Future Directions in Space Communications

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Advanced Prototype Engineering Technology Symposium

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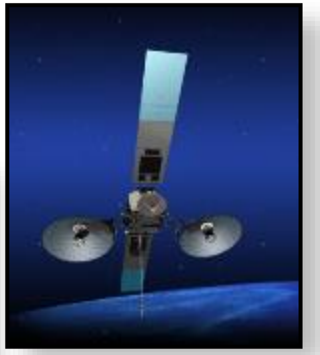
1951–2021
70 YEARS
LINCOLN LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

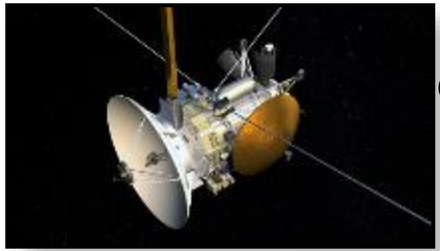
Lasercom Modeled After and Improving RF Space Comm

TDRS



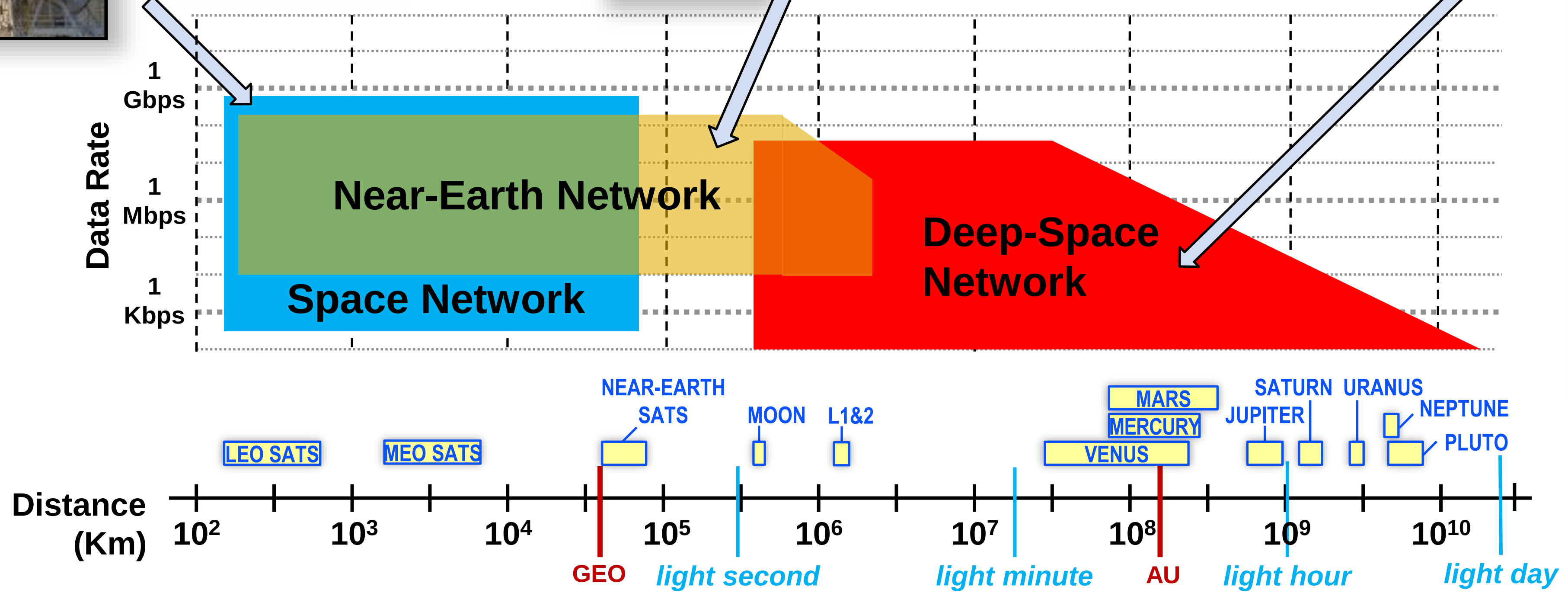
Planet Labs

Solar Dynamics Obs

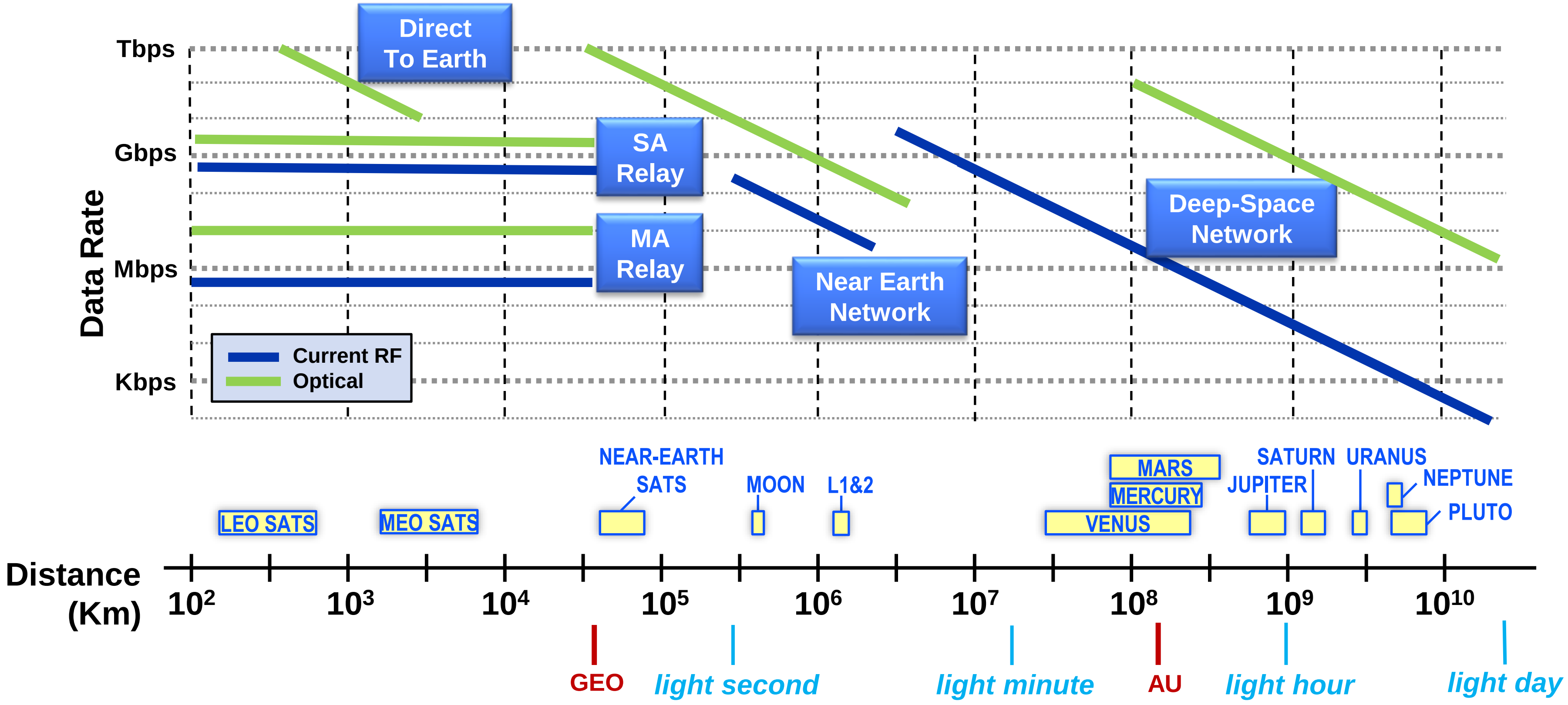


Cassini

DSN 70-m



NASA Optical Communications Network



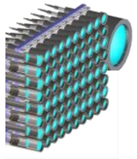
NASA Optical Communications Network

Relay

User

Single-access

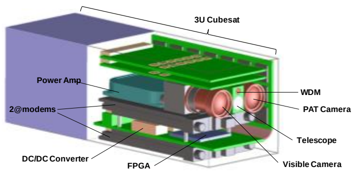
Ground



Multi-access

- Relay satellite
  - 10 SA cm telescope
  - N x M cm MA telescopes
- Ground terminal
  - 0.6 m telescope
- Next Gen user terminal
  - x-y cm scalable aperture

Direct-to-Earth



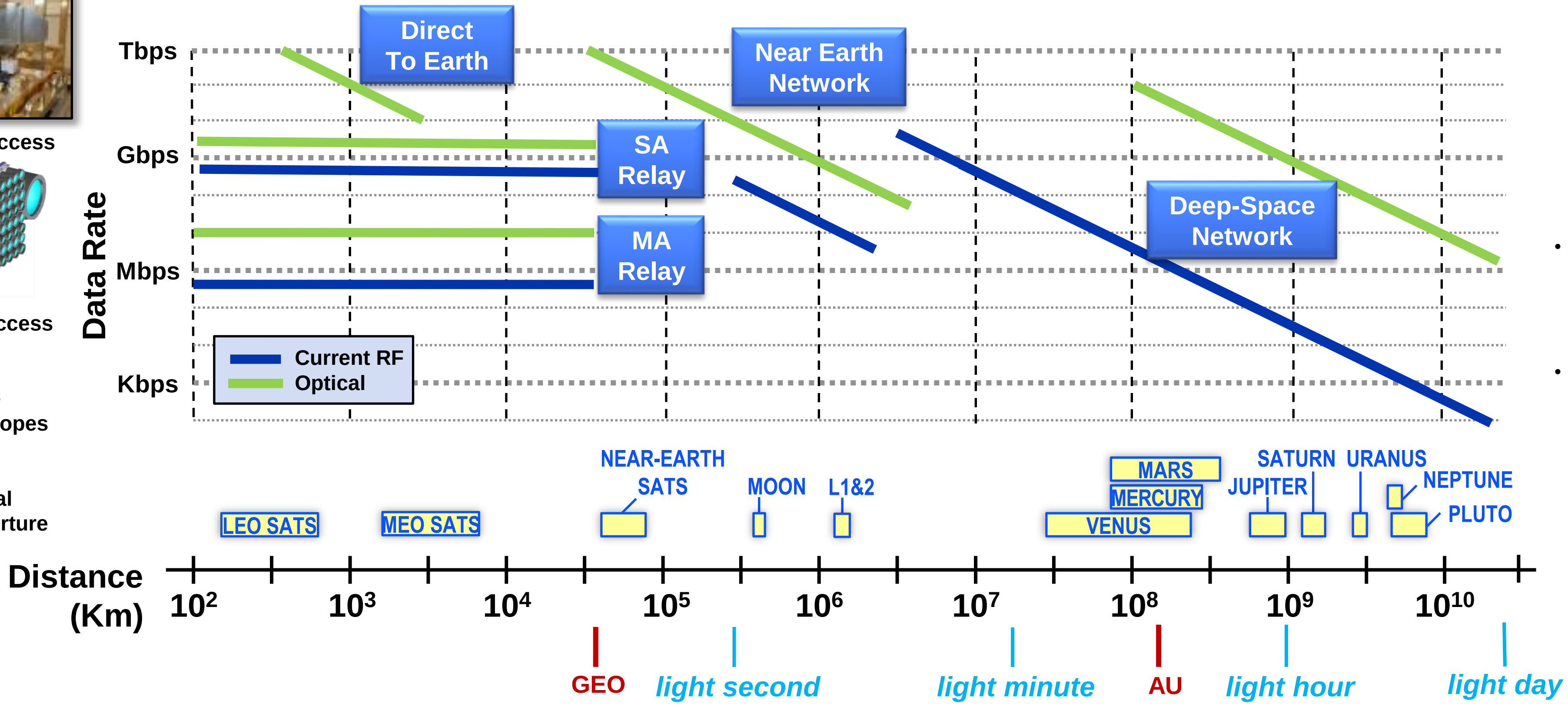
- CubeSat terminal
  - X cm telescope
  - Y mW opt amplifier
- Ground terminal
  - 0.25-0.4 m

Near Earth

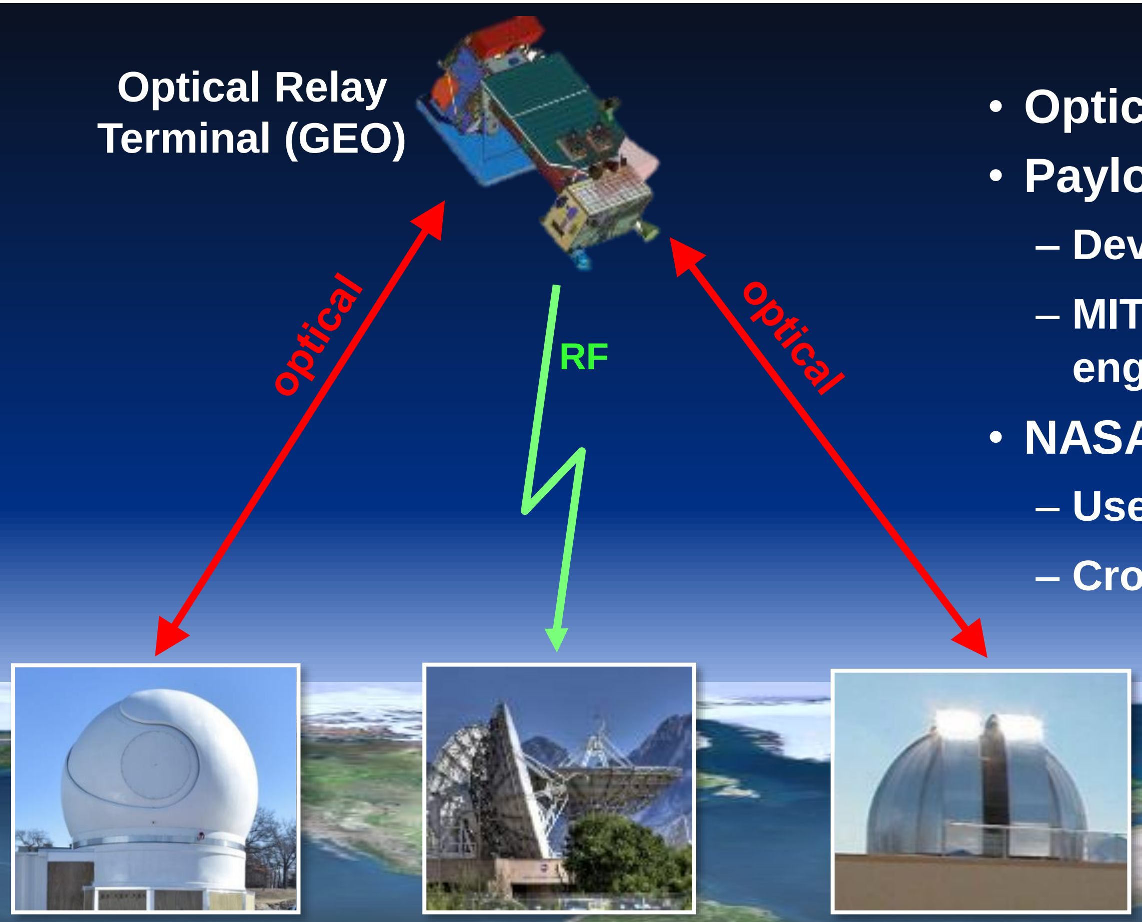
- Platform terminal
  - X cm telescope
  - Y mW opt amplifier
- Ground terminal
  - 1-2 m

Deep Space

- Advanced, High-Perf Deep-Space Terminal
  - 0.5-2-m, dual use telescope
  - 20-50 W opt amplifier
  - Star-stabilized
- Ground Terminal Array
  - 3-5 m Telescope
  - Laser Guide Star



Laser Communications Relay Demonstration



Optical Ground Station (Hawaii) MITLL

RF Antenna (White Sands) NASA

Optical Ground Station (California) NASA JPL

- Optical relay pathfinder; June 2021 launch
- Payload based on MITLL terminal designs
  - Developed by NASA Goddard
  - MITLL supporting tech transfer and systems engineering
- NASA concepts for follow-on operational gateway
  - User data rates up to 10 Gbps
  - Crosslinks and downlinks up to 100 Gbps

NASA LCRD (MIT LL Technology Transfer)
to Launch in 2021

LCRD payload (top) integrated onto STPSat-6 space vehicle, July 2020
Credits: NASA

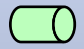
- **LCRD GEO satellite payload includes two lasercom heads and a switch based on MIT LL designs**
- **GEO heads will communicate with optical ground stations in California and Hawaii**
- **LCRD will also communicate with ILLUMA-T lasercom terminal (designed and integrated by MIT LL) on the International Space Station, in 2022**

LCRD Optical Ground Station 2 (OGS-2) in Hawaii, August 2020
Credits: NASA

Concept for Optical Multiple Access System

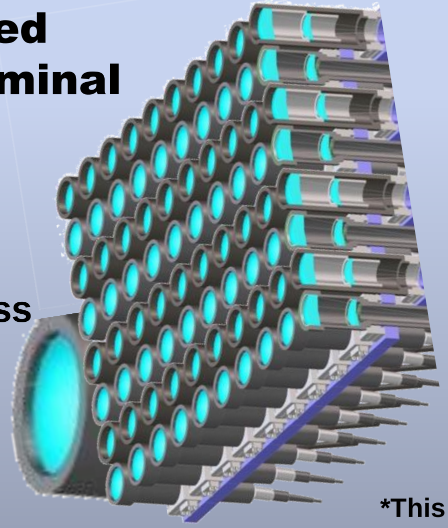
10 Mbps service for many simultaneous users

LEO/MEO
User Terminal



LEO user requires only 1-3 cm with 1 W (<2 kg)

GEO-based
OMA Terminal



Array of medium-rate duplex heads (1-3 cm)

Low-rate demand-access receiver

*This OMA grew out of ERNESt study

- LEO user transmits unscheduled service request towards GEO OMA terminal, then coordinates high-rate duplex service

- Wide-field-of-view receiver stares at entire Earth and LEO community, waiting for service request
- Hands off to large array of small, gimballed heads for duplex service

Note: This service seems unique to the NASA mission.
Likely not to be developed by commercial.
Useful both Near-Earth and cislunar.

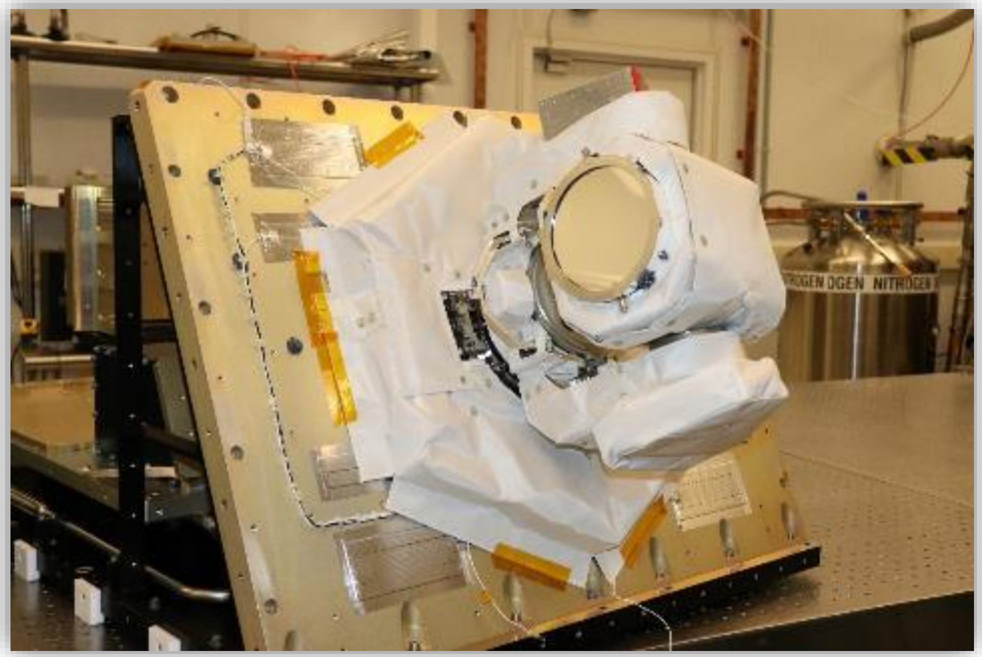
International Space Station (ISS)

- **Humans have been in low-Earth orbit continuously for nearly 2 decades aboard ISS**
- **High-rate radio-frequency relay links support human space presence and science**
  - **600 Mbps return**
  - **25 Mbps forward**
- **ILLUMA-T to provide optical relay via LCRD**
  - **1.2 Gbps return**
  - **51 Mbps forward**
  - **Can also point to ground**

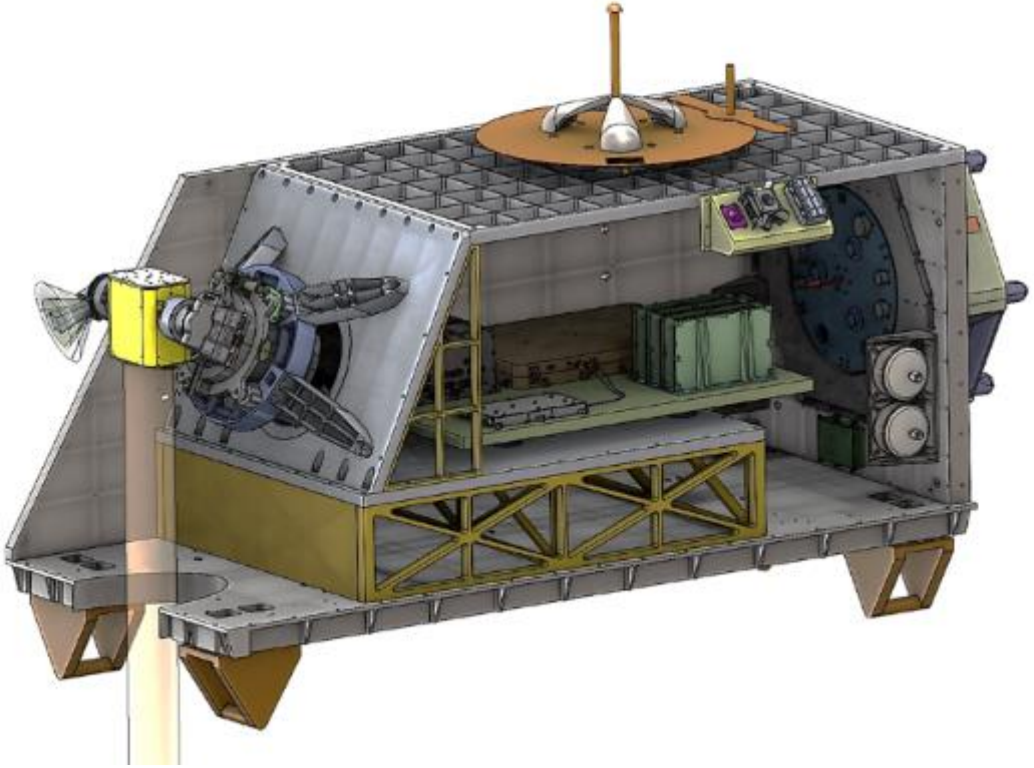
8K HD Video from ISS

Image: NASA

ILLUMA-T Sled Assembly



OM with Completed Beta Cloth MLI



NASA Artemis/Orion

- NASA Artemis missions to return humans to moon in 2020’s
  - 2022 Artemis-1 uncrewed lunar flyby
  - 2023 Artemis-2 crewed lunar flyby
  - 2024 Artemis-3+ lunar landing
- Moon provides staging ground for eventual missions to Mars
- Orion comm capability
  - S-band phased array transmitters
  - Up to ~2 Mb/s from lunar ranges to NASA Deep Space Network
- O2O to provide
  - Up to 250 Mbps return
  - 20 Mbps forward

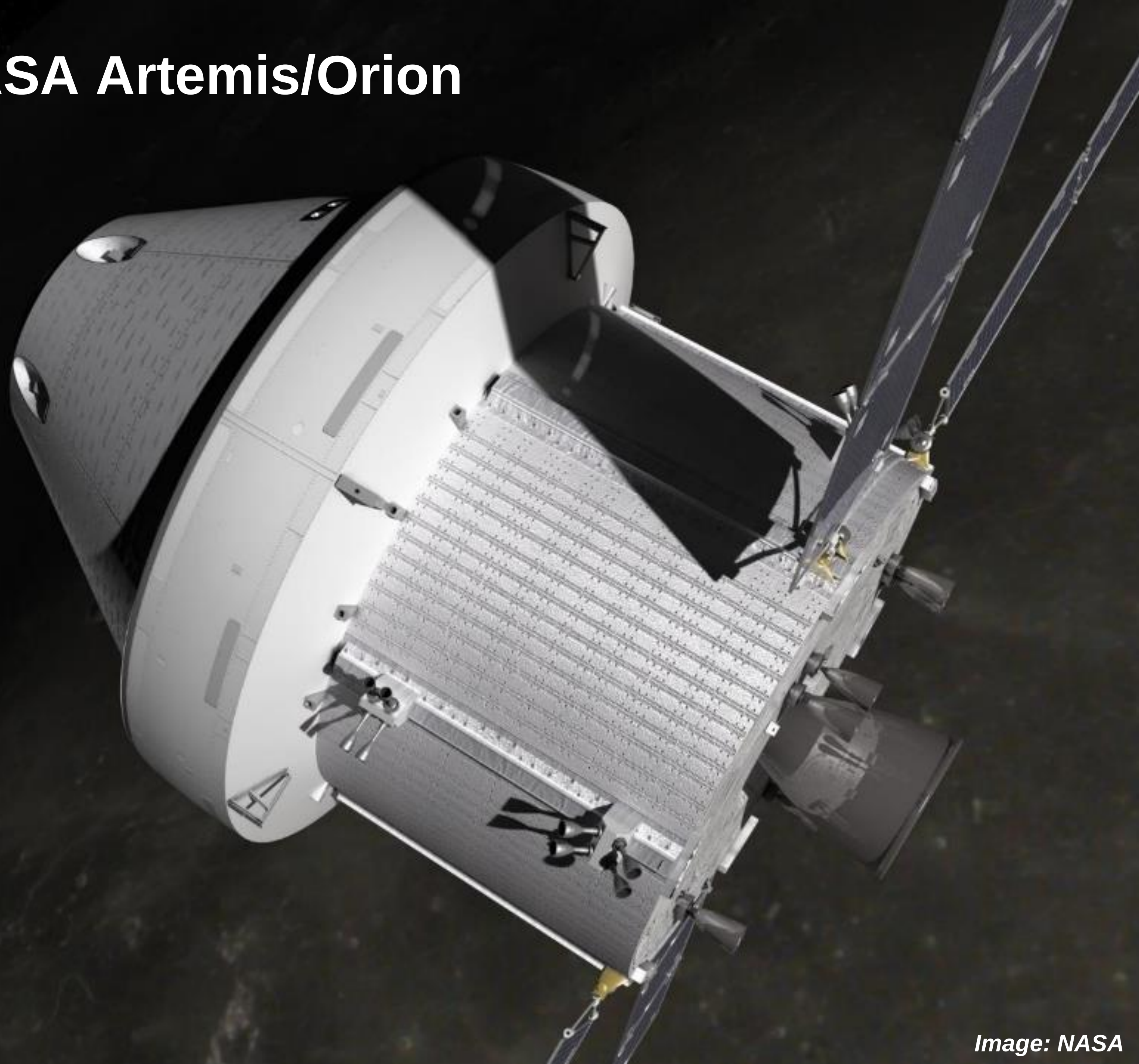
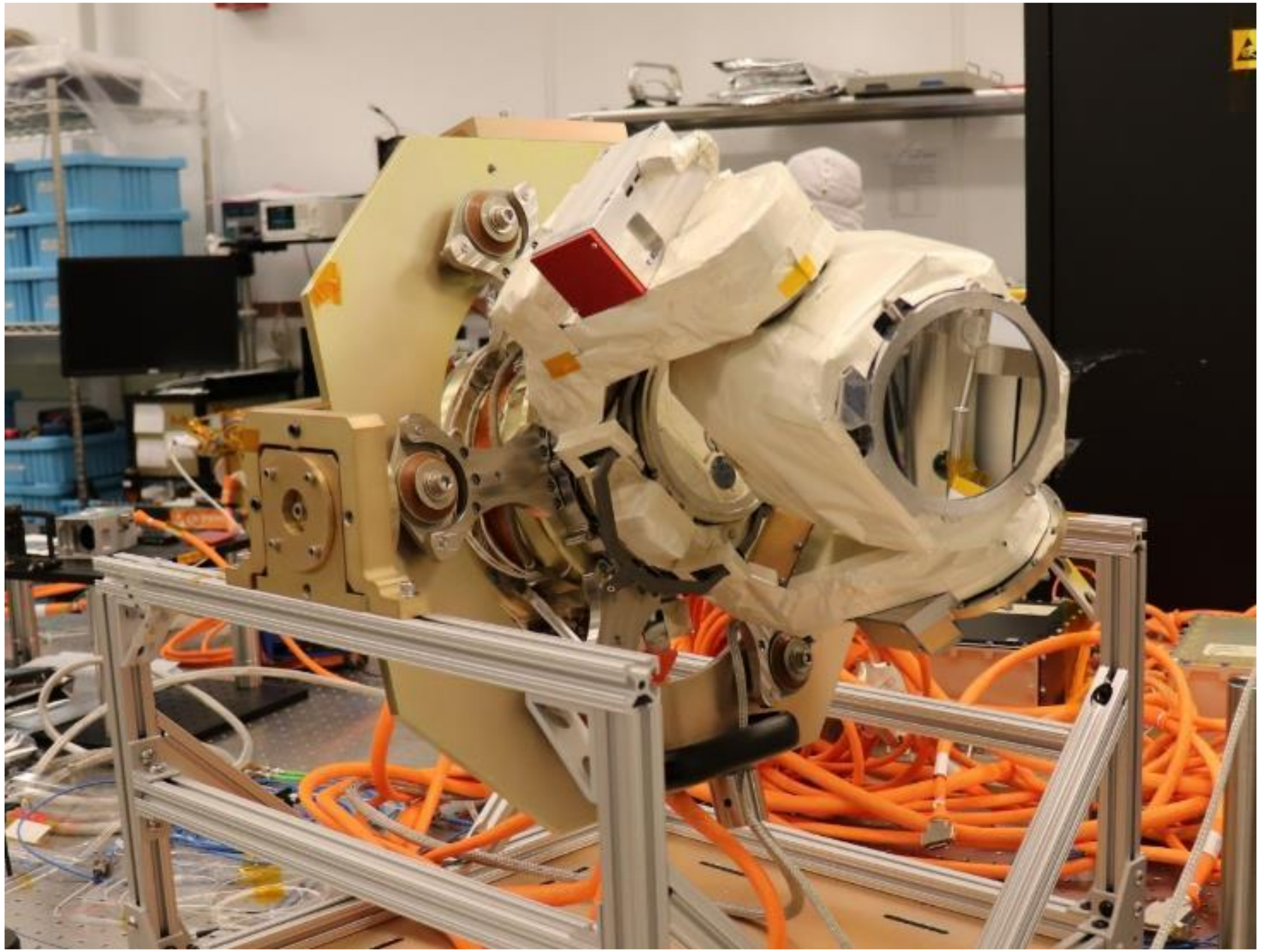
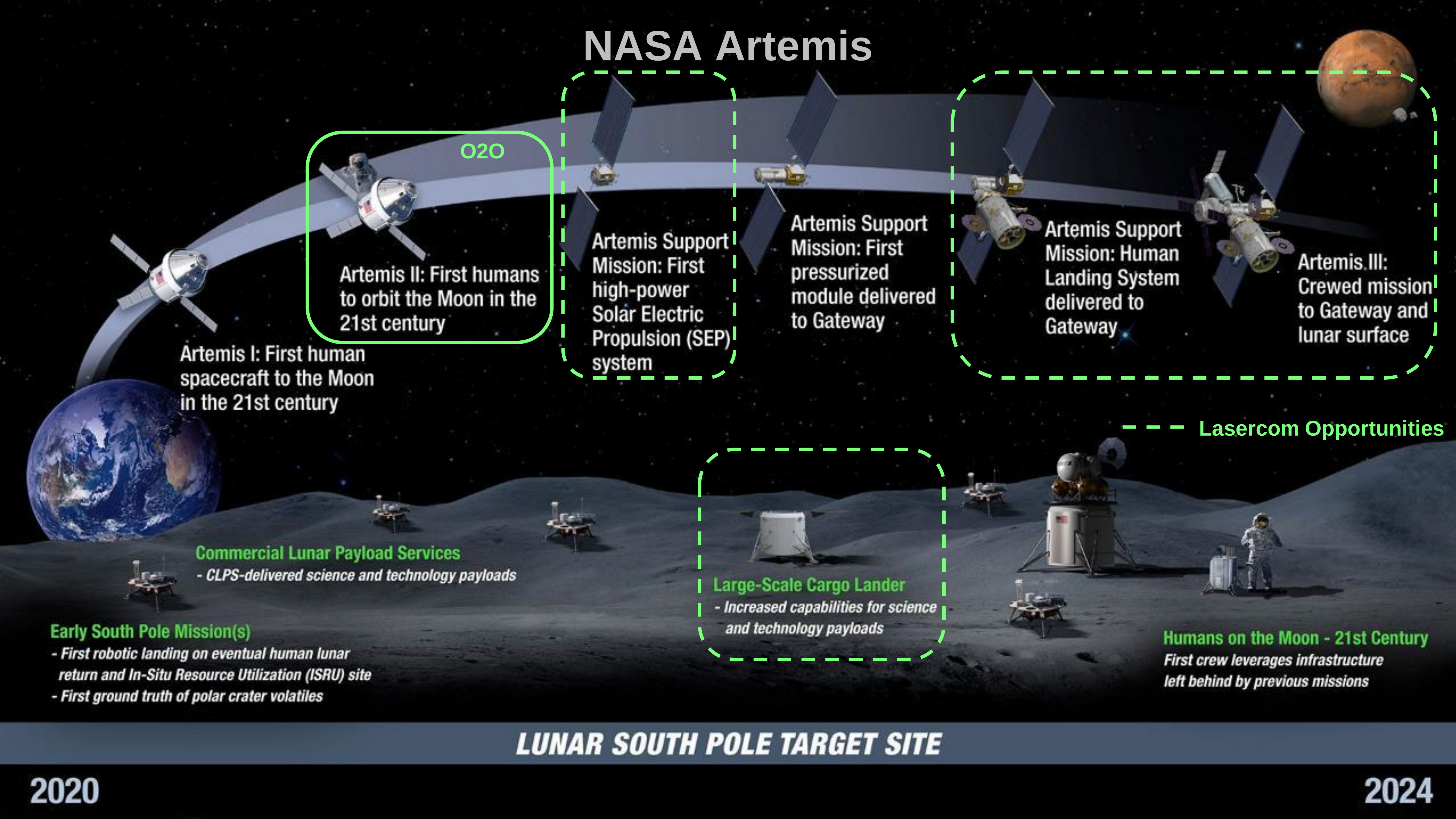


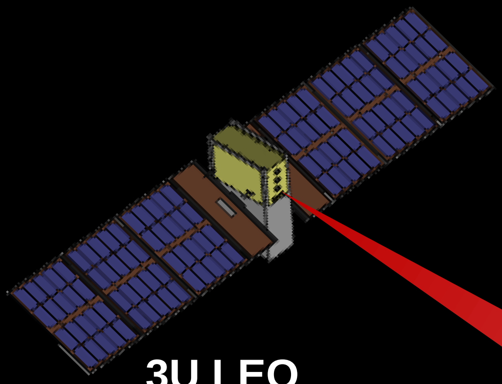
Image: NASA

Optical Module for Artemis II




NASA Artemis
O2O
Artemis I: First human spacecraft to the Moon in the 21st century
Artemis II: First humans to orbit the Moon in the 21st century
Artemis Support Mission: First high-power Solar Electric Propulsion (SEP) system
Artemis Support Mission: First pressurized module delivered to Gateway
Artemis Support Mission: Human Landing System delivered to Gateway
Artemis III: Crewed mission to Gateway and lunar surface
Lasercom Opportunities
Commercial Lunar Payload Services
- CLPS-delivered science and technology payloads
Large-Scale Cargo Lander
- Increased capabilities for science and technology payloads
Early South Pole Mission(s)
- First robotic landing on eventual human lunar return and In-Situ Resource Utilization (ISRU) site
- First ground truth of polar crater volatiles
Humans on the Moon - 21st Century
First crew leverages infrastructure left behind by previous missions
LUNAR SOUTH POLE TARGET SITE
2020
2024

TBIRD
(Terabyte Infrared Delivery)



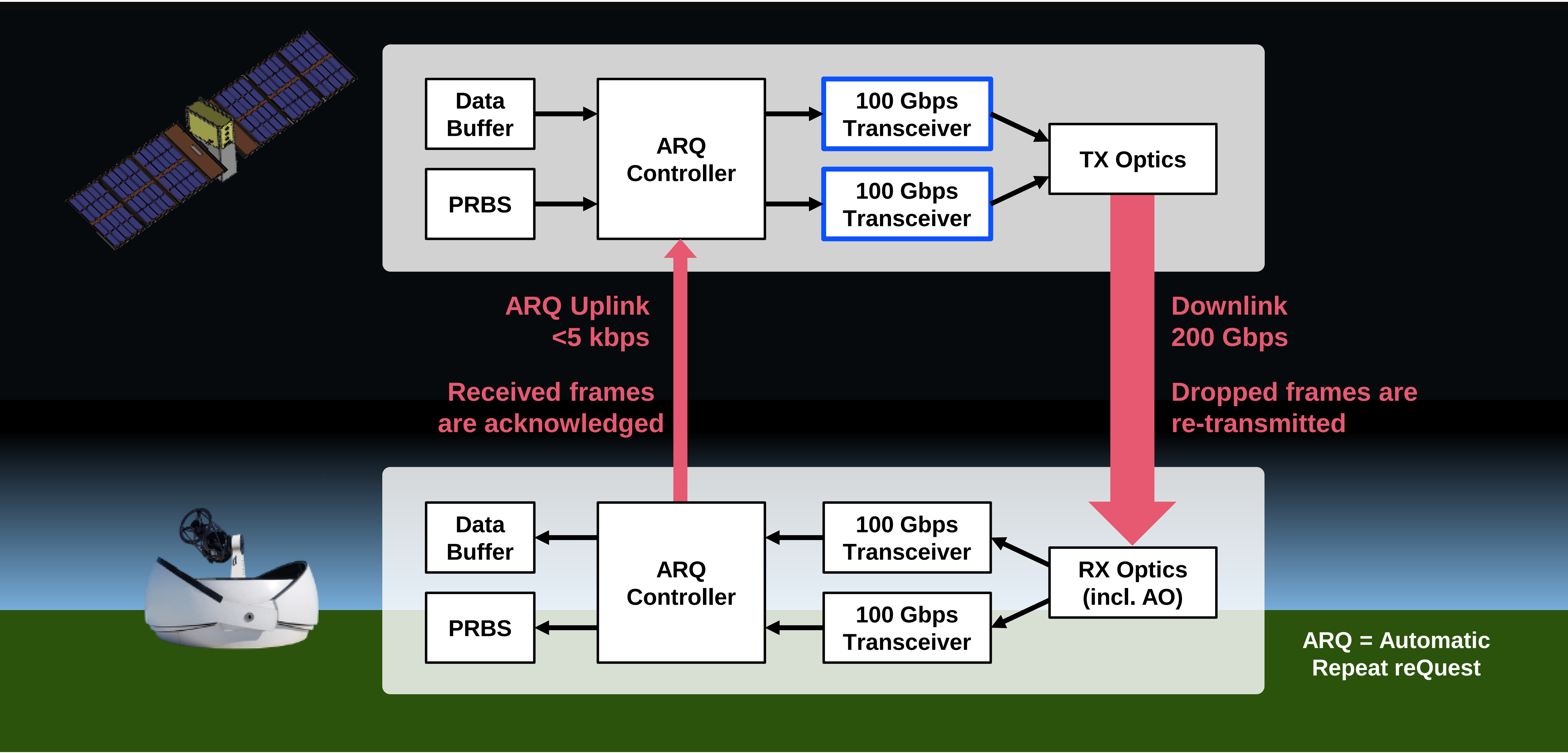
Target Goals

- Demonstrate burst data delivery architecture & protocols
- Compact, low cost space & ground terminals
- Leverage high rate COTS telecom equipment for 200 Gbps data delivery

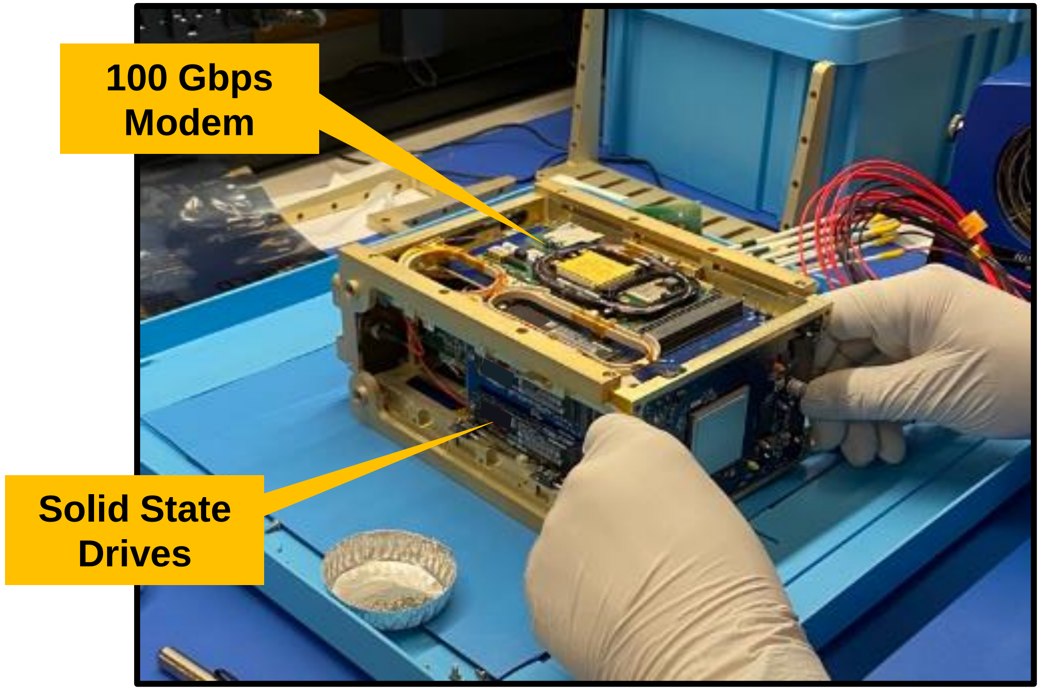
Planned Demonstration

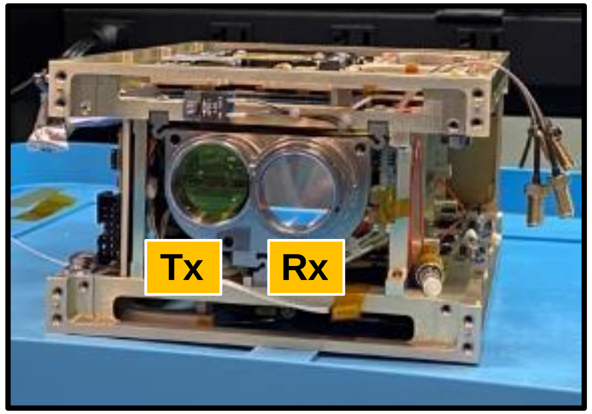
- Hosted 3U payload on 6U CubeSat
  - NASA Small Sat Pathfinder Tech Demo
- 2 x 100 Gbps coherent transceivers
- High-speed readout from space buffer
- Widely-deployable ground terminal

TBIRD Block Diagram

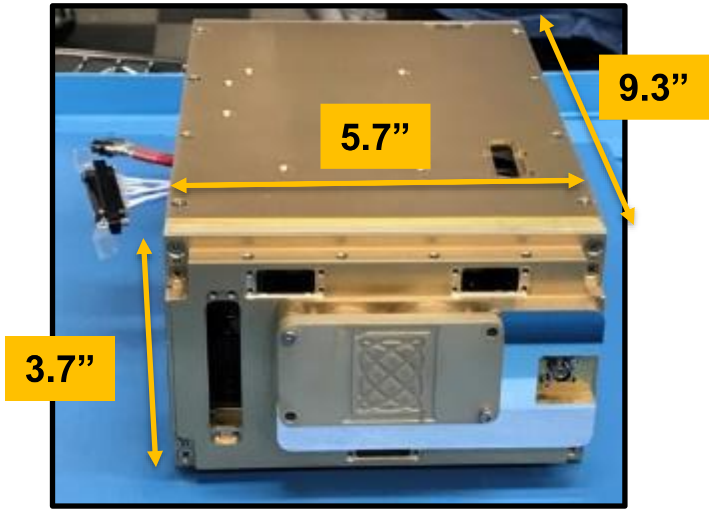


TBIRD Payload





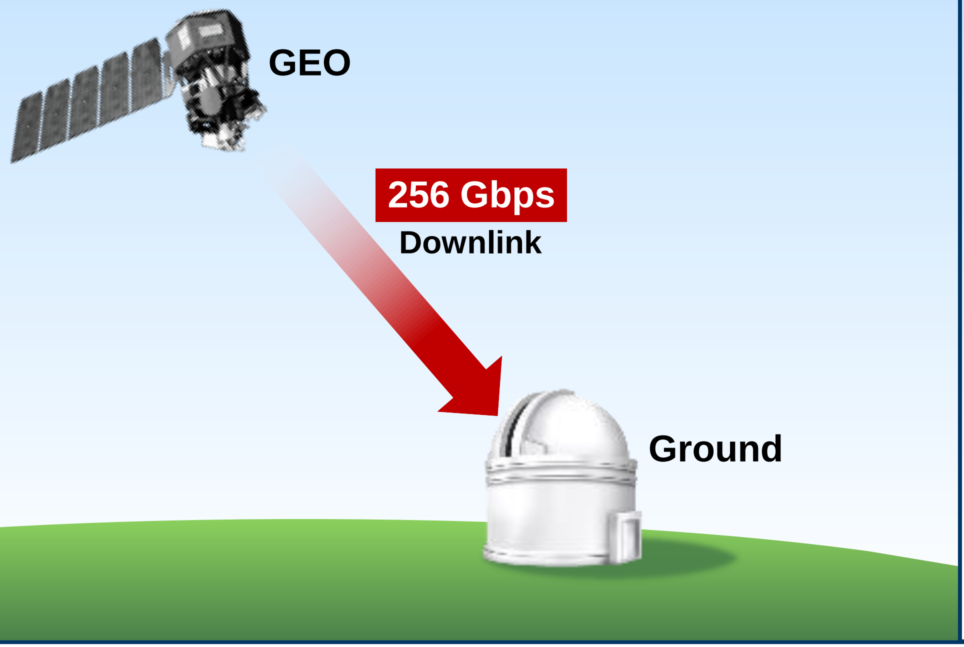
Bi-static Transmit & Receive Optics



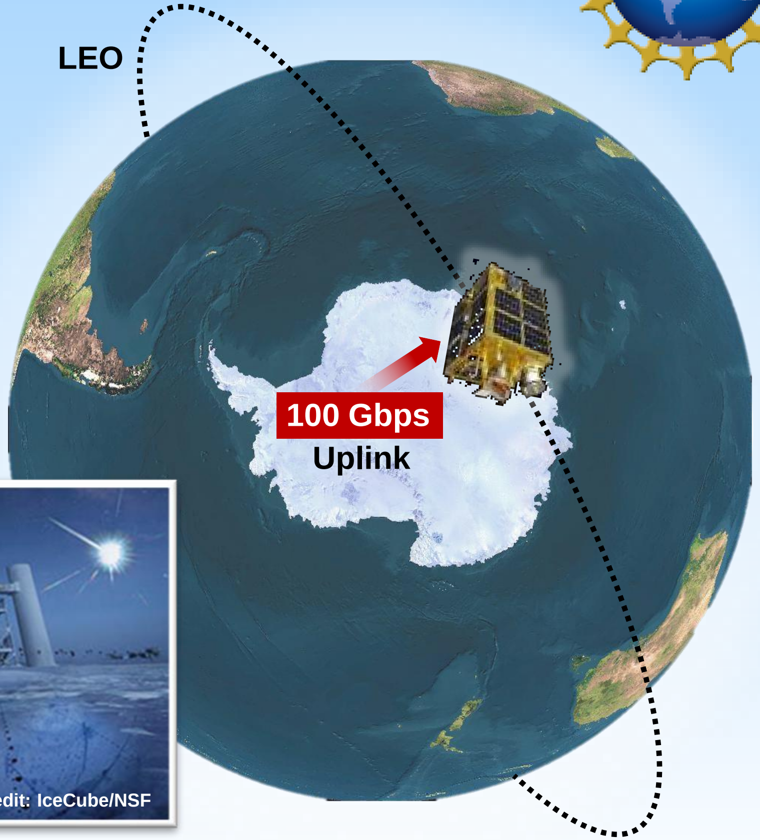
Future Applications

High-Bandwidth Space Astronomy

CENTER FOR ASTROPHYSICS HARVARD & SMITHSONIAN



Data Relay from Challenging Ground Environments



Neutrino Observatory, Antarctica
Generates >1 TB per day

NASA Lasercom Development

Moon

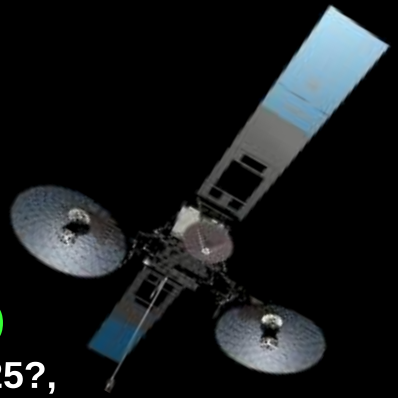
- LLCD (2013, MIT LL/GSFC)

Deep Space

- Deep Space Opt Comm (2022, JPL/MITLL-D8)
- Next-Gen Deep Space Optical Comm (2025?, JPL/MITLL/GSFC)

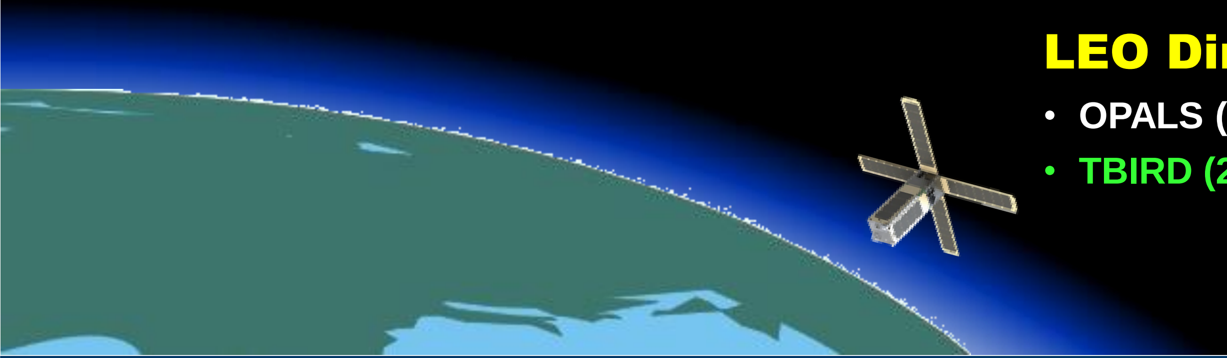
GEO Relay

- LCRD (2021, GSFC/ JPL/MIT LL)
- ISS LEO Terminal (2022, MIT LL/GSFC)
- Next-Gen Relay (2025?, GSFC/GRC/MIT LL)



Human Exploration

- Orion EM-2 (2023, GSFC/MIT LL)
- Orion EM-3+ (2024+, TBD)
- Lunar Gateway (2025, TBD)



LEO Direct-to-Earth

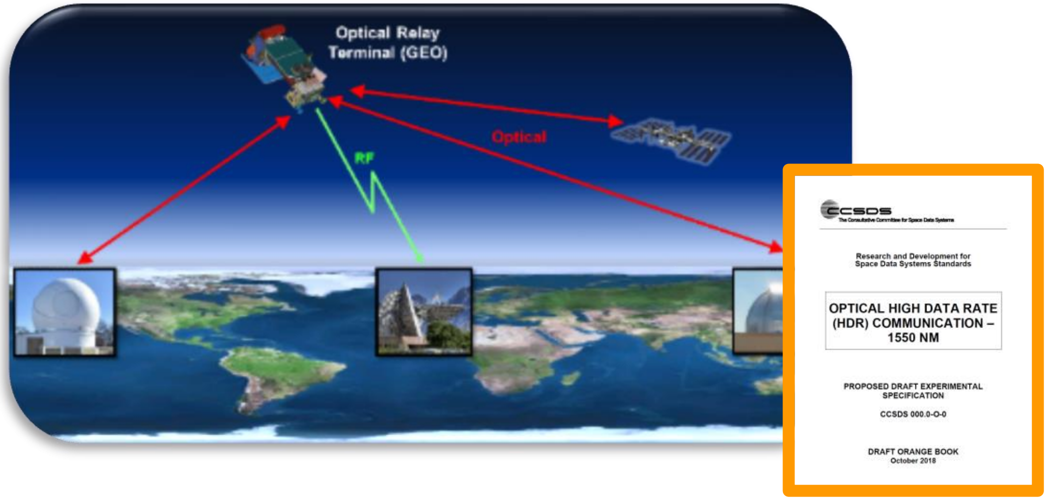
- OPALS (2015, JPL)
- TBIRD (2022, MIT LL)

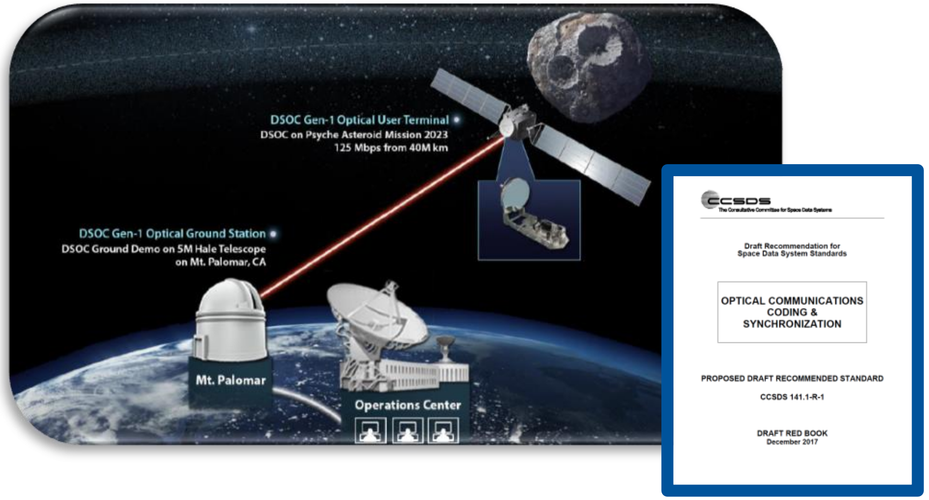
Science Observatories

- LUVOIR (2030's)
- Lynx (2030's)

Current MIT LL Efforts

Emerging Optical Communications Standards





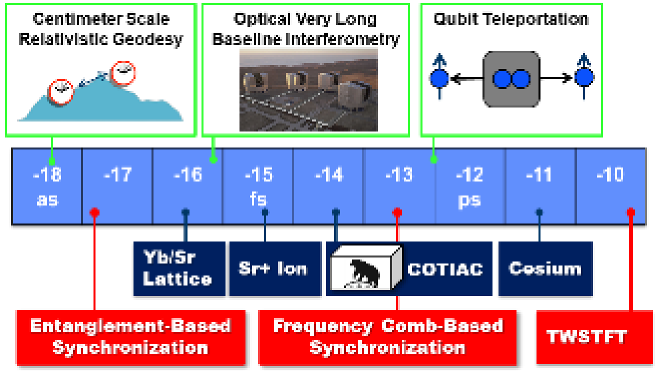
- **Near-Earth / High-Rate Standard**
  - "Orange Book" experimental standard in process
  - 1550 nm; Phase-shift keying
  - Evolved from LCRD waveform; compatible with next gen optical relay
- **Deep-Space / High-Efficiency Standard**
  - "Blue Book" standard based on international consensus in process
  - 1550 nm; Pulse-position modulation
  - Evolved from MLCD/LLCD waveform; compatible with DSOC

MITLL working with NASA/CCSDS to define lasercom standards to support near-Earth and deep space mission needs

Quantum Network Applications

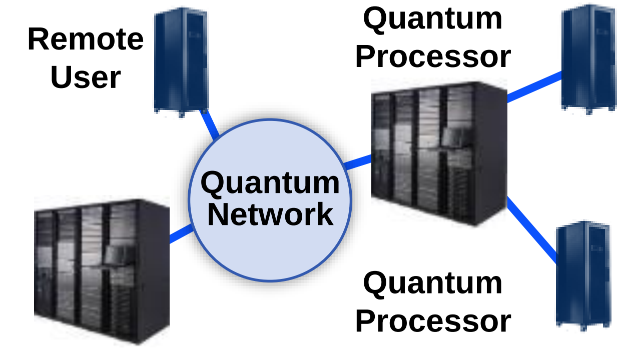
Quantum-Secure Comm Protocols

Improved Timing and Synchronization



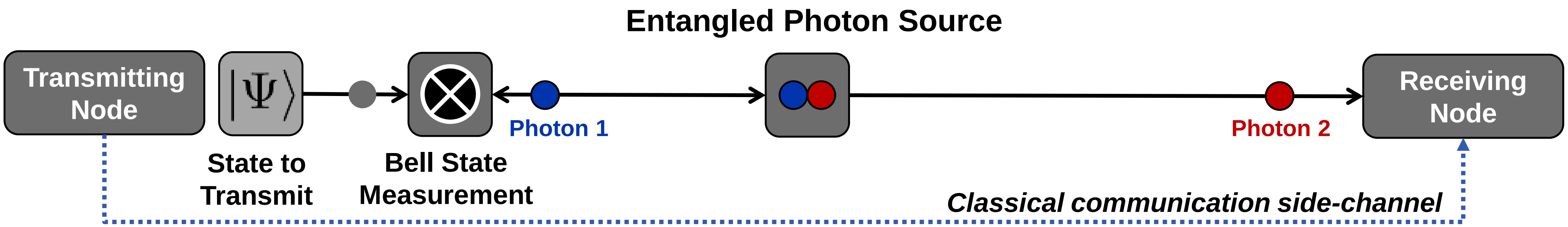
Long-Baseline Interferometry

Networked Quantum Processors



Application	Range	Rate	Benefit over Conventional Techniques
Quantum-Secure Comm Protocols	100 m to 1000 km	50 MHz to 10 GHz	Provable security of keys or comms against all future technologies
Improved Timing and Synchronization	100 m to 1000 km	10 Hz to 10 GHz	5–7 orders of magnitude improvement in timing precision
Long-Baseline interferometry	100 m to 1000 km	10 MHz to 10 THz	Arbitrary baseline increase improves angular resolution
Networked Quantum Processors	1 m to 10 km	10 Hz to 100 kHz	Earlier realization of useful quantum computer

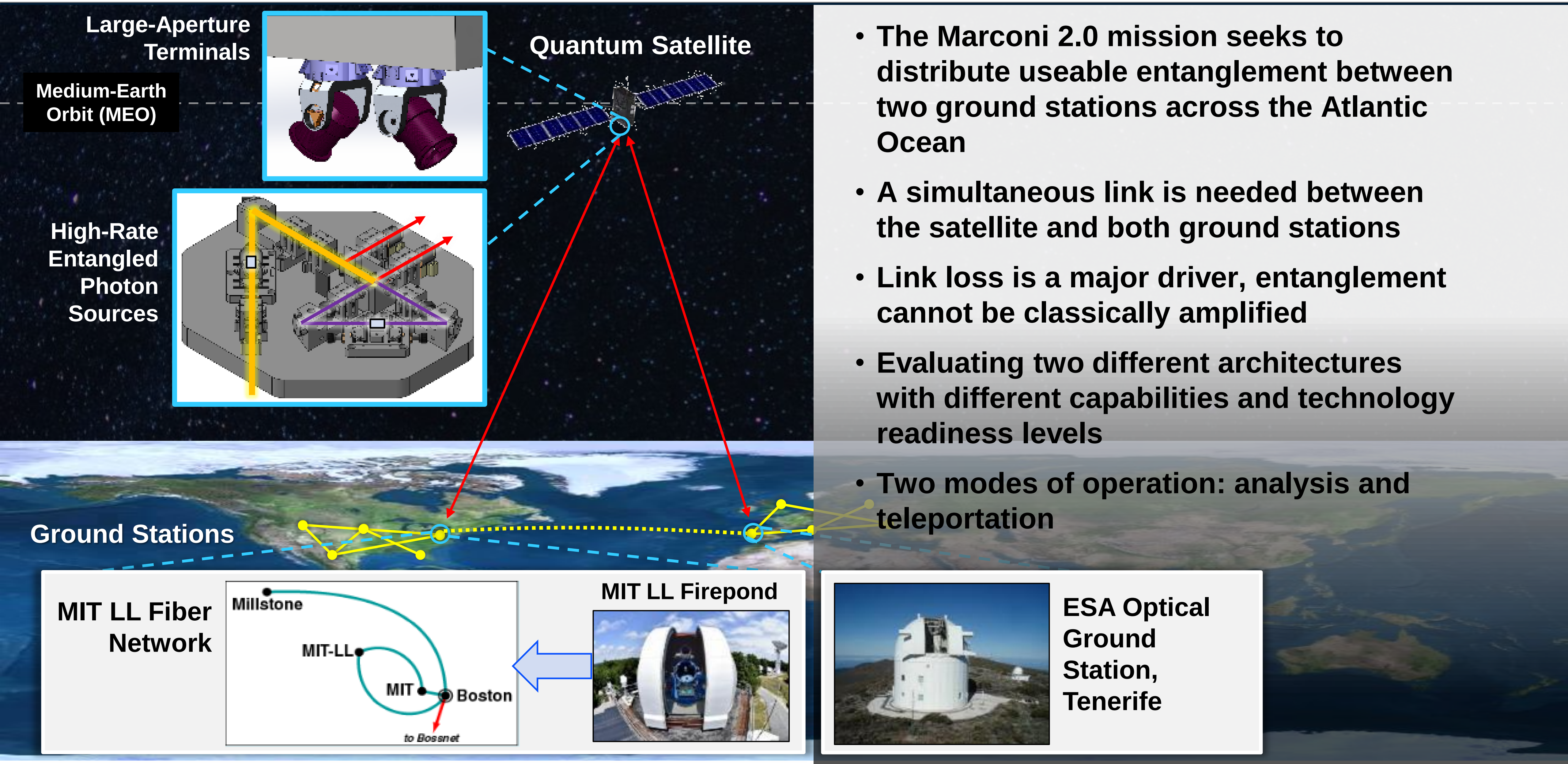
Quantum Teleportation



- Entanglement is distributed between Transmitting and Receiving Nodes
- Transmitting Node performs joint measurement between State to Transmit and Entangled Photon 1
- Transmitting Node classically transmits measurement result to Receiving Node
- Receiving Node performs local operation (based on measurement result) on Entangled Photon 2 to recover teleported State to Transmit

Quantum teleportation requires joint interaction between the state to transmit and an entangled photon

Free-Space Quantum Satellite: Marconi 2.0

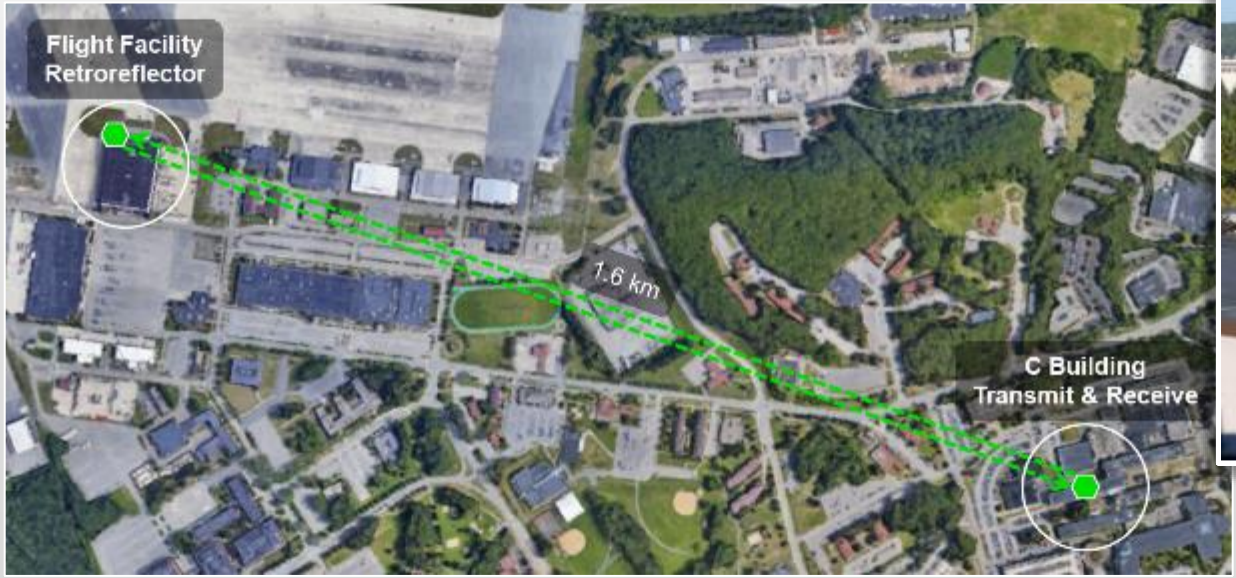


- The Marconi 2.0 mission seeks to distribute useable entanglement between two ground stations across the Atlantic Ocean
- A simultaneous link is needed between the satellite and both ground stations
- Link loss is a major driver, entanglement cannot be classically amplified
- Evaluating two different architectures with different capabilities and technology readiness levels
- Two modes of operation: analysis and teleportation

Free-Space Test Bed and Synchronization

- Test bed provides dynamic free-space optical link
- New architecture mitigates effects of dynamic free-space optical link to enable 1-ps-class synchronization at Bell state measurement (BSM)

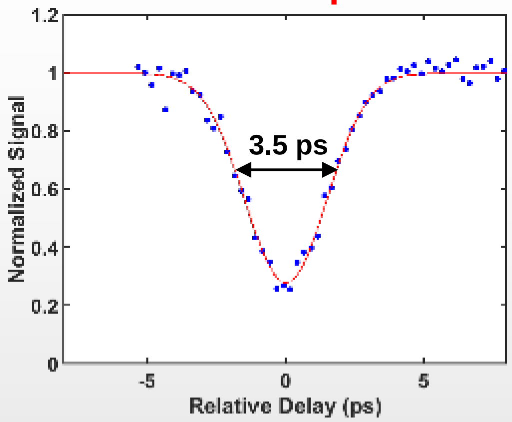
Local 3.2-km Free-Space Optical Link



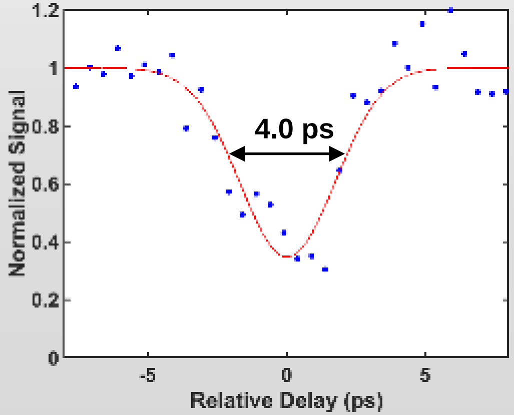
View from C-462

Partial BSM Over Free-Space Optical Link

In-Lab Loopback



Across Link



Summary

- Free-space Optical Links ready for operational use
  – Many link types already demonstrated
  – Several interesting demonstrations in progress
- Optical link standards critical to widespread adaptation/acceptance
- Quantum networks