EXPLORESPACE TECH

TECHNOLOGY DRIVES EXPLORATION

EXPLORE: Communications and Navigation
NASA Space Technology Mission Directorate

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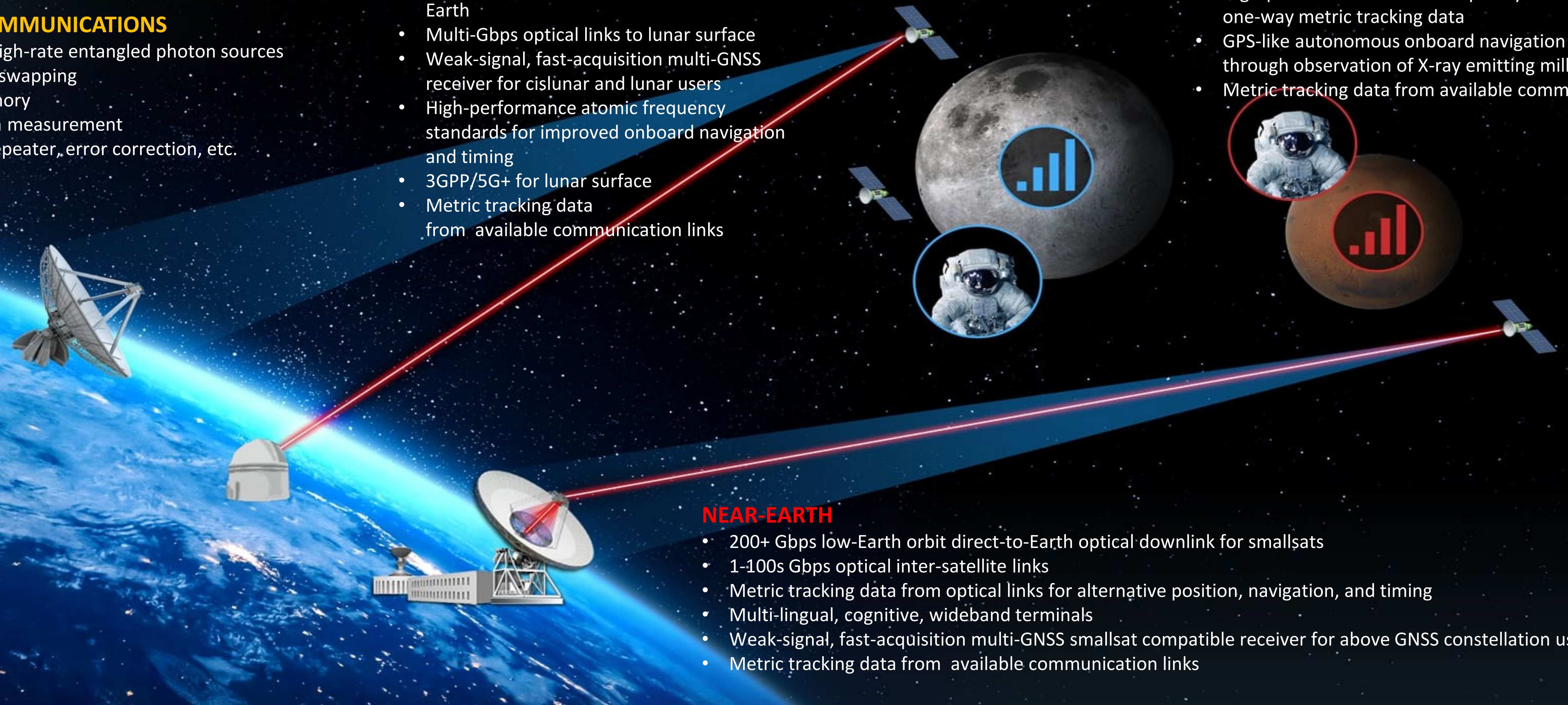
EXPLORE: Develop Next Generation Communications and Navigation Technologies

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



QUANTUM COMMUNICATIONS

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

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

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

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

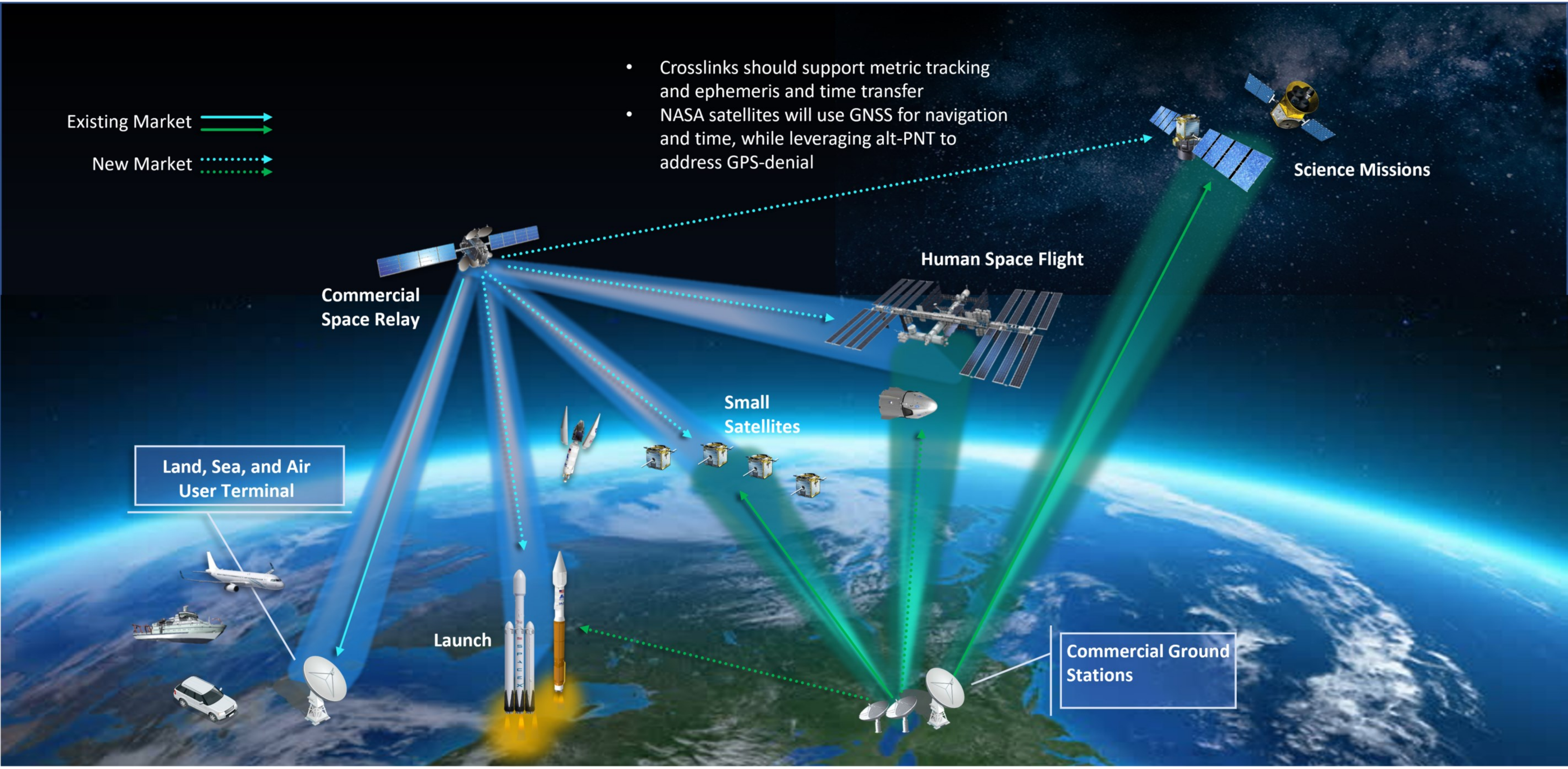
*** Quantum communications doesn’t appear in the near-term Envisioned Future because of its current low TRL. However, NASA is supporting the development of the fundamental technology.

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.

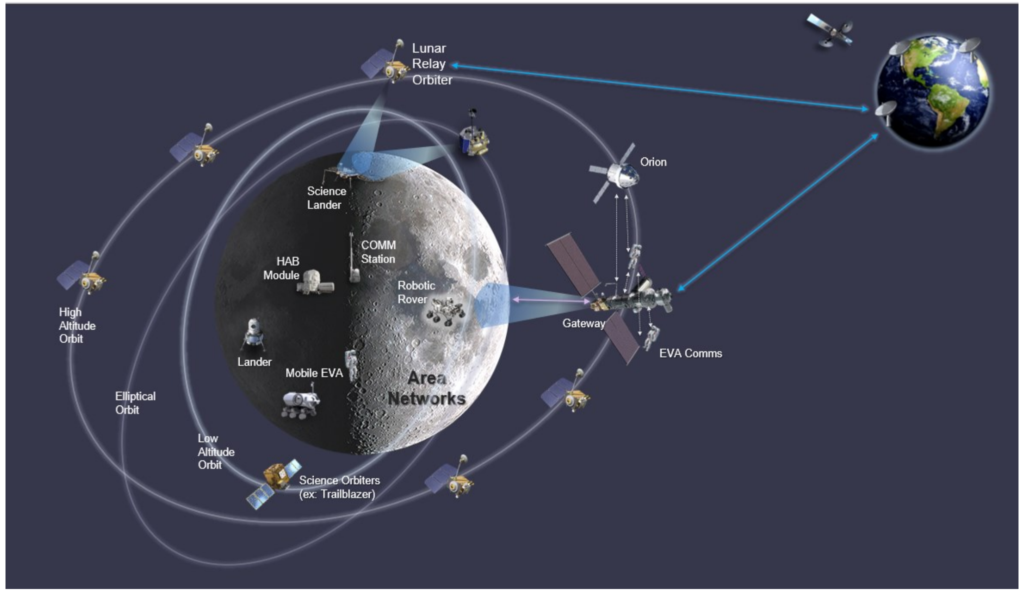
Autonomous decision making for non-routine operations
Artificial intelligence, machine learning, and similar techniques will be needed for user spacecraft to learn appropriate responses to a variety of quality of service impairments including spectral interference, weather, and network configuration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

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

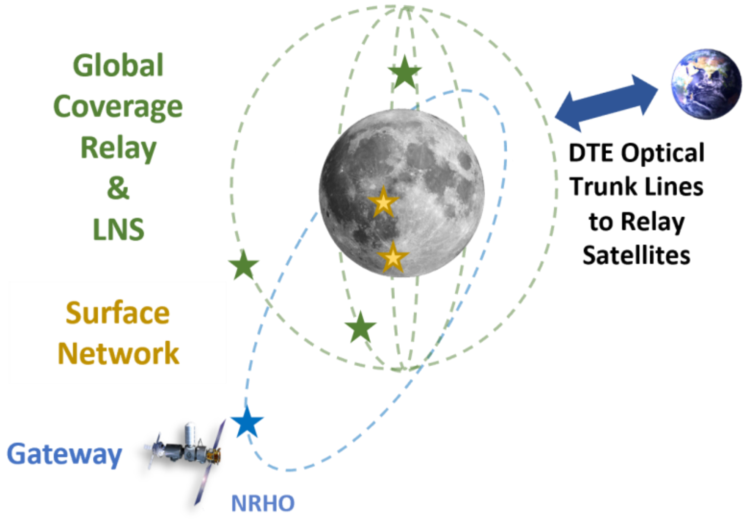


Extending the Internet to the Moon:

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

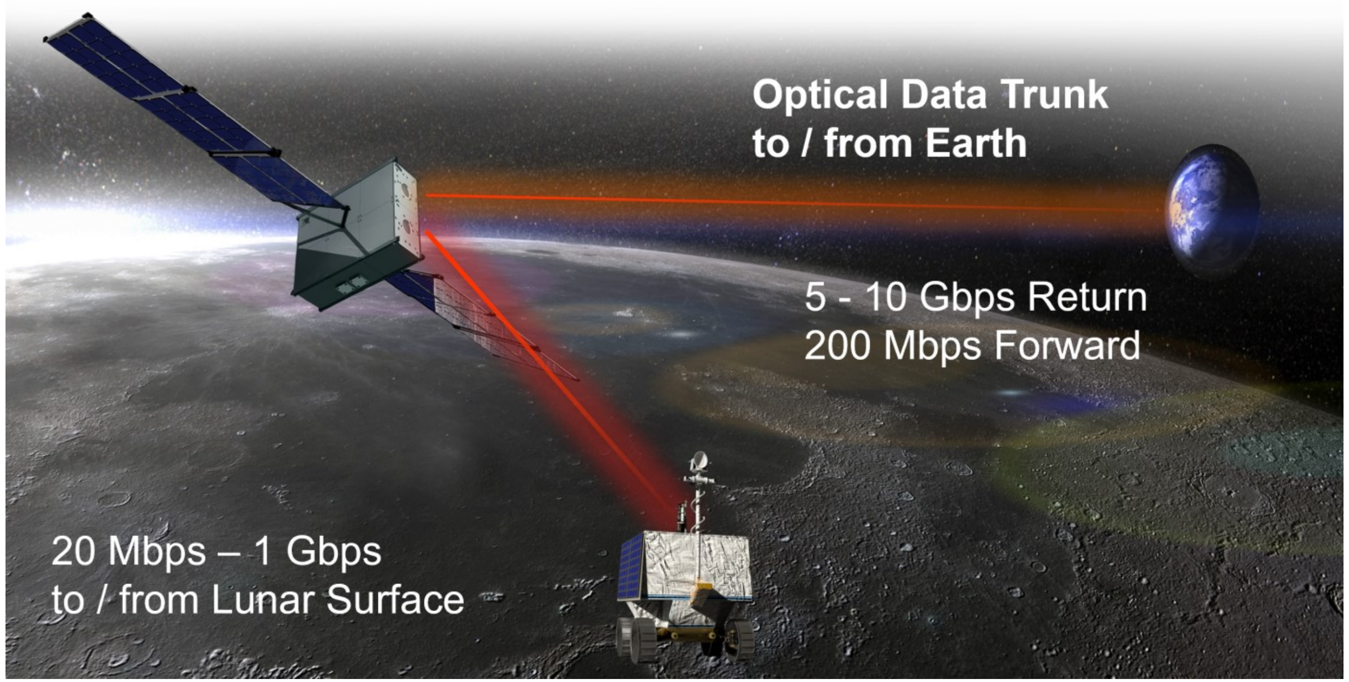
Lunar: 2030+ Lunar Comm & Nav Architecture

Desired State: 2030 and Beyond



- ❑ 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

- ❑ **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: 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

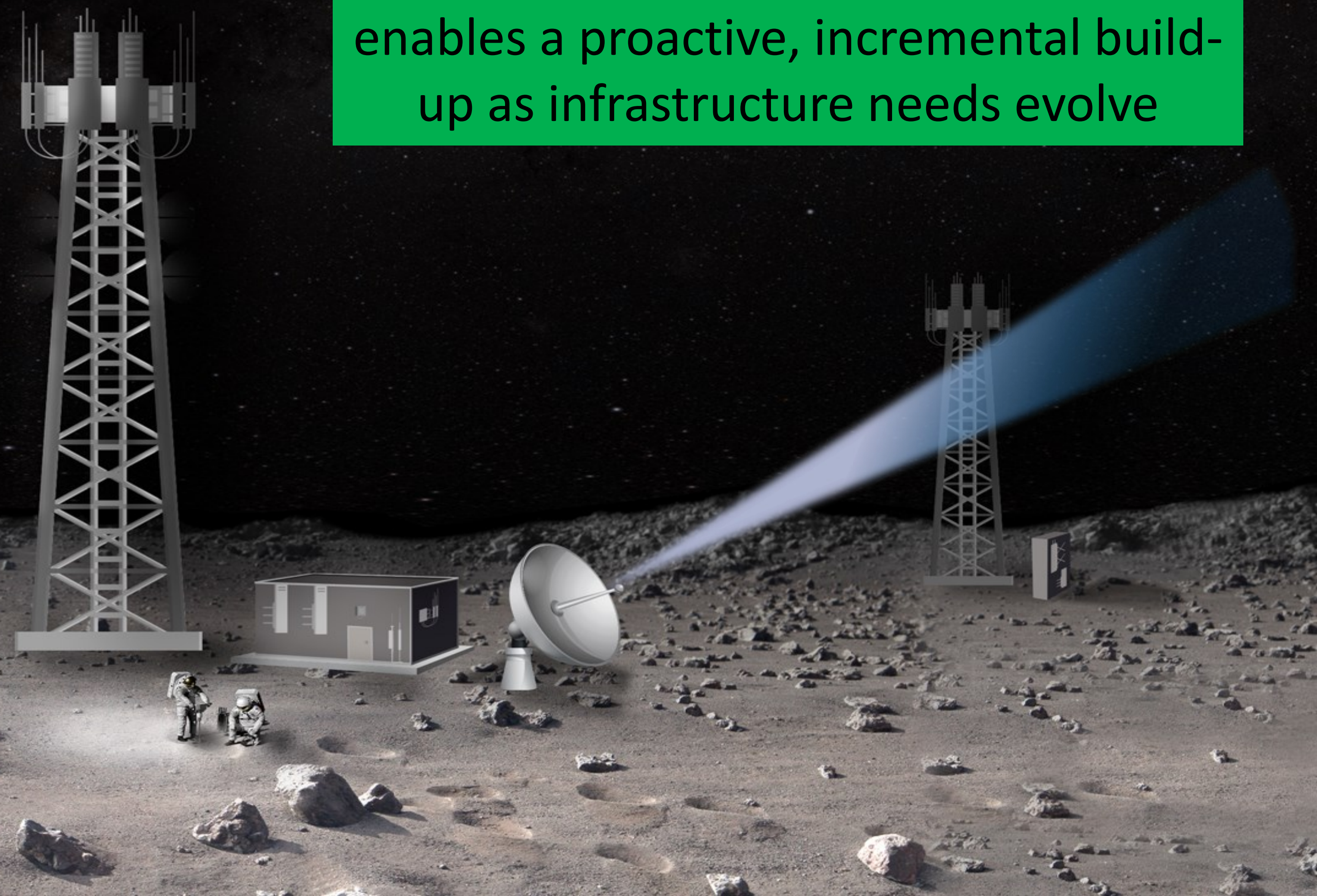
Multiple Base Stations:

- 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

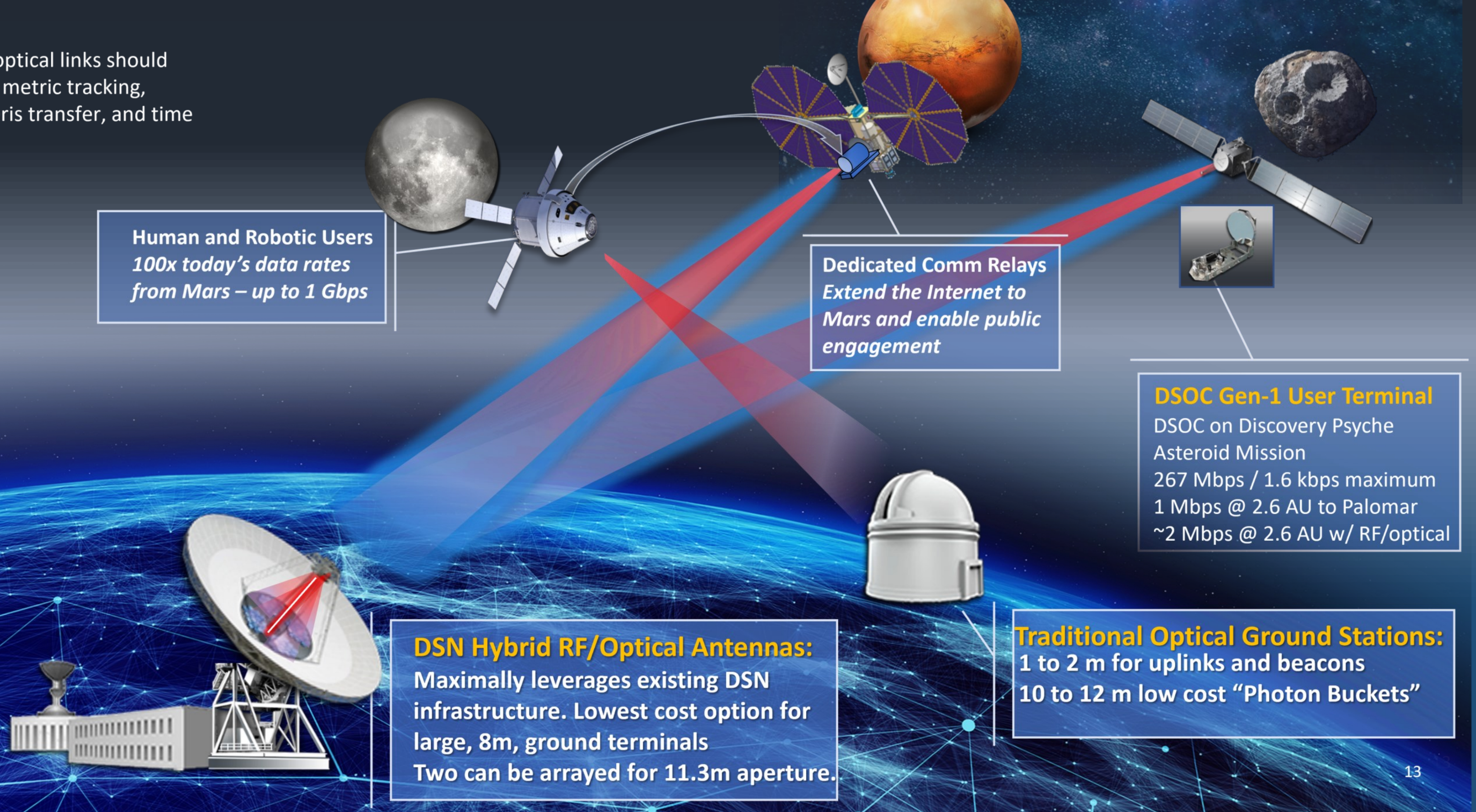
A 3GPP Cellular Lunar Surface Network enables a proactive, incremental build-up as infrastructure needs evolve



Deep Space Regime

Deep Space: 2030+ RF and Optical Communications

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

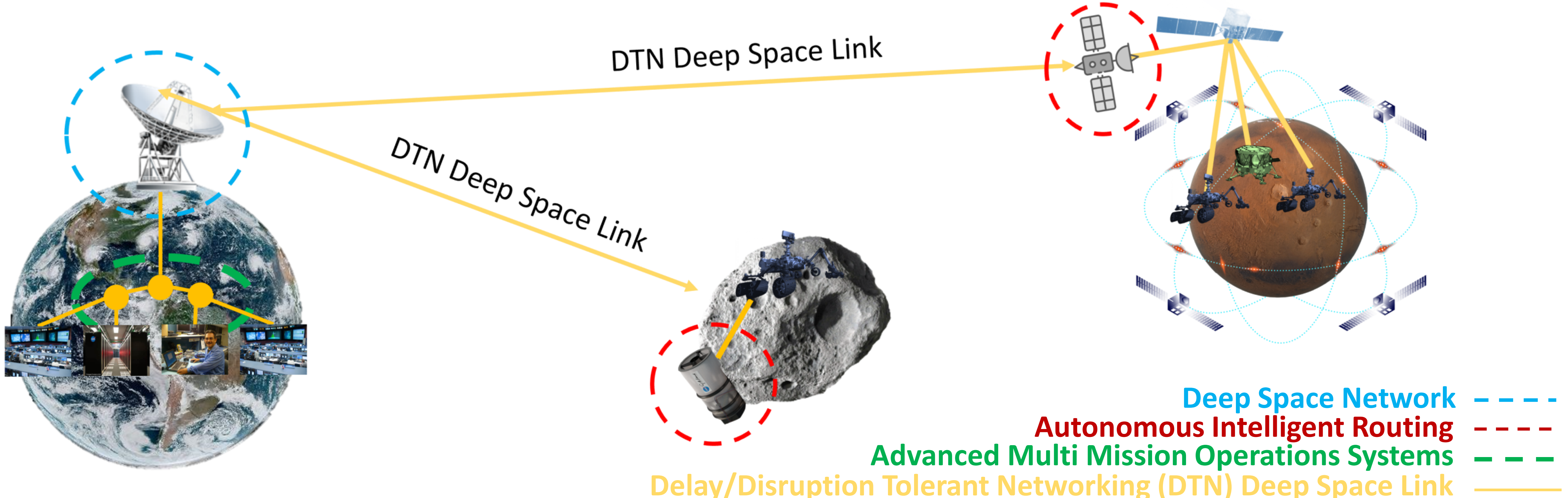


Deep Space: 2030+ DTN, Operations, and Navigation

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)

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

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