

Space-Based Optical Communications: Present Capabilities and Future Opportunities

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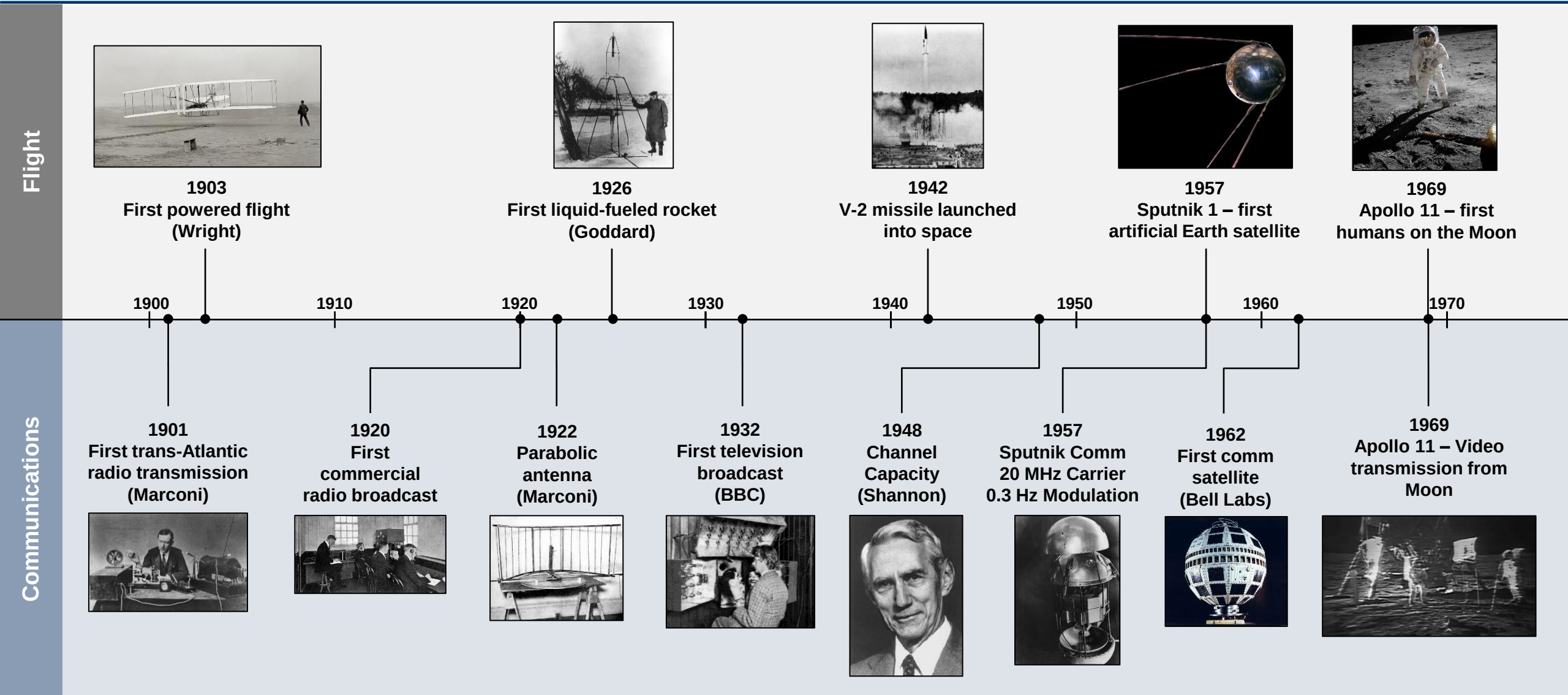
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Timeline of Early Space Exploration



Great Moments in Space Communications History

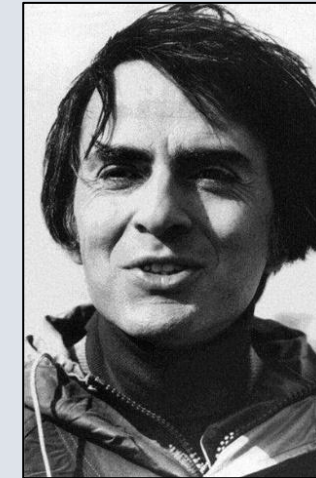
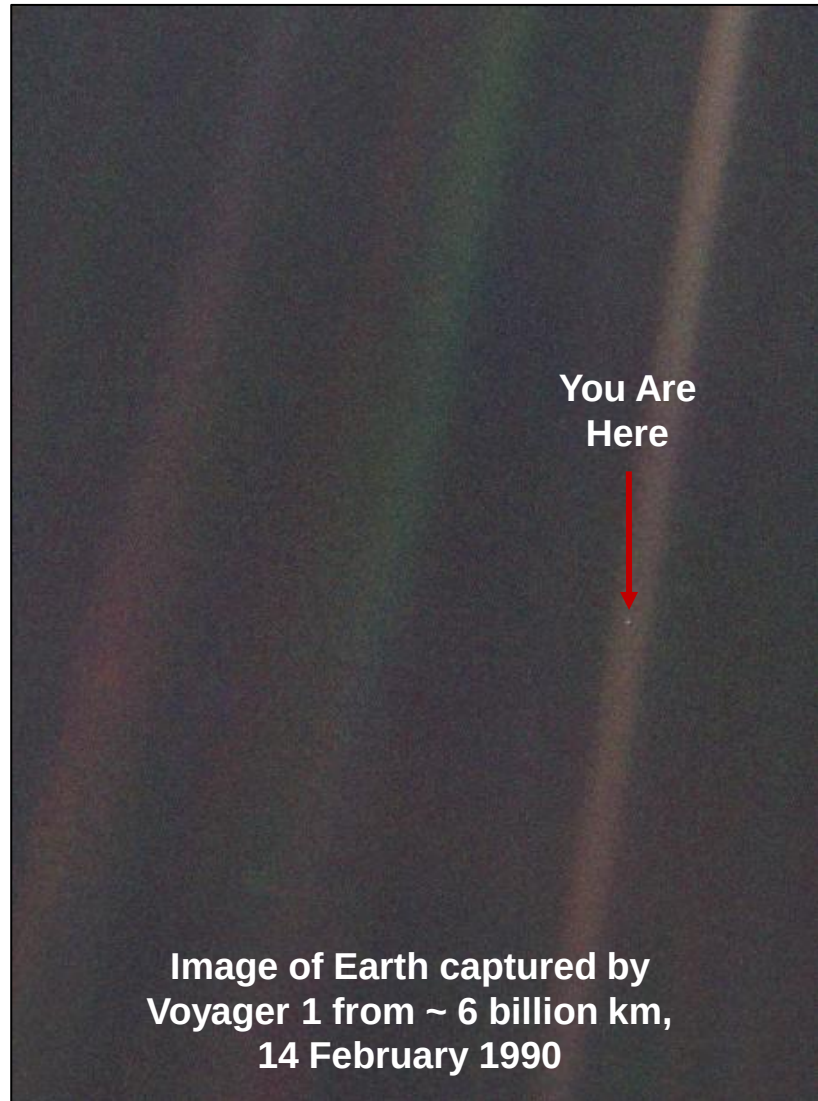
Apollo 11, 20 July 1969





Great Moments in Space Communications History

A Pale Blue Dot, 14 February 1990



“Consider again that dot. That's here. That's home. That's us. On it everyone you love, everyone you know, everyone you ever heard of, every human being who ever was, lived out their lives.”

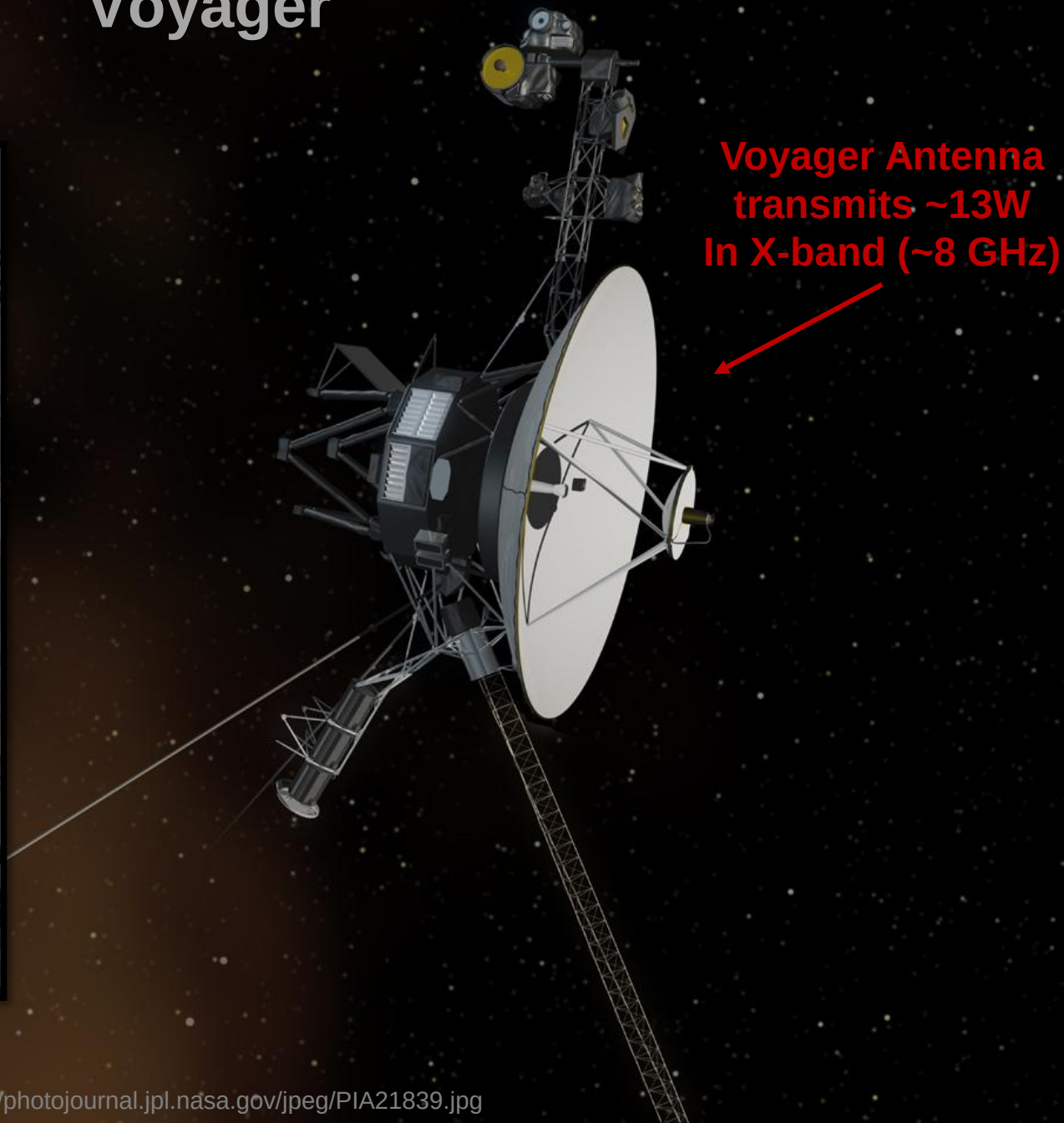
– Carl Sagan 

Voyager



**3.7-m antenna— largest antenna
that can fit in rocket fairing**

<https://photojournal.jpl.nasa.gov/jpeg/PIA21839.jpg>

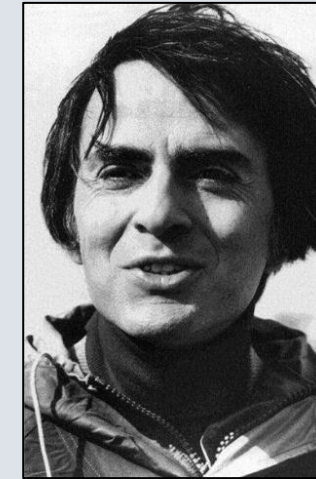


**Voyager Antenna
transmits ~13W
In X-band (~8 GHz)**



Great Moments in Space Communications History

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– Carl Sagan

Voyager Earth Receiver

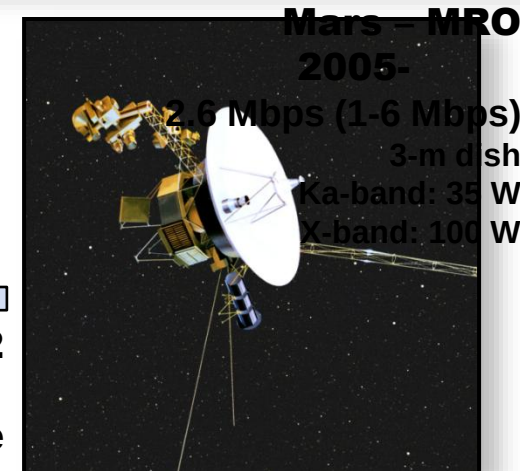
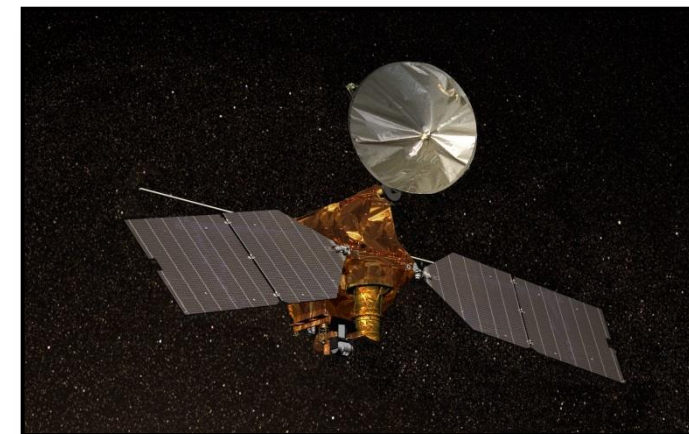
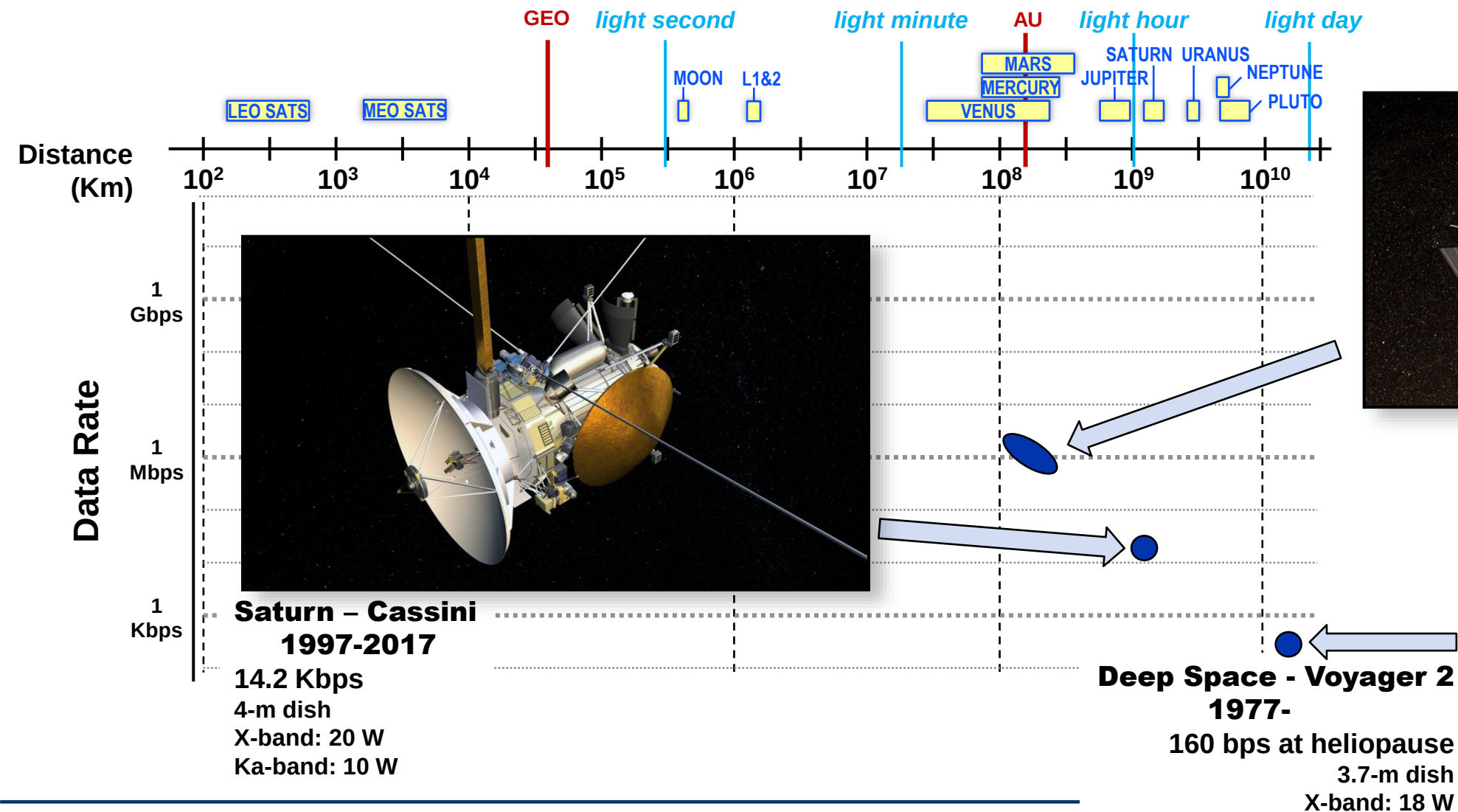
70 meters!

- Three receivers— spread around the Earth to allow contact at any time
- Received power from Voyager is 3×10^{-19} W
- Communicates with Voyager at 160 bits per second
 - Took months to deliver photos of Earth



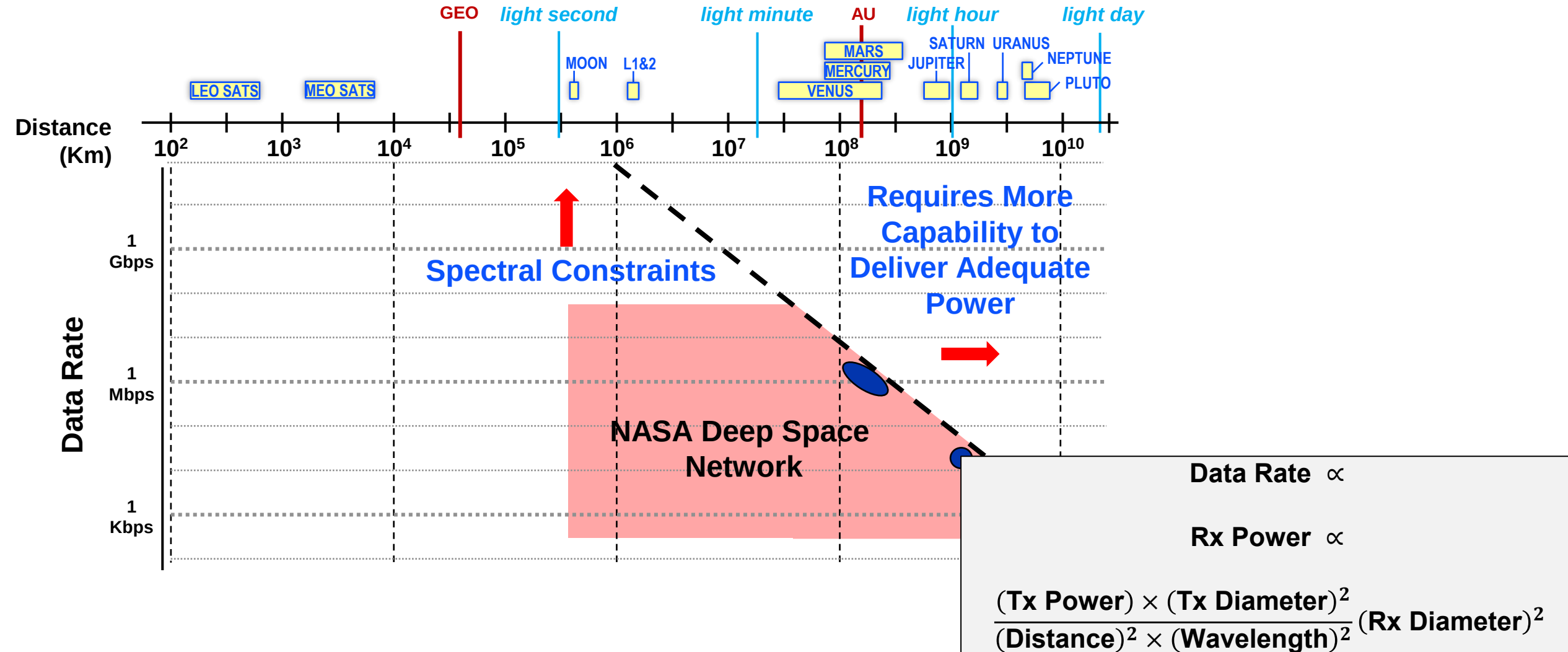


Communication Links to Great Distances



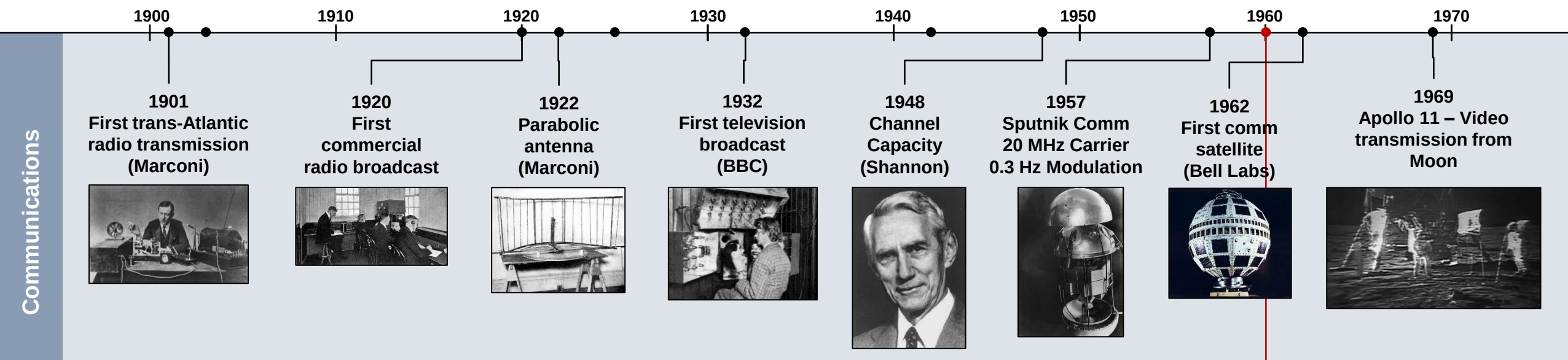


Communication Links to Great Distances





Timeline of Early Space Communications



Optical Communications—A Decade of Preparations

NILO LINDGREN

Despite the persistent work of a preciously small community of researchers, the past decade has produced so far, only the bits and pieces for future systems whose forms of implementation are in many ways still uncertain.

Moreover, the best judgement today is that practical optical communication systems lie still far in the future.

“We are shown the way to enormous increases in the present number of available communications channels”

“We should be able to project light into very high-intensity beams for space communications”

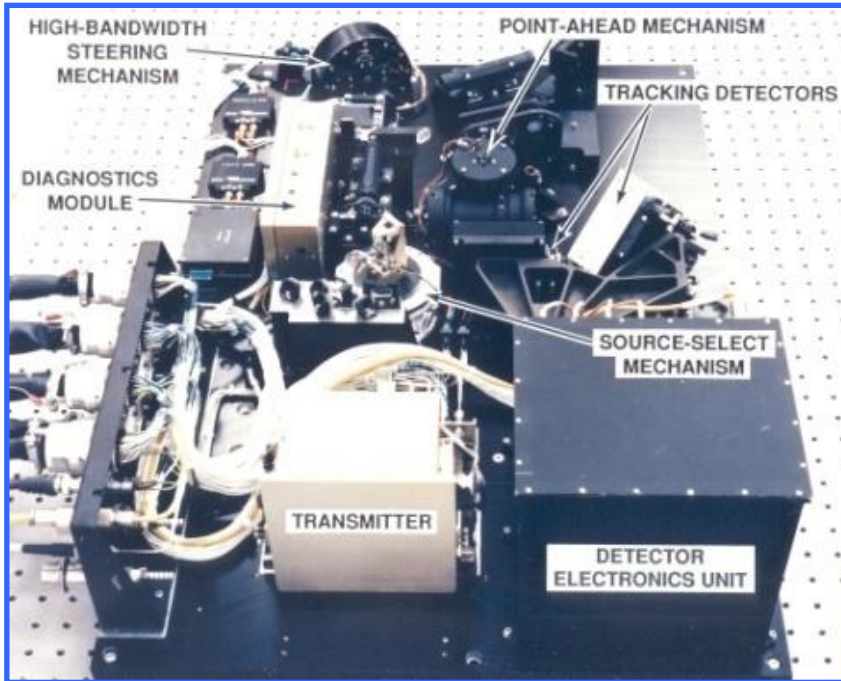
– T. Maiman, press conference
announcing invention of the ruby laser,
7 July 1960

1960
Invention of the
laser

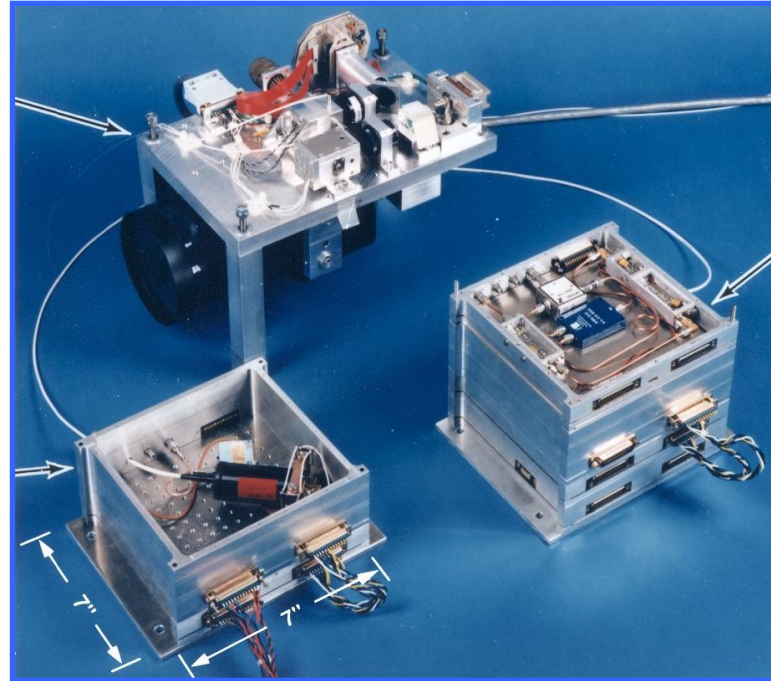




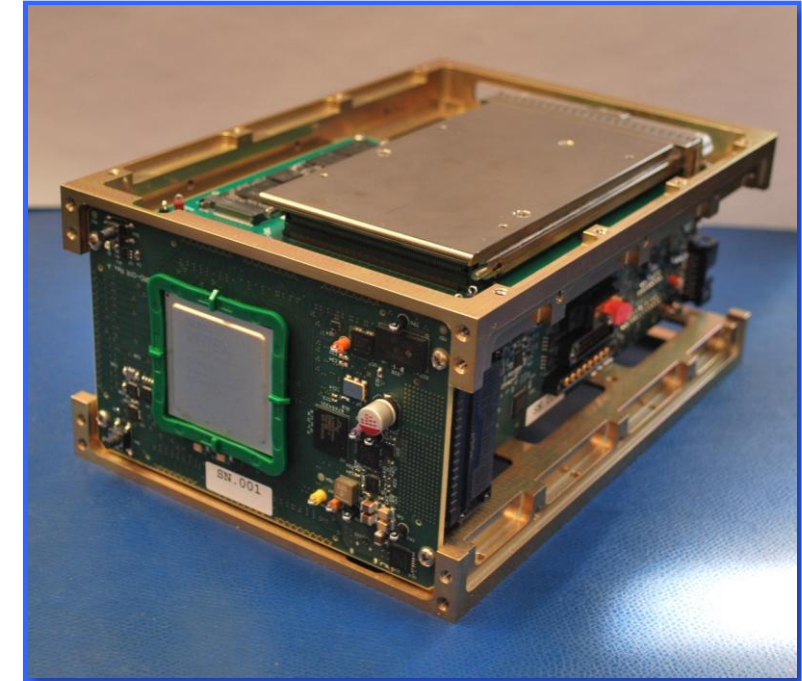
Leveraging Fiber Telecom Developments



Laser Intersatellite Transmission Experiment (LITE) Engineering Model (1988)



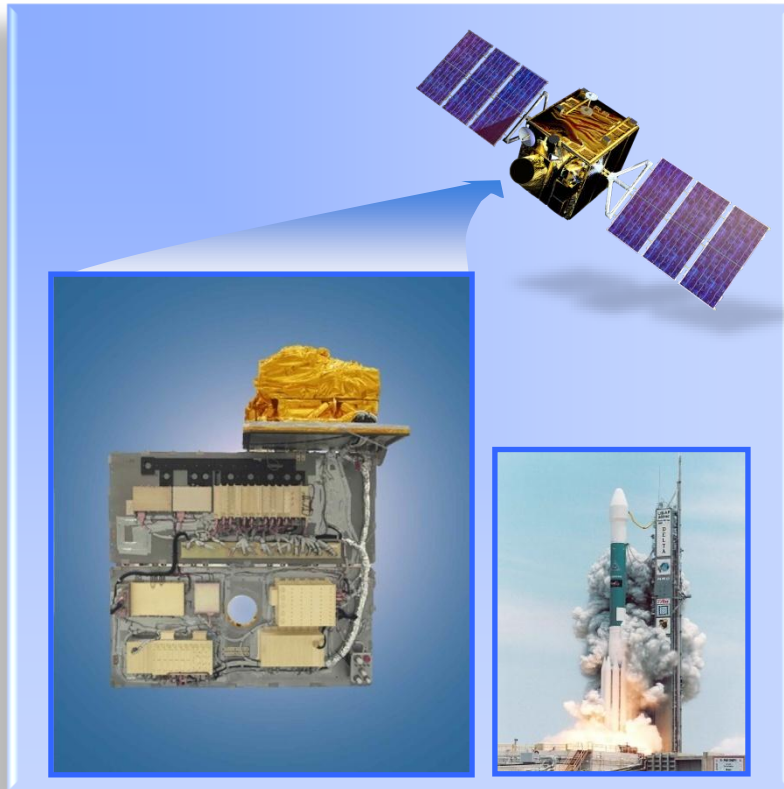
Brassboard Demo of First Terminal w/ Fiber Components (1990)



Terabyte Infrared Delivery (TBIRD) Engineering Model w/ Fiber Telecom Transceivers (2020)



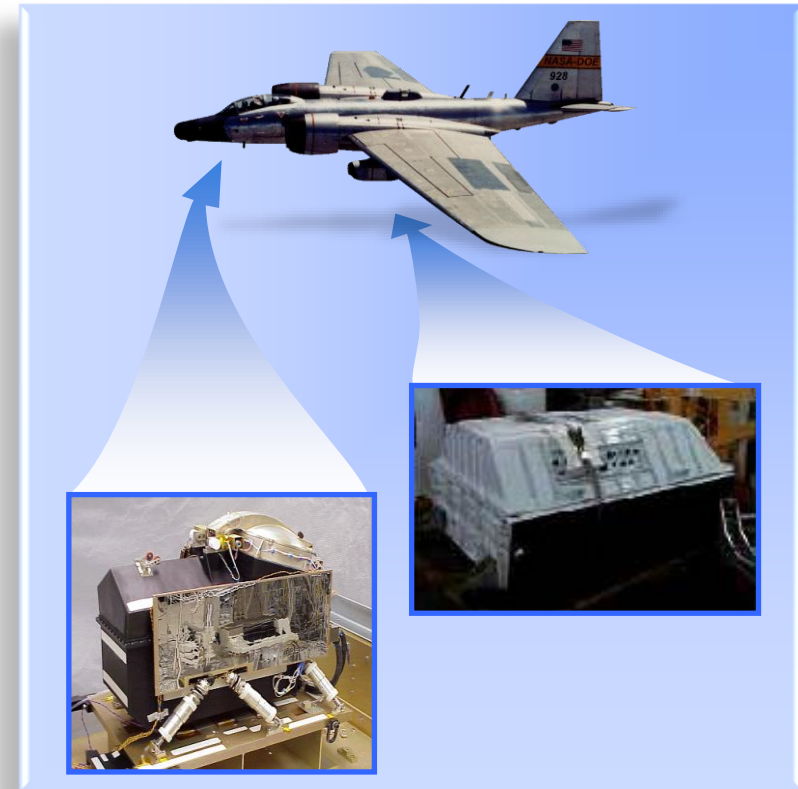
The First Space Lasercom Successes: GeoLITE and ALEX (1997–2002)



GeoLITE

Lasercom Experiment

- Launch (18 May 2001)
- *World's first successful demo of high-rate, space-based laser communications (12 June 2001)*



Airborne Laser Experiment

ALEX Demonstrations (2002)

- *World's first successful demo of air-to-space duplex laser communications*

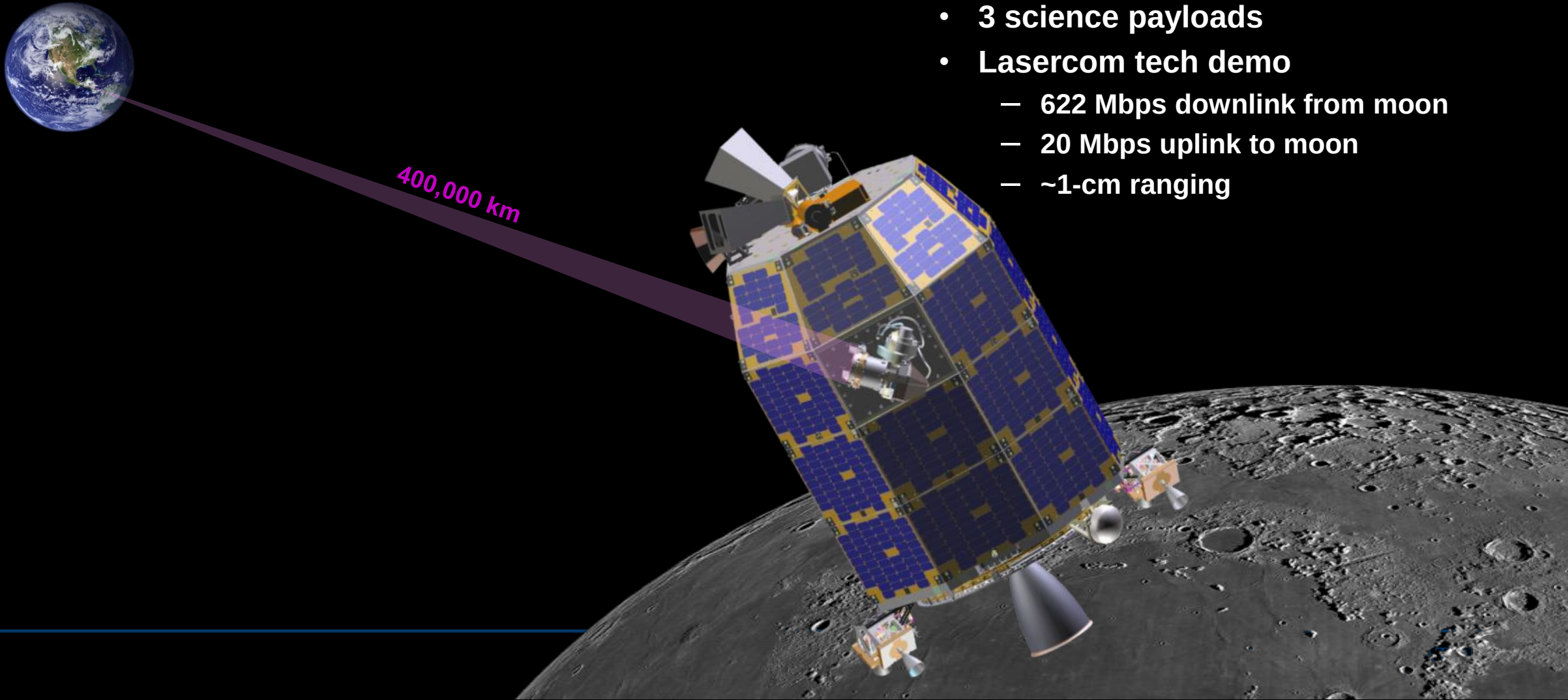


Lunar Laser Communication Demonstration (LLCD) 2013-2014



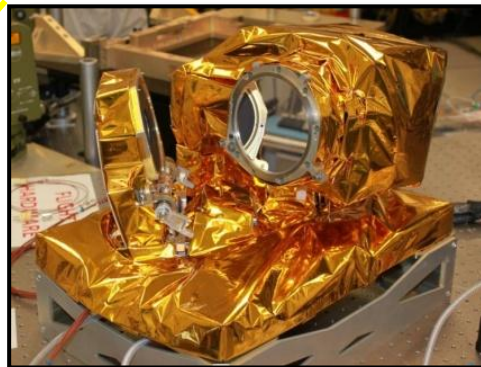
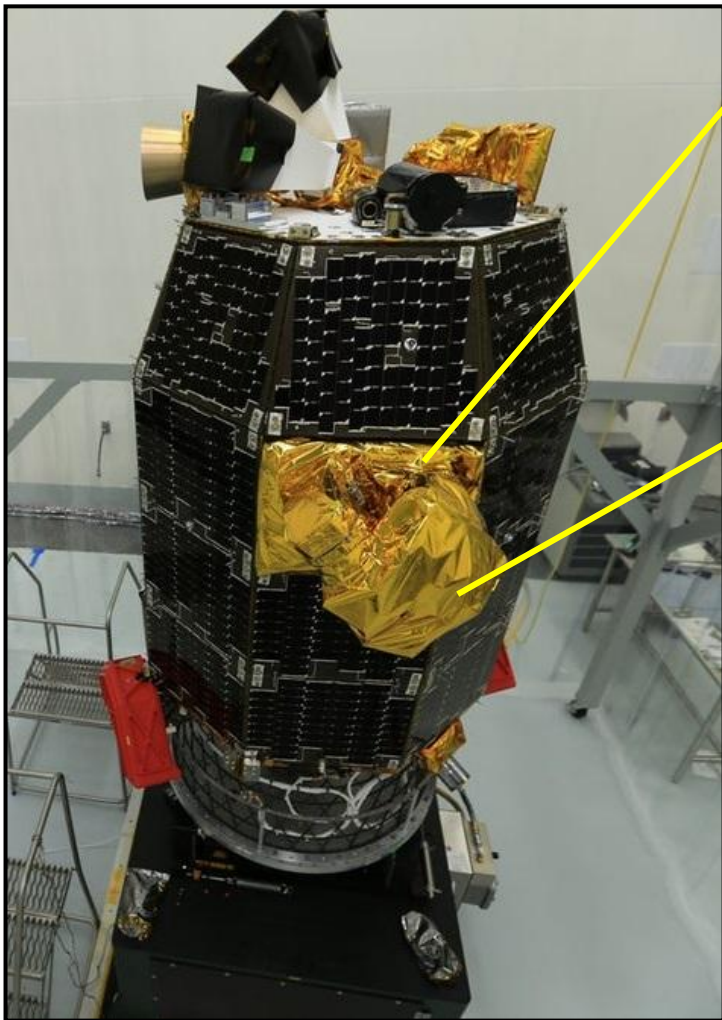
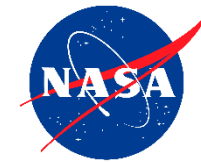
**LADEE's main science mission:
measure dust grains in lunar atmosphere**

- 3 science payloads
- Lasercom tech demo
 - 622 Mbps downlink from moon
 - 20 Mbps uplink to moon
 - ~1-cm ranging





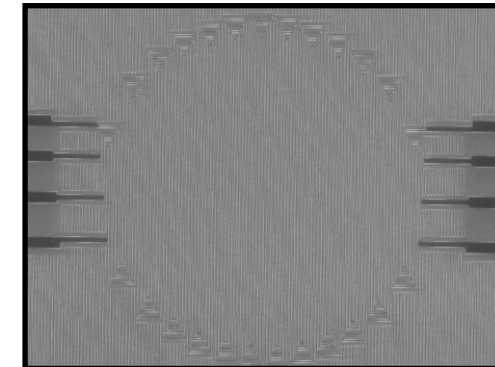
Lunar Laser Communication Demonstration 2013-2014



**LLCD Space Terminal
on LADEE***



**LLCD Ground
Terminal at WSC**



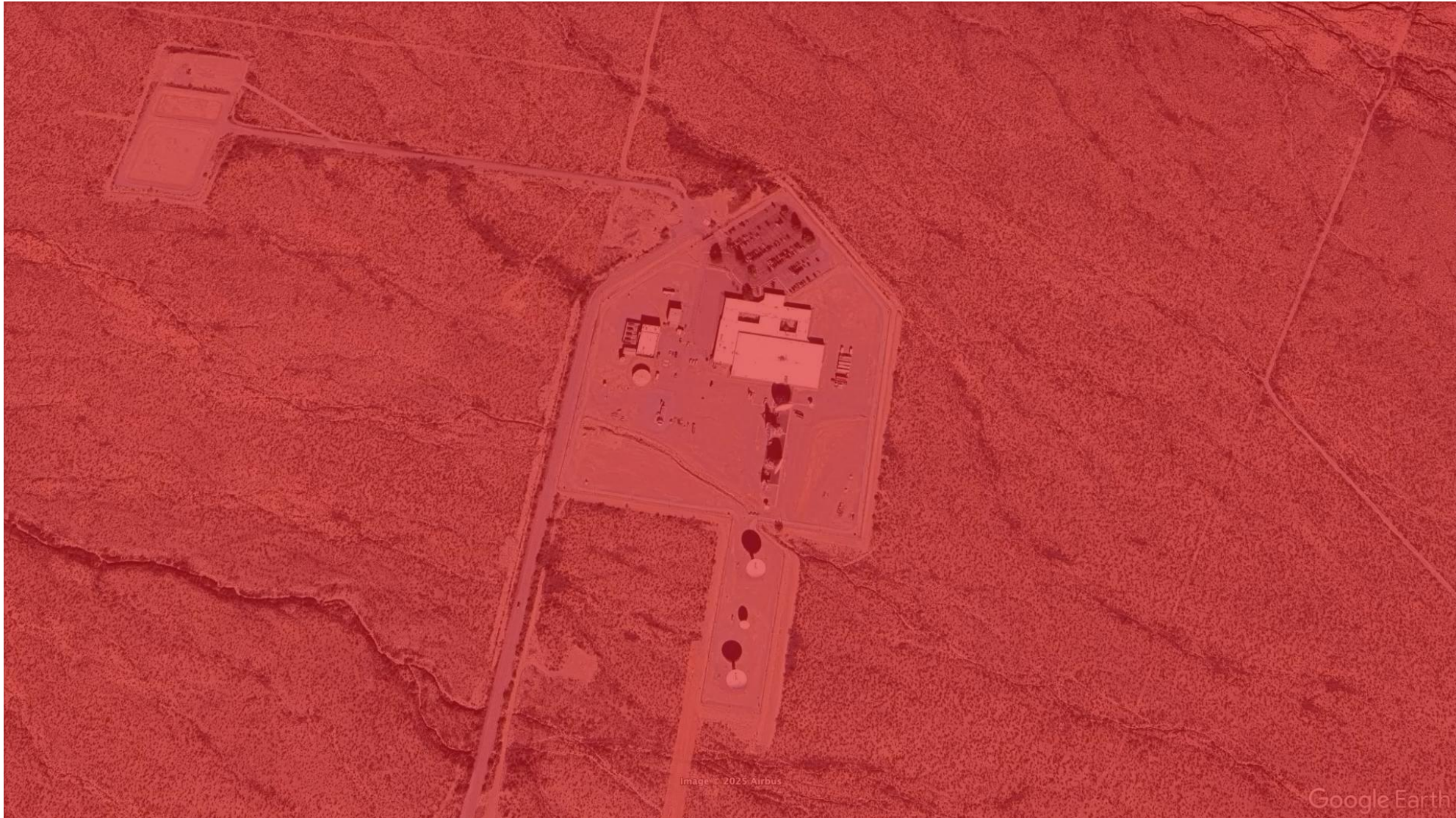
**Superconducting nanowire
single photon detecting
(SNSPD) array**

- High rate data delivery using lasercom (622/20 Mbps down/up)
- Pointing, acquisition, and tracking of narrow laser beams
 - Cooperative acquisition and tracking
 - Inertial stabilization of space terminal
- Error-free data delivery from Moon to Earth
- Site diversity for cloud mitigation
- Integration of lasercom into spacecraft and ground operations

NASA

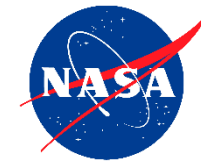


LLCD Downlink Spot Size

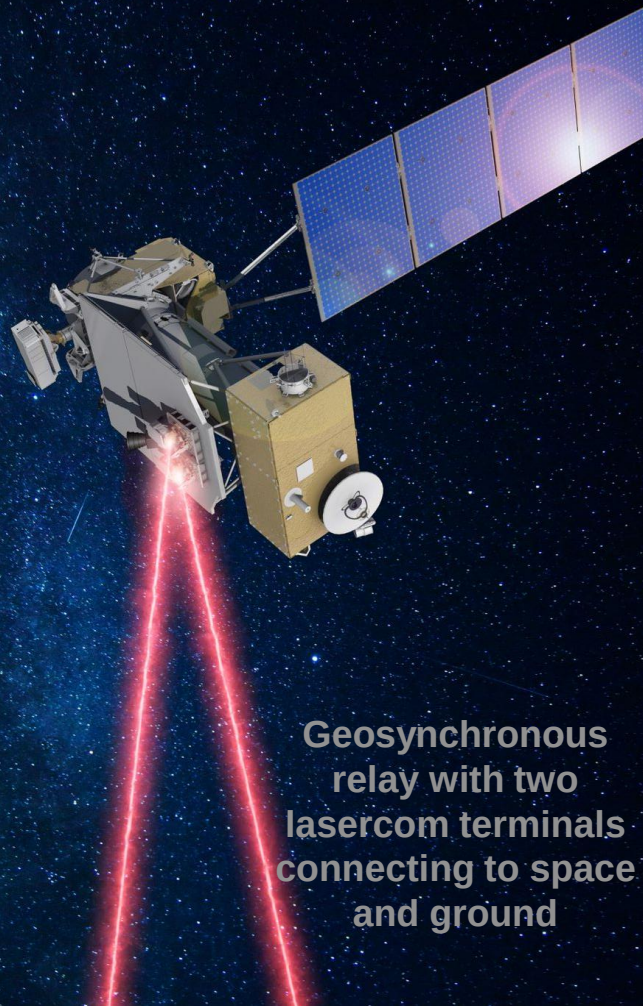




NASA Lasercom Technology Demonstrations



Laser Communication Relay
Demonstration (2022)



Geosynchronous
relay with two
lasercom terminals
connecting to space
and ground

International Space Station
(2023)



1.2 Gbps (return) and
155 Mbps (forward)
lasercom links to
ground via LCRD

Artemis (2026)



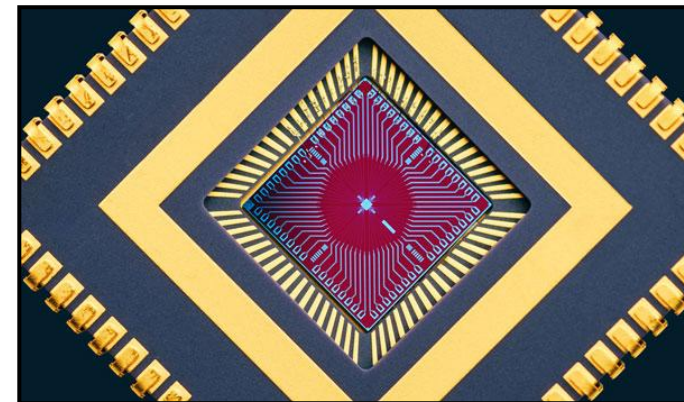
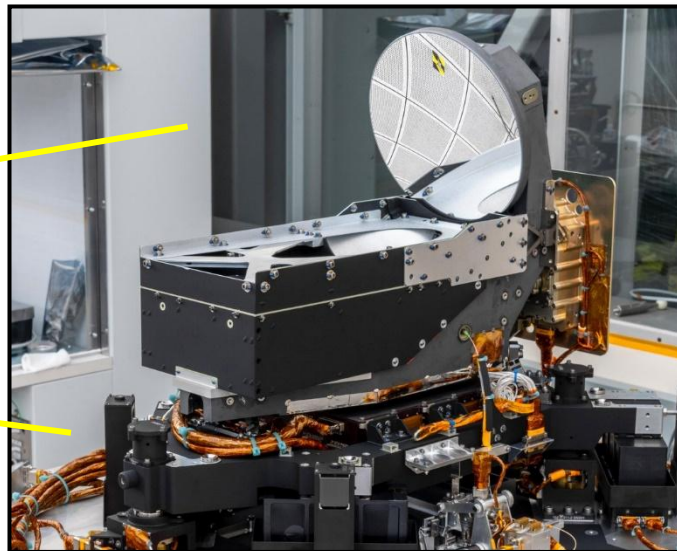
50 Mbps (return)
and 20 Mbps
(forward) lasercom
links to Earth on
first crewed
mission to Moon



NASA Deep Space Optical Comm 2023-Present



**DSOC Space Terminal
on PSYCHE**



**Superconducting nanowire
single photon detecting
(SNSPD) array**



**Hale Telescope receiver
OCTL transmitter**

- Spacecraft en route to Psyche asteroid
- NASA's first truly deep space lasercom—demonstrated at up to 3.3 a.u.
- 8.3-267 Mbps return (depending on range)
- Multiple, distributed receive apertures in southern CA

Photos courtesy of NASA

TESAT LASERCOM FROM 2008 TO 2025

- » 1997: First design for TELEDESIC, coherent 1064nm, 10 Gbps
- » 2008: First LEO-LEO laser comms link - NFIRE /Terrasar X, 5.6 Gbps Binary Phase Shift Keying (BPSK) 1064nm
- » 2014: Beginning of European Data Relay System, EDRS, 4 LEOs and 2 GEOs, >92.000 links so far and continuing beyond 2030: 1.8 Gbps BPSK 1064nm, 7 terminals in space and operational, transmission volumes of up to 40 Terabytes per day
- » 2021: Development of new space Scalable Optical Terminal SCOT 80 1st Gen for constellations like US Space Development Agency
- » 2024: In orbit validation of Scot80 laser comms for different customers
- » 2025: Roll outs for Scot135 for MEO-GEO, with up to 100 Gbps data rates and Nanosat Scot20 terminals around 1550nm
- » Other applications like Quantum Key Distribution and Navigation will be integrated into the SCOT product family



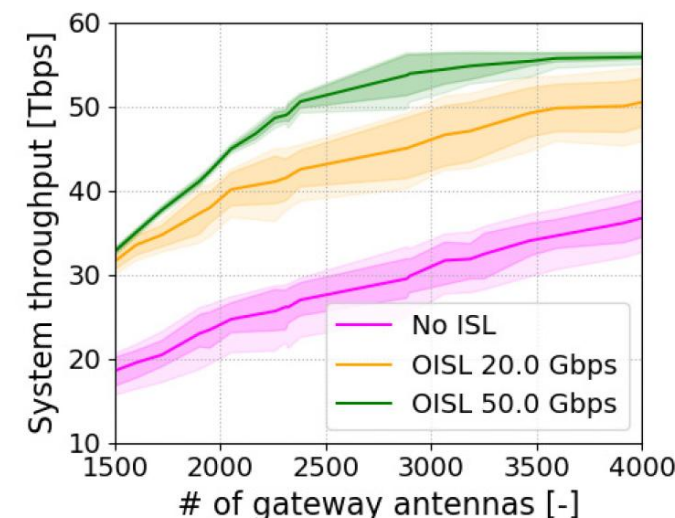


Proliferated Low Earth Orbit Systems

- Emerging LEO satellite constellations provide ubiquitous high-bandwidth untethered terrestrial communications
- SpaceX, Amazon, Telesat, US Space Development Agency, Qianfan, ...
- Optical intersatellite links greatly increase system capacity
- Example: SpaceX Starlink*
 - 200-Gbps crosslinks, in plane and cross plane
 - >9,000 lasercom terminals in orbit
 - >250,000 acquisitions per day
 - >42 PB daily traffic over lasercom links
- Capacity ultimately constrained by (RF) space-to-ground links



Starlink Satellites in launch configuration





TeraByte InfraRed Delivery (TBIRD) Mission

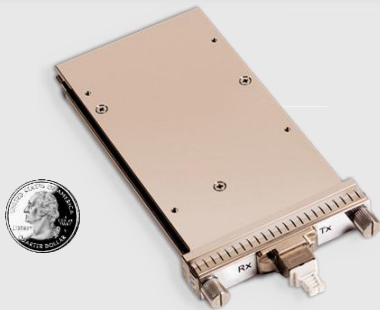


6U CubeSat in LEO (~12 kg)
3U Lasercom Payload



- Achieve robust data transfer through atmospheric channel
- Demonstrate body pointing architecture with payload pointing feedback
- Leverage fiber telecom equipment for 200 Gbps burst delivery (TBs per pass)

**Enabling Technology:
100 Gbps Commercial
Transceivers**



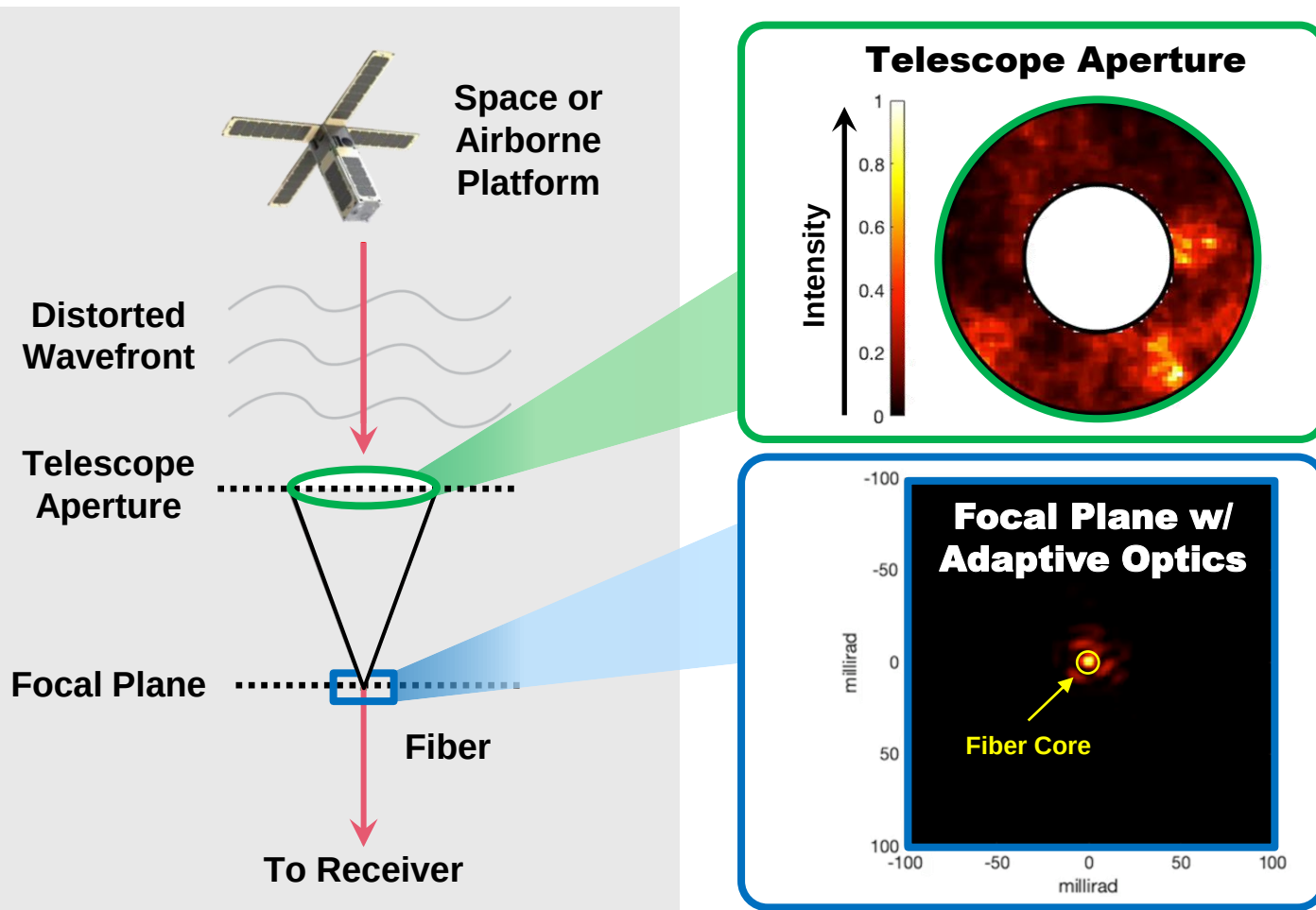
200 Gbps downlink



**Ground terminal at JPL's
Optical Communication
Telescope Laboratory (OCTL)
in Southern California**



Impact of Atmospheric Turbulence on Fiber-Based Receivers



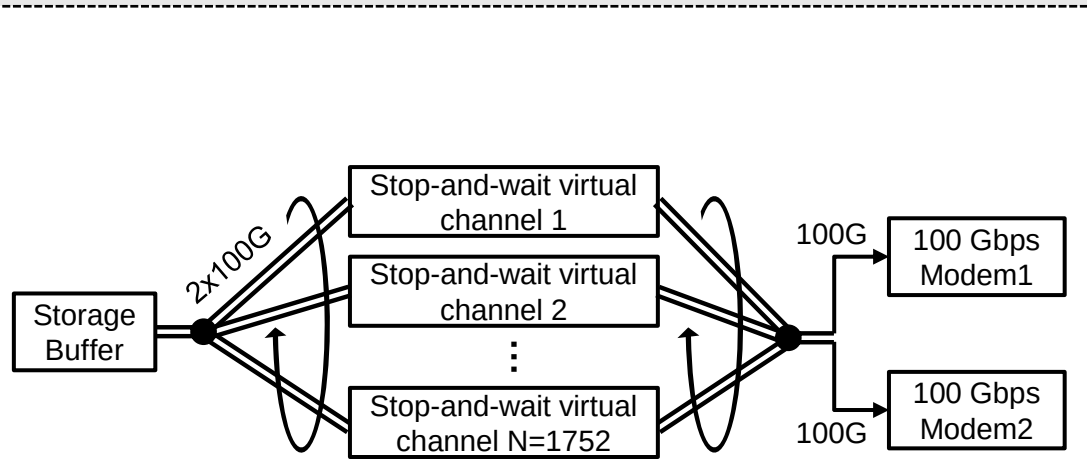
- Turbulence causes **scintillation**
 - Power-in-bucket fluctuations
- Turbulence causes **coupling loss**
 - Adaptive optics system attempts to correct wavefront
 - Spot wanders and breaks up

Communications architecture must be robust to atmospheric fading



TBIRD Automatic Repeat ReQuest (ARQ)

Space Terminal

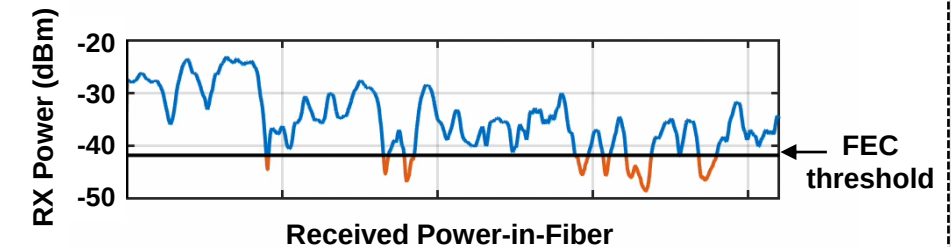
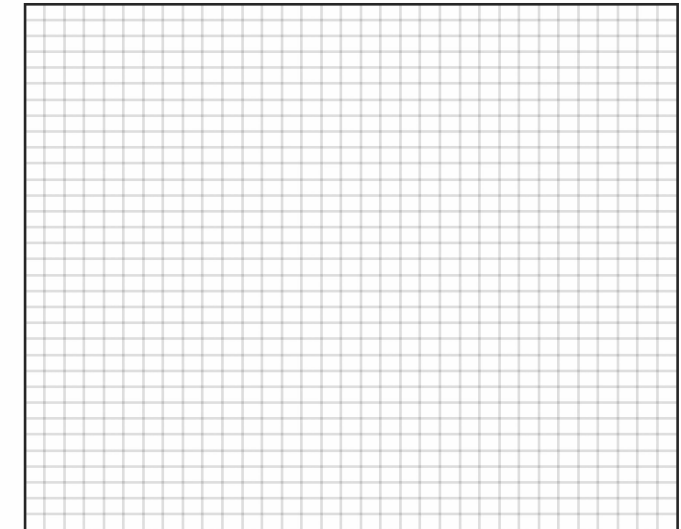


- Selective-repeat ARQ
- Large ARQ frames (15/30 MB)
- ~2000 virtual channels

Ground Terminal

Data Buffer

□ = 15 MB ARQ frame



100 or 200 Gbps
Downlink

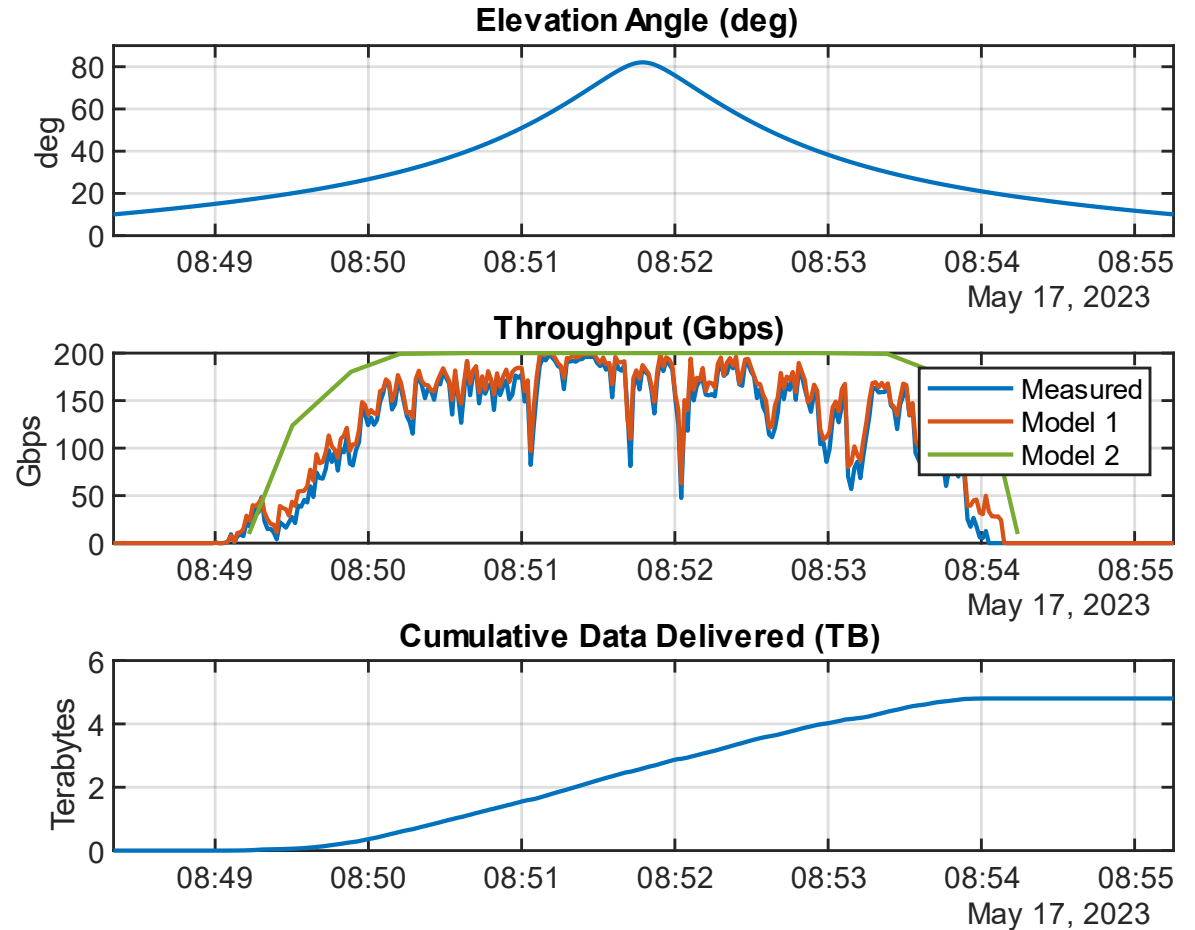
~2 kbps Uplink
Feedback

~kbps sufficient for
kHz class fading
dynamics



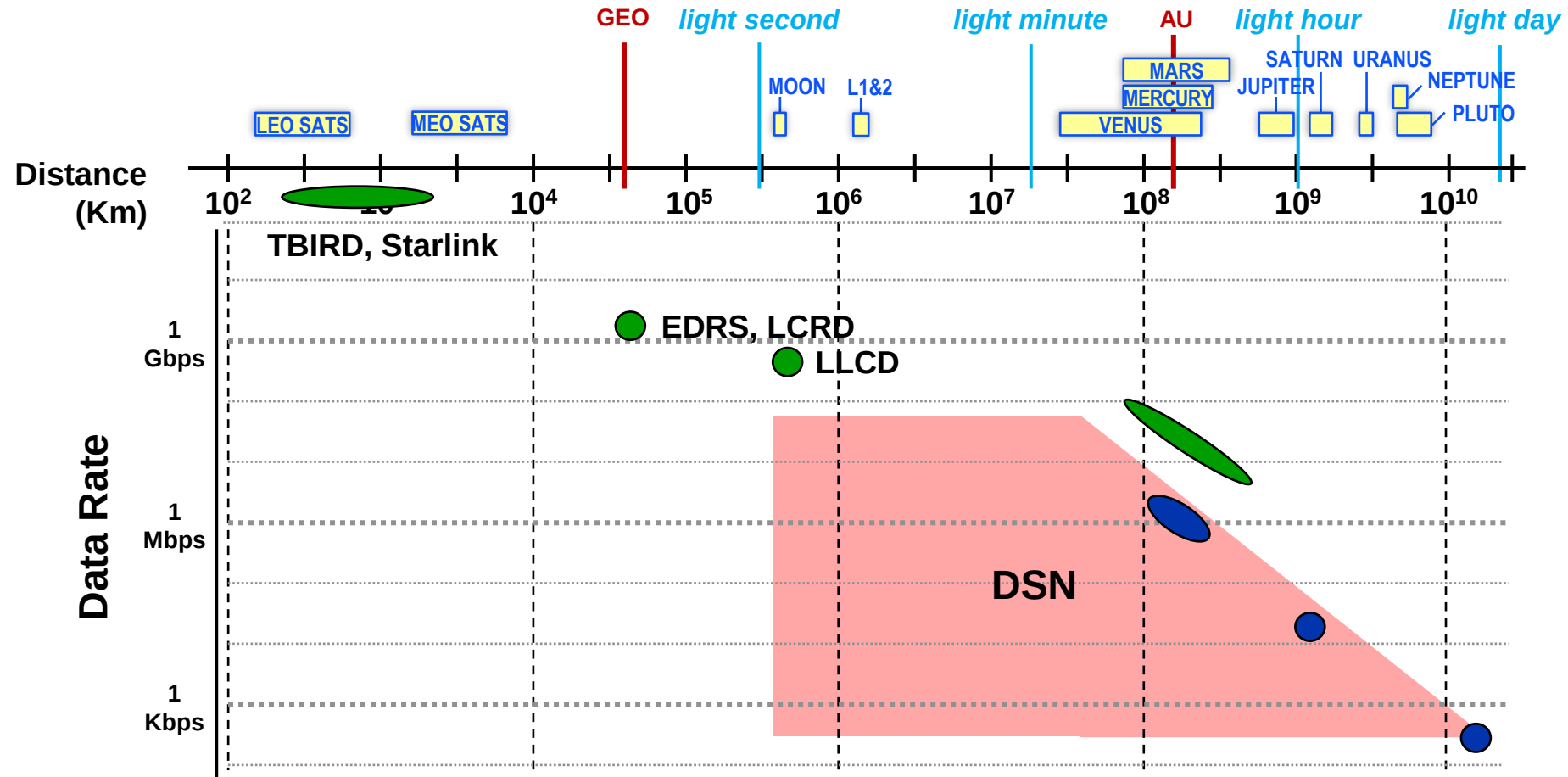
TBIRD Pass Example 5/17/23

- Link operated at 200 Gbps
- ARQ results in lower throughput of reliable data; varies through pass due to atmospheric fading and changing link range
- Downlinked 4.8 TB error-free in 5 minutes
- Fastest demonstrated fastest downlink from space; largest data volume delivered from LEO to ground





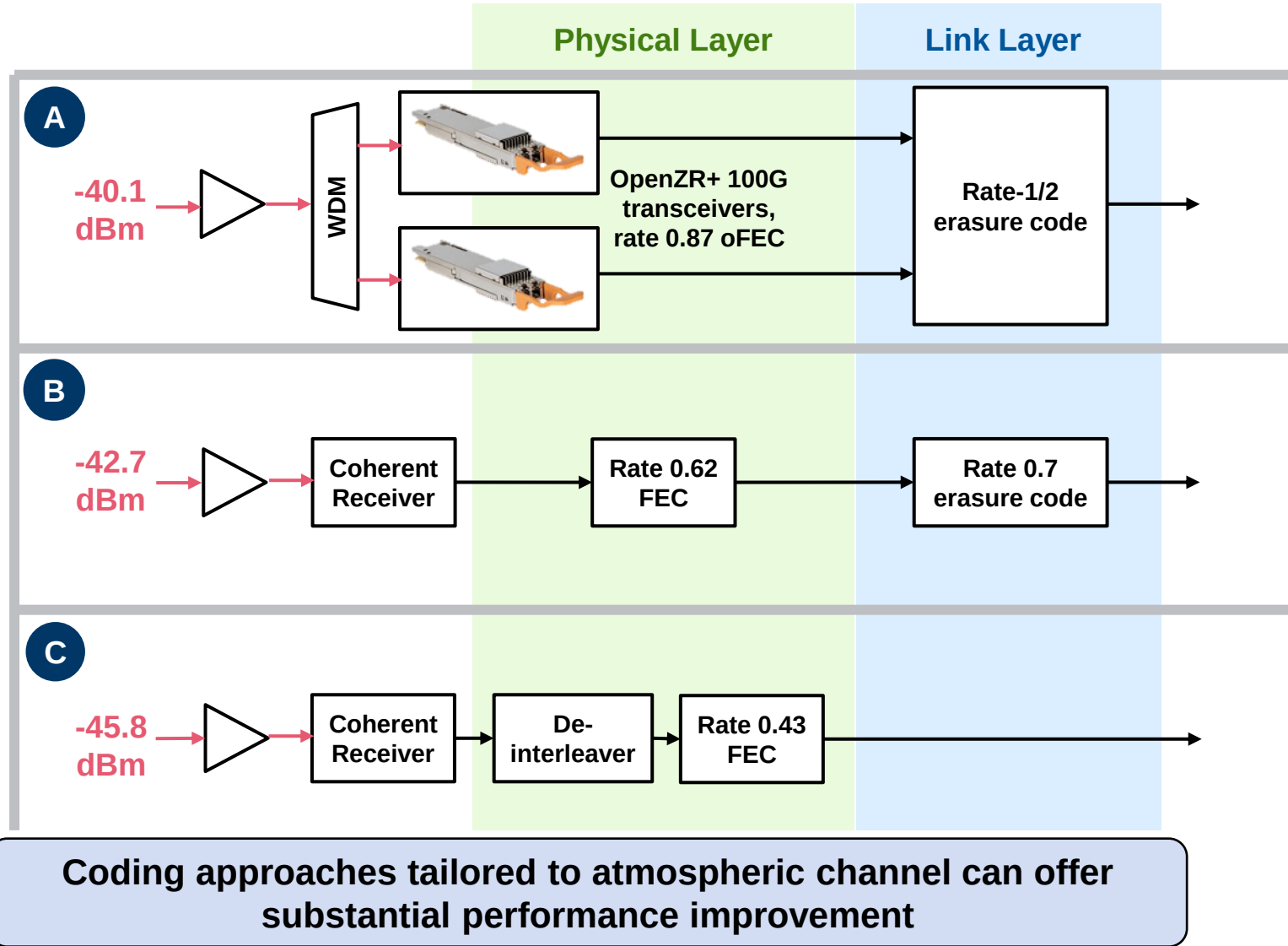
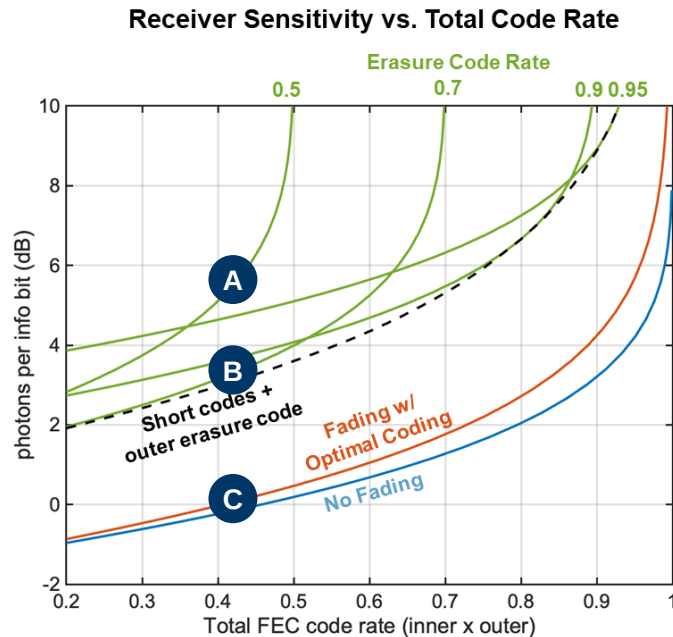
Communication Links to Great Distances





Improving Performance in the Atmospheric Channel

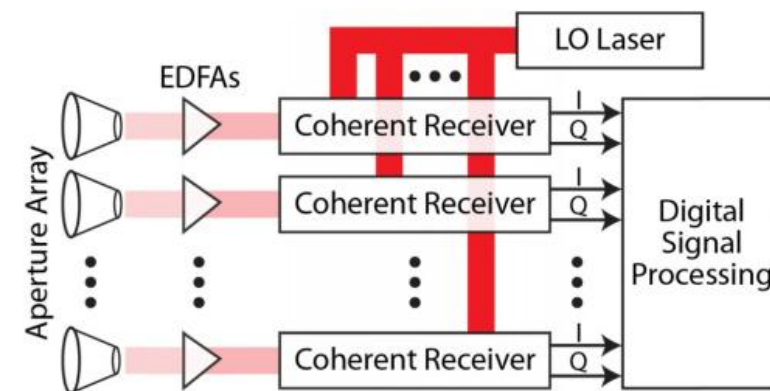
- **Example:**
 - User rate: 100 Gbps error-free
 - Total code rate 0.435
 - Baud rate 57.5 Gbaud



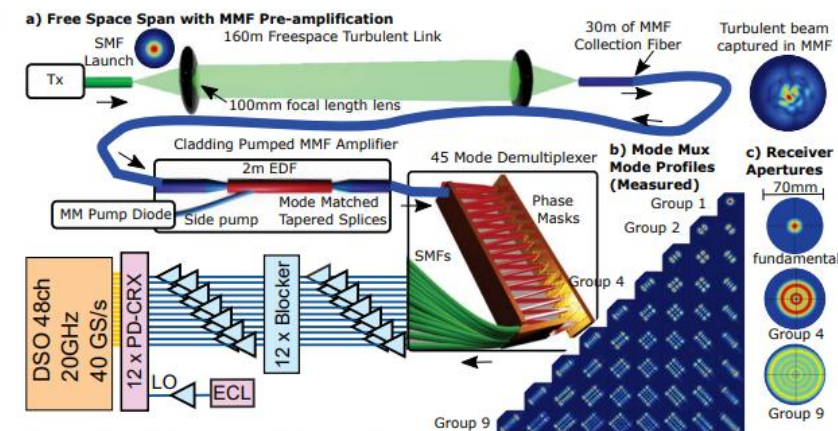


Reducing Atmospheric Losses

- Atmospheric turbulence increases coupling losses to single-mode receivers
- Adaptive optics traditionally used to mitigate losses (e.g. TBIRD, LCRD)
 - Complex; expensive
 - Does not correct amplitude variations
- Geisler, et al., demonstrated mitigation approach of combining small apertures after digital coherent detection*
- Telecom developments for spatial mode multiplexed systems may be applicable
 - Multi-mode amplifiers**
 - Photonic lanterns for mode multiplexing



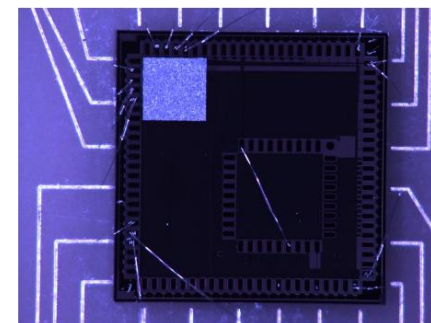
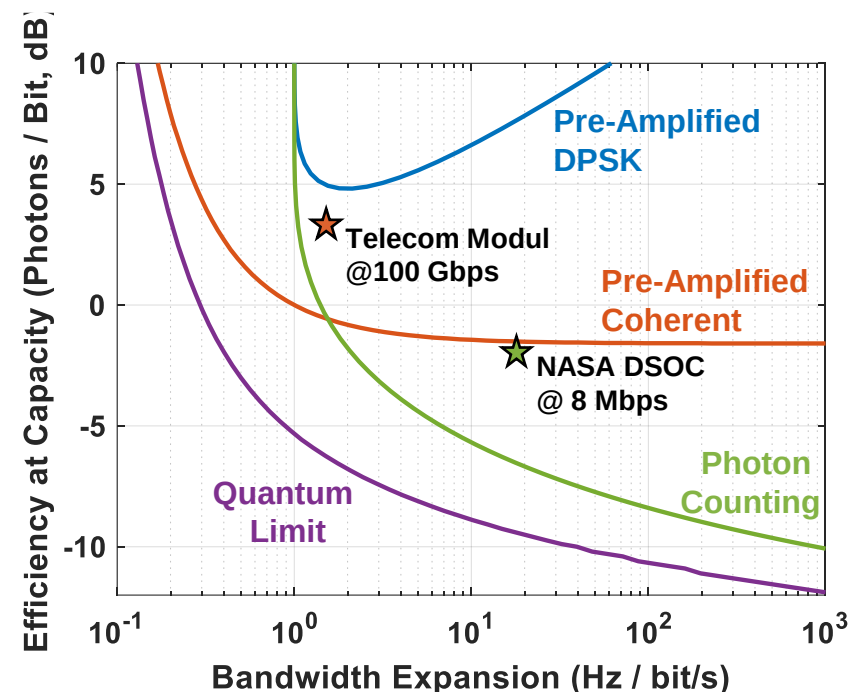
Multi-aperture digital coherent combining





Improving Receiver Sensitivity

- Photon-counting receivers offer potentially 10+dB improvement in sensitivity over telecom coherent receivers
- Nokia Bell Labs demonstrated 14 bits per photon demonstrated– 4X better than theoretical best performance from coherent receiver*
- NASA LLCD, DSOC demos used superconducting nanowire photon counting arrays with ~Gcount/s capabilities, providing ~100 Mbps data rates
- Larger arrays with more sophisticated read-outs (e.g. SFQ) could enable ~10 Gbit/s links
- Needs
 - High-count-rate high-bandwidth photon counters
 - High-bandwidth high-peak-power efficient transmitters
 - Good background rejection (spatial and spectral) for ground receivers



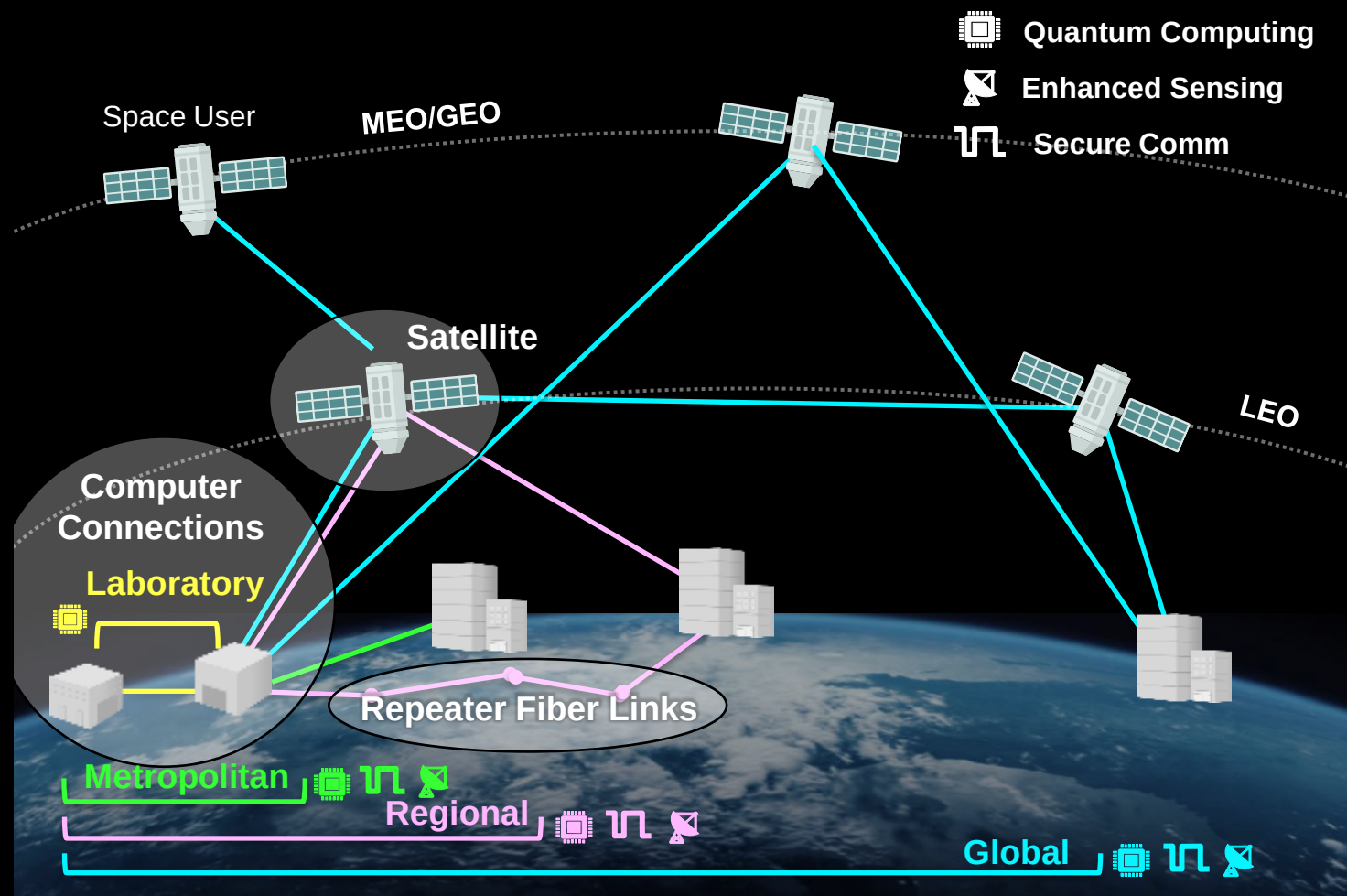
Hybrid superconducting photon counting array + SFQ readout (MITLL)**



Quantum Networking Ranges and Applications

Quantum entanglement distribution across large distances enables distributed applications

- Quantum networking enables
 - Distributed quantum computing
 - Enhanced long-baseline sensing
 - Enhanced / Secure communications
- Link losses directly impact quantum entanglement distribution— mid-span amplification not possible
- Fiber losses between regional sites may exceed free-space transmission losses
 - E.g. Boston to Washington, D.C., fiber losses >170 dB





Summary

- **40 years after invention of the laser, the utility of lasercom for space communications has finally been realized**
- **Today, optical communications is enabling revolutionary capabilities**
 - **Broadband ubiquitous untethered terrestrial communications**
 - **High-rate deep space communications**
- **Future developments will lead to advanced performance**
 - **Advanced signal processing**
 - **Photon counting detectors**
 - **Atmospheric compensation**
 - **Quantum state distribution**

