EXPLORESPACE TECH
TECHNOLOGY DRIVES EXPLORATION

Communications and Navigation

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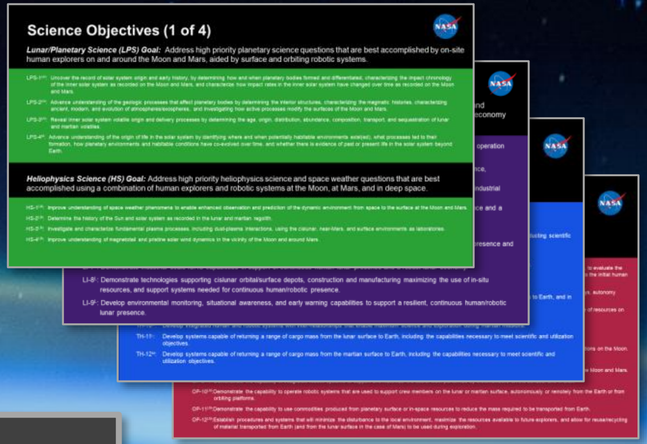
September 2023

Agenda

- NASA's Moon to Mars Blueprint Objectives
- Envisioned Future for Communications & Navigation
  - Supporting the Moon to Mars Blueprint Objectives and the Science Mission Directorate in General
- 3GPP on the Lunar Surface
- Optical Communications
- Technology Needs

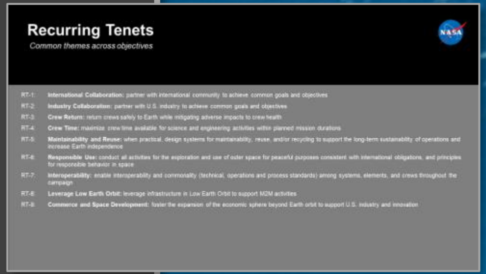
NASA's Moon to Mars Blueprint Objectives

- **Latest released in September 2022**
- **63 Top-Level Objectives across 10 Top-Level Goals**
  - 26 Science (6 Goals) – Led by SMD
  - 13 Infrastructure (2 Goals) – Led by STMD
  - 12 Transportation & Habitation (1 Goal) – Led by ESDMD
  - 12 Operations (1 Goal) – Led by SOMD



- **9 Recurring Tenets (RT)**
  - Common themes across objectives

RT-1: **International Collaboration**
RT-2: **Industry Collaboration**
RT-3: **Crew Return**
RT-4: **Crew Time**
RT-5: **Maintainability and Reuse**
RT-6: **Responsible Use**
RT-7: **Interoperability**
RT-8: **Leverage Low Earth Orbit**
RT-9: **Commerce and Space Development**



Infrastructure Objectives Relevant to Comm & Nav

Lunar Infrastructure (LI) Goal: Create an interoperable global lunar utilization infrastructure where U.S. industry and international partners can maintain continuous robotic and human presence on the lunar surface for a robust lunar economy without NASA as the sole user, while accomplishing science objectives and testing for Mars.

LI-2^{L}: Develop a lunar surface, orbital, and Moon-to-Earth communications architecture capable of scaling to support long term science, exploration, and industrial needs.

LI-3^{L}: Develop a lunar position, navigation and timing architecture capable of scaling to support long term science, exploration, and industrial needs.

Mars Infrastructure (MI) Goal: Create essential infrastructure to support initial human Mars exploration campaign.

MI-2^{M}: Develop Mars surface, orbital, and Mars-to-Earth communications to support an initial human Mars exploration campaign.

MI-3^{M}: Develop Mars position, navigation and timing capabilities to support an initial human Mars exploration campaign.

Superscripts indicate applicability to Lunar (L), Martian (M), or both (LM)

Envisioned Future Communications & Navigation

EXPLORE: Develop Next Generation Communications and Navigation Technologies

Develop communications, navigation, and sensing infrastructure capable of handling high data volumes with near real-time communication (cislunar), and increased onboard navigation and time-keeping autonomy

OTHER CELESTIAL BODIES AND DEEP SPACE

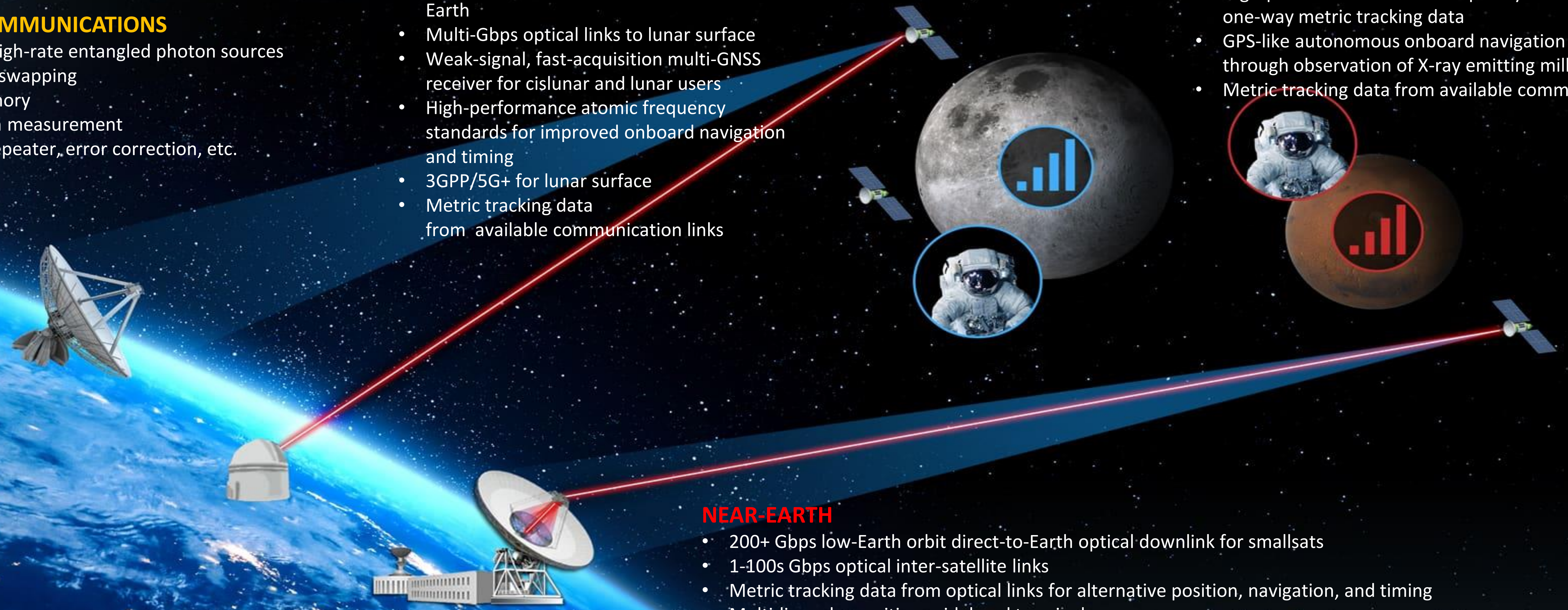
- Extension of LunaNet framework beyond Earth-Moon for interplanetary and deep space network
- High Photon Efficiency optical links for 100s Mbps direct-to-Earth downlink
- High-performance atomic frequency standards enabling one-way metric tracking data
- GPS-like autonomous onboard navigation and timing through observation of X-ray emitting millisecond pulsars
- Metric tracking data from available communication links

CISLUNAR AND MOON

- LunaNet framework for interoperable and resilient communication and navigation
- 1-10+ Gbps coherent optical links direct-to-Earth
- Multi-Gbps optical links to lunar surface
- Weak-signal, fast-acquisition multi-GNSS receiver for cislunar and lunar users
- High-performance atomic frequency standards for improved onboard navigation and timing
- 3GPP/5G+ for lunar surface
- Metric tracking data from available communication links

QUANTUM COMMUNICATIONS

- High-quality, high-rate entangled photon sources
- Entanglement swapping
- Quantum memory
- Nondemolition measurement
- Networking: repeater, error correction, etc.



NEAR-EARTH

- 200+ Gbps low-Earth orbit direct-to-Earth optical downlink for smallsats
- 1-100s Gbps optical inter-satellite links
- Metric tracking data from optical links for alternative position, navigation, and timing
- Multi-lingual, cognitive, wideband terminals
- Weak-signal, fast-acquisition multi-GNSS smallsat compatible receiver for above GNSS constellation users
- Metric tracking data from available communication links

Communications & Navigation Envisioned Future

- Envisioning the 2030 + timeframe

- Presented in 3 Separate Regimes:
  - ✓ Near Earth Regime
  - ✓ Lunar Regime
  - ✓ Deep Space Regime

- Technology Needs:
  - ✓ Optical Communications
  - ✓ Networking Technology
  - ✓ Planetary Surface Communications and Navigation
  - ✓ Position, Navigation, and Timing (PNT)
  - ✓ Radio Frequency Communications
  - ✓ Quantum Communications (***)

Range from Earth*	***Regime***	***Notation***
Deep Space > 2M km Mars 54.6M-400M km 	Deep Space	>2M km from Earth is considered **Deep Space****
Sun-Earth L1/L2 1.5 M km Cislunar 455,000 km Earth-Moon L1/L2 61,000km from center of Moon Lunar Proximity 70,000km from center of Moon 	Lunar	**Near Space** is considered from 80km to 2 million km from the Earth **
Earth Proximity Below 36,000 km	Near Earth	

*Unless otherwise noted
** Per the Space Communications and Navigation System Requirements Document

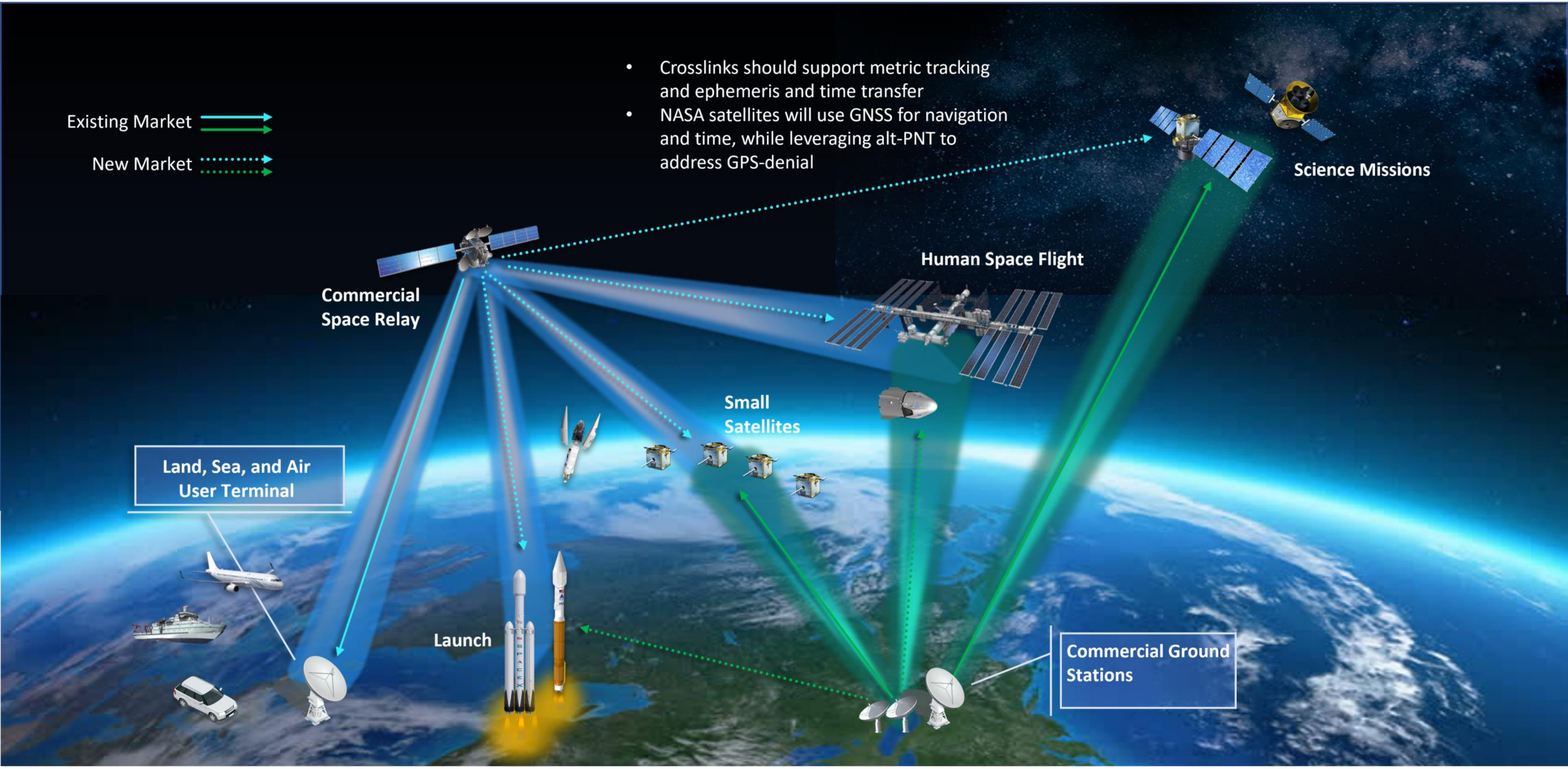
*** Quantum communications doesn't appear in the near-term Envisioned Future because of its current low TRL. However, NASA is supporting the development of the fundamental technology.

Envisioned Future
Near Earth Regime

Near Earth: NASA Commercial Communications Services Efforts and Impacts

Trends	Current NASA activities	Impact on 2030+ Near Earth communications
Transition to commercial SATCOM	End-to-end commercial services demonstrations using various technologies, orbits, and data pathways are taking place through 2030.	Users will transition from the NASA Tracking and Data Relay Satellite System to commercial SATCOM services.
Growing direct-to-Earth market	NASA is establishing a broader direct-to-Earth commercial market and is transitioning from service provider to commercial user.	Users will be able to access and seamlessly switch between a variety of service provider options based on real-time mission needs.
Adoption of standards and technologies	NASA is increasing engagement with standards bodies such as 3GPP (3rd Generation Partnership Project) Cellular Standards Group and investing in critical technologies like wideband terminals.	Adoption of commercial standards will provide operational efficiencies and interoperability benefits to NASA missions.

Near Earth: Extending Commercial Capabilities to Space



Near Earth: 2030+ NASA Comm & Nav Needs

Capability needs for interoperability

Application and network layer needs
NASA users will need shared standards and protocols to reliably and securely transfer data across and obtain navigation and timing information from multiple service provider networks.

Physical layer needs
Wideband and multilingual terminals, along with phased arrays, integrated optical systems, and cognitive radios will allow users to access the full suite of service provider options.

Capability needs for autonomous operations

Information needs for autonomous decision making
Users will need access to service provider's estimated cost, waveform configurations, availability, and other key information to support decision making.

Autonomous decision making for routine operations
Users will need technologies to sense and provide awareness of the communication environment, along with a decision making process to schedule services, select waveform and protocol configurations, and identify available networks among other routine tasks.

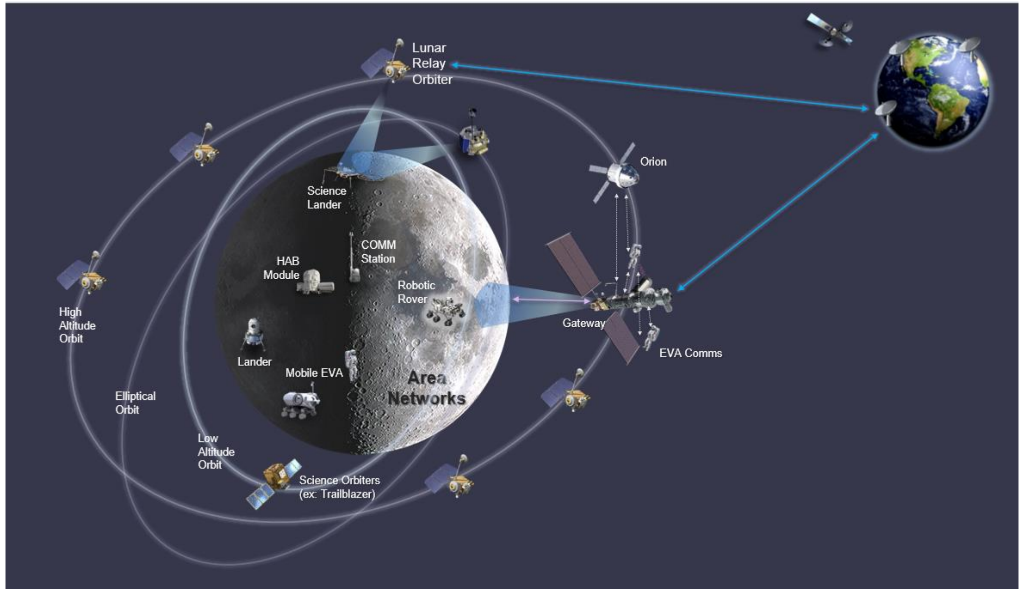
Autonomous decision making for non-routine operations
Artificial intelligence, machine learning, and similar techniques will be needed for user spacecraft to learn appropriate responses to a variety of quality of service impairments including spectral interference, weather, and network configuration or topology changes.

Envisioned Future Lunar Regime

Lunar: 2030+ NASA Comm & Nav Needs

Future state beyond 2030 is anticipated to include:

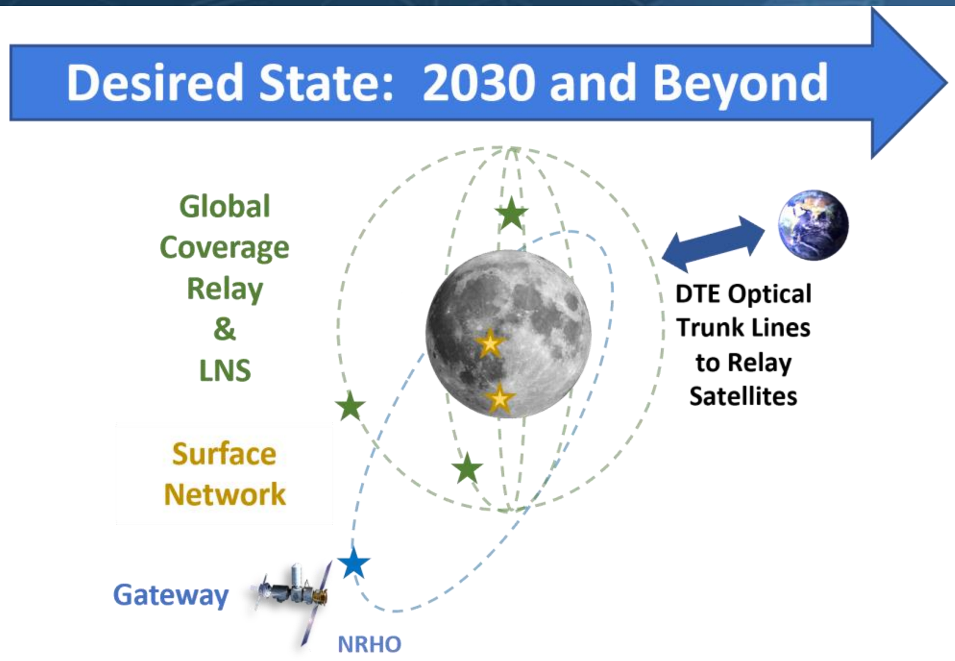
- Commercial industry (at least on the near side) needing precise location and timing services and communications relay services to/from Earth
- Human exploration and science experiments on both the near and far-side of the moon, with longer durations
- Sustained Artemis basecamp operations with high data volumes even when crew are not present
- More frequent, longer, and more complex human and robotic mobility operations needing precise location services on demand
- Increased connectivity between surface elements, including crew – surface-to-surface high-rate traffic a significant portion of all communications
- Greater diversity of missions in general – including international and commercial participants
- Commercial service providers meeting the needs of NASA and other participants



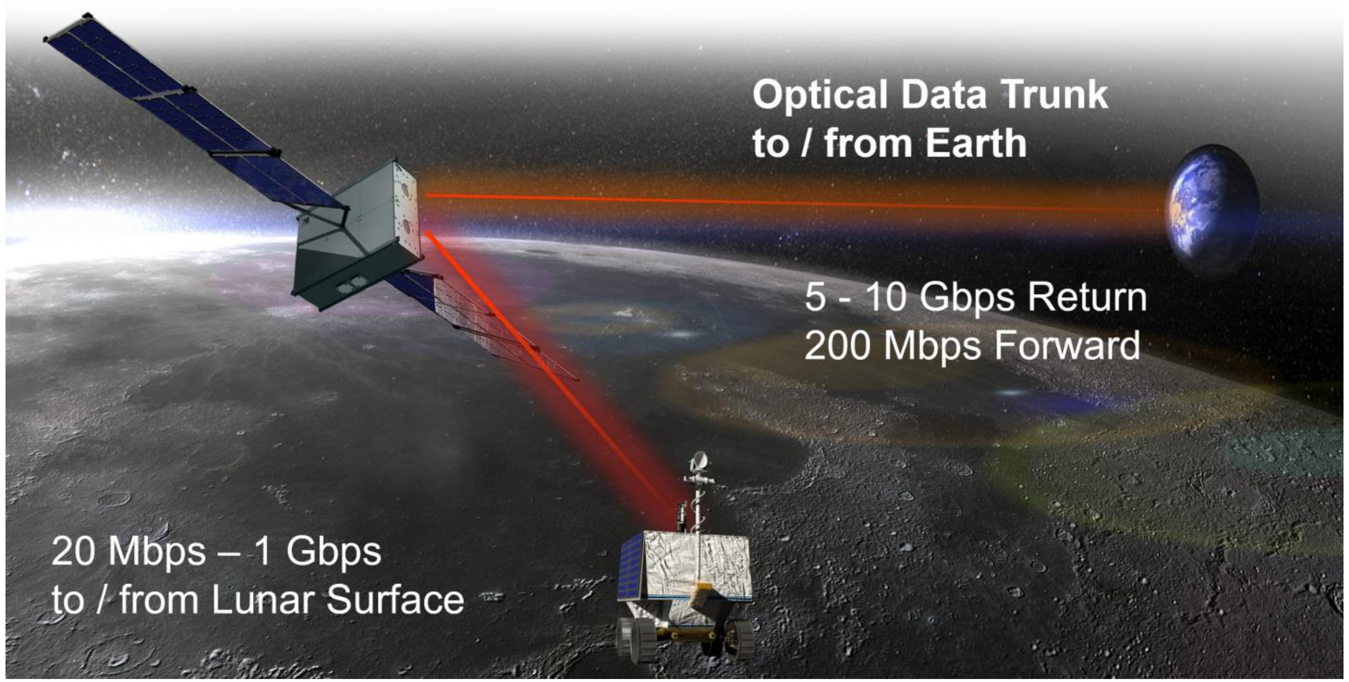
Extending the Internet to the Moon:

Crew, robotic science, and commercial surface operations mimic Earth terrestrial ops – service-based wireless connectivity with seamless support

Lunar: 2030+ Lunar Comm & Nav Architecture



- ❑ **S, X, and Ka-Band Radio Frequency links** in the lunar vicinity
  - Between lunar elements in orbit and on the surface
  - S, X, and Ka-Band RF link to and from the Earth
- ❑ **Coherent Optical links** for trunk lines between lunar relays and Earth stations
  - Provide 5 to 10 Gbps from the Moon to the Earth in the near term (coherent signaling can support 10's to 100's of Gbps)
  - Future relays could also support optical intersatellite links between relays and surface users
  - 1-Meter class optical ground stations on Earth
- ❑ **Metric tracking** on RF and optical links



❑ Lunar Navigation Service

- Provides the necessary geometric diversity, local dynamics, and simultaneous observations for rapid navigation knowledge
- More relays improve real-time accuracy, enabling mission ops flexibility and meeting user requirements
- Designed for incremental growth to extend service beyond south pole to global coverage as demand warrants

Lunar: 2030+ Surface Communications via 3GPP

Initial Artemis missions can be supported with One Base Station

- Could be integrated on the HLS
- 3GPP Cellular signals at the hardware level can support improved PNT if protocols pass required measurements from the physical layer

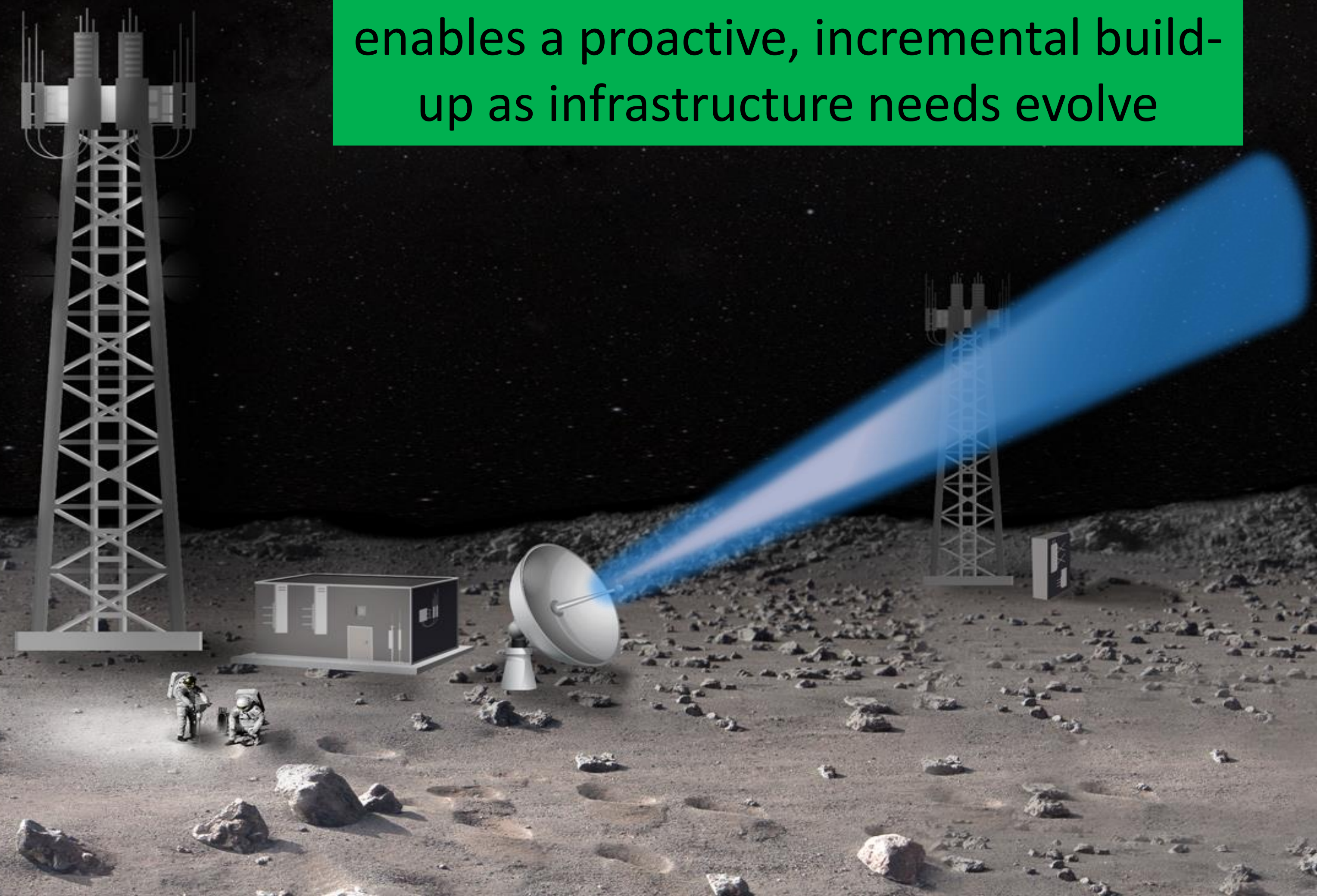
Multiple Base Stations:

- Cross-links connect base stations to *central hub*
  - Surface links via point-to-point, fiber, lunar relay satellite system, or other connectivity
- Base stations beacons enhance surface PNT
- Evolving standards could provide enhanced PNT

3GPP Cellular Non-Terrestrial Networking (NTN) lunar relay augmentation:

- Seamlessly tie to the surface network
- Surface User Equipment routes via relay satellite or base station

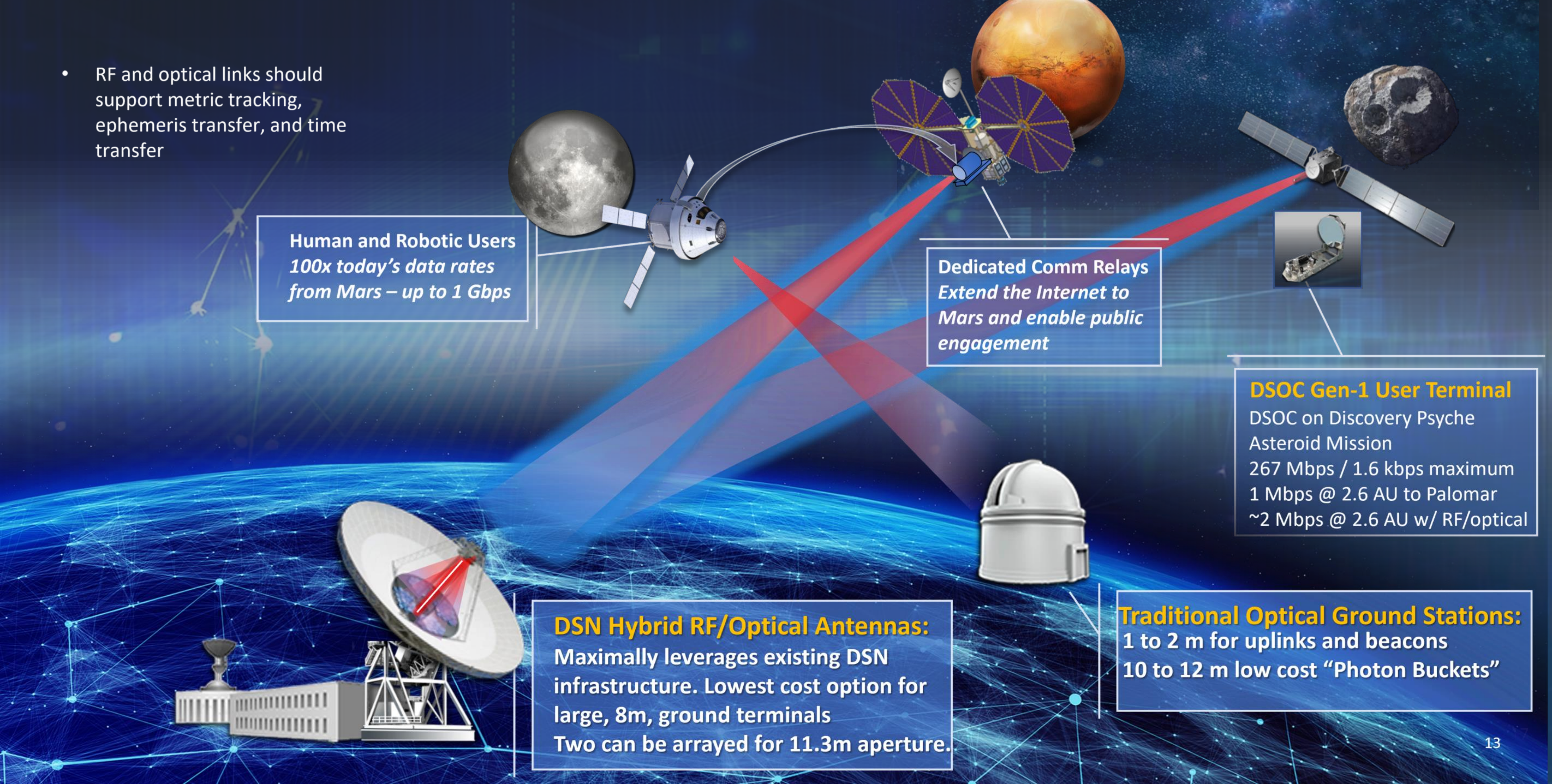
A 3GPP Cellular Lunar Surface Network enables a proactive, incremental build-up as infrastructure needs evolve



Envisioned Future
Deep Space Regime

Deep Space: 2030+ RF and Optical Communications

- RF and optical links should support metric tracking, ephemeris transfer, and time transfer



Human and Robotic Users
100x today's data rates from Mars – up to 1 Gbps

Dedicated Comm Relays
Extend the Internet to Mars and enable public engagement

DSOC Gen-1 User Terminal
DSOC on Discovery Psyche Asteroid Mission
267 Mbps / 1.6 kbps maximum
1 Mbps @ 2.6 AU to Palomar
~2 Mbps @ 2.6 AU w/ RF/optical

DSN Hybrid RF/Optical Antennas:
Maximally leverages existing DSN infrastructure. Lowest cost option for large, 8m, ground terminals
Two can be arrayed for 11.3m aperture.

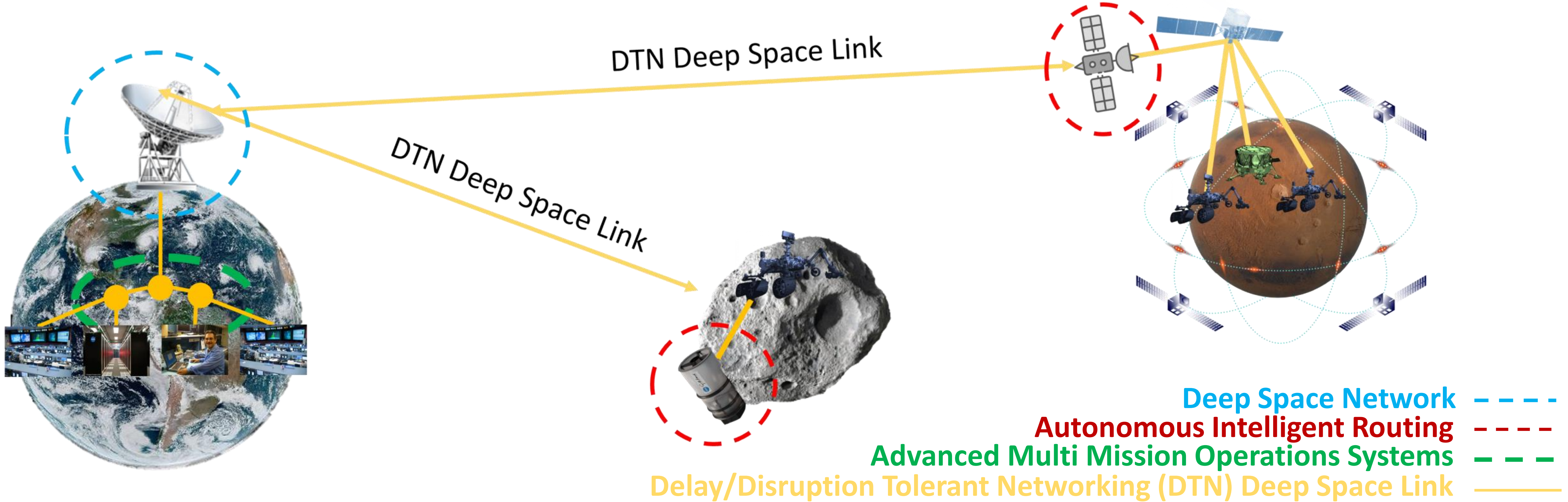
Traditional Optical Ground Stations:
1 to 2 m for uplinks and beacons
10 to 12 m low cost "Photon Buckets"

Deep Space: 2030+ DTN, Operations, and Navigation

Space-based Disruption / Delay Tolerant Network (DTN) links will be RF and optical. DTN nodes need to have an onboard capability to process trajectories, telecom capabilities, and schedules for all active assets, then be able to decide the most appropriate path for communications. Also, they will need to ensure time coordination. They must also be able to point antennas and optical communications telescopes. Enables:

- Fewer ground antennas and optical communications telescopes for more spacecraft
- Elimination of manual scheduling & contact graph routing.
- More responsive communications & navigation.

Deep Space Network (DSN) continues to provide ranging, Doppler, and Delta-DOR (Differential One Way Ranging) to support navigation



Recent RFIs and Interoperability Activities

- Lunar Communications Relay and Navigation Services
  - *[Seeking]* information from potential providers of space communications relay and navigation services in support of the Artemis program and its planned missions to the Moon; closed 2020-10-30
- Communications Services Project (CSP)
  - *[Seeking]* commercial TDRSS replacement for Earth-based relay services through staged sequence of capability demonstrations via Funded Space Act Agreements (FSAAs); closed 2021-09-03
- Near Space Network Services (NSN)
  - Sources Sought Notice (SSN) for capabilities, ideas and information that will lead to commercialization of the Near Space Network (NSN) Communications and Tracking services to support multiple missions across the full NASA portfolio to include LEO, MEO, GEO, Sun/Earth L1, L2 and Lunar orbital regimes; closed 2021-10-22
- Draft LunaNet Interoperability Specifications
  - *Living* document meant for technical industry members to provide feedback on NASA's plan for communications and navigation interoperability at the Moon
- Primary Reference Oscillator for Onboard Navigation
  - Industry poll for mid/high performance local spacecraft oscillators (clocks) for cis-lunar and lunar applications; closed 2021-12-08
- Near Space Network Services (NSN) solitication (draft)
  - *[Seeking comments on]* acquisition of Communications and Navigation services to support multiple customer missions across the full Near Space Network portfolio to include Low Earth Orbit (LEO), Medium Earth Orbit (MEO), Geostationary Orbit (GEO), and Lunar orbital regimes; closed 2022-07-29.
- Continuing Involvement with the Inter-Agency Operations Advisory Group (IOAG) and the Consultative Committee for Space Data Systems (CCSDS)
- NASA is an official member of the 3rd Generation Partnership Project (3GPP)

3GPP on the Lunar Surface

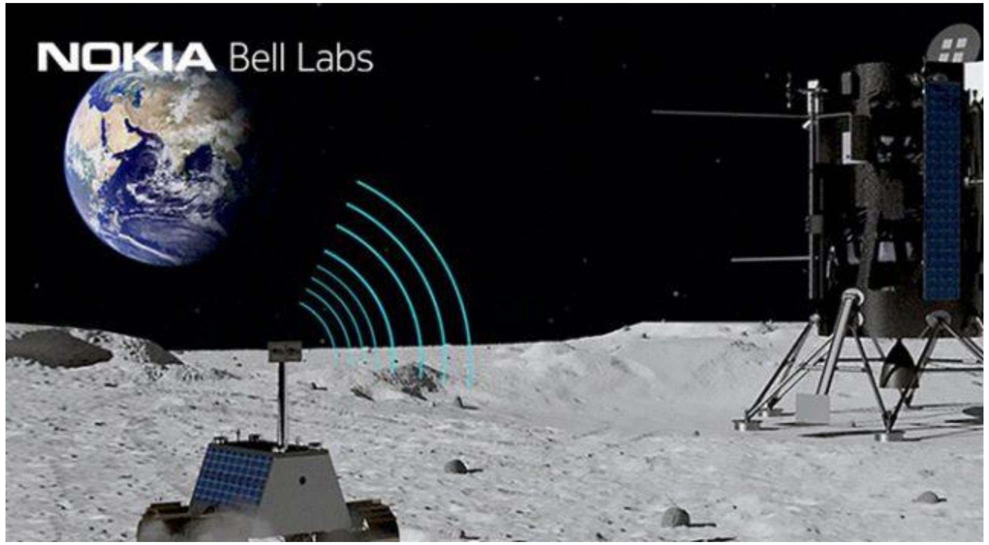
3GPP in the Lunar Environment

NASA awarded a 2020 Tipping Point contract to Nokia Bell Labs to demonstrate space rated 4G/LTE hardware near the Lunar South Pole

- Base station on lander, deployable rover with user equipment (UE)
- Demonstration will support detail analysis into 4G/LTE performance
- Will fly in early 2024 on Intuitive Machines IM-2 mission

NASA has also internally been investigating the use of 3GPP technologies in the lunar environment:

- LunarLiTES: A SCaN effort to emulate and characterize LTE networks within NASA's lunar communications architecture
- CCSDS 883.0-R-1 (2022) recommends interoperable LTE configurations for high-data-rate proximity wireless networks
- Artemis Program Issue Resolution Team Analysis of lunar surface wireless needs against 3GPP capabilities, recommending 3GPP for Artemis-V and beyond
- SCaN/Nokia Bell Labs Artemis-V systems engineering and integration (SE&I) study, estimating system architectures, size/weight/power, cost and schedule to achieve a full 3GPP EVA capability



STMD Tipping Point was awarded to Nokia and Intuitive Machines for a 4G/LTE demonstration on the Moon

While our focus to date has been on 4G / LTE, we think future operational lunar networks will evolve to 5G and beyond

Current 10 km Surface Wireless Gap

Current Artemis Surface Communications Architecture

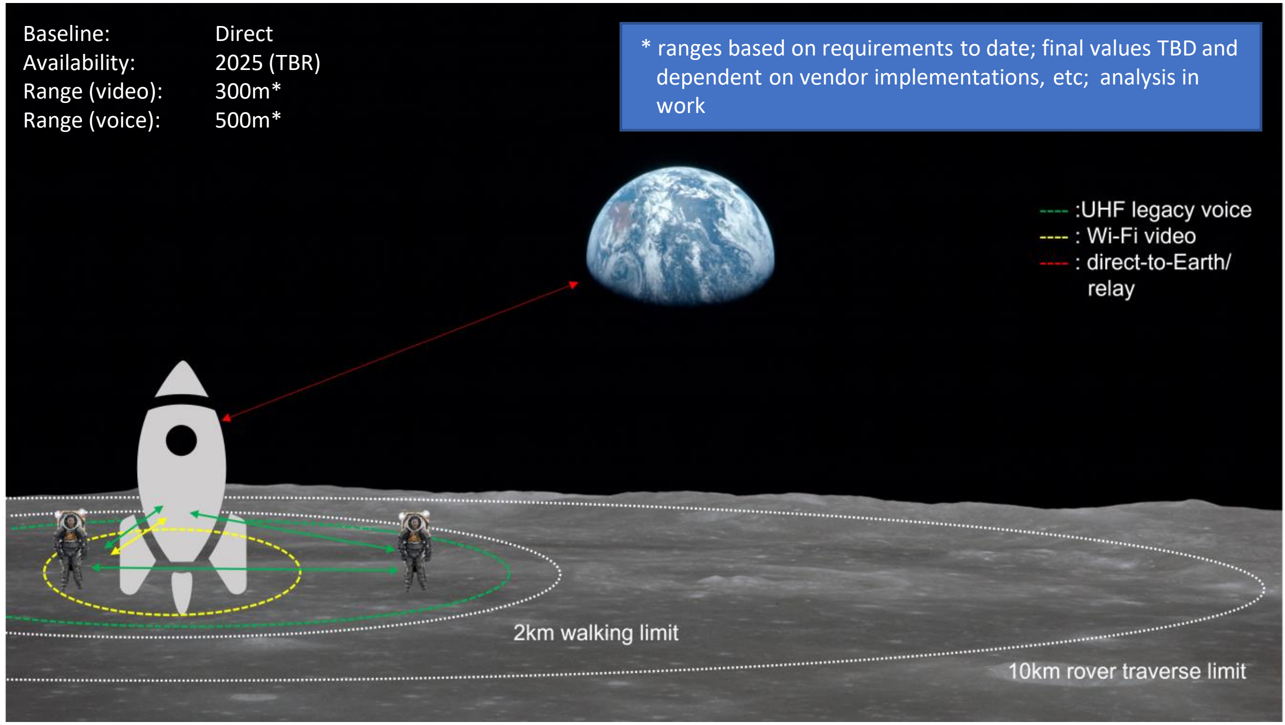
- Wi-Fi for video and legacy UHF for Voice
- Range requirements of 300m (video) to 500m (voice), dependent on vendor antenna choice, placement, max radiated power, etc.

Current Artemis surface communications architecture ***does NOT meet*** the Lunar Terrain Vehicle (LTV) 10 km traverse limit requirement

- Point-to-point links scale poorly, demanding additional capacity and management effort

3GPP equipment preferred for operational deployment

- Supports high throughput while mobile
- Provides Quality of Service (QoS) provisions for different kinds of traffic, e.g., mission critical voice vs. science video, etc.
- Proven technology in multipath environment
- Scales capability as assets are added
- Interoperable with international partners
- Efficient and responsible use of spectrum resources
- Leverages terrestrial commercial advancements for affordability
  - Future PNT and Sidelink/V2X functions of great interest.
  - Non-Terrestrial-Networking (NTN) could be employed by future Lunar relays to provide ubiquitous Lunar comm



Current Artemis Surface Communications Architecture

In the 21st century, NASA does not have to invent its own special purpose surface wireless communications system

Lunar Surface Communications via 3GPP

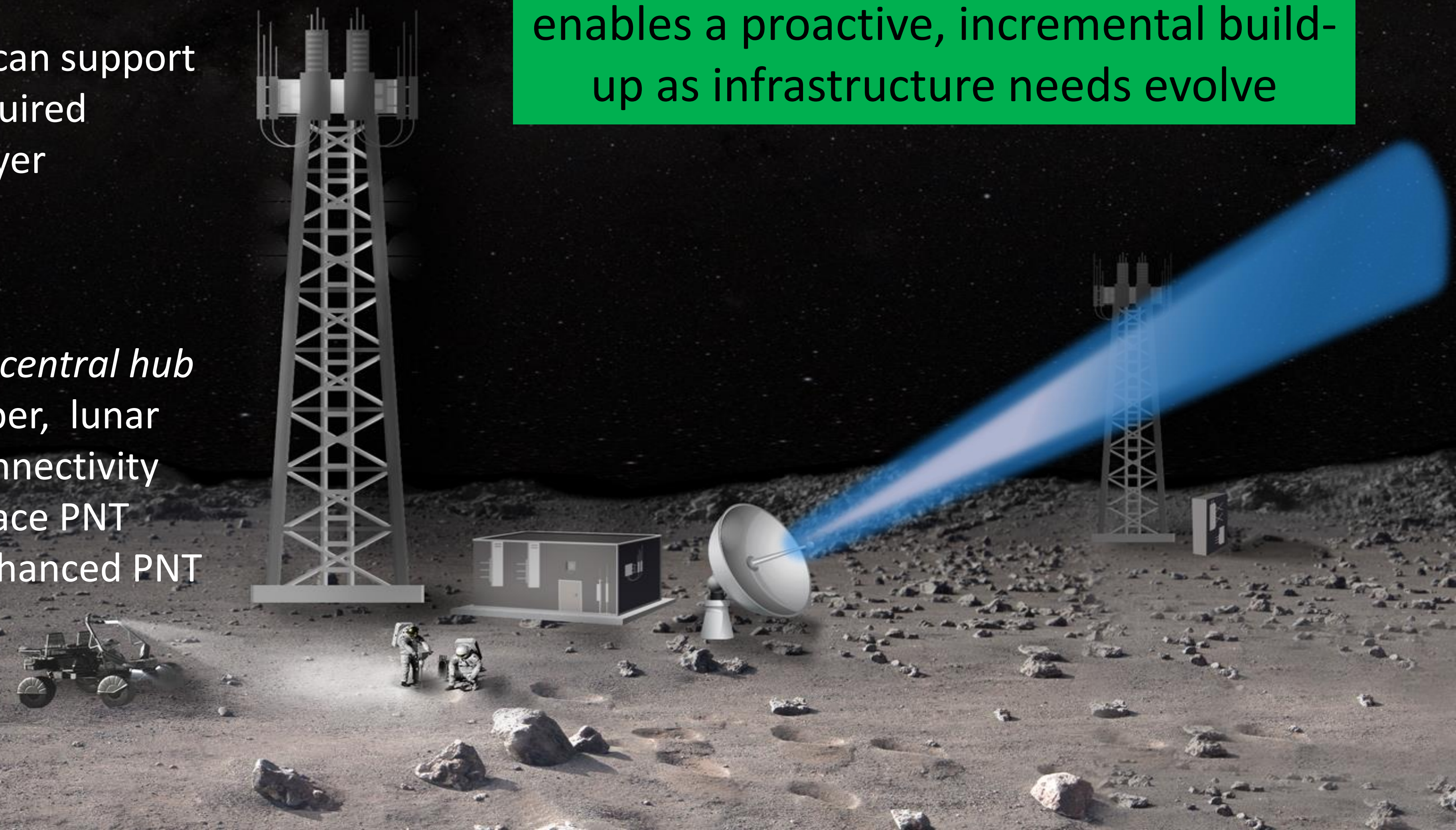
Initial Artemis missions can be supported with one or two base stations, existing host vehicles

- could be integrated on the HLS/LTV
- 3GPP signals at the hardware level can support improved PNT if protocols pass required measurements from the physical layer

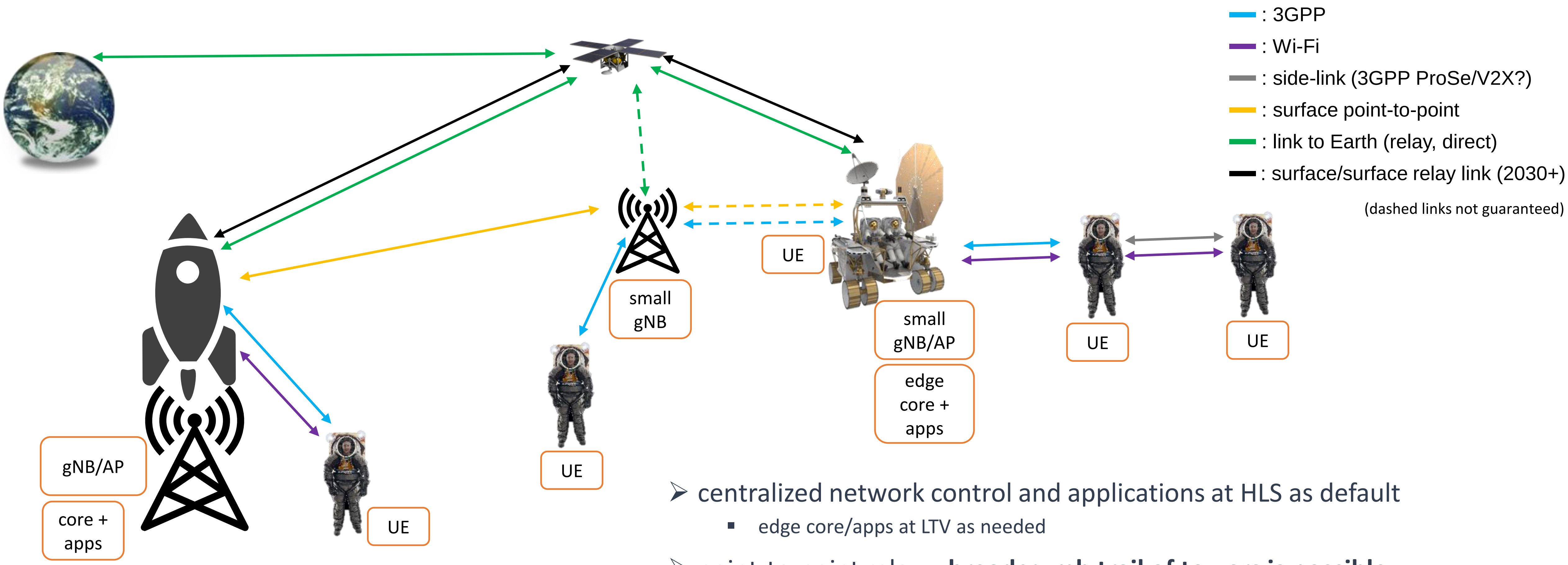
A 3GPP Cellular Lunar Surface Network enables a proactive, incremental build-up as infrastructure needs evolve

Multiple Base Stations:

- Cross-links connect base stations to *central hub*
  - surface links via point-to-point, fiber, lunar relay satellite system, or other connectivity
- Base stations beacons enhance surface PNT
- Evolving standards could provide enhanced PNT



Artemis V + Architecture (notional)



- centralized network control and applications at HLS as default
  - edge core/apps at LTV as needed
- point-to-point relay – **breadcrumb trail of towers is possible**
  - may also use orbital relay between select elements (e.g., LTV, HLS) in LCRNS evolved operating capability (2030+)
- all users/elements connected with low latency
- seamless handover between gNodeBs
  - no data loss
  - connection is maintained and IP address does not change

Gap Closure: From 4G Tipping Point to Artemis V

Lunar LTE Tipping Point

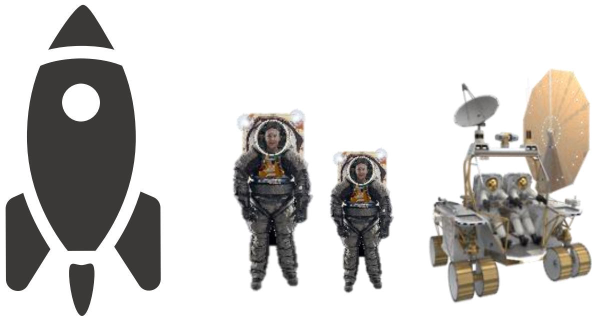
- Robotic-class
- Single band (non-compliant)
- Older 3GPP release (4G)

Interim Goals:

- Build industry experience supporting human missions with 3GPP
- Build NASA confidence in 3GPP for mission-critical applications
- motivate the lunar spectrum push
- build the Artemis V feature set

…. suggests A-III/A-IV demonstrations

Artemis Base Camp (multi-tower)



Artemis V+ Surface Network

- Human-rated, mission critical
- updated band(s) (SFCG-compliant)
- likely updated 3GPP release

2024

2029

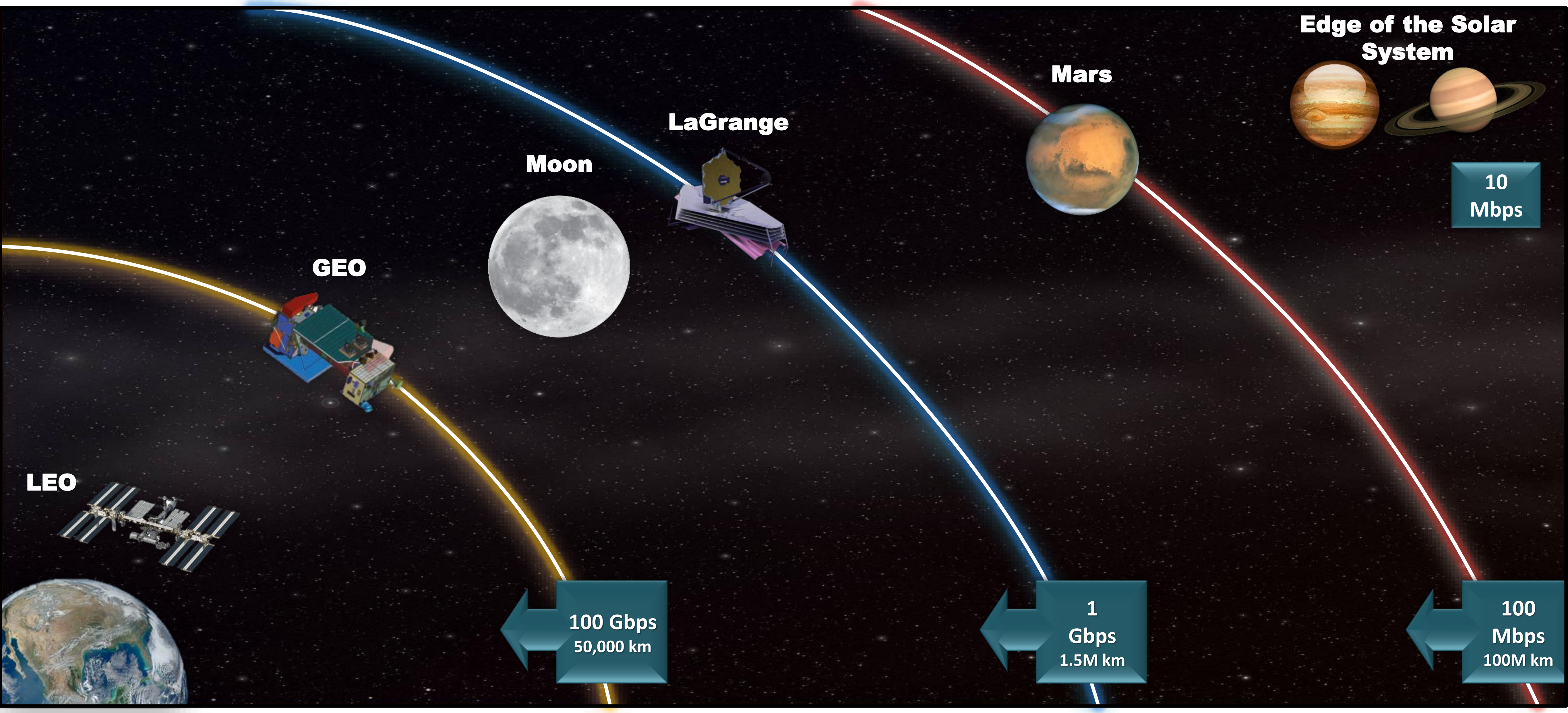
3GPP as
"super Wi-Fi"

3GPP as
"phone company"

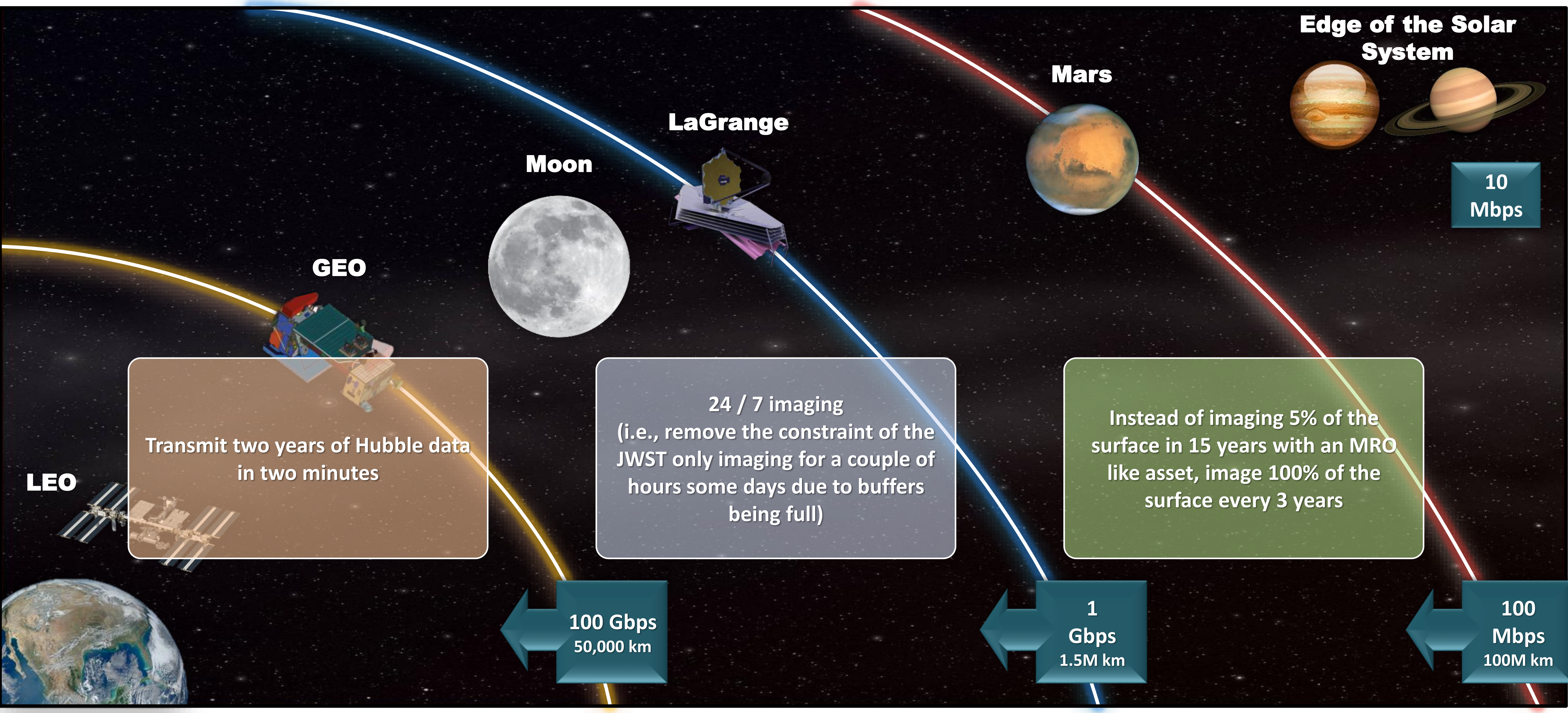
Optical Communications

A Vision for NASA Communications

Contour Map for the Solar System



Notional Examples of the Impact of Achieving the Communications Vision



Near Earth Optical (1 of 3)

Direct-to-Earth User and Ground Terminals – Investments Paving the Way for Future Ops

COTS-based Small User Terminal is demonstrated on the TeraByte InfraRed Delivery (TBIRD) mission

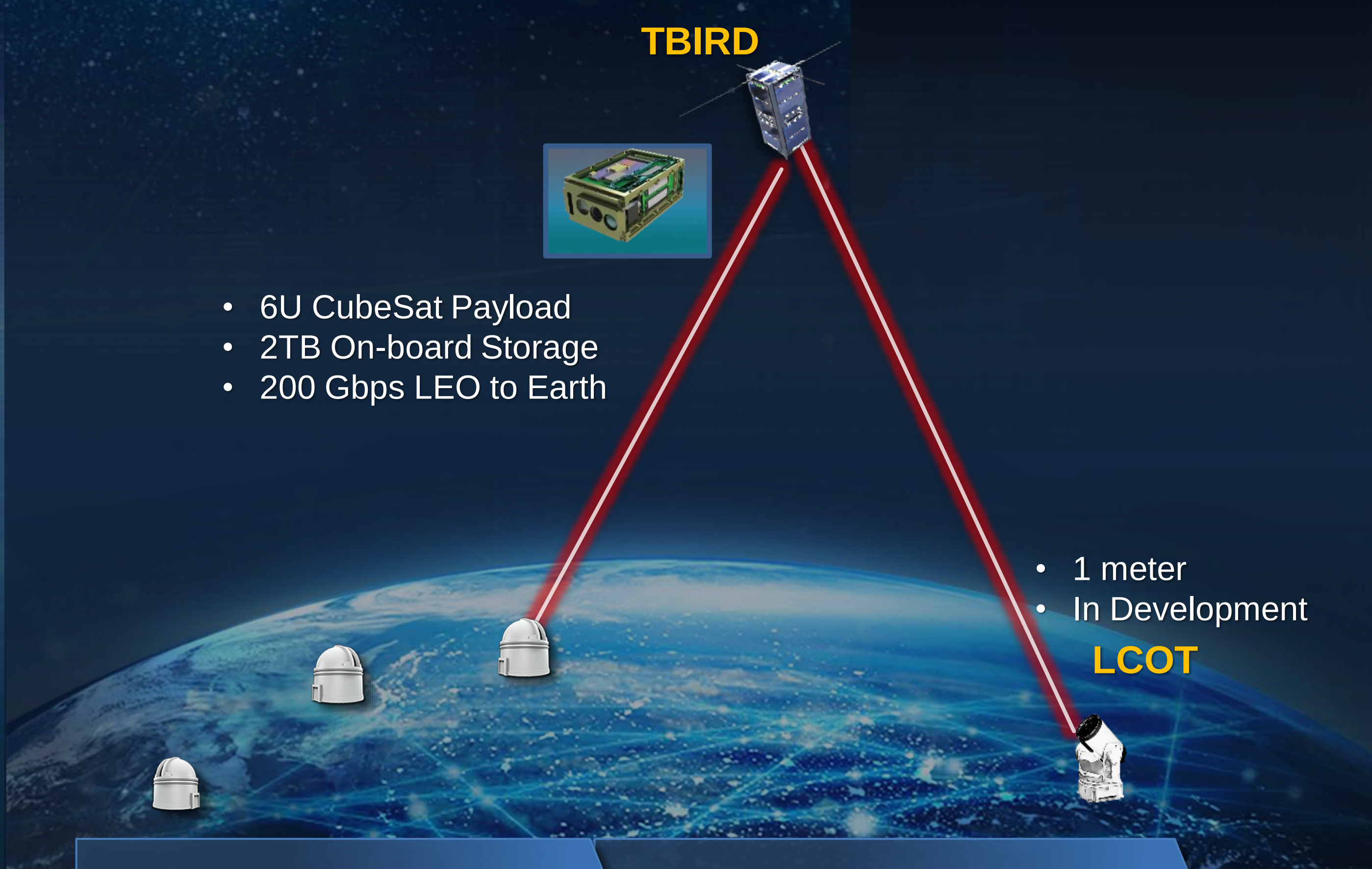
- Launch: May 2022, 6-month primary mission
- Data rate: 200 Gbps
- Collaboration with STMD/SST
- Ready for operational infusion once TBIRD has completed full capability testing

Low-Cost Optical Terminal (LCOT)

- Initial Article: 2026
- 1 m aperture capable of coherent lunar DTE support
  - International collaboration target
- Atmospheric correction system
- In development

Optical Ground Terminals – Need minimum set of ground locations

- Would like to use commercial ground terminals
- *NASA Experimental* optical grounds stations in HI, CA and NM



TBIRD
Launch: May 2022

LCOT
Initial Article 2026

Optical User + Ground Terminals

Near Earth Optical (2 of 3)

Experimental GEO Relay Optical Terminal in Operations

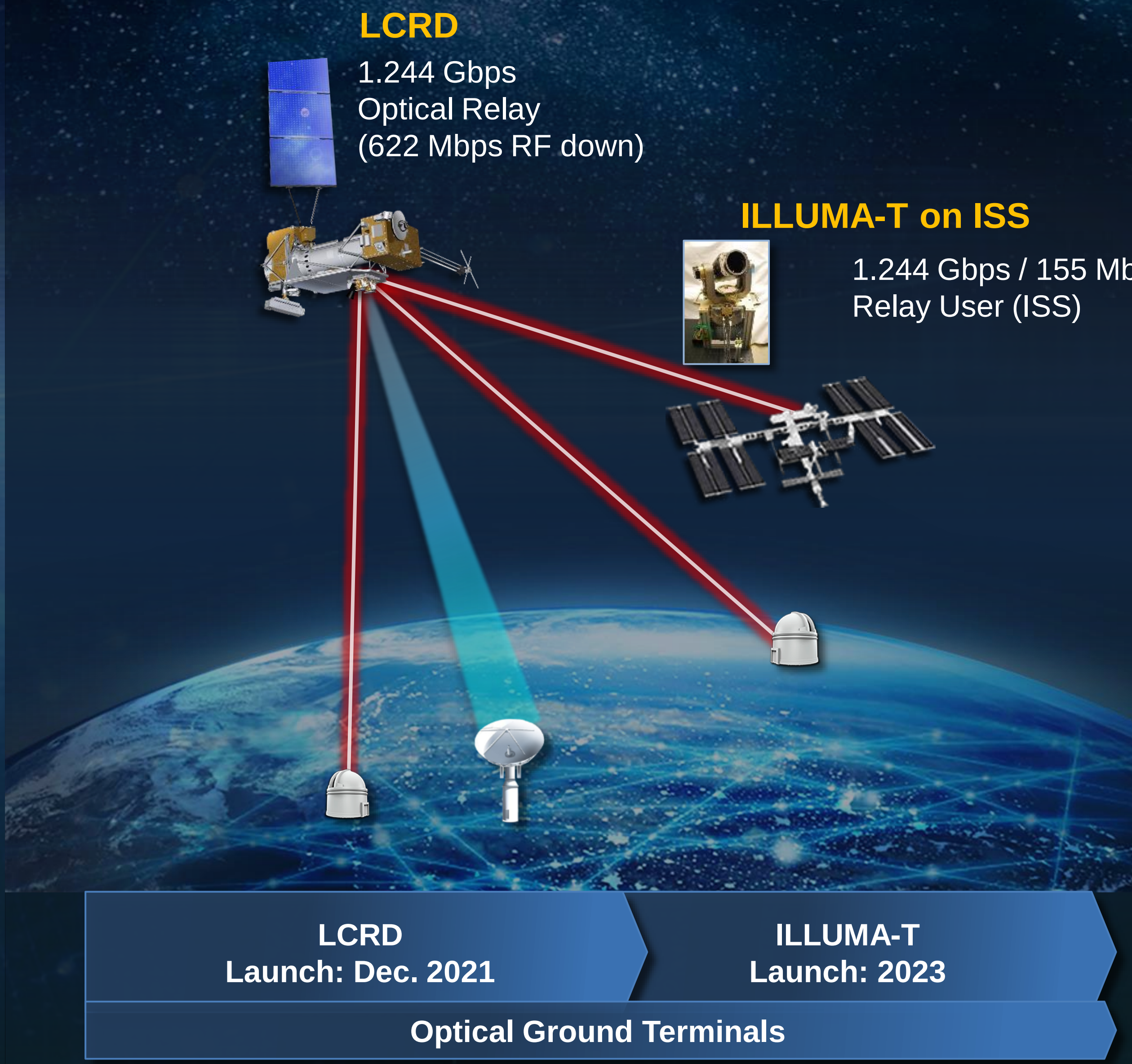
Laser Communications Relay Demonstration (LCRD)

- Launch Date: December 2021
- Purpose: Demonstrate GEO optical relay (Similar to TDRS for RF)
- Hosted payload: US Air Force; STPSat-6 (GEO satellite)
- Date rate: 1.244 Gbps user rate (2.88 Gbps uncoded)

LEO User Relay Terminal ready for Demonstration

Integrated LCRD LEO User Modem and Amplifier Terminal (ILLUMA-T)

- Launch Date: Late 2023 on SpaceX-27 to ISS
- 6-month primary mission
- Purpose: Demonstrate optical communication via GEO relay with ISS/ILLUMA-T as the LEO user



Near Earth Optical (3 of 3)

- Six SATCOM vendors were selected in June 2022 for the first cycle of development and demonstration activities, laying the groundwork to replace TDRS with commercial services
- Two of the six will demonstrate optical communication
- Numerous commercial communications service providers and aerospace companies are developing optical communications with primary focus on intersatellite links

Inmarsat

- Commercial GEO L-band relay network
- Low-rate SATCOM services
- Support to routine missions, contingency operations, launch, ascent, and early operations

Kuiper Government Solutions

- Optical LEO network
- High and low-rate services
- Supporting routine, contingency, and early operations

SES Government Solutions

- GEO and MEO network with C-band and Ka-band
- High and low-rate services
- Supporting routine, contingency, launch and ascent, and early operations

SpaceX

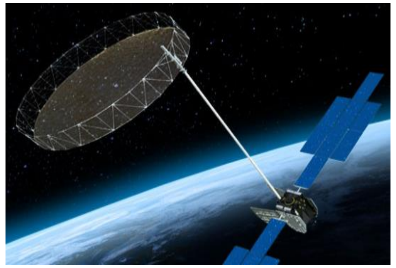
- Optical LEO network
- High-rate services
- Routine, contingency, launch and ascent, and early operations support

Telesat U.S. Services

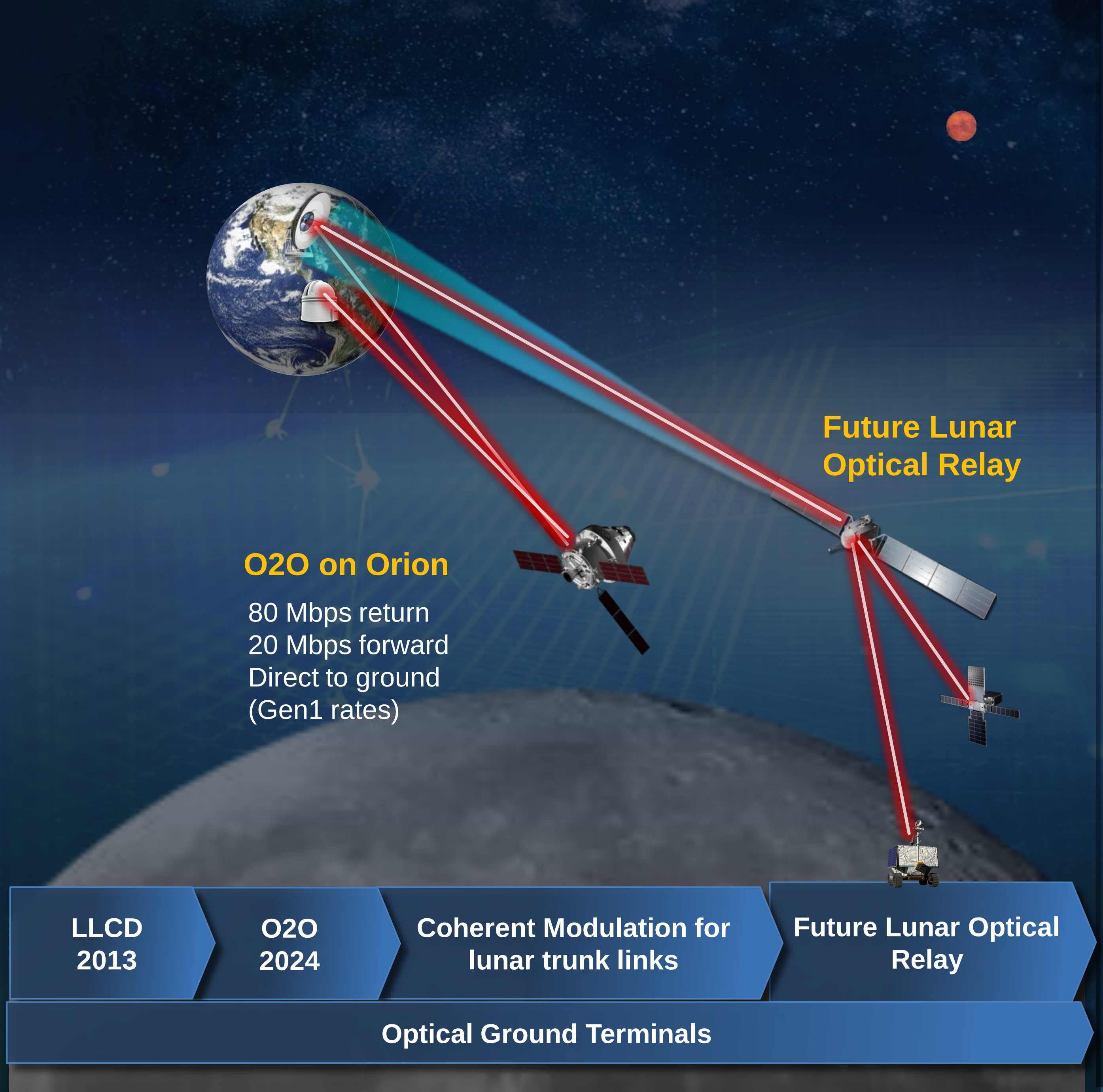
- RF relay networks offering C- and Ka-band services for high and low-rate communications
- Support to routine missions

Viasat

- GEO Ka-band relay network
- High- and low-rate communications services
- Routine launch and mission support



Lunar Optical



Lunar Optical Capabilities ready for infusion with investment and user commitment

Lunar Laser Communications Demonstration (LLCD)

- Launch Date: Sep 2013
- Demonstrated fundamental concepts of laser communications from Moon for Direct-to-Earth links at 622 Mbps

Lunar user optical terminal demonstration on Orion Artemis II Optical (O2O)

- Lunch Date: 2024 (Artemis II)
- Demonstrate crewed DTE optical link capability from Moon
- Enables return of all onboard data before vehicle Earth return

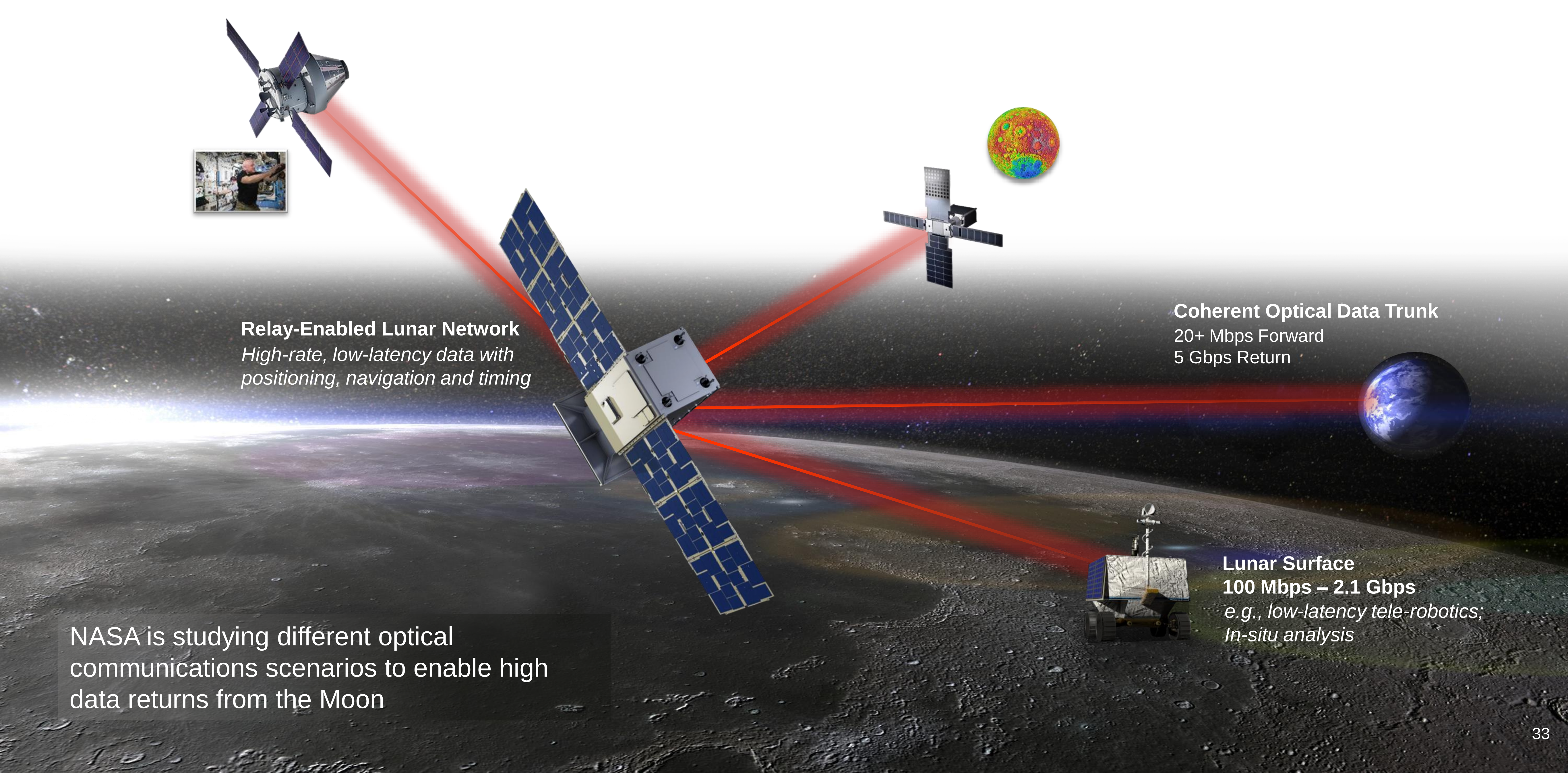
Higher data rates for lunar trunk links

- Current deep space optical links support data rates < 1 Gbps
- Coherent optical links enable 5–10 Gbps from Moon
- Could be available for lunar demo in late 2020s

Lunar Optical Ground Terminals for Artemis

- Existing *experimental* optical ground terminal in HI, CA, and NM
- Would like an additional 3-4 optical ground terminals around the globe to support Artemis; gaining southern hemisphere coverage is especially important

Potential Optical Communications for Future Artemis Missions



Deep Space Optical

Deep Space Optical Capability is ready to be demonstrated; deep space mission adoption to follow

Deep Space Optical Communications (DSOC) on Discovery Pysche Mission

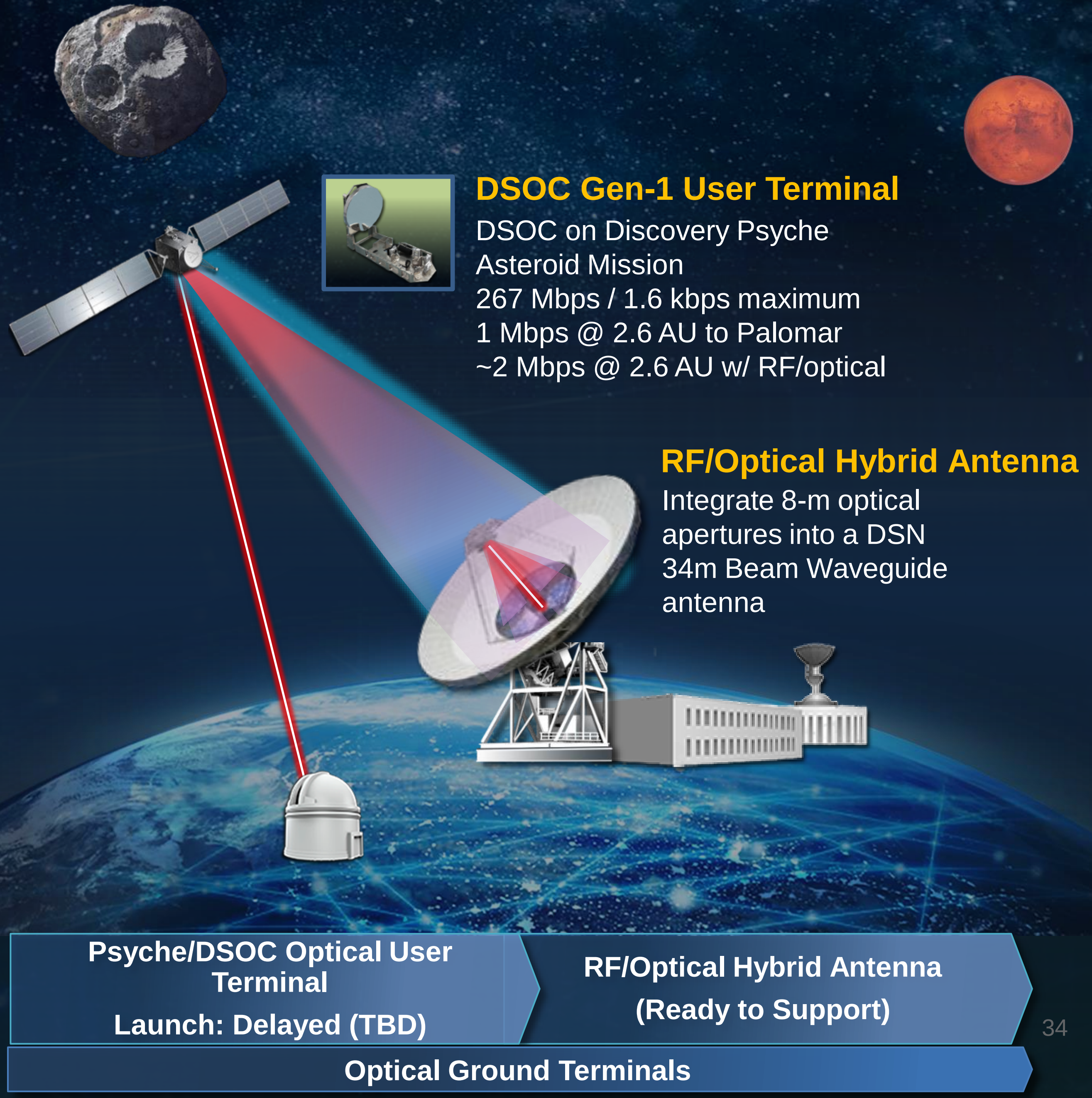
- Launch Date: Oct 2023
- Purpose: Demonstrate deep space optical links on outbound trajectory to 2.6 AU (Mars-far-like distance)
- Collaboration with STMD/GCD and SMD

RF/Optical Hybrid Antenna

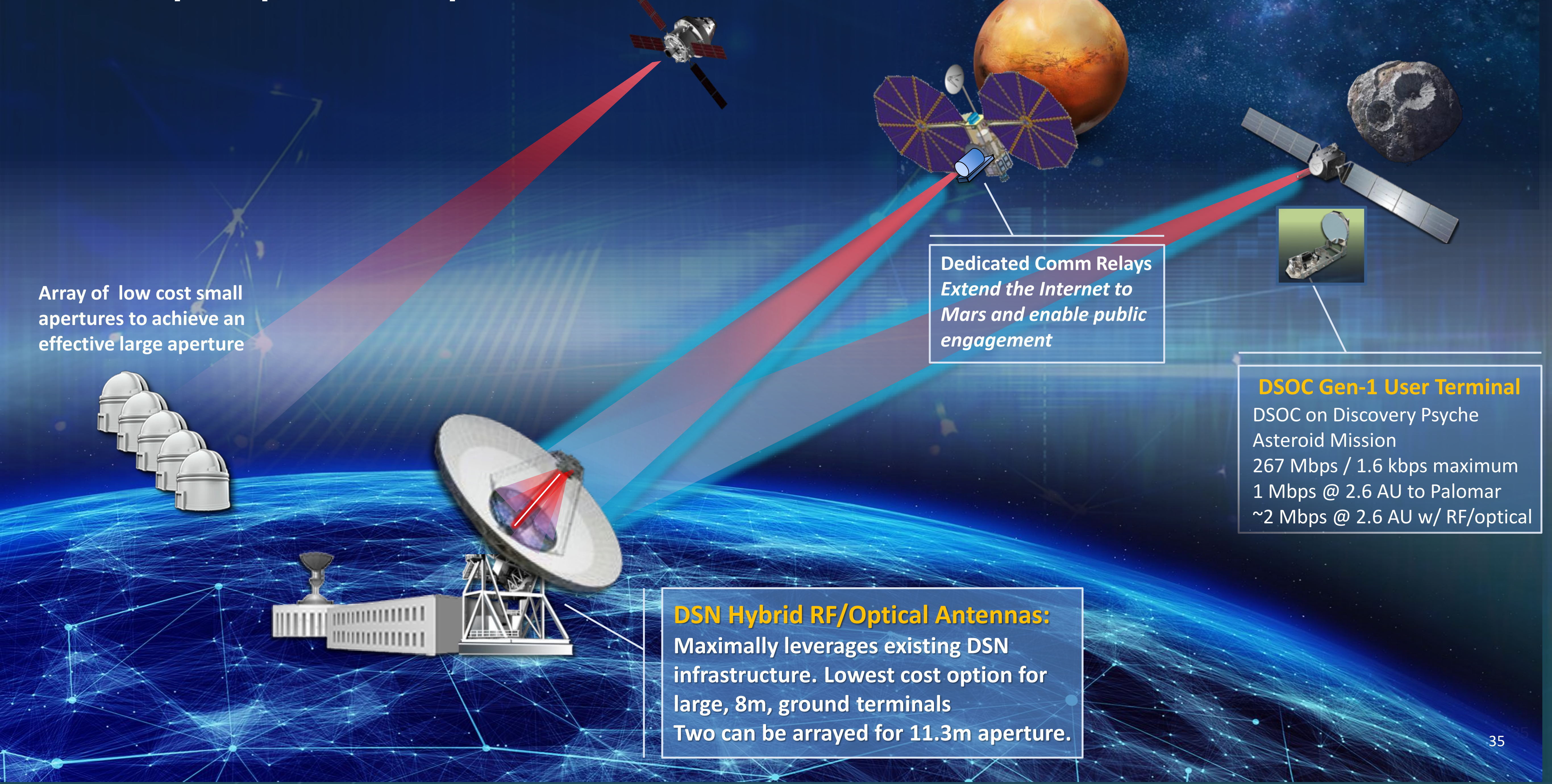
- Lowest cost option for large, 8m, ground terminals
- Two can be arrayed for 11.3m aperture
- Maximally leverages existing DSN infrastructure

Optical will be essential for future human missions to Mars

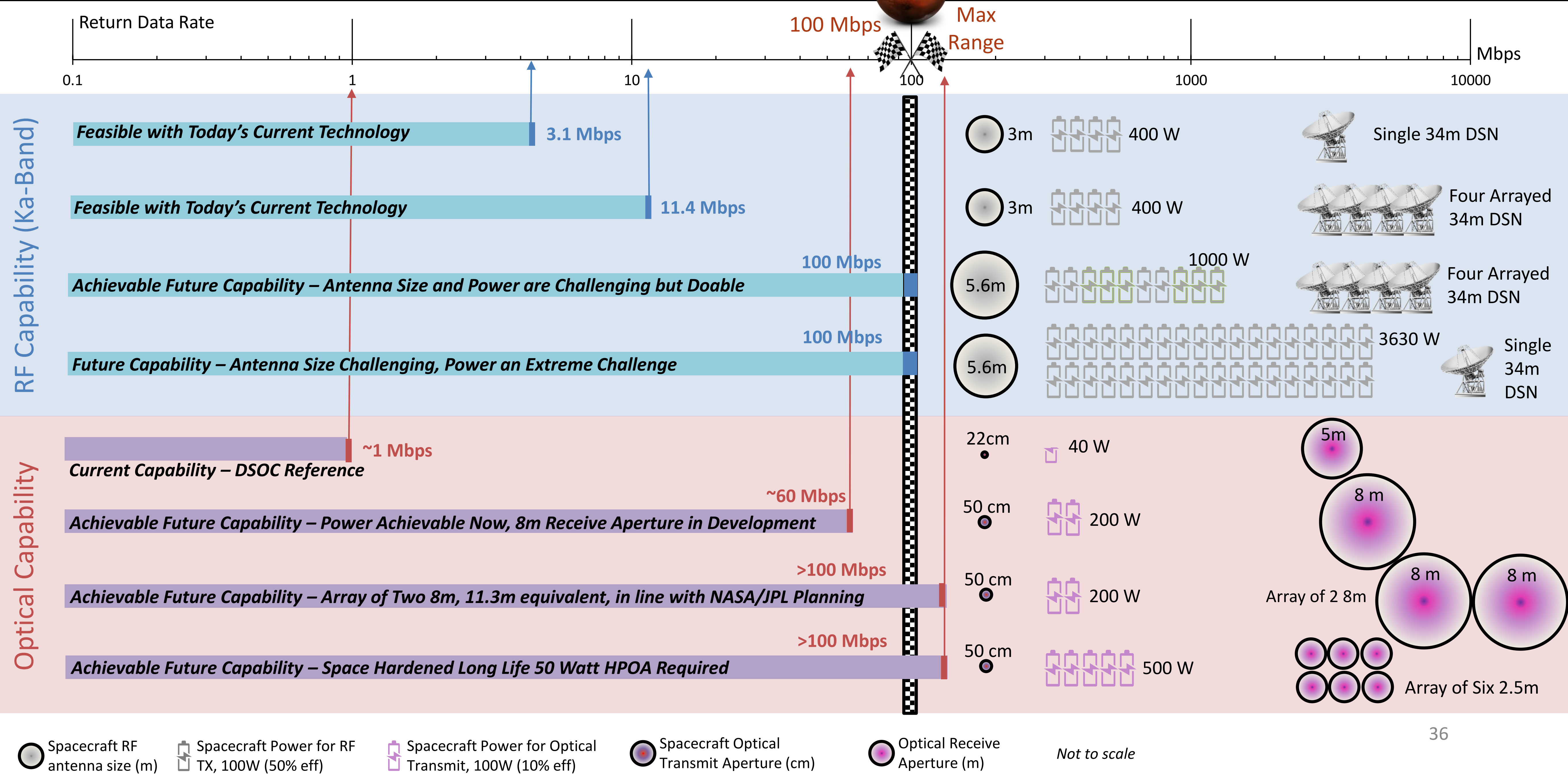
- RF insufficient even for first missions to collect planning data/imagery
- Up/down-link rates needed for crewed operations



Deep Space Optical Architecture



Mars Direct to Earth Example



Technology Needs

Top 3 Overall Priorities That Are Not Funded (1 of 2)

- ❑ 5 to 10 Gbps Coherent Optical Communications Transceiver (GCD)

- ❑ Lunar PNT
  - Precision clocks, network synchronization via simple entanglement (GCD/ECI/ESI)
  - DSACv2+* (TDM)
  - Flight opportunity for cislunar multi-GNSS receiver (NavCube3-mini) prior to lunar communications support

- ❑ Space Qualified 3GPP (5G) Cellular Technology* (GCD/LSII)

Top Priorities That Are Not Funded – by TRL (2 of 2)

High-TRL

1. Flight opportunity for cislunar multi-GNSS receiver (NavCube3-mini) prior to lunar communications support (SST/TDM)
2. DSACv2+ (TDM)
3. Operational Large Aperture Optical Ground Stations (Deep Space)* (GCD)

Mid-TRL

1. 5 to 10 Gbps Coherent Optical Communications Transceiver (GCD)
2. Low-Cost Operational Optical Ground Stations (GCD)
3. Efficient High Power Optical Amplifiers (SBIR/GCD)
4. High-Efficiency Solid-State Power Amplifiers (SBIR/GCD)
5. 20 W Laser Transmitter for > 100 Mb/s from Mars farthest range (GCD/ECI/ESI)
6. Large aperture space terminal (GCD/ECI/ESI)
7. Precision clocks, network synchronization via simple entanglement (GCD/ECI/ESI)

Low-TRL

1. Storage and Network Processing Nodes to support 10 to 100 Gbps Communication Links (GCD/SST)
2. Cognitive radios networking with DTN (GCD/SST)
3. Space Qualified WiFi Technology* (GCD/LSII)
4. Space Qualified 3GPP (5G) Cellular Technology (GCD/LSII)
5. Absorption-Based Quantum Memories (GCD)
6. High Fidelity Entangled and Single Photon Sources (GCD)
7. Low-Cost Space Compatible Cryocoolers (GCD)

Optical Communications

- Space Terminal Technologies
  1. Flexible, power-efficient, coherent transceivers – 5 Mbps to 20 Gbps transmit and receive
  2. Power-efficient optical amplifiers – 20 to 50 W, coherent or low-duty-cycle PPM
  3. Low-mass, low-cost, telescopes with sub-beam-width pointing actuation– 1 mm to 50 cm aperture
  4. Vibration isolation systems for large apertures
  5. Space-compatible photon counters for spatial acquisition (wide field of view) and/or communications (high count rate)
  6. Processing-efficient, power-efficient forward-error correction codes (e.g. 5G codes)
  7. High-bandwidth mass memories for store-and-burst data architectures
  8. Wide-field-of-view multi-access optical communications terminals
  9. Enhanced capability spatial acquisition systems– e.g. beaconless pointing, acquisition without external coordination, utilize optimetrics for navigation
  10. Autonomous onboard observations / measurements from optical links and onboard sensors for onboard navigation
  11. Low-cost lunar surface based optical terminals

- Ground Terminal Technologies
  1. Operational large aperture optical ground stations– 1 m to >5 m, able to operate within ~3 deg of Sun
  2. High-power optical transmitters– 100W to >10 kW
  3. Wide field-of-view narrow band optical filters
  4. Low-cost operational ground stations for mission-specific applications
     - Low-cost 20-70 cm telescopes
     - Efficient multi-spatial-mode receivers
     - Low-cost adaptive optics
  5. Superconducting nanowire single photon detectors
     - Spatially-resolved cameras for spatial acquisition, and adaptive optics
     - High operating temperature for low-cost ground terminals

Networking Technology

1. Storage and Network Processing Nodes to Support 10 to 100 Gbps Links
   - Including DTN processing, and high speed secure DTN bundle protocol
2. Space Qualified Network Implementations to Support High Speed Optical and RF
   - Leverage early work on hardware acceleration via FPGA
3. Interoperable Network Management across Multiple Nodes from Different Providers
   - Security for management interfaces and protocols
4. High Speed Multi-Terabit Radiation Tolerant Mass Memory for Store and Forward
5. Standard Protocols for Dynamic Storage and Bandwidth Allocation for Emergency Communication

Planetary Surface Communications and Navigation

1. Space Qualified WiFi Technology
   - Rad-hard Wi-Fi 6 chipsets for mission-critical local networking (access points and end users)
2. Space Qualified 3GPP (4G and 5G) Cellular Technology
   - Rad-Hard 3GPP eNodeBs/gNodeDs, cores, and user equipment for mission-critical, multi-km class mobile networking
   - Spectrum allocation for multi-band (carrier aggregated) 3GPP lunar surface networking
   - Advanced lunar surface 3GPP propagation models to plan deployments
   - Backhaul solutions for interlinking multiple 3GPP cores to enable lunar surface roaming
   - Self-erecting lunar communication towers to enable 50m-class elevation
3. Through-ice communications
   - Need wireless methods to enable exploration of subsurface oceans away from Earth
   - Magneto-Inductive Antenna Concepts
4. Harsh Environment Communications
   - Need communication systems capable of withstand extreme environments such as those on the surface of Venus
   - All Metal, Multi-beam Steerable Antennas for Harsh Environments Communications and for RF Communications through Hypersonic Plasma
5. Wireless links need to support metric tracking and time transfer wherever possible

Position, Navigation, and Timing

Sensors

1. Lunar capable reduced SWaP-C multi-GNSS receivers
2. Multi-function cameras supporting full 6-DOF
3. Reduced SWaP-C high and extreme stability clocks
4. X-ray pulsar detector
5. Improved and modular LiDAR systems
6. POSE cameras w/ adjustable visible magnitude and near/far-field
7. Reduced SWaP-C accelerometers, and other relevant GNC sensors (*OSAM overlap)*
8. Quantum sensing for nav observables (accelerometers, gyros, combined to IMUs, magnetometers, and gravimeters).
9. Improved clocks capable of extreme stability over both long and short time intervals.

Onboard Processing

1. Advanced filtering & data fusion
2. 6-DOF path planning & closed-loop real-time controllers
3. Multi-spectrum vision-based optical navigation (OpNav)
4. Improved space and surface location algorithms
5. Improved fault detection for autonomous systems

Knowledge

1. Improved time keeping and dissemination systems
2. Improved Cartography and Digital Elevation Map (DEM) generation (*EDL overlap)*

Radio Frequency Communications

1. Multi-Band Radios
2. Multi-Band Antennas:
    - Tri-Band Antennas (S-, X-, and Ka-Band) and tri-band frequency selective surfaces
    - Dual-Band High-Gain Antennas (X- and Ka- or S- and Ka-Band, covering lunar up- and downlinks (full duplex) in both frequency schemes)
3. Ka-band wideband terminal able to communicate with NASA, commercial and DoD nodes (for of support roaming users across multiple systems)
4. Electronically Steerable Phased Arrays for crosslinks and orbit to ground links
5. Flight Receivers for the proposed 22 GHz band and the proposed 27 GHz band
6. Flight Transmitter developments in the proposed 22 GHz band
7. Simultaneous Transmit and Receive (STAR) / In-Band Full Duplex (IBFD) technology (enabling support for more users per frequency band)
8. Low SWAP-C space-qualified rake receiver for CDMA applications to address near/far issues
9. Ultra-High Efficiency Solid-State Power Amplifiers using GaN (>50% would render them competitive with TWTAs)
10. High-bandwidth radio transmitters (>100 MHz to support advanced positioning (Pseudo Noise Delta-DOR) transmissions at Ka-band)
11. Multiple Uplinks per Antenna (MUPA) for DSN ground antennas
12. Compact optical reference cavities for space laser/frequency comb stabilization
    - 10^{-14} stability at 1 s averaging time with <1 l volume, <2 W of power consumption and 10^{-10}/g acceleration sensitivity
13. Spectrally pure oscillators (-120 dBc/Hz or better at 10 kHz offset at 100GHz) for W- and G-band radars & VLBI applications
14. High stability low SWaP W- and G-band clocks for radio occultation
15. High-stability, compact space clock (DSAC v2: order of magnitude smaller SWaP, with performance similar to masers)
16. Opportunistic Multiple Spacecraft Per Antenna (OMSPA) for DSN ground antennas (using post-processing of digitized Ifs)
17. Autonomous onboard observations / measurements from radio links and onboard sensors for onboard navigation
18. Demand Access Communications (spacecraft-initiated, including inter-spacecraft links)
19. Low-cost, reliable, High power-DSN transmitters (based on tubes or solid-state, up to 1 MW at up to 34 GHz)
20. Cognitive and Smart Software Defined Radios (capable of ad hoc networking and cross-platform communications for spacecraft constellations)

Quantum Communications

1. Large aperture space terminal
   - 30-cm considered for LEO TDM and 80-cm considered for MEO M2.0 system. Required for long-haul trunk lines.
2. Large aperture ground terminals
   - Greater than 1 meter apertures and high-performance AO systems that mitigate uplink turbulence via cubesat beacons.
3. Demonstrate the feasibility of using simple entanglement sources to achieve precision clock network synchronization that mitigates the requirement for a wideband mode locked laser comb source
   - Supports GPS-denied PNT
4. Absorption-Based Quantum Memories
5. Low-Loss Optical Switching to Support Multiplexing of Quantum Signals
6. High Fidelity Entangled and Single Photon Sources
7. Flight-qualified SNSPDs for space-to-ground quantum communication demonstrations
8. Low-Cost Space Compatible Cryocoolers
9. Radiation-tolerant time-to-digital converter ASICs for space-to-ground quantum communication demonstrations
10. Ultra-low jitter waveguide SNSPDs for quantum communication at clock rates >20 GHz
11. Integrated photonic circuits for quantum – high efficiency transceivers
12. Doppler shift and synchronization compensators

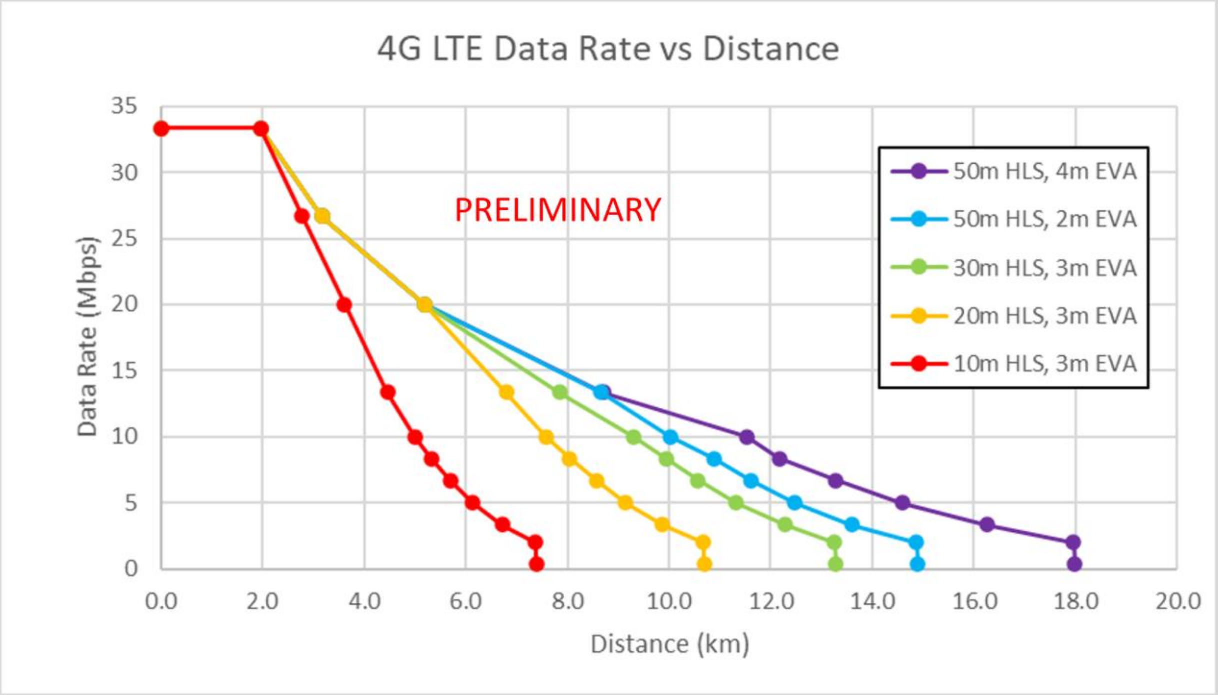
BACKUP

Acronyms

- 3GPP: 3rd Generation Partnership Project
- AO: Adaptive Optics
- ASIC: Application-Specific Integrated Circuit
- CDMA: Code-Division Multiple Access
- CSP: Communications Services Project
- DoD: Department of Defense
- DSAC: Deep Space Atomic Clock
- DSOC: Deep Space Optical Communications
- DSN: Deep Space Network
- EDL: Entry, Descent, and Landing
- FPGA: Field-Programmable Gate Array
- GaN: Gallium-Nitride
- GCD: Game Changing Development
- GEO: Geostationary Network
- GPS: Global Positioning System
- IBFD: In-Band Full Duplex
- LEO: Low Earth Orbit
- LNS: Lunar Network Satellite
- LSII: Lunar Surface Innovation Initiative
- MEO: Medium Earth Orbit
- MUPA: Multiple Uplinks Per Antenna
- NASA: National Aeronautics and Space Administration
- NSN: Near-Space Network
- NTN: Non-Terrestrial Networking
- NRHO: Near-Rectilinear Halo Orbit
- OMSPA: Opportunistic Multiple Spacecraft Per Antenna
- PNT: Position, Navigation, and Timing
- RF: Radio Frequency
- SATCOM: Satellite Communications
- SBIR: Small Business Innovation Research
- SNSPD: Superconducting Nanowire Single-Photon Detector
- SST: Small Spacecraft Technology
- STAR: Simultaneous Transmit and Receive
- STMD: Space Technology Mission Directorate
- SWaP: Size, Weight, and Power
- TDM: Technology Demonstration Missions
- TRL: Technology Readiness Level
- TWTA: Traveling-Wave-Tube amplifiers
- VLBI: Very-Long-Baseline Interferometry

3GPP Range Example – Smooth Moon

- Analysis assumed:
  - Curved surface (lunar diameter, no craters)
  - Various HLS and EVA antenna heights
  - 4G LTE (20 MHz channel) Band 7 (2.5 GHz)
  - +23 dBm UE TX power
  - 7.5 dBi total TX+RX gain
  - shows 1/3 of calculated capacity to guarantee high-criticality application support
  - aggregate capacity over all users shown



(analyses show similar results for 5G configurations)

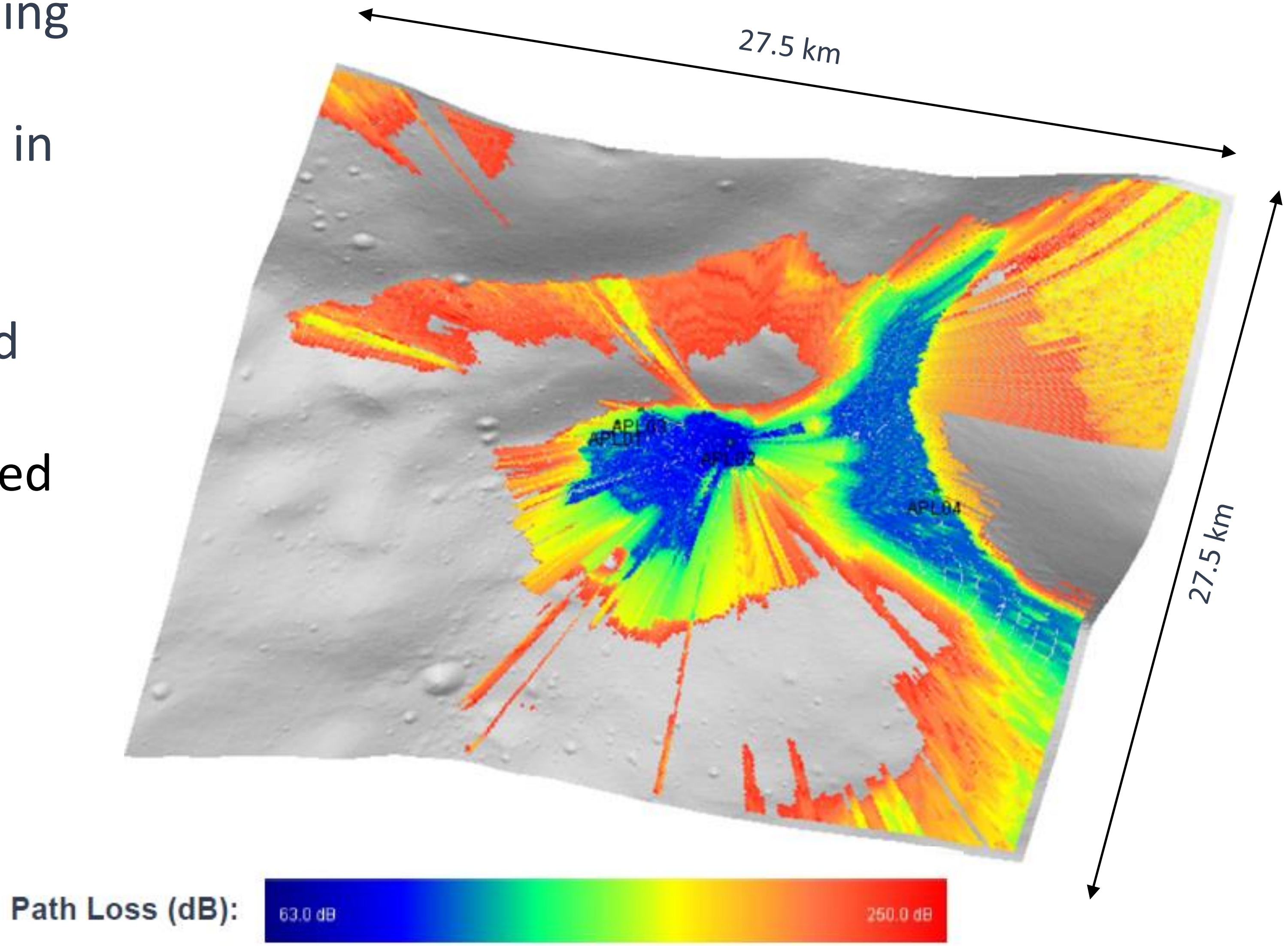
- HLS-EVA max range: 10-12 km (after adjusting to 25m HLS, 2m EVA) without local terrain effects
  - Range is very similar for 5G, but data rates higher with 5G
  - Additional users would not reduce range, but may reduce individual data rates

3GPP Range Example – Realistic Lunar Terrain

- coverage from representative HLS landing site near Shackleton connecting ridge
  - shows dependency on line-of-sight in rugged south pole region

- 30m HLS cell and 3.5m LTV UE assumed

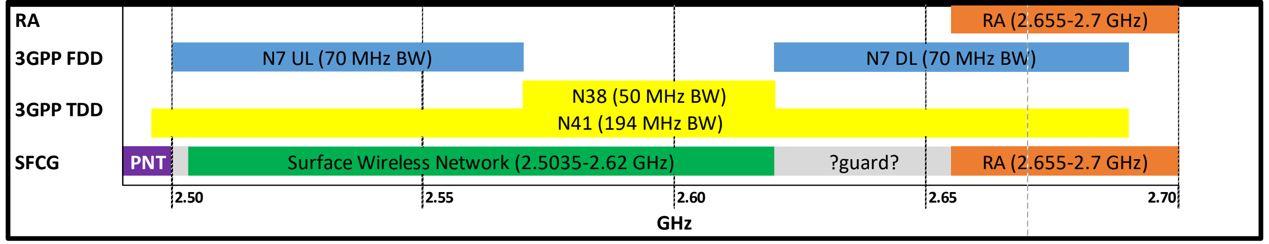
- 3GPP band (2.6 GHz) path loss calculated
  - green/blue easily closed link
  - yellow/orange intermittent, low throughput connectivity
  - red/gray unlikely to close



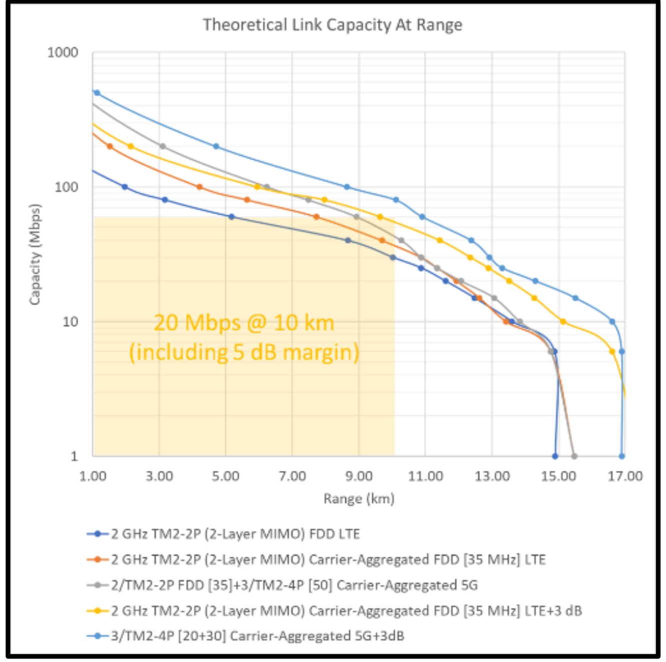
Spectrum & Implementation Options

- NASA is teaming with university experts to study and guide a near-term and long-term implementation approach.
  - University of Colorado Boulder, Simon Fraser University, and the Johns Hopkins University Applied Physics Laboratory
  - Expertise in establishing 3GPP networks in remote locations that emulate the lunar environment
  - Extensive laboratory equipment and testing capability

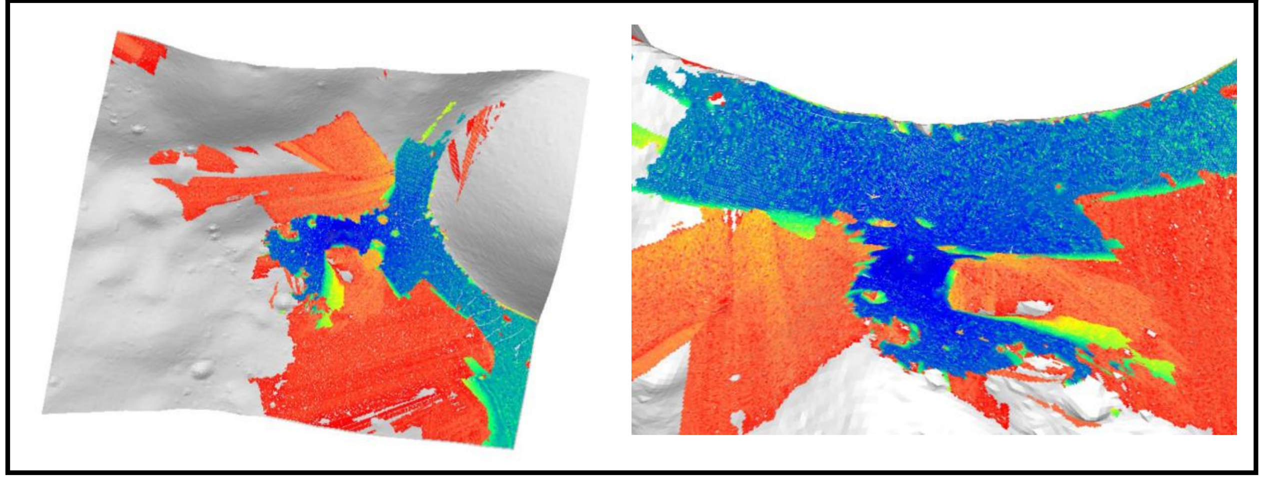
Initial spectrum requests through the SFCG and ITU



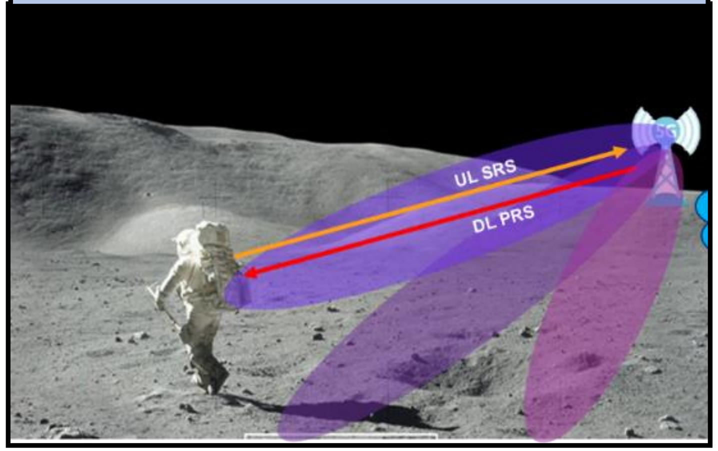
General payload equipment options for Artemis



Initial coverage map analyses



PNT capabilities to enhance LunaNet navigation solutions



Tall Tower Efforts Relevant to a 3GPP Effort

- NASA's Space Technology Mission Directorate (STMD) has 3 companies under contract to build vertical solar array tower prototypes and perform environmental testing (Next Chart)

- NASA's Space Communications and Navigation (SCaN) program is studying the concept of a 10-meter deployable communications and navigation tower on a rover that can be transported over the lunar surface.
  - 10-meters would limit surface 3GPP coverage to about ~5 Km
  - 10-meter tower would be easier to independently land on the surface and transport

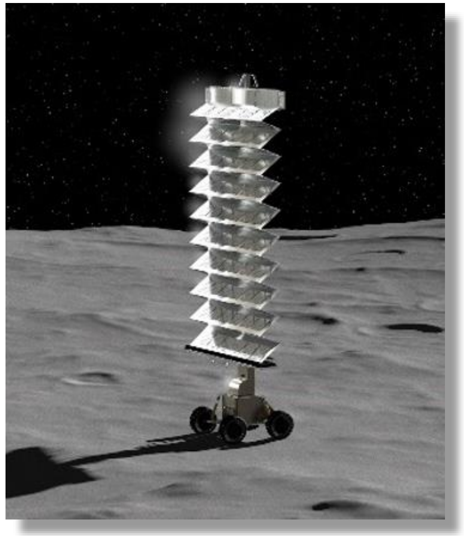
STMD GCD Vertical Solar Array Technologies (VSAT) Program

In August 2022, STMD's Game Changing Development (GCD) program awarded 3 companies to pursue autonomously deployable/ relocatable tower designs (~10-m height) for solar power generation

Astrobotic Technology

Honeybee Robotics

Lockheed Martin



- A 30 m tower located at the proposed Artemis sites at the Lunar South Pole could reduce the period of darkness down to 2-4 days depending on the exact location
- Such a tower could be enhanced with 3GPP equipment to provide more coverage to the lunar surface

Other Lunar Tower Concepts

- A mobile deployable tower could be moved between Artemis missions

- Even small towers would be helpful in closing communications coverage gaps, especially if able to take advantage of terrain

- NASA's Tall Lunar Tower (TLT) In-Space Assembly (ISA) team aims to design, model, fabricate, autonomously assemble, and characterize a TLT engineering development unit (EDU). Cross-cutting truss assembly technology will be developed enabling construction of infrastructure in the lunar environment.