

National Aeronautics and
Space Administration



Unlocking New Capabilities in Space Communications for NASA

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Outline

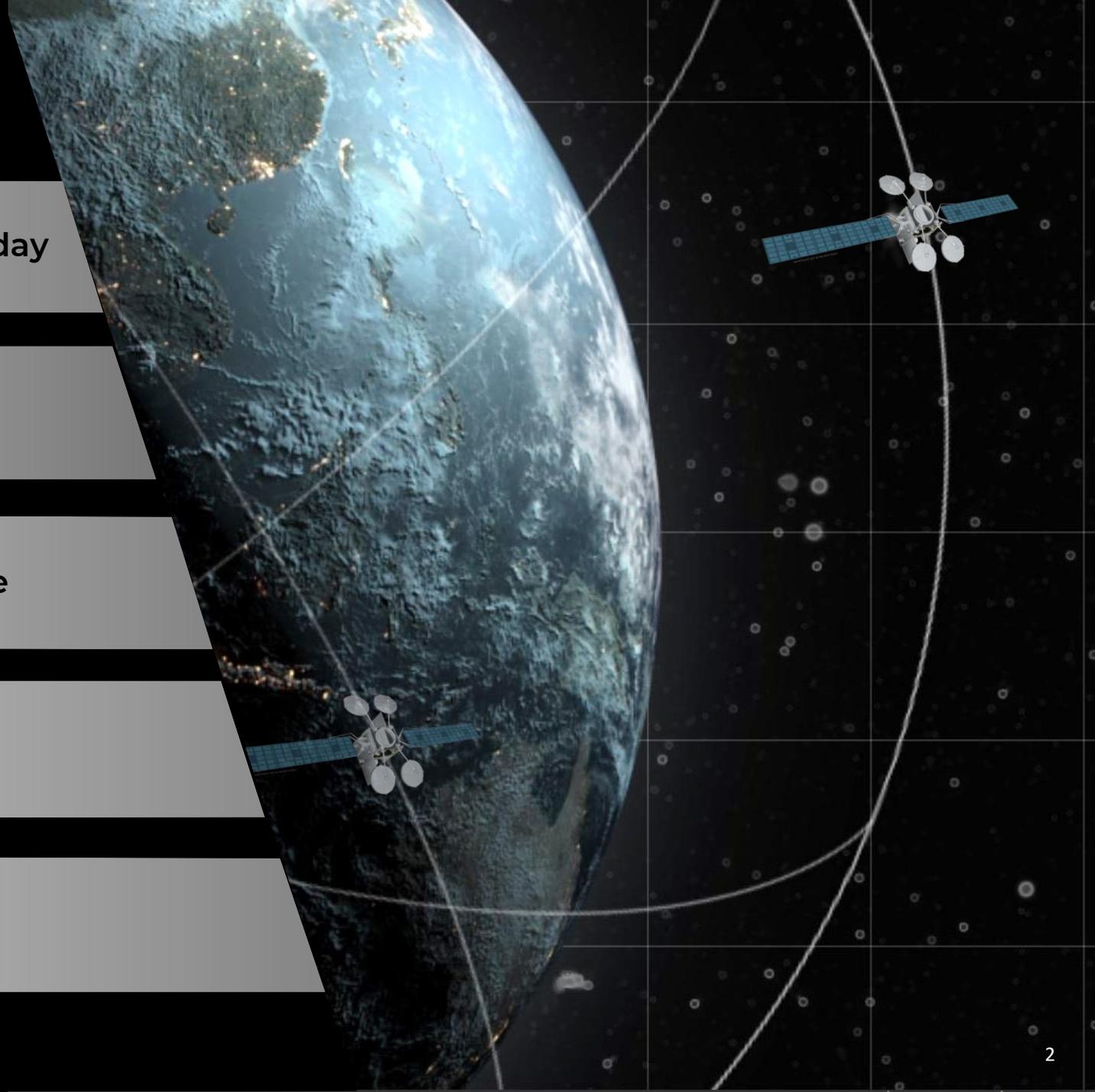
1 NASA Communications Networks Today

2 Pivot to Commercial Capabilities

3 Space Technology Mission Directorate

4 Lunar Communications

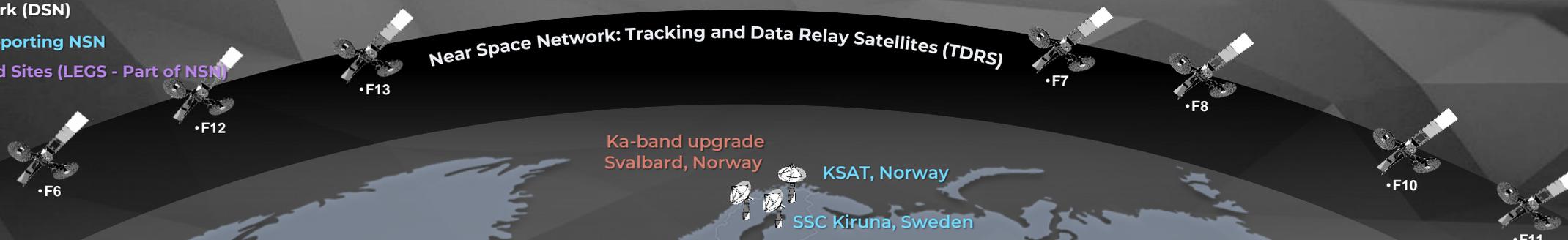
5 Deep Space Communications



NASA's Communications Networks

- NASA Near Space Network (NSN)
- NASA Deep Space Network (DSN)
- Commercial Stations Supporting NSN
- Lunar Exploration Ground Sites (LEGS - Part of NSN)
- Optical
- Future Upgrades

Near Space Network: Tracking and Data Relay Satellites (TDRS)



Ka-band upgrade
Svalbard, Norway
KSAT, Norway
SSC Kiruna, Sweden

Madrid, Spain
- DAEP Ka-band Upgrade
Sardinia, Italy

White Sands Complex, New Mexico
Blossom Point, Maryland
Wallops Island, Virginia

ASF, Alaska
NOAA, Alaska
North Pole, Alaska
Goldstone, California
- Ka-band Upgrade
- Table Mtn, California
- Ka-band Upgrade
Alaska
LEGS 1, White Sands
White Sands, New Mexico

LEGS 2, Matjiesfontein, South Africa
NSN Station, SSC Hartebeesthoek, Africa

KSAT Singapore

Ka-band Commercial Upgrade
Punta Arenas, Chile

LEGS 3, Alice Springs, Australia

SSC Dongara, Australia

Canberra, Australia
DAEP Ka-band Upgrade
Canberra, Australia

Guam Remote Ground Terminal

SSC Hawaii
Hawaii

KSAT TrollSat, Antarctica

McMurdo, Antarctica

Today's High Data Intensive Missions

- Evolving instruments, payloads, and needs are driving data volume demand
 - The Plankton, Aerosol, Cloud and Ocean Ecosystem (PACE) mission, launched in 2024, produces 5 terabits of data per day
 - The NASA-Indian Space Research Organization (ISRO) Synthetic Aperture Radar (NISAR) mission, to be launched in 2025, will produce 85 terabytes of data per day
- This class of mission creates three orders of magnitude more data than the Hubble Space Telescope (HST)
- Exponential demand growth will strain NASA's current network capabilities

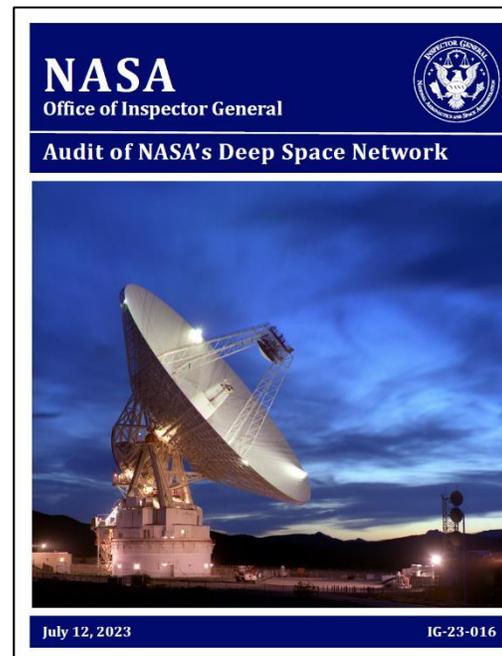


The Deep Space Network

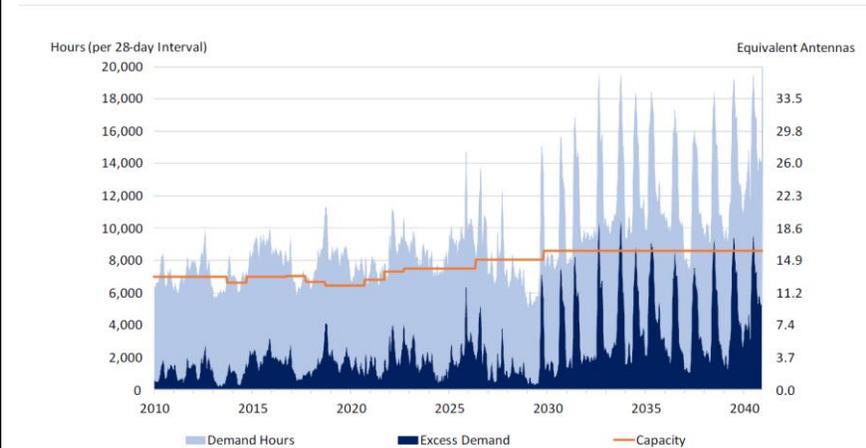
- Today, NASA's deep space communications are provided by the Deep Space Network (DSN), a worldwide network of radio frequency ground stations located in Australia (Canberra), Spain (Madrid), and the United States (Goldstone, California).
- Each of the three DSN sites has at least four antennas with ultra-sensitive receiving systems:
 - One 70-meter antenna
 - Three or more 34-meter beam waveguide antennas
- The DSN has been a huge success since its inception. However, the DSN is at capacity and oversubscribed.
 - At times, demand exceeds capacity by > 40%
- Furthermore, future deep space science missions will require higher data rates than possible today. The sustained human exploration of the Moon and eventually Mars will also exceed the current capabilities of the DSN.



The screenshot shows the top portion of an Ars Technica article. The header includes the 'ars TECHNICA' logo, a 'SUBSCRIBE' button, and search/sign-in options. The article title is 'NASA officials sound alarm over future of the Deep Space Network'. A quote from Stephen Clark is visible: 'I'm not sure who thought it was a good idea to put up CubeSats with Artemis I.' The byline reads 'STEPHEN CLARK - 8/30/2023, 2:12 PM'.



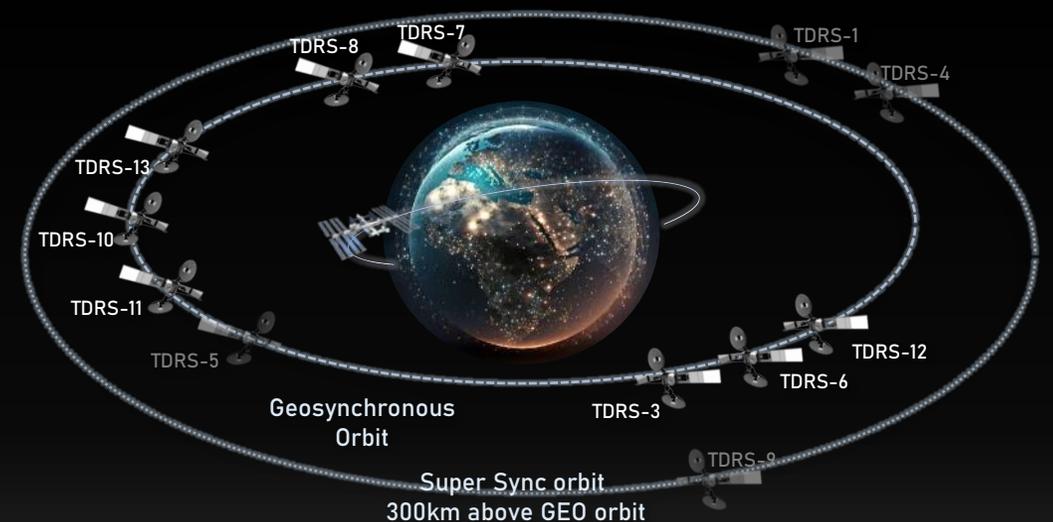
The image shows the cover of a report from the NASA Office of Inspector General. The title is 'Audit of NASA's Deep Space Network'. Below the title is a photograph of a large satellite dish antenna at night. At the bottom, the date 'July 12, 2023' and the report number 'IG-23-016' are displayed.



The Tracking and Data Relay Satellite System

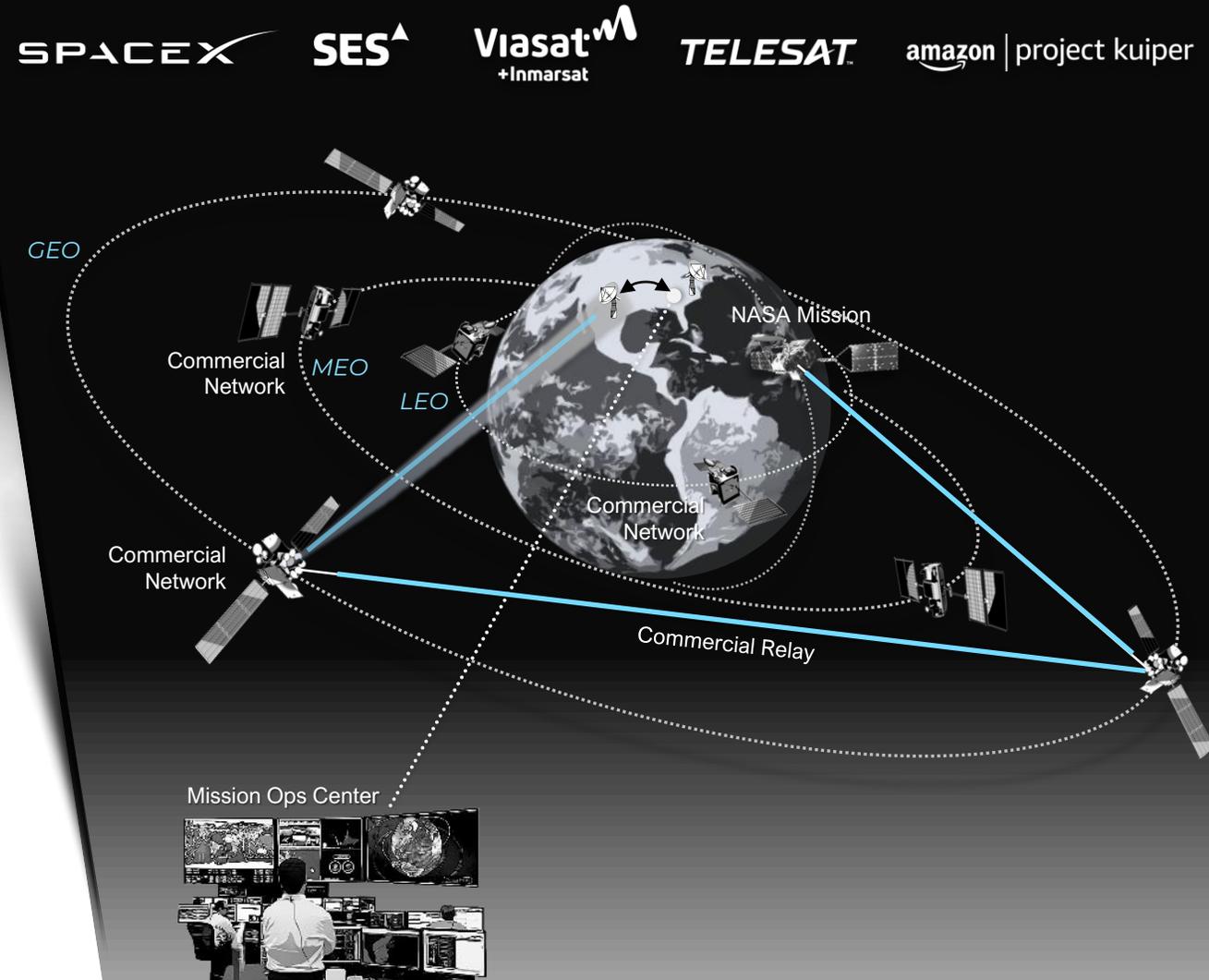
- **Origins of NASA's Tracking and Data Relay Satellite (TDRS) System were with the Space Shuttle and the driving need for 24x7 coverage**
 - Built up over decades with three generations of satellites – the first launched in 1983 and the last satellite in 2017
 - Capabilities incrementally improved, but the fundamental architecture remained consistent over 40+ years
- **The TDRS Fleet is anticipated to be reduced to 3 satellites as early as 2028**
 - Preventing new missions from entering the service queue is critical to risk mitigation
 - O&M of the remaining fleet will be focused on retaining global coverage into the 2040s for current users (e.g., Hubble Space Telescope)

- Options for new TDRS spacecraft is not supported by US National Space Policy
- As of August 8, 2024, NASA suspended acceptance of new mission commitments for TDRS support.



A Pivot to Commercial Space Relay

- In 2020, NASA's Space Communications and Navigation (SCaN) Program defined a strategy to transition NASA's Low Earth Orbit missions to commercial Space Relay services
 - Commercial services will provide transformative new capabilities to science missions
 - Communications Services Project (CSP) is targeting operational commercial space relay service by 2031



Unlocking Next Generation Technology & Services Through CSP

- Commercial Geosynchronous Orbit (GEO) L-band relay network



- Optical Low Earth Orbit (LEO) network



- GEO C-band and Medium Earth Orbit (MEO) Ka-band networks



- Optical LEO network



- RF relay networks offering C-band and Ka-band services



- GEO Ka-band relay network



Communications Services Project (CSP)

NASA announced on April 20, 2022 that the CSP awarded contracts totaling **\$278.5 million** to demonstrate how commercial satellites can support NASA missions.

Six providers are matching / exceeding the awards with own funds. Estimated total investment of **\$1.5 billion** over five years.

Vendors are progressing successfully through their agreed to milestones. Demonstrations will continue through mid-2027

WHAT IS STMD?



NASA's Space Technology Mission Directorate (STMD) is charged with developing the technology base for civil space, enabling key capabilities for all aspects of space exploration and discovery.

This is accomplished with limited resources and a need for balanced portfolios across various technologies.

A critical technology area for NASA is
Communications & Navigation

What can STMD do in this area?



Civil Space Shortfalls

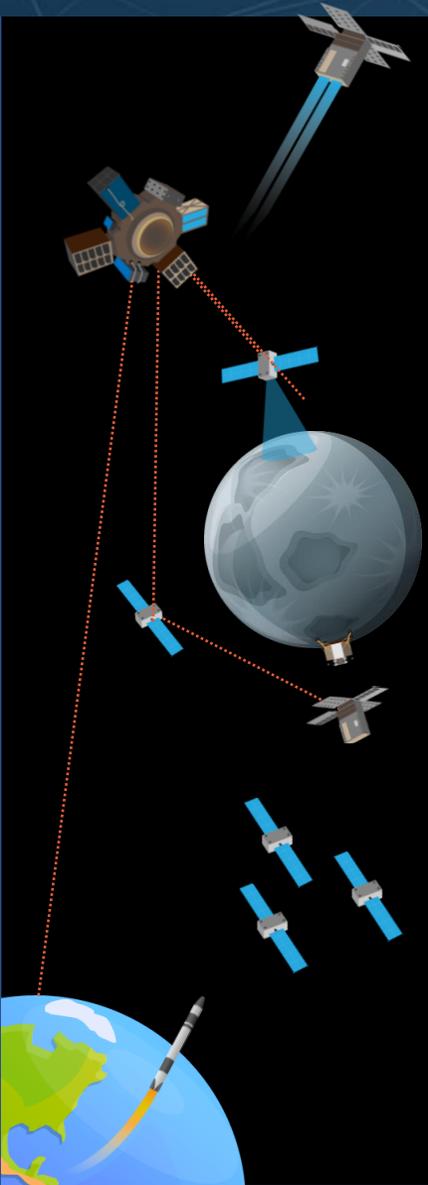
- In 2024 STMD compiled an initial list of **187 shortfalls** organized into **20 capability areas**
- The shortfall description document and feedback form were organized accordingly



STMD identified an initial list of 187 shortfalls and invited the community to give input on your critical technology needs using this feedback mechanism.

Capability Categories	# of Shortfalls
Advanced Habitation Systems	16
Advanced Manufacturing	12
Advanced Materials & Structures	4
Autonomous Systems & Robotics	23
Avionics	7
Communication & Navigation	4
Cryogenic Fluid Management	5
Dust Mitigation	3
Entry, Descent & Landing	13
Excavation, Construction & Outfitting	9
In-Situ Resource Utilization	10
In-Space Servicing, Assembly & Manufacturing	9
Orbital Debris	3
Power	8
Propulsion	18
Sensors & Instruments	12
Small Spacecraft	8
Surface Systems	10
Thermal Management Systems	8
Miscellaneous	5

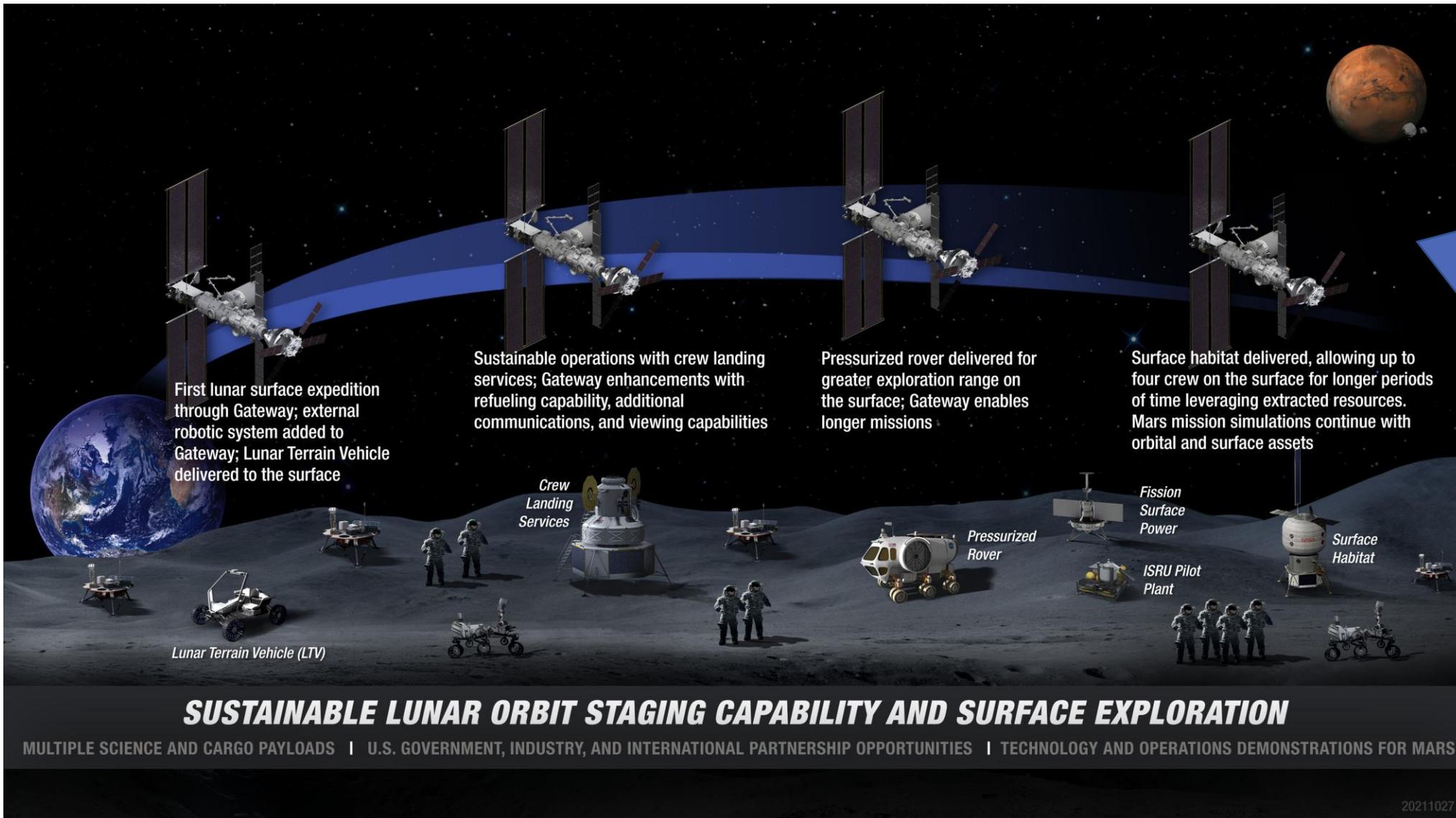
Communications & Navigation Shortfalls



Driven by stakeholder needs, four high-priority Communications & Navigation technology shortfalls were identified:

- In-Situ Position, Navigation, and Timing (PNT) for In-Orbit and Surface Applications
- High-Rate Communications Across the Lunar Surface
- Deep Space Autonomous Navigation
- High-Rate Deep Space Communications

Moon to Mars – First Step is Artemis

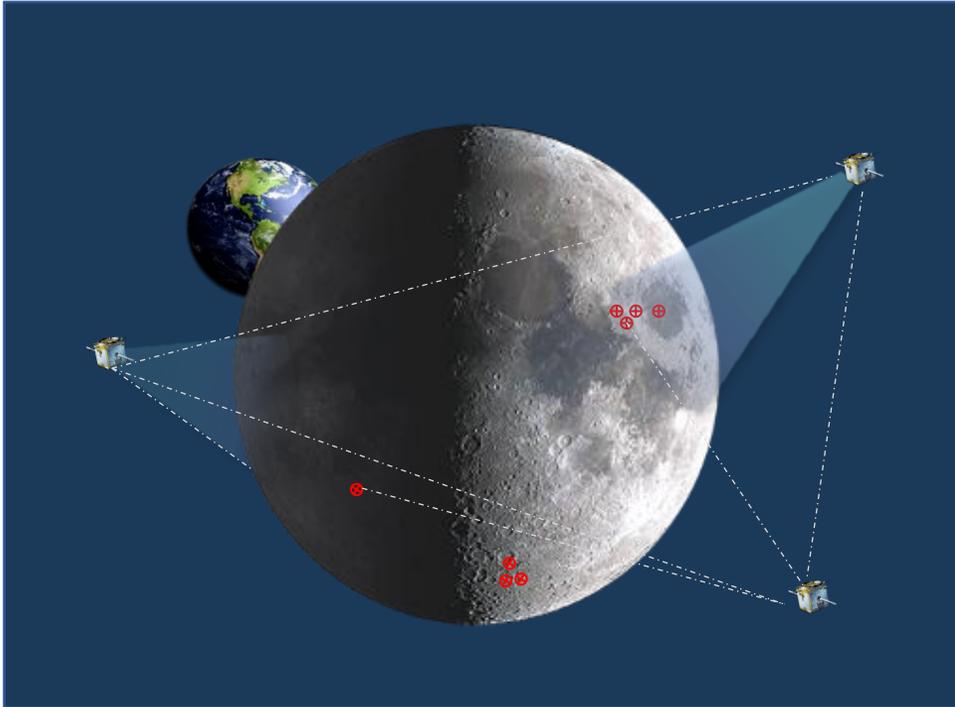


Beyond the establishment of the lunar outpost and more sustainable operations, emphasis shifts to moon-to-Mars, implying increasing communications demands

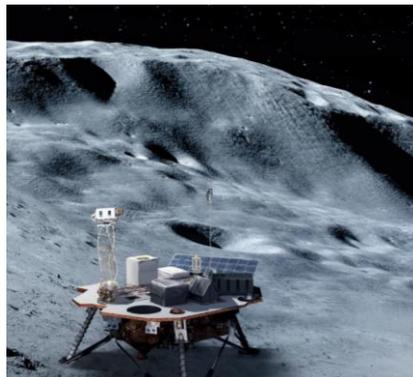
Communications & Earth Visibility – Lunar South Pole

For two weeks Earth is visible for DTE communication; two weeks it is not

Lunar Relay



- ❑ Some spacecraft and missions to the Moon will require relay spacecraft services to maintain a communications link with Earth
 - Exploration missions to the South Pole region have constrained operational windows for Direct-to-Earth communications and limitations imposed by local terrain and multipath losses due to the Earth being very low on the horizon. Relying on Direct-to-Earth communication, without a relay, limits consistent landing site availability throughout the year.
 - All robotic science missions to the far side, as well as some missions to other regions, will require relay services.
- ❑ Other lunar missions benefit from a relay capability due to the Size, Weight, & Power advantages it can offer with a shorter link length and increased availability
- ❑ Lunar Relay Capability – initial capability to be provided via commercial services:
 - Initial South Pole / Far Side focused coverage
 - Ka-band: return (50 Mbps), forward (10 Mbps), radiometric tracking
 - S-band: forward and return (36 kbps), radiometric tracking
 - Networking Services: IP and DTN
 - PNT: Continuous radio navigation broadcast (analogous to GNSS) and radiometric tracking – initial step toward a lunar counterpart to GPS



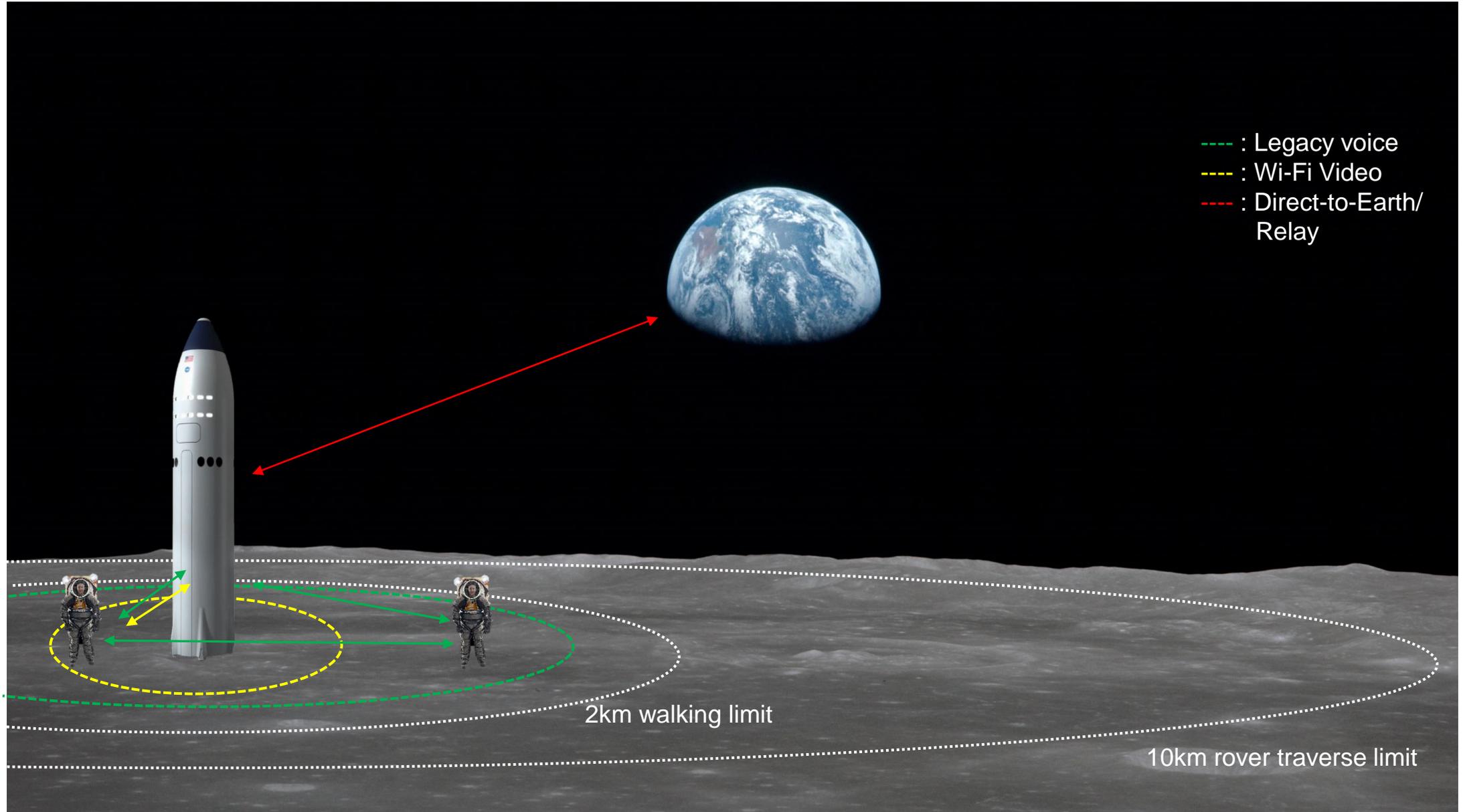
STMD Shortfall 1558: High-Rate Communications Across the Lunar Surface

Description

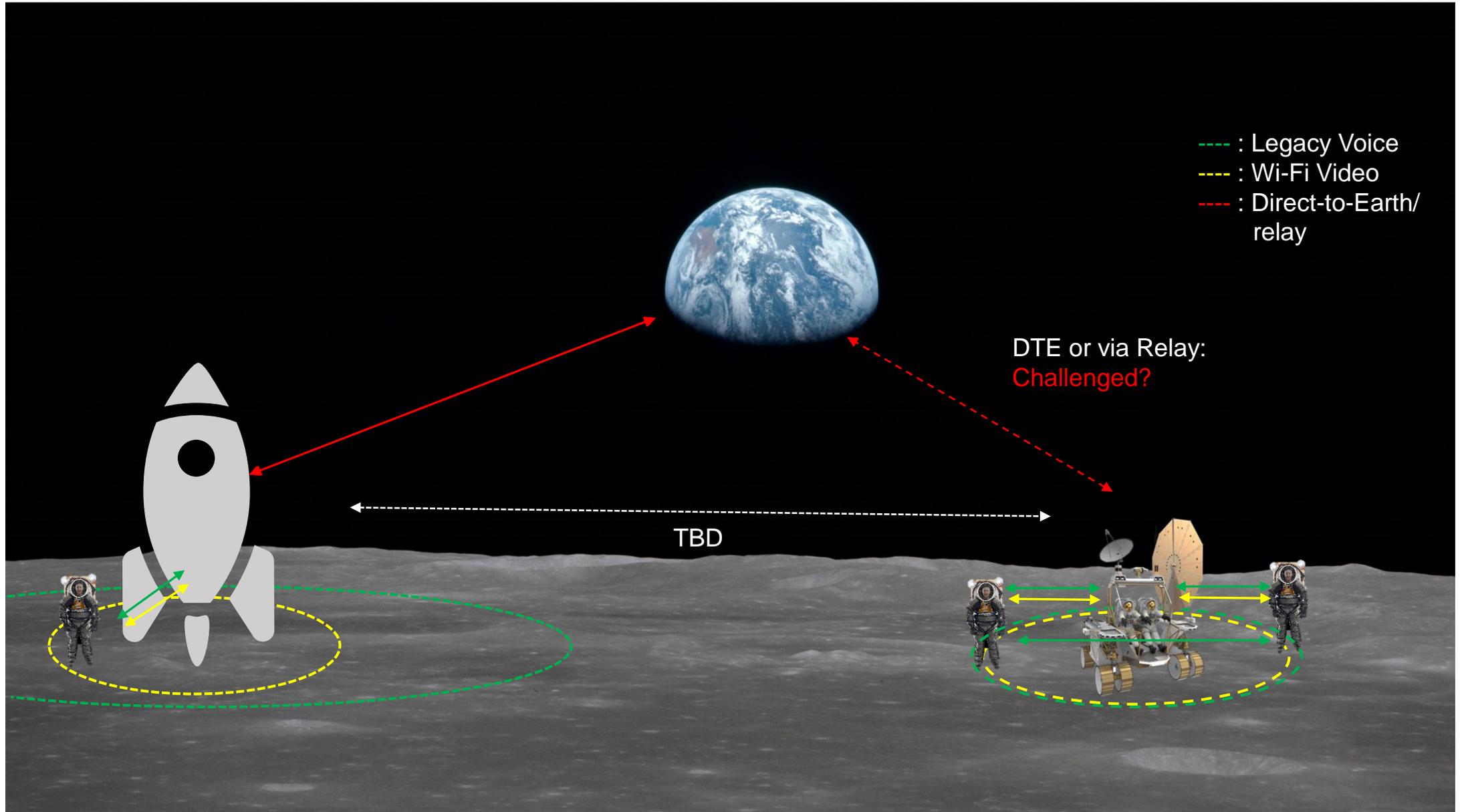
Eventually there will be a proliferation of devices on the lunar surface whose communication needs exceed the scheduling capacity of lunar orbital relays and direct-to-Earth (DTE) links or whose individual size, weight, and power (SWaP) constraints prohibit use of relay/DTE for Earthbound communication. High-rate surface links will be required to interface to these devices and mediate access of their on-demand communications needs to the more managed, long-haul links back to Earth. ***Use of standardized protocols is desired to maintain broad compatibility and interoperability between end users of these services and a diversity of commercial communication providers.***

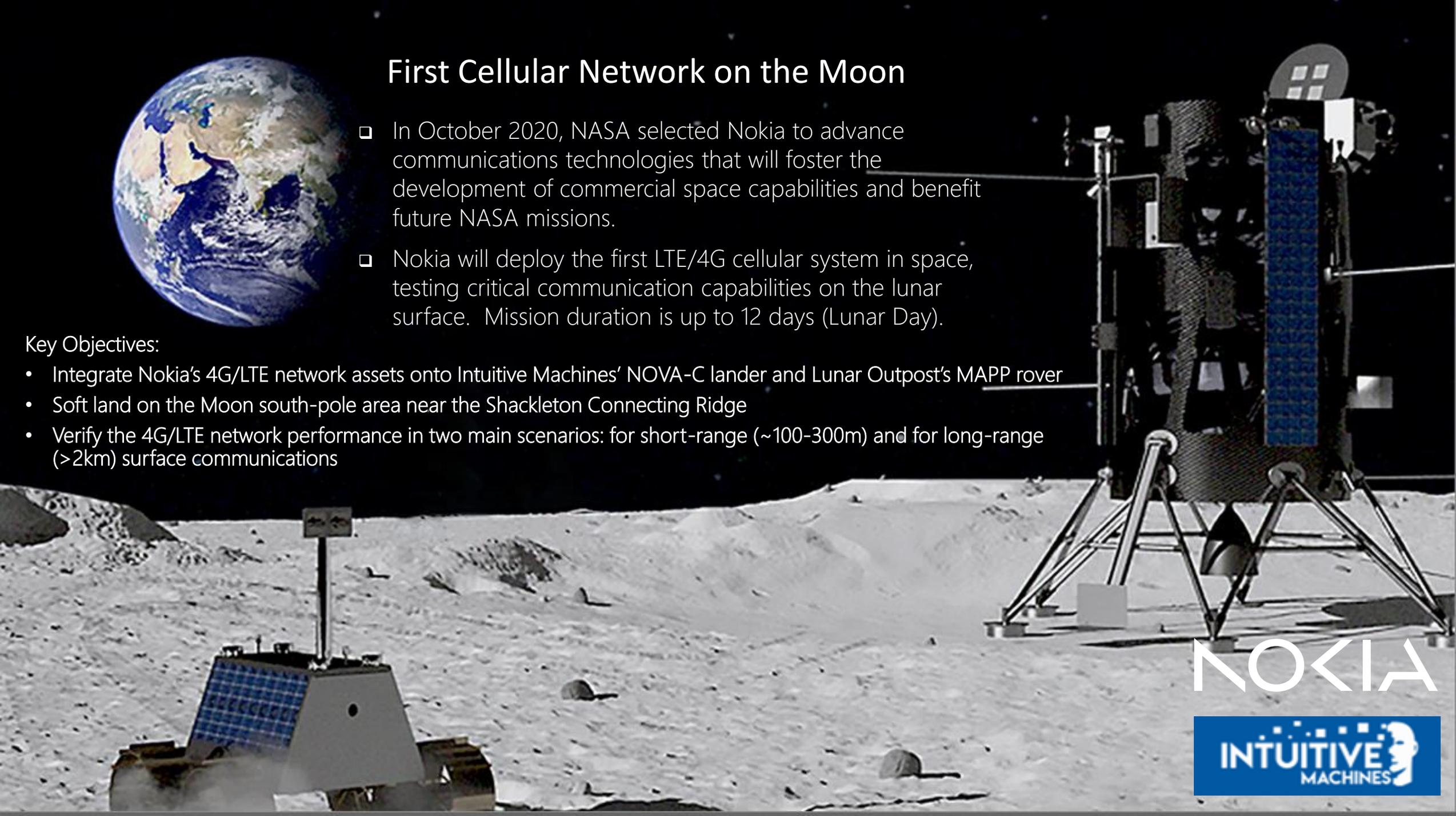


Baseline Artemis III Surface Communications Architecture



Notional Artemis V Surface Communications Architecture





First Cellular Network on the Moon

- ❑ In October 2020, NASA selected Nokia to advance communications technologies that will foster the development of commercial space capabilities and benefit future NASA missions.
- ❑ Nokia will deploy the first LTE/4G cellular system in space, testing critical communication capabilities on the lunar surface. Mission duration is up to 12 days (Lunar Day).

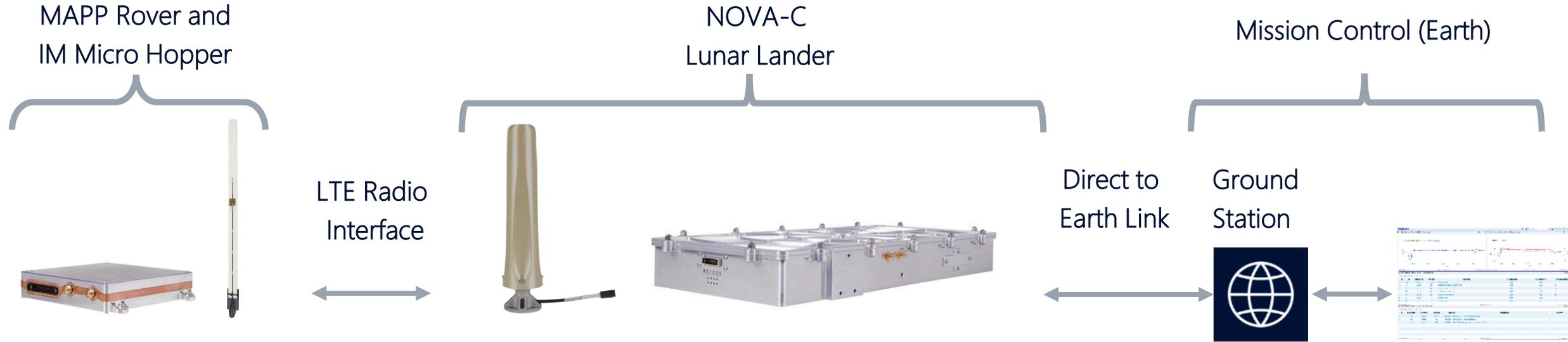
Key Objectives:

- Integrate Nokia's 4G/LTE network assets onto Intuitive Machines' NOVA-C lander and Lunar Outpost's MAPP rover
- Soft land on the Moon south-pole area near the Shackleton Connecting Ridge
- Verify the 4G/LTE network performance in two main scenarios: for short-range (~100-300m) and for long-range (>2km) surface communications

NOKIA

INTUITIVE
MACHINES

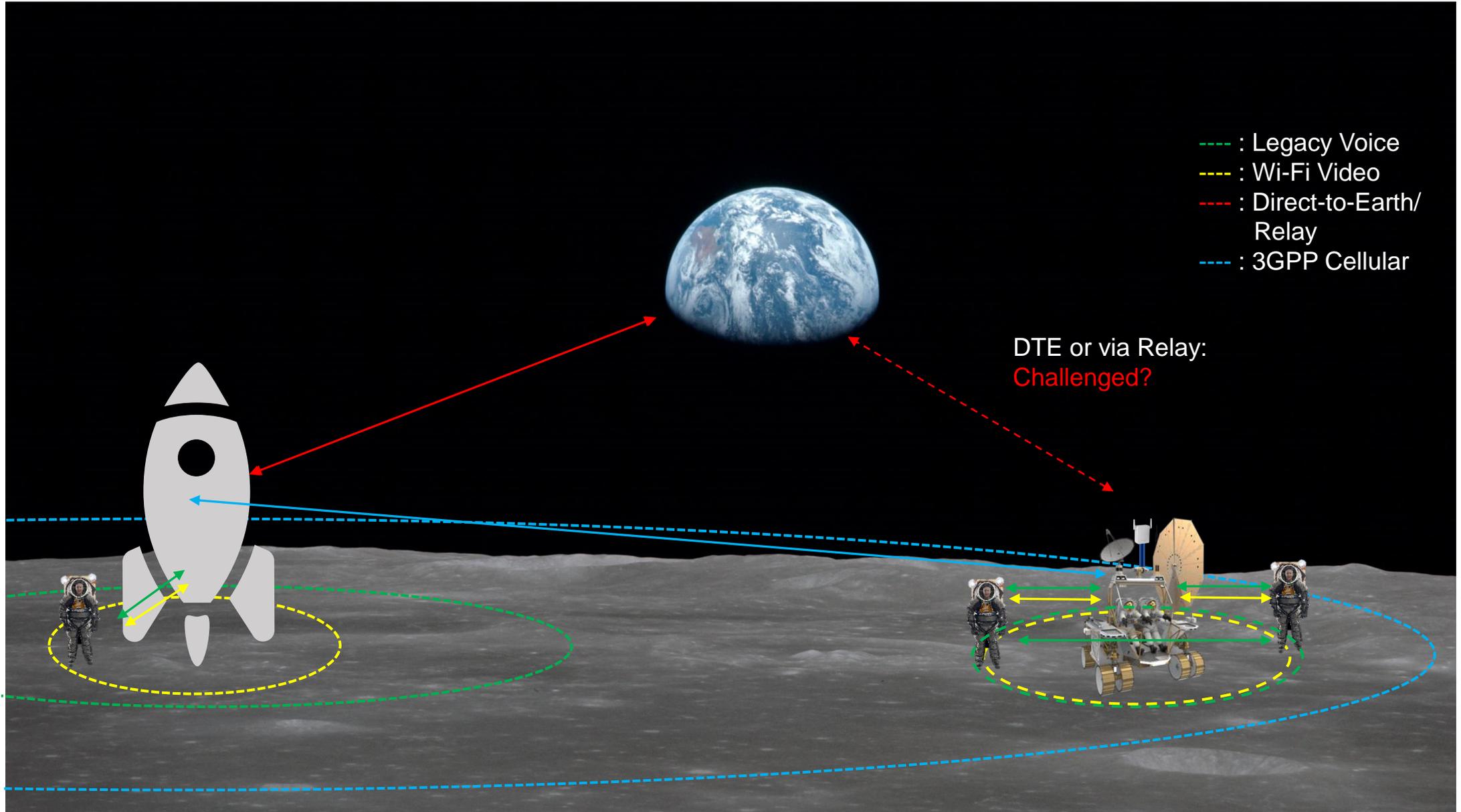
Nokia 4G/LTE Lunar network key components



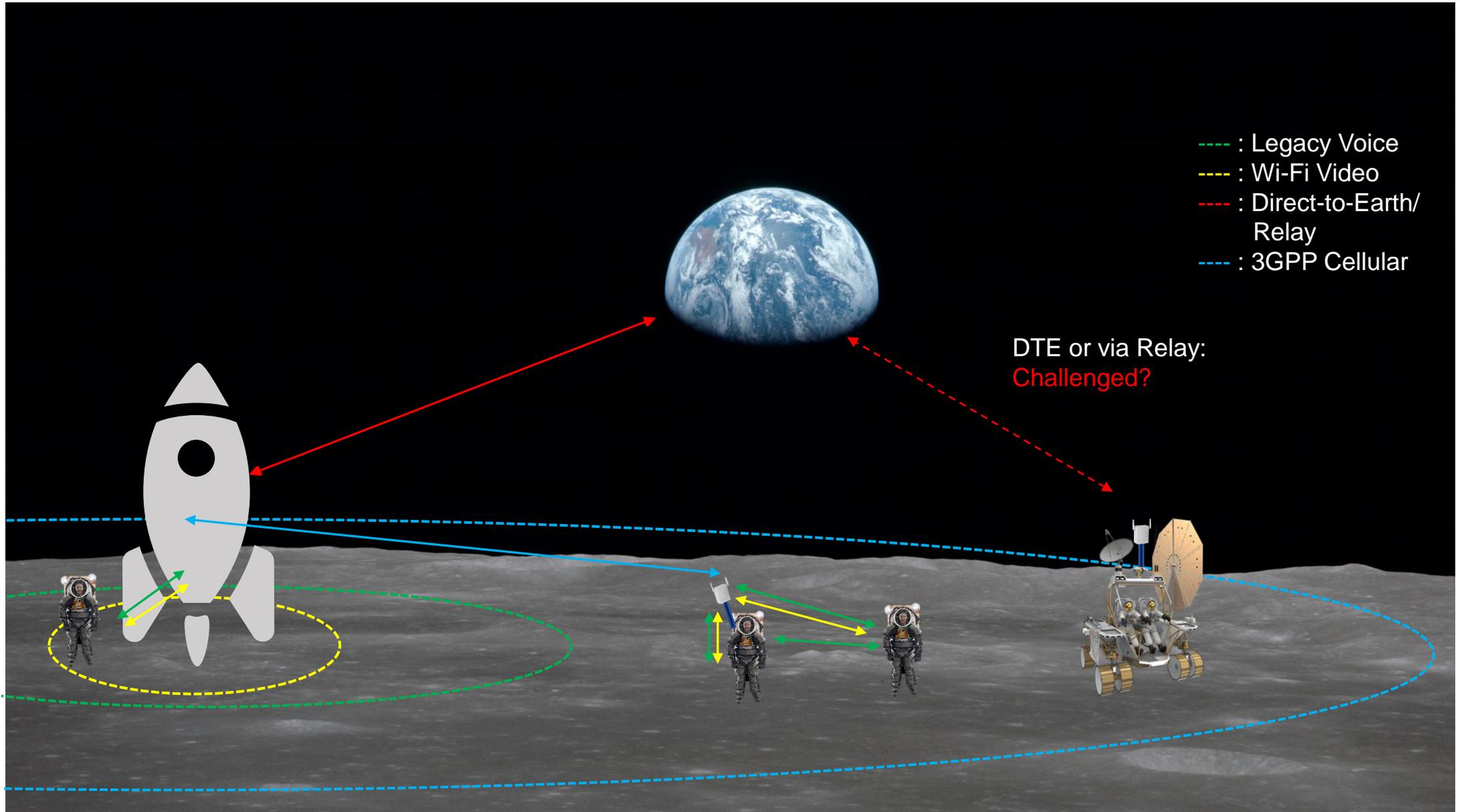
4G/LTE User Equipment	4G/LTE UE Antennas	4G/LTE BTS Antennas	4G/LTE Network in a Box (NIB)	Ground Network Control
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Nokia 4G/LTE Solution Components

Notional Artemis V 3GPP Extension (Nominal EVA)



Notional Artemis V 3GPP Extension (Emergency Walkback)



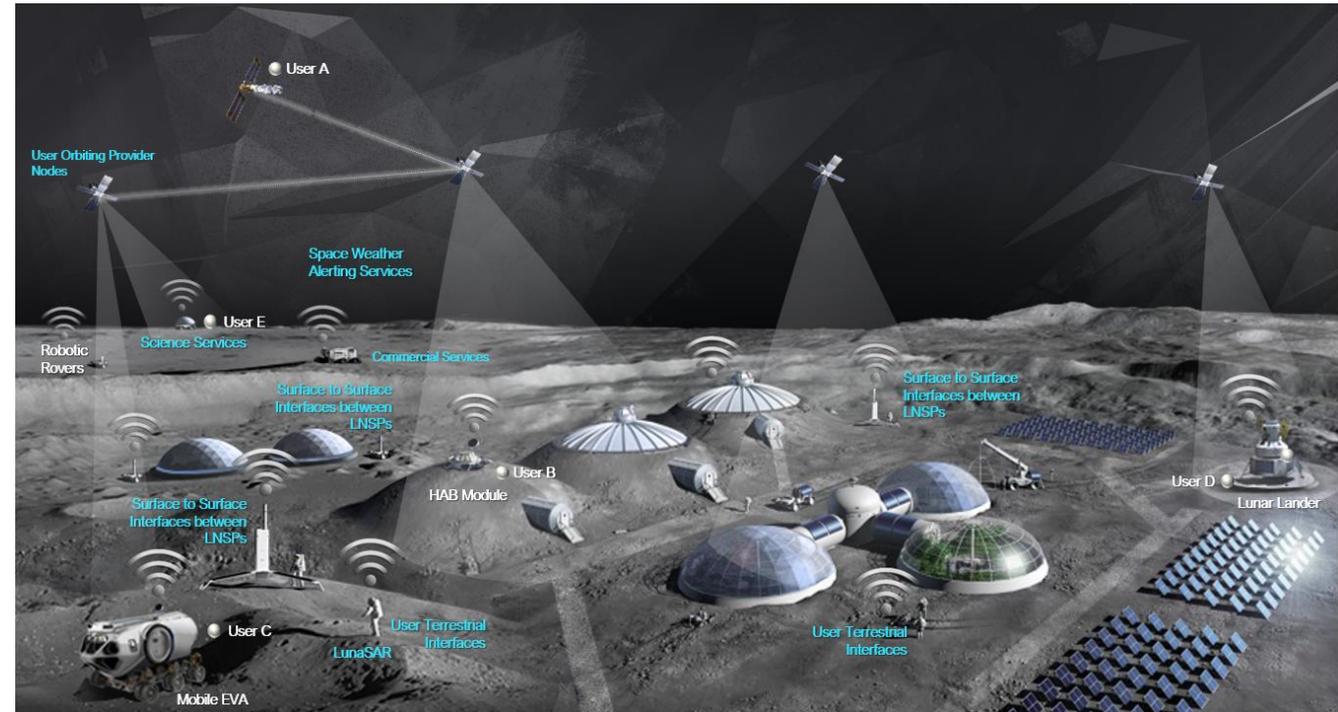
3GPP/5G Surface Wireless Network

What and Why:

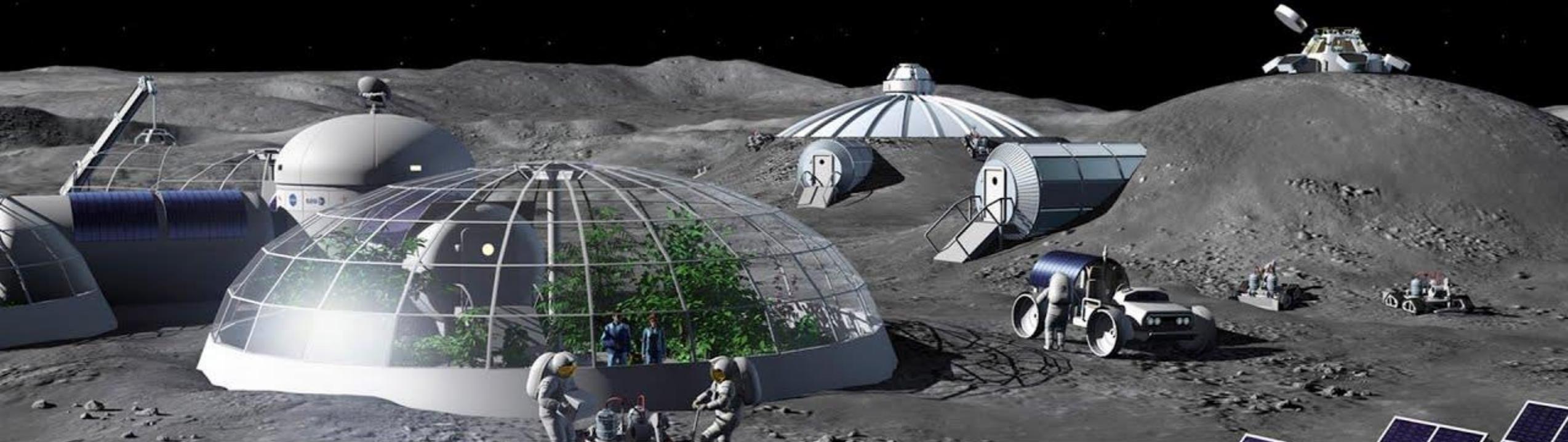
- 3GPP/5G cellular technology will provide a robust lunar surface communications and navigation infrastructure that is incrementally scalable to enable long-term exploration and industrial needs
- Essential to address surface and orbital link proliferation
- Enables direct surface/local communication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



Communications is crucial to a future lunar economy

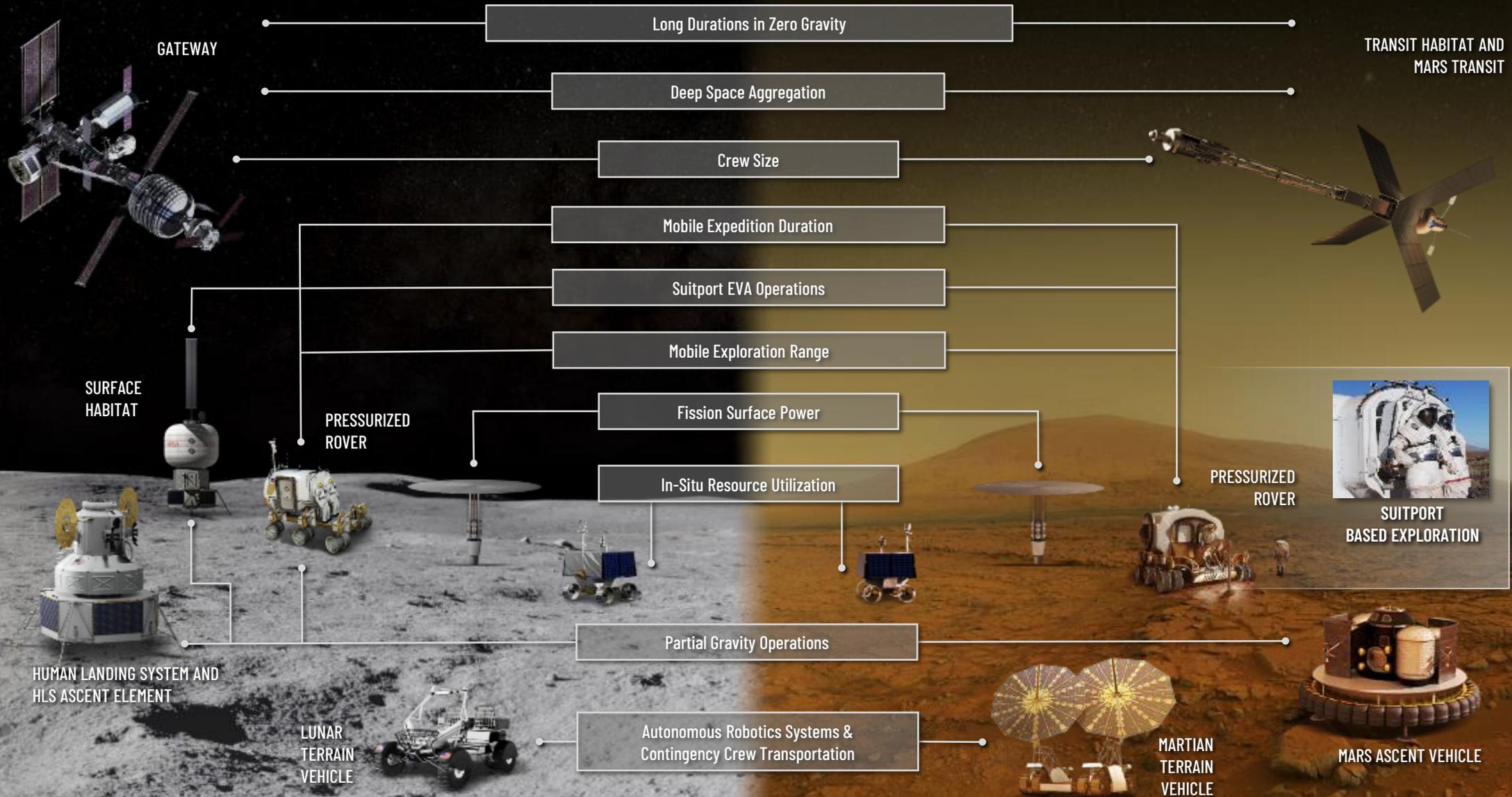


All future lunar deployments, economic and industrial activities need advanced voice, video, data and control communication solutions.

A standardized deployment and solution architecture leveraging commercial 3GPP technologies will benefit all government, commercial and private stakeholders.

Moon to Mars Exploration

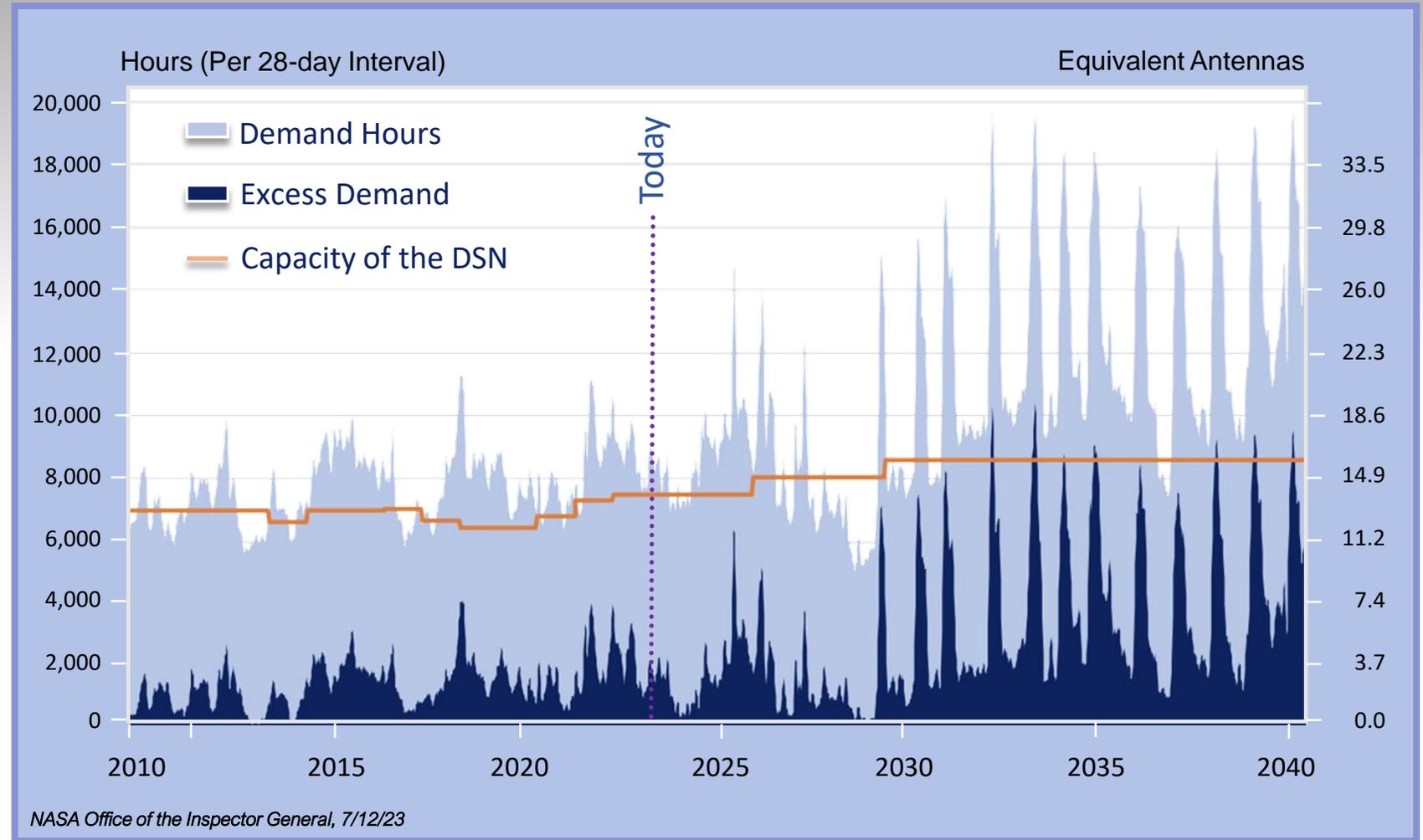
Campaign elements and systems have common applications, enabling versatility across missions



Already Spiking Deep Space Network Demand

High-demand missions are already impacting the Deep Space Network

- JWST alone uses 10% of DSN capacity
- Each Artemis launch leads to a major demand spike; these challenges grow with later missions
- Infrastructure support has not kept up



STMD Shortfall 1560: High-Rate Deep Space Communications

Description

High-rate communications from the Moon and beyond is needed to enable future space exploration and science missions. For example, a robust communications infrastructure will be needed to support a sustained human presence on the Moon and its eventual industrialization. High data rate trunk lines between the Earth and the Moon are needed to reduce the number of individual links. **The human exploration of Mars will also require high-rate communications between Earth and Mars. Return data rates to Earth, for example, are anticipated to be > 100 Mbps; forward data rates to Mars, based on experience from the International Space Station, are anticipated to be > 20 Mbps.** Future deep space science missions will also require higher data rates than possible with today's technology.

Mars Telecommunications Challenges

Telecommunications scales as the *square* of distance

- A transmit-receive system that can support 1 **Megabit**-per-second on a Moon-Earth link would only support 1 **bit**-per-second from Mars!
- Drives the need for **larger apertures** and **higher transmit power** or **NEW TECHNOLOGIES**

Large Earth-Mars distance also results in long Round-Trip Light Time (up to ~45 min at max range)

- Drives need for high levels of autonomy on Mars spacecraft



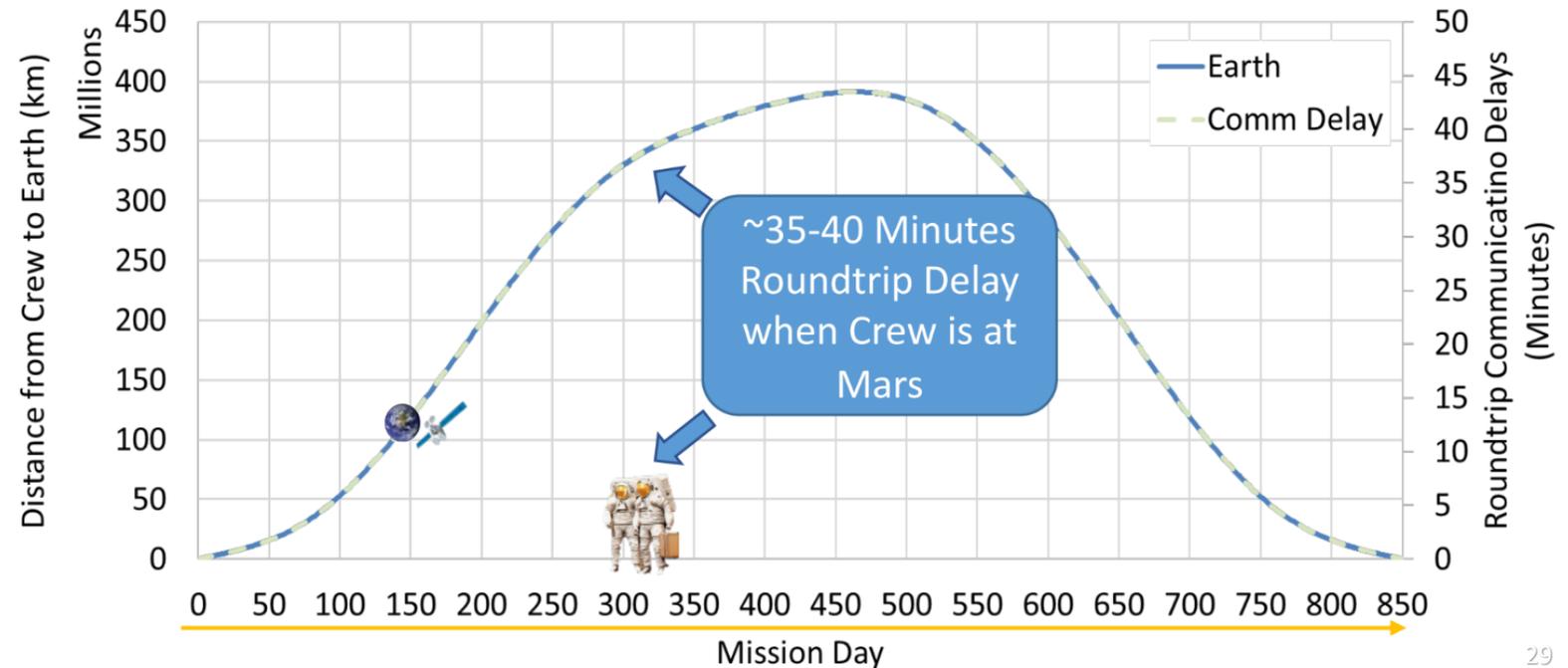
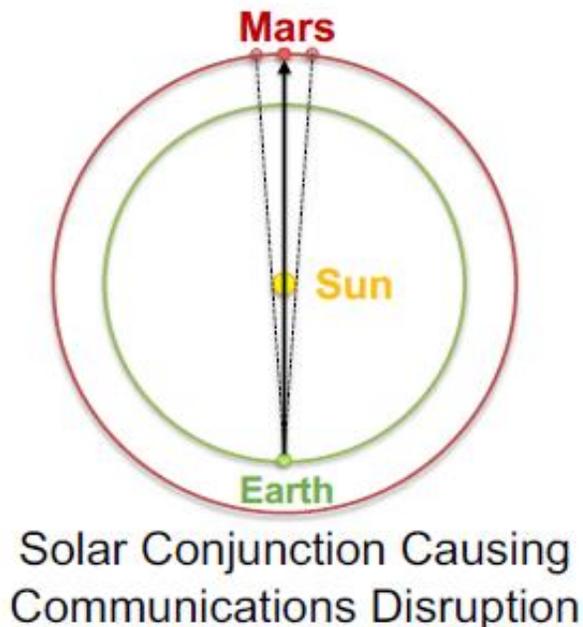
DESTINATION	DISTANCE	NORMALIZED R ²
Geostationary Orbit	~40,000 km	1
Moon	~400,000 km	100
Mars	Up to ~400,000,000 km	100,000,000

STMD's Mars Capability Goal: 20 Mbps Forward / 100 Mbps Return

- Today, the highest data rate used to date to a single 34m DSN terminal at maximum Mars range is 500 Kb/s (when Mars is closest to Earth, data rates of ~5 Mb/s can be achieved).
- STMD envisions a future at Mars where a return data rate to Earth for a single link for crewed exploration will be on the order of 100 Mb/s. Likewise, forward data rates to Mars to support crewed exploration will be on the order of 20 Mb/s, based on experience from the International Space Station. These data rates will be required when Mars is at maximum distance from Earth, which is the baseline distance used for all Mars planning analyses.

From the 2024 Moon to Mars Architecture Workshops:

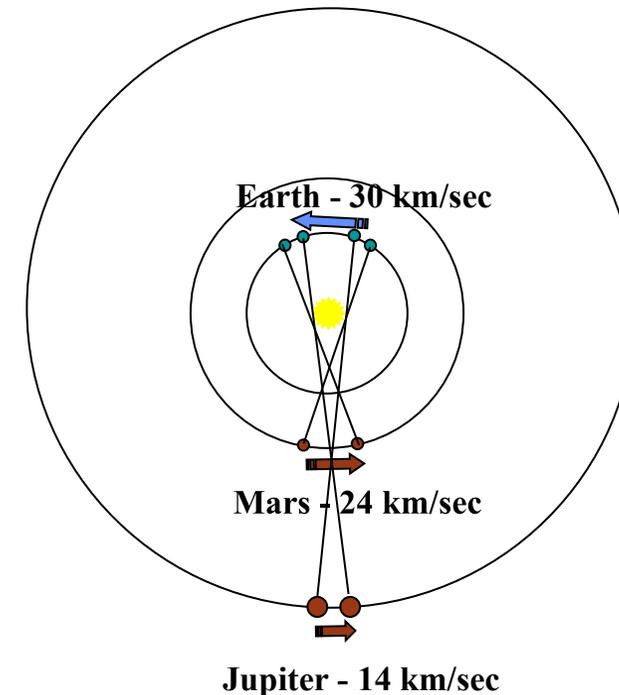
Example 850-day Roundtrip Mission



Have to Operate within a Few Degrees of the Sun

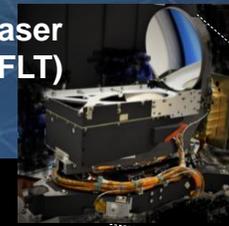
- A critical design driver is developing an Earth terminal concept that can operate to within a few degrees of the Sun to minimize the days of outage.
- However, being able to operate with small Sun angles is not as critical for Jupiter and beyond.

Planet	12 deg	6 deg	3 deg	1 deg
Mars	86 days	43 days	22 days	7 days
Jupiter	32 days	16 days	8 days	3 days
Saturn	28 days	14 days	7 days	2 days
Uranus	26 days	13 days	6 days	2 days
Neptune	25 days	13 days	6 days	2 days
Pluto	25 days	13 days	6 days	2 days



Deep Space Optical Comm

Flight Laser Transceiver (FLT)



First Optical communications demo beyond earth-moon system

- Sponsors**
- STMD/Technology Demonstration Mission
 - Flight terminal
 - Project Lead
 - SOMD/Space Communications and Navigation
 - Ground network
 - SMD
 - Host Mission

Risk Category 7120.5E, Category 3, 8705.4 Payload Risk Classification D

Psyche Host PI Lindy Elkins-Tanton (ASU)
PM Henry Stone (JPL)

Lifetime 2 year

Ground Laser Transmitter (GLT)
Table Mtn., CA



Ground Laser Receiver (GLR)
Palomar Mtn., CA



Deep Space Network (DSN)
RF-Optical Hybrid (RFO)

Psyche Ops Center

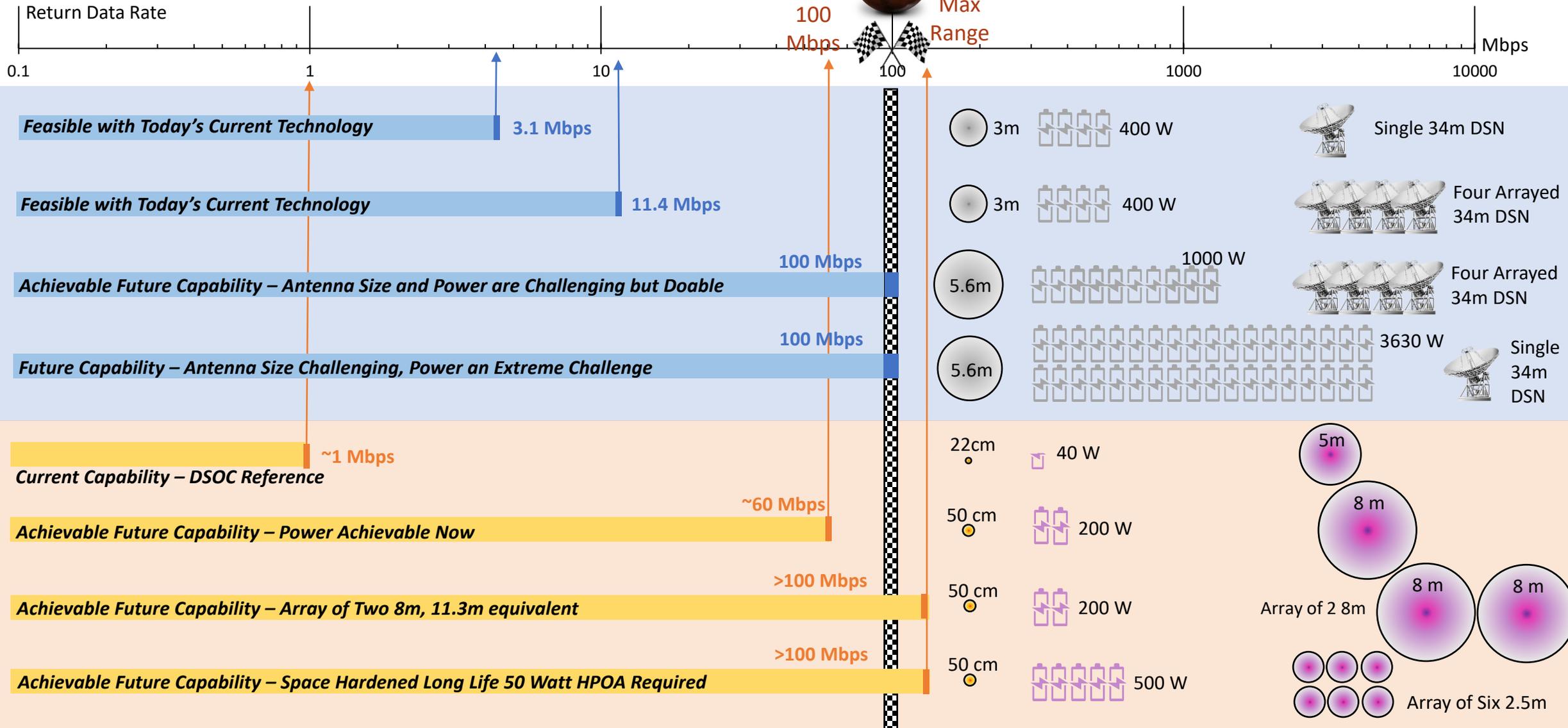
DSOC Ops Ctr.



1550 nm downlink
1064 nm uplink beacon

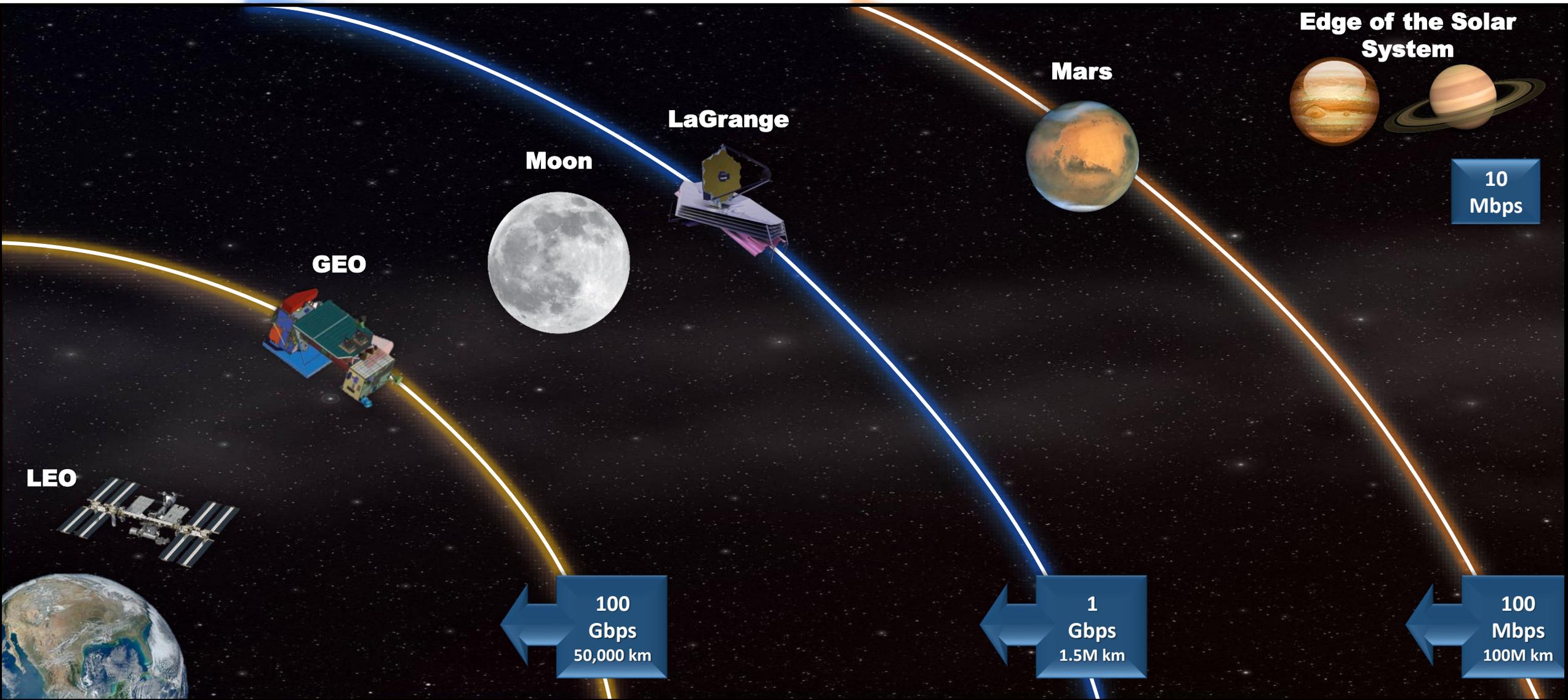
DSOC-PROG1 <i>(on ground pre-launch)</i>	133 Mbps @ 0.25 AU > 200 Kbps @ 2.8 AU
DOC-PROG2	> 6.3 Mbps < 1.5 AU ✓ > 1 Mbps > 1.5 AU
DSOC-PROG3 <i>(numerous times)</i>	1.6 Kbps @ 0.25 – 1AU
DSOC-PROG4	Operate in space for at least 1 year

Mars Direct to Earth Examples

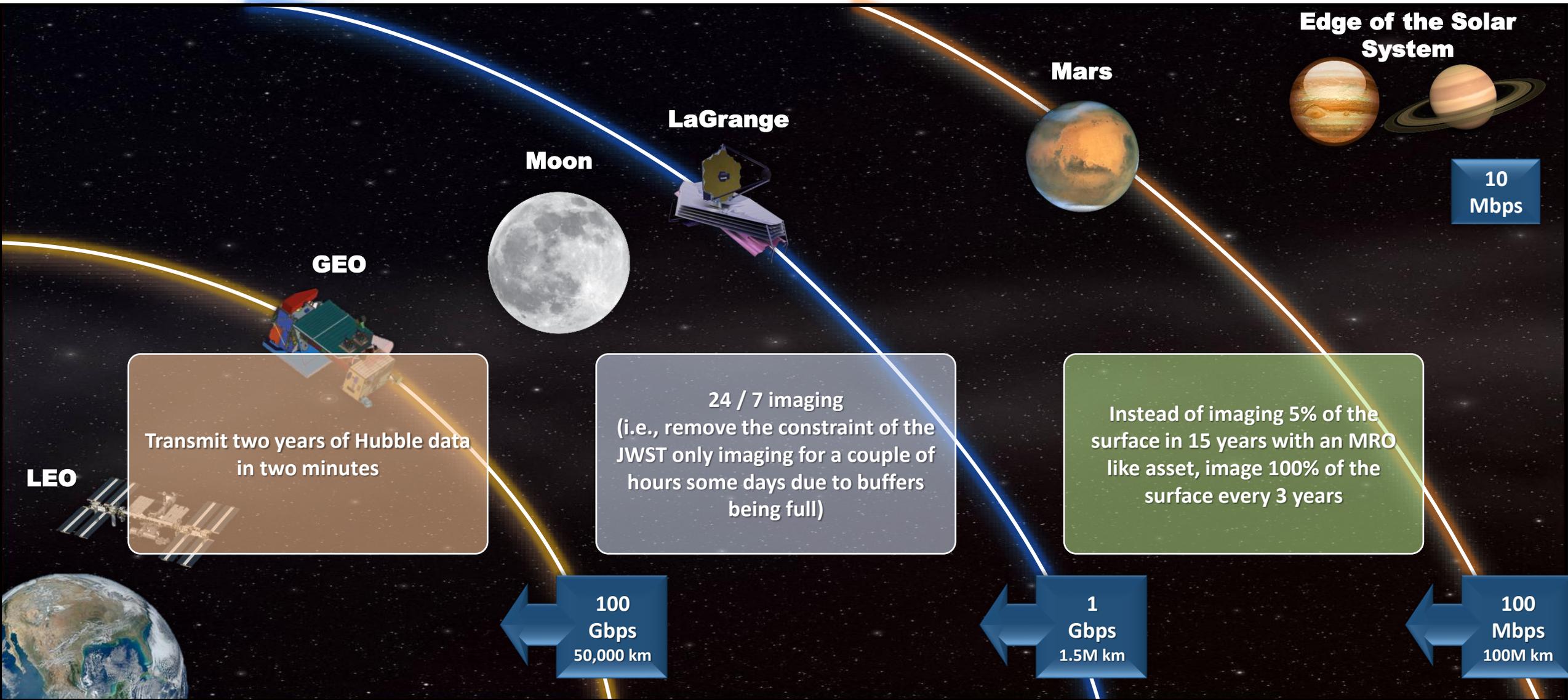


Spacecraft RF antenna size (m)
 Spacecraft Power for RF TX, 100W (50% eff)
 Spacecraft Power for Optical Transmit, 100W (10% eff)
 Spacecraft Optical Transmit Aperture (cm)
 Optical Receive Aperture (m)
 Not to scale

A Vision for NASA Communications *Contour Map for the Solar System*



Notional Examples of the Impact of Achieving the Communications Vision





STMD's Envisioned Future Priority Packages

- NASA's Envisioned Future for each Strategic Outcome
- NASA's understanding of the State of the Art
- NASA's near-term high priorities relative to each outcome
- Presentations and videos available at:
 - techport.nasa.gov/framework

Space Technology Mission Directorate (STMD)

STMD rapidly develops, demonstrates, and transfers revolutionary, high pay-off space technologies, driven by diverse ideas.

NASA's Space Technology Mission Directorate (STMD) organizes the agency's technology investments into the Strategic Framework, with the goal of addressing its desired outcomes through technology development. The framework is comprised of 18 Capability Areas, grouped into four categories of investment called Thrusts: *Go, Land, Live, and Explore*.

Each strategic outcome includes an Envisioned Future that further describes possible futures enabled by achieving the outcome. NASA is engaging the community to validate and improve the end state described in these Envisioned Futures, and update the framework as appropriate. STMD will use these updates to collect technology gaps, prioritize, and plan future content and investments.

Read more about STMD Envisioned Futures 715.7 KB

Feedback: Evaluate the Envisioned Futures Priorities

Go

Rapid, Safe, and Efficient Space Transportation

Space Nuclear Propulsion
Develop nuclear technologies enabling fast in-space transits.



2.1 MB PDF Watch

Cryogenic Fluid Management
Develop cryogenic storage, transport, and fluid management technologies for surface and in-space applications.



1.9 MB PDF Watch

Advanced Propulsion
Produce advanced propulsion technologies that enable future science/commercial/exploration missions.



2.3 MB PDF Watch

Land

Expanded Access to Diverse Surface Destinations

Precision Landing and Hazard Avoidance
Develop capabilities to enable lighting-independent precise landing on any terrain.



5.5 MB PDF Watch

Entry, Descent, and Landing to Enable Science Missions
Develop capabilities enabling small to large missions to efficiently enter any atmospheres within our solar system.



2.8 MB PDF Watch

20t and Lunar/Mars Global Access
Develop capabilities to support global access to the moon and Mars including accurate prediction of plume surface interaction.



3.2 MB PDF Watch

Live

Sustainable Living and Working Farther from Earth

Advanced Habitation Systems (AHS)
Keep astronauts healthy and productive while living in space and planetary vehicles.



2.4 MB PDF Watch

In-Situ Resource Utilization
Develop scalable ISRU production/utilization capabilities including sustainable commodities on the lunar and Mars surface.



2.8 MB PDF Watch

Power and Energy Storage Systems
Develop sustainable power sources and other surface utilities to enable continuous lunar and Mars surface operations.



2.6 MB PDF Watch

Explore

Transformative Missions and Discoveries

Advanced Avionics
Develop advanced avionics to meet agency objectives, including radiation-hardened space-flight computing technologies.



2.2 MB PDF Watch

Advanced Manufacturing
Develop both terrestrial and in-space manufacturing technologies to make commercial and exploration missions more capable and affordable.



2.6 MB PDF Watch

Autonomous Systems and Robotics
Develop autonomy and robotics technologies that enable and enhance the full range of science and exploration missions (both with and without crew).



4.7 MB PDF Watch

Communications and Navigation
Develop communication, navigation, and timing approaches to support diverse asset (human or robotic) needs including establishing asset location in-space.



6.1 MB PDF

In-space Servicing, Assembly, and Manufacturing (ISAM) and Rendezvous, Proximity Operations, and Capture (RPOC)
Develop technologies for in-space creation, maintenance, and evolution of space assets leveraging expanding in-space infrastructure.



5.9 MB PDF Watch

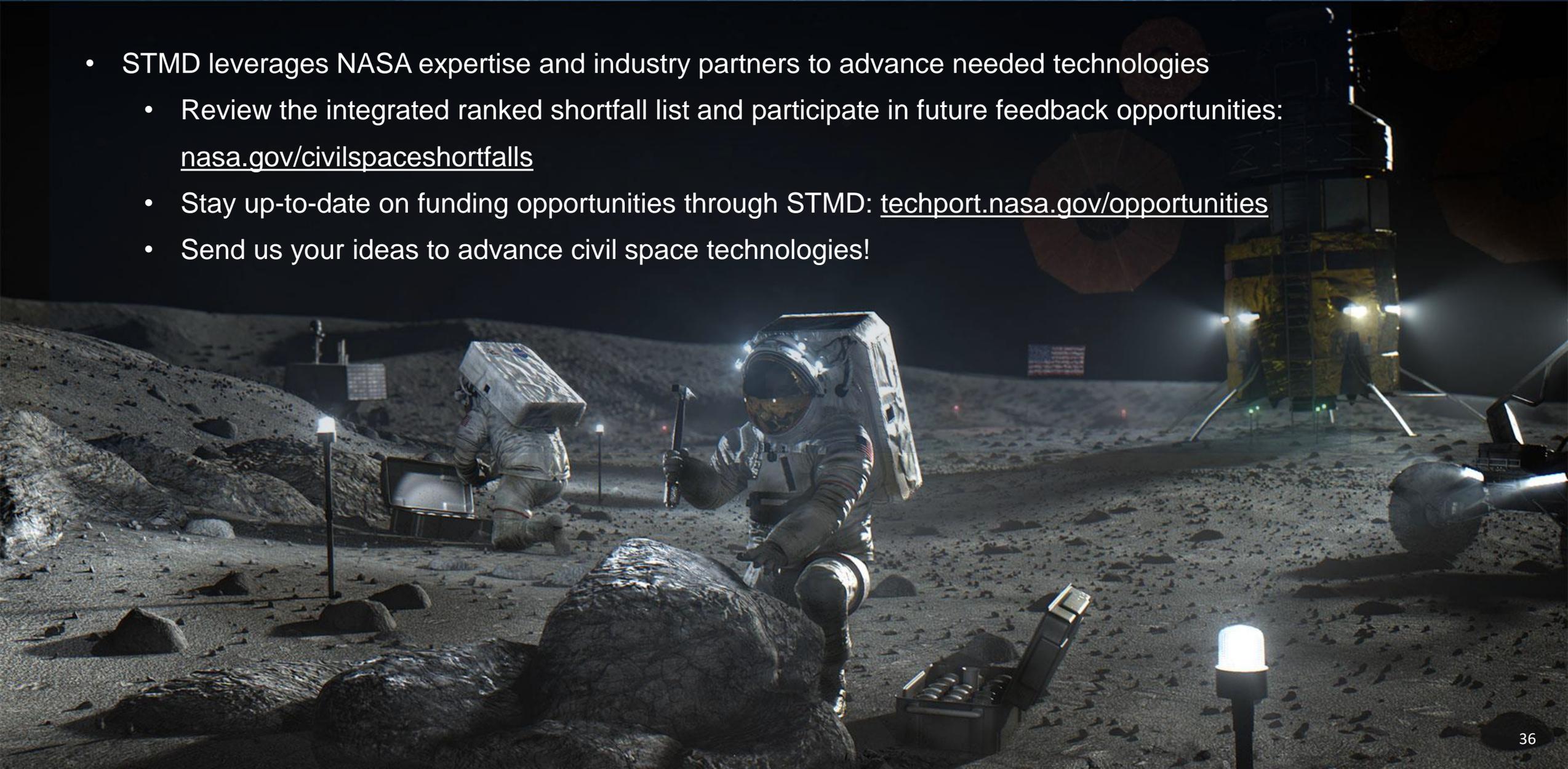
Small Spacecraft Technologies
Develop technologies for small spacecraft and responsive launch to rapidly expand space capabilities at dramatically lower costs.



1.6 MB PDF Watch

Work with Us!

- STMD leverages NASA expertise and industry partners to advance needed technologies
 - Review the integrated ranked shortfall list and participate in future feedback opportunities: nasa.gov/civilspaceshortfalls
 - Stay up-to-date on funding opportunities through STMD: techport.nasa.gov/opportunities
 - Send us your ideas to advance civil space technologies!



BACKUP



Data Rate Examples

- POTS Voice Grade Channel: 64 Kbps
- 1080p Video: 3 – 6 Mbps (depending on the codec)
- 4K Video: 15 -32 Mbps (depending on the codec)
- Typical 4G/LTE Cell Phone Download: 12-30 Mbps (Max is 150 Mbps)
- Typical Residence Internet Connection in the United States: 42.86 Mbps (from HighSpeedInternet.com) - 242.38 Mbps (from Speedtest.net)
- Space Shuttle: 216 Kbps Forward / 50 Mbps Return
- Space Station: 25 Mbps Forward / 600 Mbps Return
- Gateway: 20 Mbps Forward / 100 Mbps Return
- HLS: 10 Mbps Forward / 24 Mbps (48 Mbps in Discussion) Return

Comm Online Activity on Earth	Minimum Data Rate	Recommended Data Rate
E-Mail Checking	0.5 Mbps	1 Mbps
Web Browsing	1 Mbps	2 – 5 Mbps
HD Video Streaming	5 Mbps	8 Mbps
Video Conferencing	2 Mbps	8 Mbps
4K Video Streaming	15 Mbps	25 Mbps

Maximum Data Return from Mars TODAY at Maximum Range with one 34m Antenna:

Approximately 0.5 Mbps, at X-band, on MRO, with its 3m HGA and 100W TWTA. That HGA and TWTA are the largest ever flown to Mars. Cassini, however, had a 4m antenna.

Approximately 0.5 Mbps at Ka-Band, on MRO, with a 35W TWTA. However, the Ka-Band system was only used near Earth due to a transistor failure in an amplifier.

NASA's Moon-to-Mars Blueprint Objectives



- **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

Science Objectives (1 of 4)

Lunar/Planetary Science (LPS) Goal: Address high priority planetary science questions that are best accomplished by on-site human explorers on and around the Moon and Mars, aided by surface and orbiting robotic systems.

- LPS-1: Uncover the record of past habitable environments on Mars, by identifying key sites and other planetary bodies (near and distant), characterizing the record resulting from the interplay between the heat and cold, and understand how these sites have changed over time to become uninhabitable.
- LPS-2: Advance understanding of the planet processes that affect habitability by characterizing the interior structure, measuring the magnetic field, measuring atmospheric structure, and evolution of atmospheric chemistry, and measuring low surface processes (such as the surface of the Moon and Mars).
- LPS-3: Investigate how solar system bodies have evolved by measuring the age, size, chemical composition, structure, and atmospheric structure and surface evolution.
- LPS-4: Advance understanding of the role of life in the solar system by identifying when and how planetary habitats environments formed, and processes led to their formation, how planetary environments and habitats evolved over time, and whether there is evidence of past or present life in the solar system beyond Earth.

Heliophysics Science (HS) Goal: Address high priority heliophysics science and space weather questions that are best accomplished using a combination of human explorers and robotic systems at the Moon, at Mars, and in deep space.

- HS-1: Improve understanding of space weather phenomena to enable improved observation and prediction of the system environment from space to the surface of the Moon and Mars.
- HS-2: Increase understanding of the Sun and solar system as a system of the Sun and solar system.
- HS-3: Investigate and characterize fundamental plasma processes, including dust plasma interactions, using the natural near-Sun, and surface environments as laboratories.
- HS-4: Improve understanding of magnetospheric and plasma wave interactions in the vicinity of the Moon and around Mars.

LI-10: Demonstrate technologies supporting cultural, off-surface deposits, construction and manufacturing maximizing the use of in-situ resources and support systems needed for continuous human/robotic presence.

LI-9: Develop environmental monitoring, situational awareness, and early warning capabilities to support a resilient, continuous human/robotic lunar presence.

LI-11: Develop systems capable of returning a range of cargo mass from the lunar surface to Earth, including the capabilities necessary to meet scientific and cultural objectives.

LI-12: Develop systems capable of returning a range of cargo mass from the Martian surface to Earth, including the capabilities necessary to meet scientific and cultural objectives.

OP-10: Demonstrate the capability to operate (orbit) systems that are used to support crew members at the lunar or Martian surface, automatically or remotely from Earth or from orbiting partners.

OP-11: Demonstrate the capability to use resources produced from planetary surface or in-orbit resources to reduce the mass required to be transported from Earth.

OP-12: Establish processes and systems that will minimize the pollution to the host environment, maximize the resources available to Moon explorers, and allow for re-use/recovery of resources transported from Earth and from the lunar surface in the case of items to be used during operations.

Recurring Tenets
Common themes across objectives

- RT-1: International Collaboration: partner with international community to address common goals and objectives
- RT-2: Industry Collaboration: partner with U.S. industry to advance common goals and objectives
- RT-3: Crew Return: return crew safely to Earth while mitigating adverse impacts to crew health
- RT-4: Crew Time: maximize crew time available for research and engineering activities while ensuring mission stability
- RT-5: Maintainability and Reuse: when practical, design systems for maintainability, reuse, and/or recycling to support the long-term sustainability of operations and increased Earth sustainability
- RT-6: Responsible Use: conduct all activities for the exploration and use of outer space for peaceful purposes consistent with international obligations and principles of responsible behavior in space
- RT-7: Interoperability: enable interoperability and commonality (technical, operational and process standards) among systems, elements, and crews throughout the program
- RT-8: Leverage Low Earth Orbit: leverage infrastructure in Low Earth Orbit to support M2M activities
- RT-9: Commerce and Space Development: foster the expansion of the economic sphere beyond Earth orbit to support U.S. industry and innovation

Infrastructure Objectives (1 of 2)

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-1^L: Develop an incremental lunar power generation and distribution system that is evolvable to support continuous robotic/human operation and is capable of scaling to global power utilization and industrial power levels.

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.

LI-4^L: Demonstrate advanced manufacturing and autonomous construction capabilities in support of continuous human lunar presence and a robust lunar economy.

LI-5^L: Demonstrate precision landing capabilities in support of continuous human lunar presence and a robust lunar economy.

LI-6^L: Demonstrate local, regional, and global surface transportation and mobility capabilities in support of continuous human lunar presence and a robust lunar economy.

LI-7^L: Demonstrate industrial scale ISRU capabilities in support of continuous human lunar presence and a robust lunar economy.

LI-8^L: Demonstrate technologies supporting cislunar orbital/surface depots, construction and manufacturing maximizing the use of in-situ resources, and support systems needed for continuous human/robotic presence.

LI-9^L: Develop environmental monitoring, situational awareness, and early warning capabilities to support a resilient, continuous human/robotic lunar presence.

Infrastructure Objectives (2 of 2)

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

- MI-1^M: Develop Mars surface power sufficient for an 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.
- MI-4^M: Demonstrate Mars ISRU capabilities to support an initial human Mars exploration campaign.