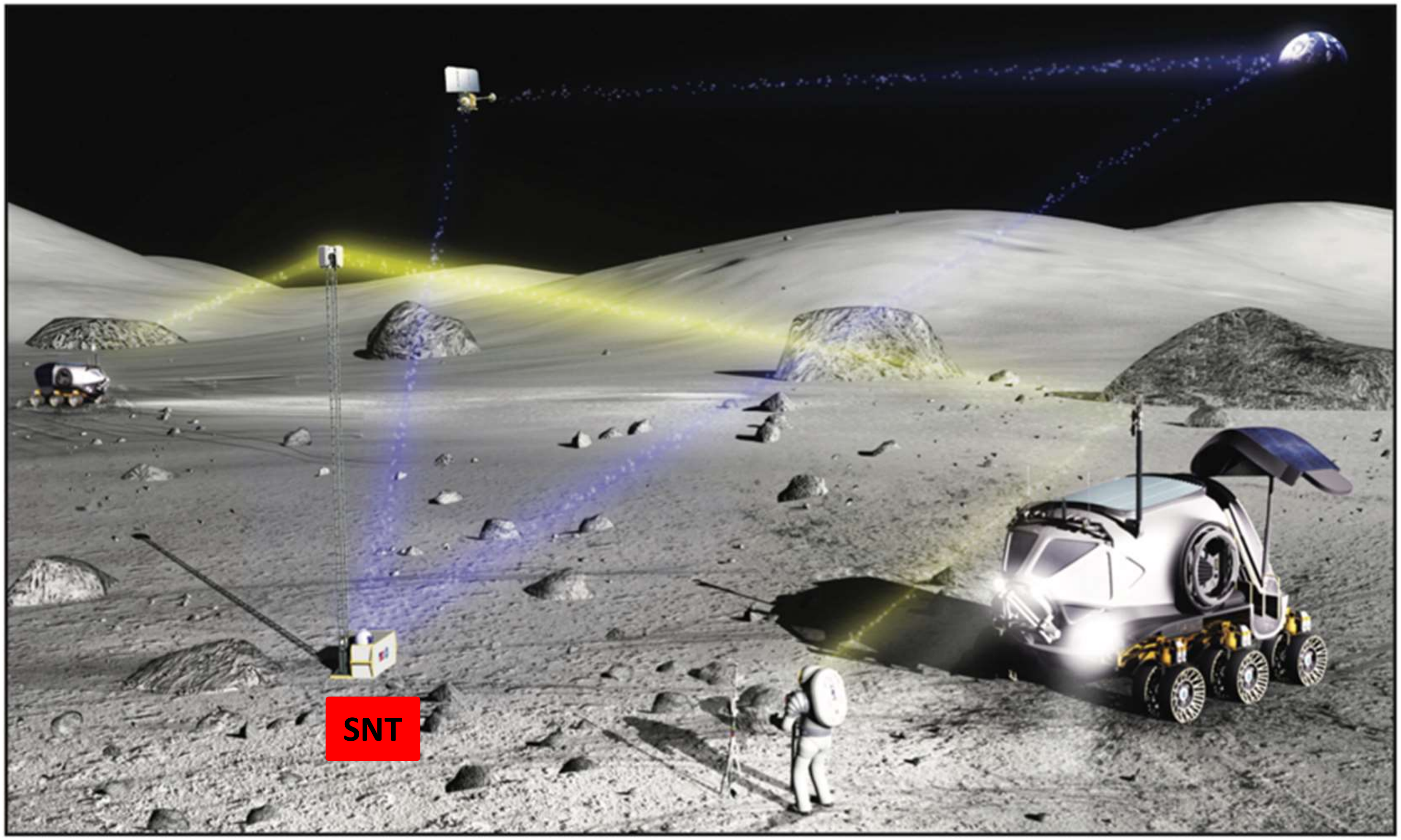
Execution

- 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
  - High quality and/or atomic clocks for long-term clock stability
- LunaNet defines messages and outlines signal structure(s) to ensure interoperability
- Excellent topic for international collaboration



Lunar Surface Network

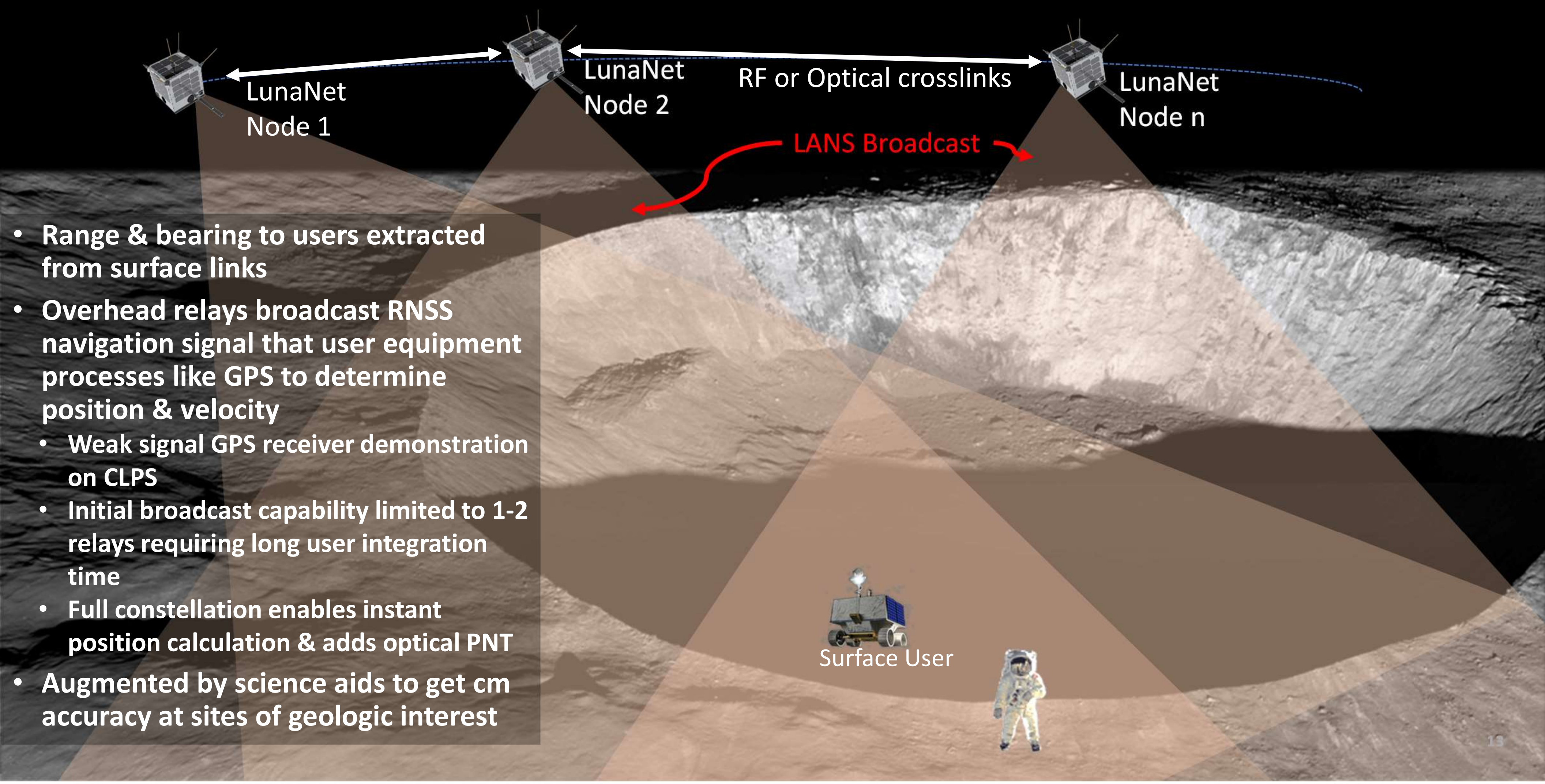
- **Point-to-point links between surface systems & Surface Network Terminal (SNT) that multiplexes & demultiplexes among users and links to overhead relays**
- **Initial capability limited to specific sites, e.g., Base Camp**
  - **IP and DTN network protocols supported**
  - **UHF, WiFi and 4G/5G options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



Legend
Blue links = Ka-band
Yellow links = S-band, WiFi or 5G (trade in work)

NASA

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 cm accuracy at sites of geologic interest

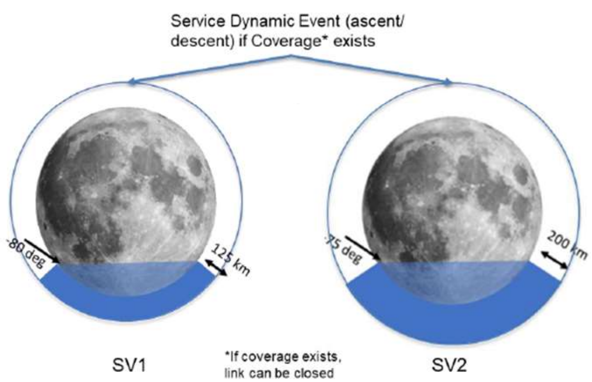
Lunar Comm Relay & Nav Services Phased Capabilities

Increases in Service Volume, coverage period, and service type establish minimum requirements for the RFP based on Artemis campaign needs

Interoperability Spec and Requirements released publicly to facilitate industry and international collaboration

Services Include:

- Forward and return data delivery, real-time and store-and-forward (DTN)
- PNT: 1-way Forward Doppler and Ranging
- PNT: 2-way Doppler and Ranging
- PNT: Time Transfer



Increment	Alpha			Bravo				Charlie		
Service Type	Ka-band	S-band	AFS	Ka- band	S- band	AFS		Ka- band	S- band	AFS/ LANS
Number of Simultaneous Links	1	1	1	1	1	2	3	2	2	4
Forward/ Return Services	R only	F+R	F only	F+R	F+R	F only	F only	F+R	F+R	F only
Service Volume	SV1			SV1				SV2		
Min. % Coverage of an Earth Day	70%			75%	90%	70%	40%	75%	90%	40% [2]

The Lunar relay service requirements do <u>not</u> prescribe number of nodes, only service attributes.

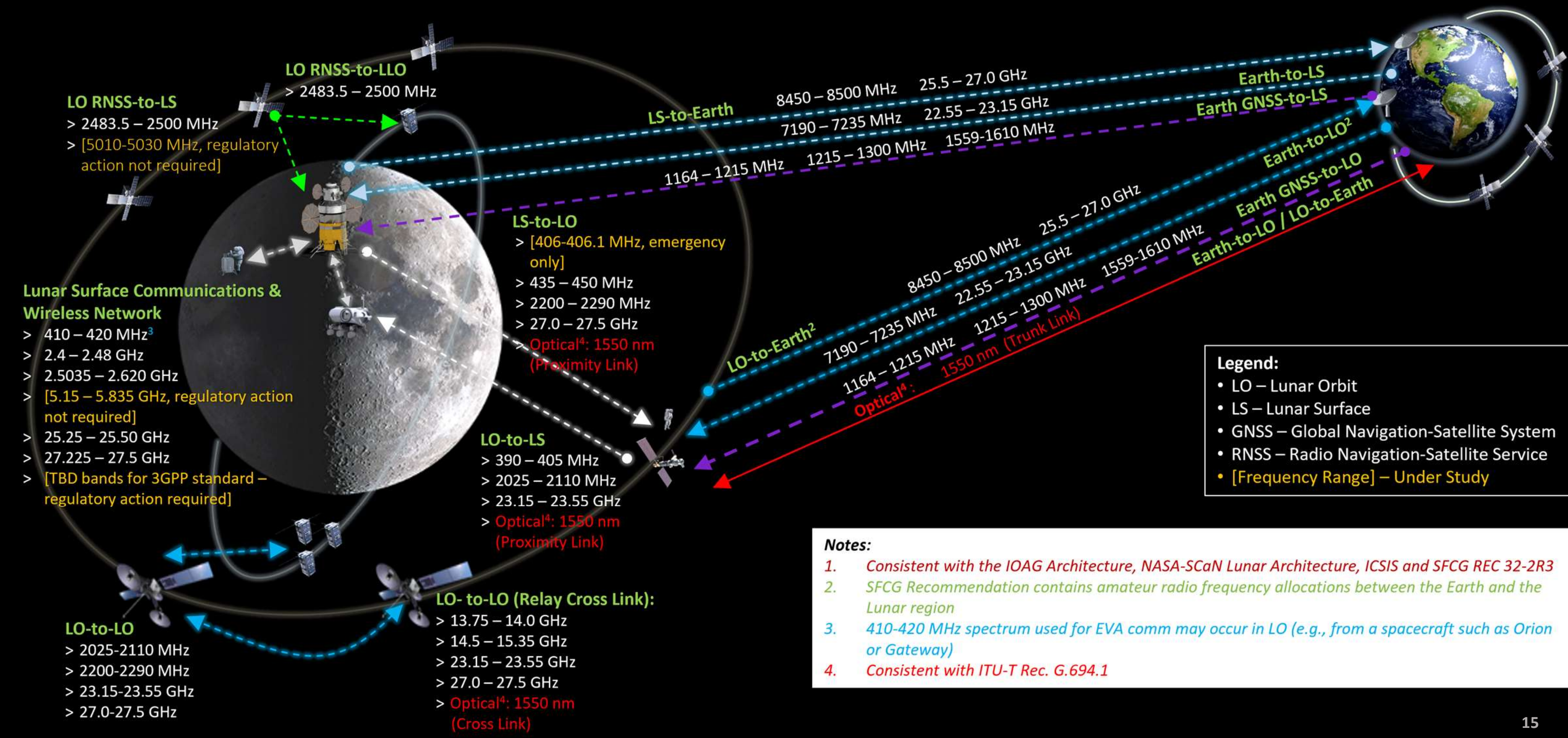
Service Band	Ka-Band	S-band
User Data Rates	F: 1 Mbps – 10 Mbps R: 1 Mbps – 50 Mbps	F: 0.25 kbps – 2 Mbps R: 0.25 kbps – 2 Mbps

PNT Observation Accuracy	Value
Range [1]	0.93 m (3-sigma) @ 10 sec
Doppler [1]	0.33 mm/s (3-sigma) @ 10 sec
[1] Error represented as one-way [2] (with spatial GDOP<6)	

LNIS: LunaNet Interoperability Specification; **AFS**: Augmented Forward Signal (PNT); **LANS**: Lunar Augmented Navigation System; **GDOP**: Geometric Dilution of Precision

LunaNet Spectrum Architecture[1]

Radio Frequency and Optical

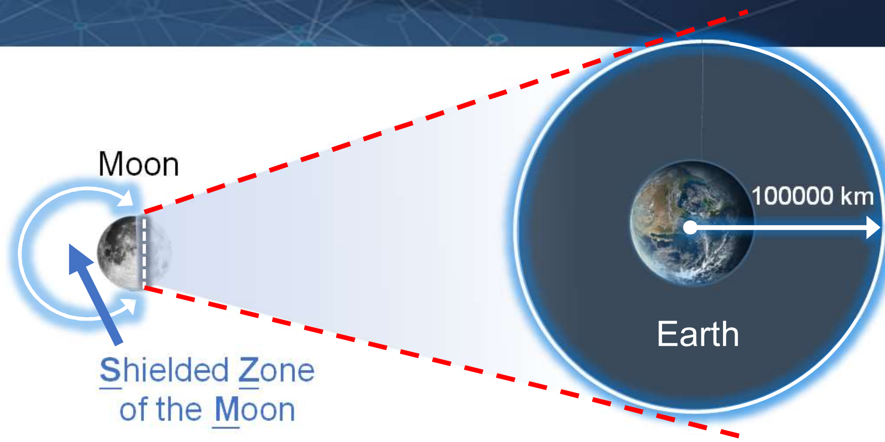


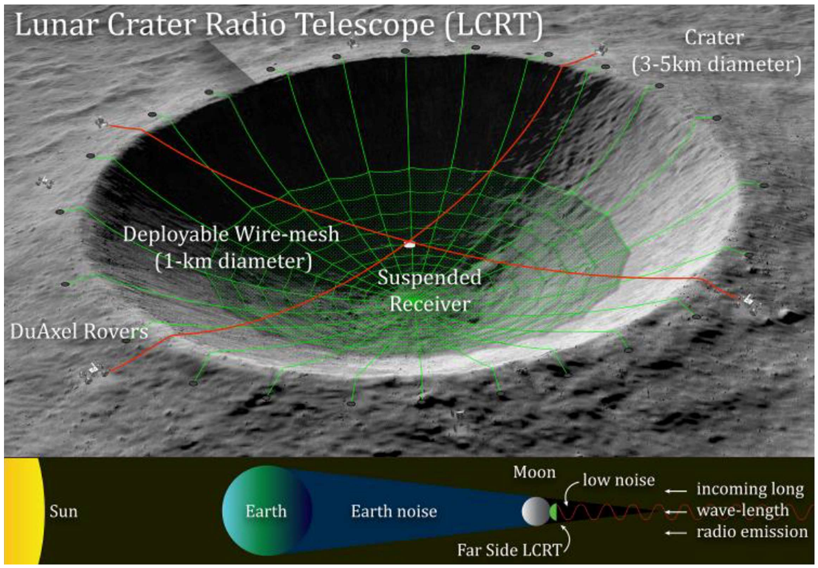
Legend:
- LO – Lunar Orbit
- LS – Lunar Surface
- GNSS – Global Navigation-Satellite System
- RNSS – Radio Navigation-Satellite Service
- [Frequency Range] – Under Study

Notes:
1. *Consistent with the IOAG Architecture, NASA-SCaN Lunar Architecture, ICSIS and SFCG REC 32-2R3*
2. *SFCG Recommendation contains amateur radio frequency allocations between the Earth and the Lunar region*
3. *410-420 MHz spectrum used for EVA comm may occur in LO (e.g., from a spacecraft such as Orion or Gateway)*
4. *Consistent with ITU-T Rec. G.694.1*

Shielded Zone of the Moon (SZM)

- **Rec. ITU-R RA.479-5, Protection of frequencies for radio-astronomical measurements in the shielded zone of the Moon**
  - **All frequencies below 2 GHz in the SZM should be accessible to radio Astronomy**
- **The XXIIth General Assembly of IAU …recommends:**
  1. **that two alternative bands must be allocated to the necessary active services in the SZM to retain access by the passive services to the whole spectrum on a time-coordinated basis;**
  2. **that radiocommunication in the shielded zone of the Moon be limited to the band 2 000-3 000 MHz;**
  3. **that the alternative frequency band at least 1 GHz wide be identified to permit future operations on a time coordinated basis between radioastronomy and lunar communication systems.**
- **Space Frequency Coordination Group Resolution SFCG 23-5, Protection Of Future Radio Astronomy Observatories In The Shielded Zone Of The Moon, calls for SFCG members planning a far side radio observatory to coordinate with the SFCG to refine the recommendations**



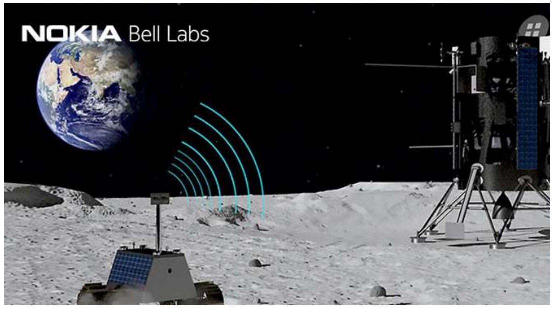


NIAC 2020 Phase I Selection: Far side Lunar Crater Radio Telescope (LCRT) concept, with 1 km diameter[1]

[1] Lunar Crater Radio Telescope (LCRT) on the Far-Side of the Moon | NASA

Technology Development

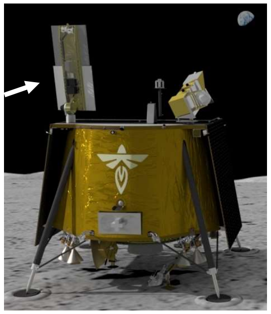
- Next demonstration of optical comm & PNT capabilities flies on Artemis II (2024)
  - Techniques used to perform OSIRIS-REx Touch & Go maneuver to 0.75m of landing site
  - Developing high-resolution LuNaMaps as part of the STMD Game Changing Development
- Delay/Disruption Tolerant Networking (DTN) technology based on the Bundle Protocol (BP) is in development and will complement Internet Protocol (IP)
- First 4G/Long Term Evolution (LTE) demo on CLPS IM-2 (mid-2023)
  - Nokia's lunar network consists of an LTE Base Station with integrated Evolved Packet Core (EPC) functions, LTE User Equipment, RF antennas and high-reliability operations and maintenance (O&M) control software.
- CLPS LunarNode-1 payload will demonstrate an S-band beacon from the surface
- Radio Navigation Satellite Service (RNSS) synchronizes GNSS to lunar PNT services
  - Lunar GNSS Receiver Experiment (LuGRE) funded for Commercial Lunar Payload Services (CLPS) mission in FY23 to characterize weak-signal GNSS reception (GPS & Galileo)
- Deep Space Atomic Clock (DSAC) recently demonstrated better stability than a GPS rubidium clock at half the SWaP on STPSat-6
- Core Flight System (cFS) is being integrated with autoNGC to provide an onboard application suite that integrates and autonomously controls spacecraft navigation, guidance, and control (NGC)
  - Built upon Goddard Enhanced Onboard Navigation System (GEONS) autonomous navigation flight software
- Lunar Reference System (LRS) in development to parallel International Terrestrial Reference System
  - Will lead to standards for inertial & rotating reference frames, time systems, perturbations modeling, gravity model, geodetic models, and integrators



Nokia's rover talks to the base station on the lander via LTE

Credit: Nokia Bell Labs

GNSS antenna



Firefly Aerospace's Blue Ghost lander has Next Gen Lunar Retro-reflectors (NGLR), Reconfigurable, Radiation Tolerant Computer System (RadPC), & LuGRE

Credit: Firefly Aerospace

Summary

- LunaNet is an investment in establishing communications and PNT infrastructure for the benefit of all lunar missions
- LunaNet is architected to be open, interoperable, and scalable enabling it to grow and evolve as the lunar economy expands
- LunaNet requirements have been baselined by the Artemis Program & Interoperability Spec (LNIS)
  - Gateway will be a LunaNet relay node
- NASA's portion of LunaNet is funded (DLEU, LEGS, LCRNS)
  - RFP released to procure commercial cislunar communication & PNT services from multiple vendors
- ESA's Moonlight Program also procuring commercial services complying with LNIS
- LunaNet moves the networks into space for space users – not just "uplink/downlink"
  - Communications & networking standards exist; PNT standards need to be developed
- Spectrum architecture deals with frequency band bottlenecks & unique limitations
  - Protects far side Shielded Zone for radio astronomy – no emissions below 2 GHz except safety/emergency
  - Establishes lunar region equivalent to near Earth region – primary links are between cislunar systems
- International civil space agencies collaborating through the Interagency Operations Advisory Group (IOAG) and associated organizations (e.g., SFCG, CCSDS, IETF, ICG) to establish a committee to study how to govern the international LunaNet

➢ Growing international acceptance