Laser Communications to Enable Space Exploration

Dr. Farzana Khatri

Senior Technical Staff

10 January 2025

LINCOLN LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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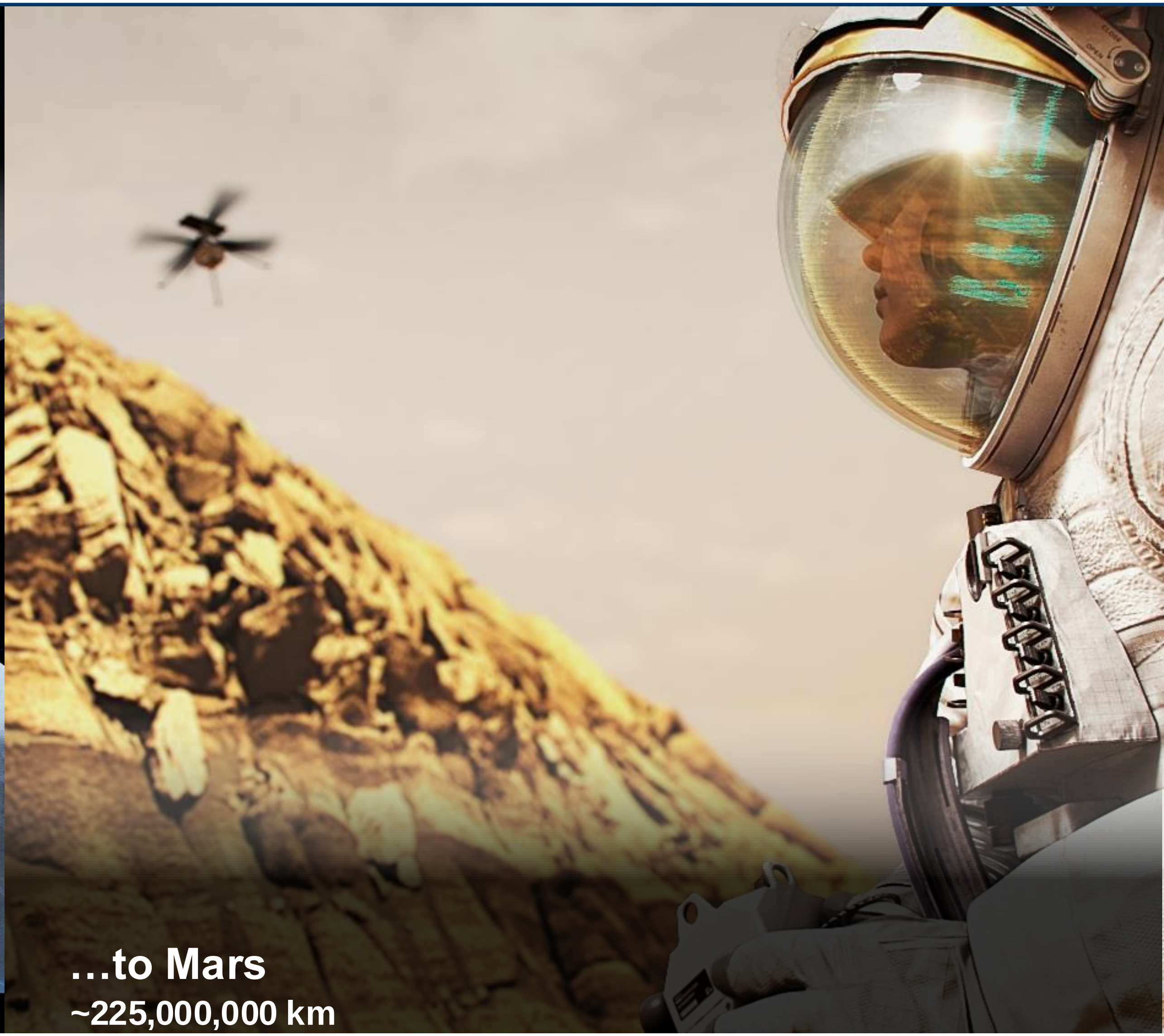
Outline

- **Human Space Exploration**
- **Laser Communications**
  - **Motivation**
  - **History**
  - **Missions**
  - **Future**

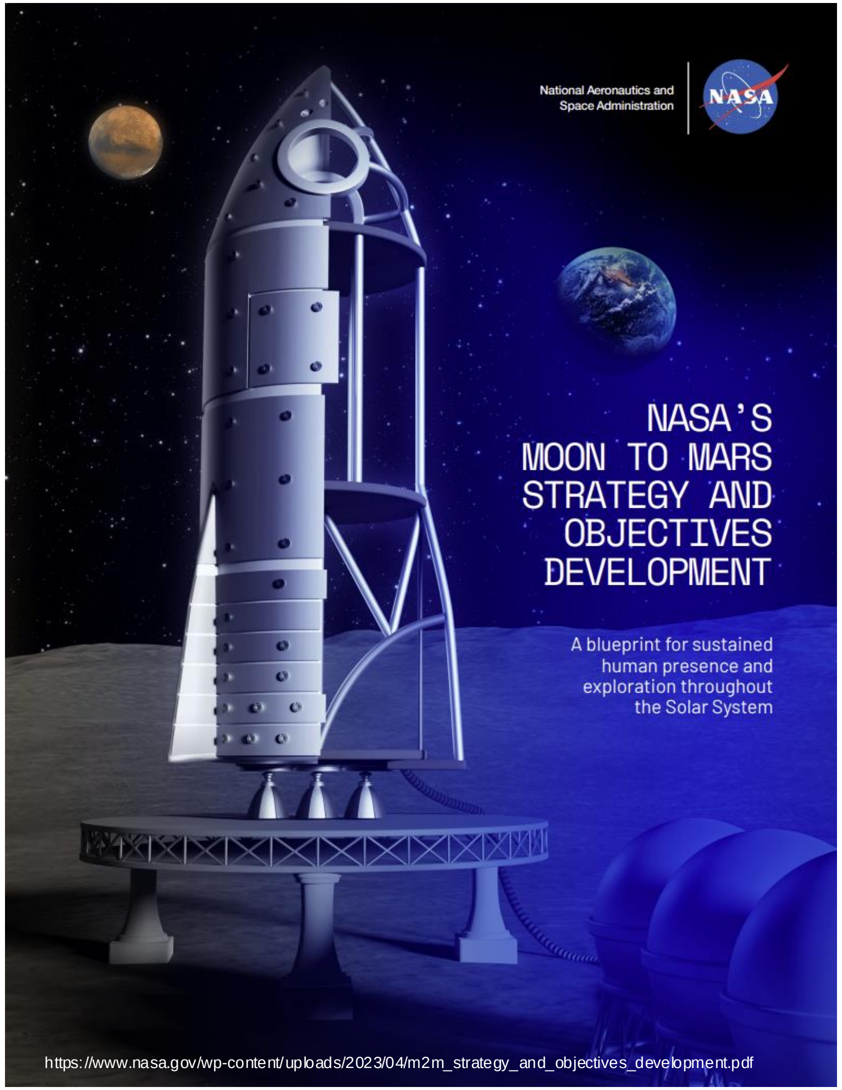
NASA Human Exploration

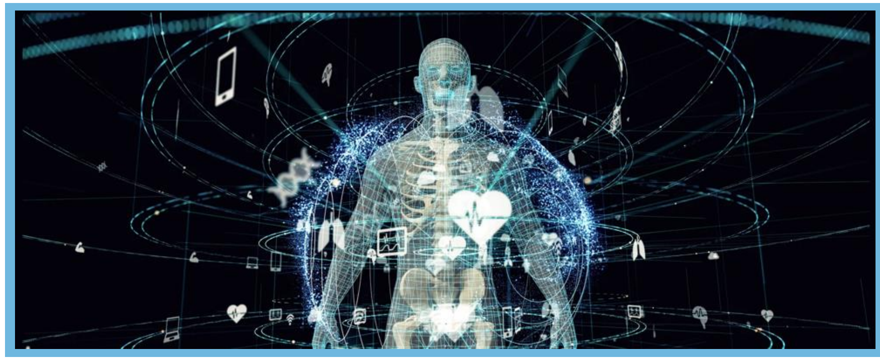


All graphics courtesy of NASA

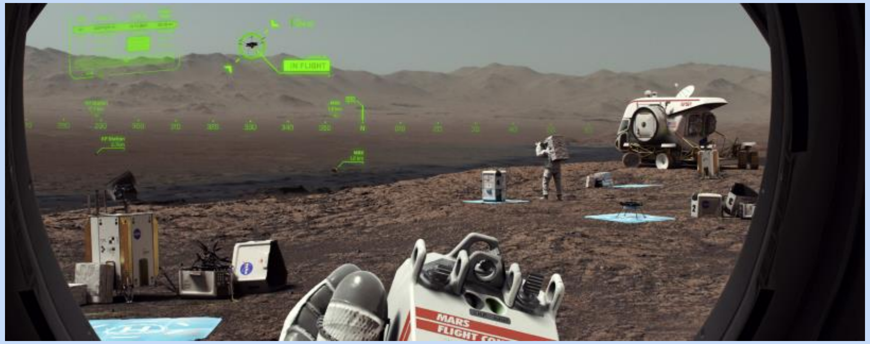
This chart provided by NASA (J. Free, Cislunar Security Conference 2024)

Communications for Human Space Exploration





Monitor and maintain crew health



Characterize and monitor space and surface environments

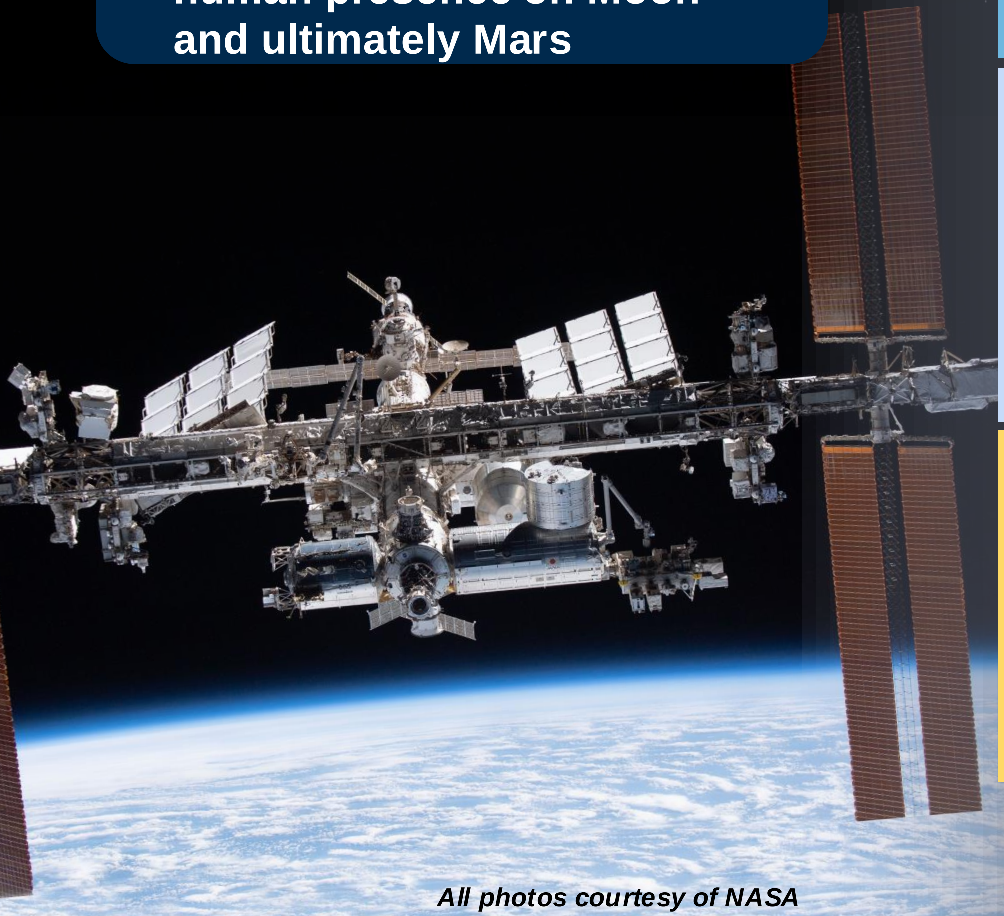
Remote support of astronaut and science missions

All graphics courtesy of NASA

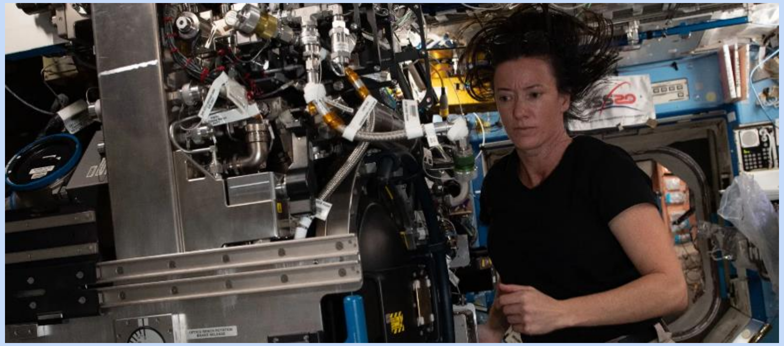
International Space Station (ISS):

Continued human presence in space since Nov 2, 2000

Critical proving ground for human presence on Moon and ultimately Mars



Ultrasound scan on Canadian astronaut Chris Hadfield



Scientific experiments

8K HD Video

All photos courtesy of NASA

Why Optical / Laser Communications?

- **Extremely narrow beams with small apertures**
  - **Small, low power terminals**
  - **Security (harder to detect, or jam)**

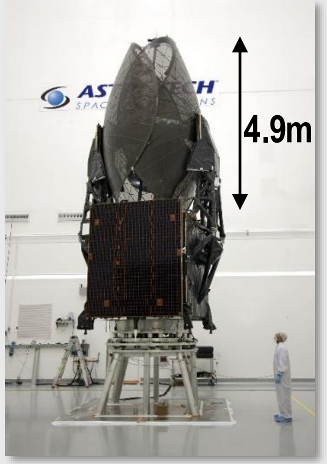
- **Unlimited, unregulated spectrum**

- **High data rates**
  - **Provides high speed real-time data (e.g. for video)**
  - **Enables shorter contact times**
  - **Delivers large data volume over the duration of mission**

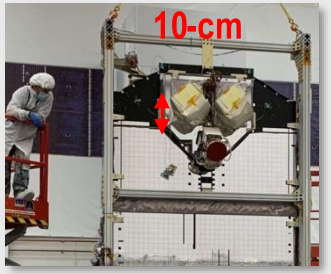
Beam Size From Geosynchronous Orbit (GEO)

Radio Frequency Ka Band (26 GHz)
4.9m Antenna → 100 km Spot

Optical C-Band (1550 nm)
10-cm Antenna → 0.6 km Spot



TDRS



LCRD

TDRS: Tracking and Data Relay Satellite
LCRD: Laser Communications Relay Demonstration

All photos courtesy of NASA

Lasercom Beam Examples

Quarter from across a football field
218 µrad
0.012 degrees

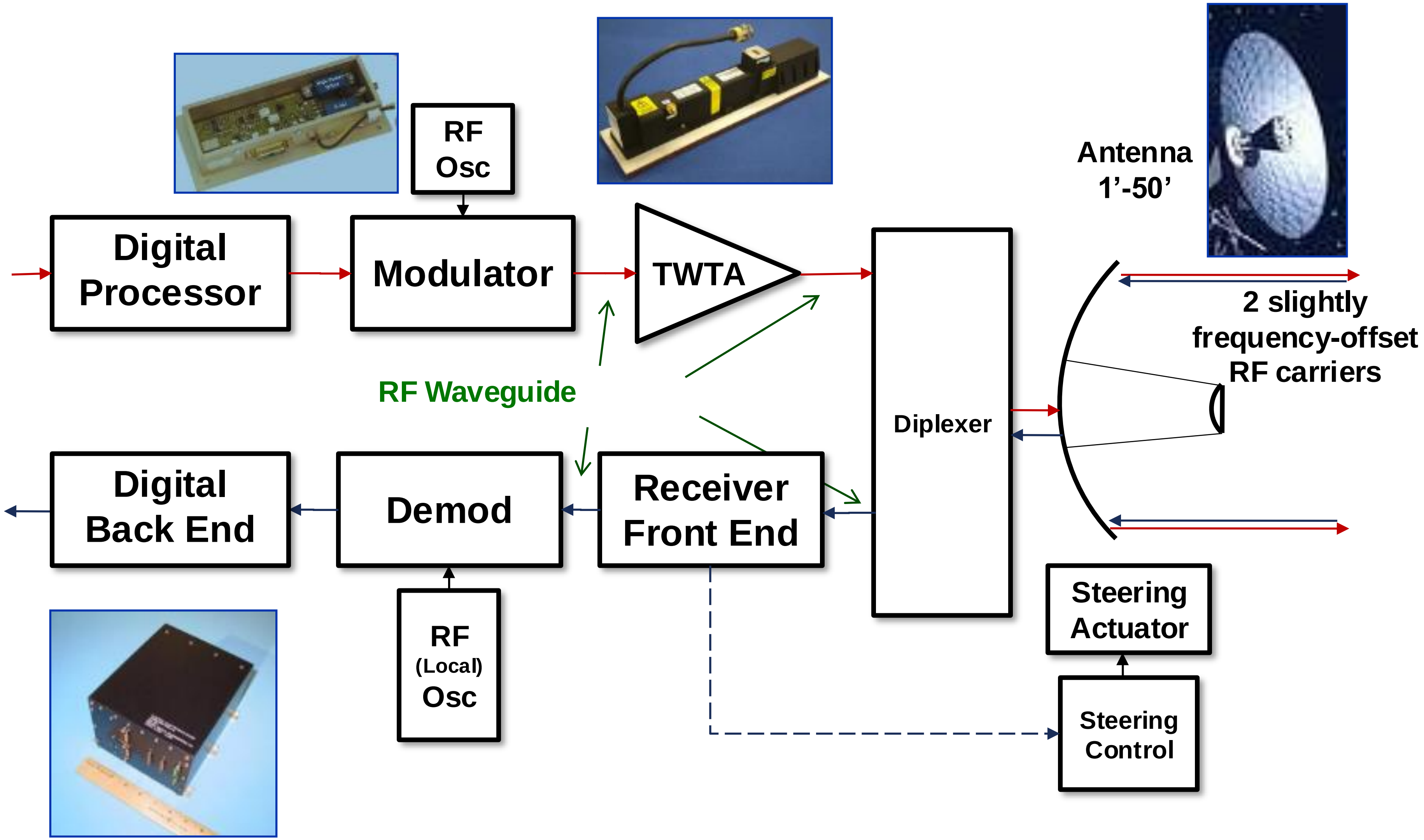
ISS as seen from Earth:
275 µrad
0.015 degrees

Operational Differences between RF & Optical Comm Systems

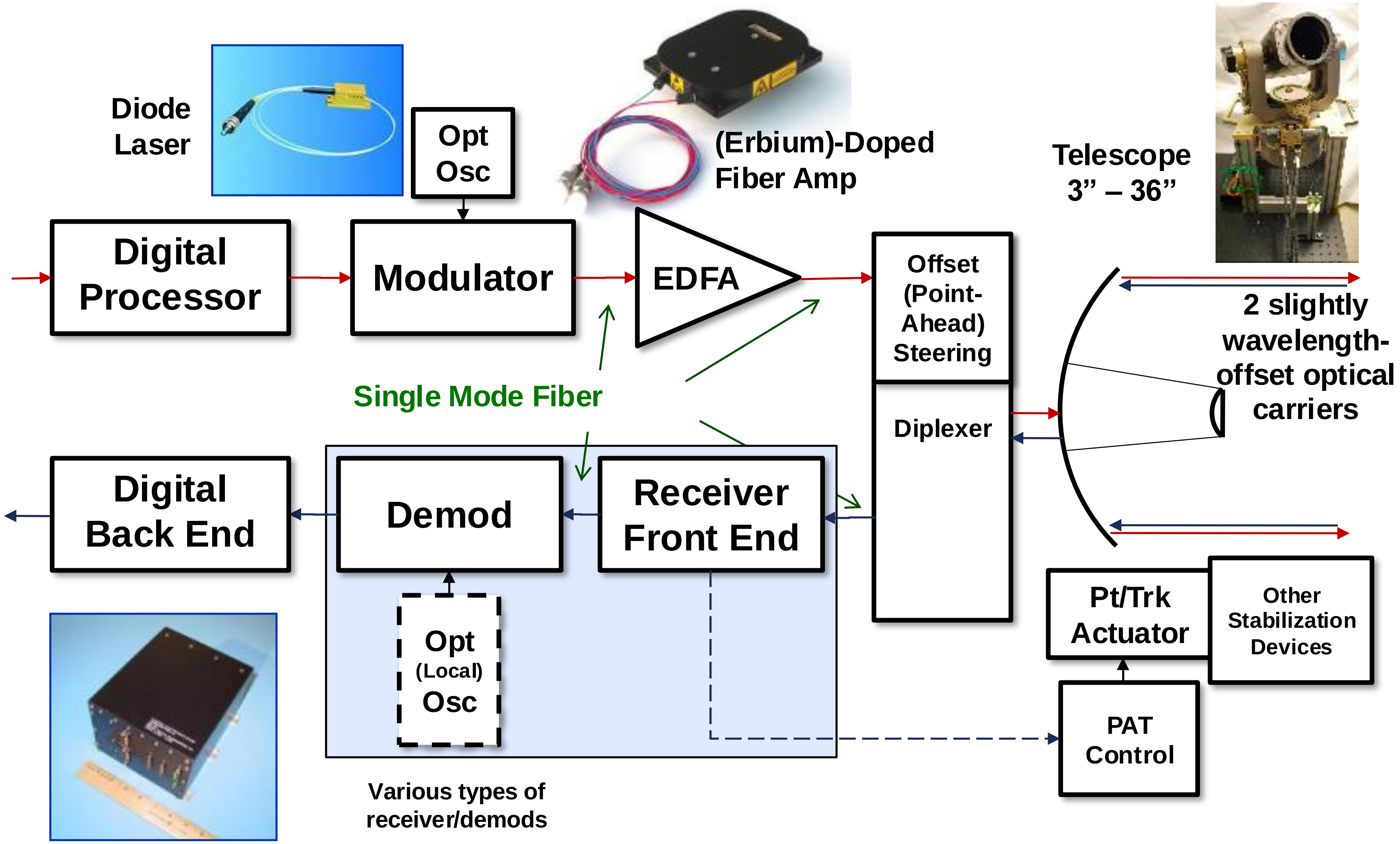
	RADIO	OPTICAL
Beam width	0.5 - 30º	1 - 100 μrad (<0.006º)
Point / Acquire Beam	Open loop	Scan or wide-field sensor (cooperative)
Stabilize / Track Beam	N/A	Optical-based tracking (cooperative), inertial sensors-based tracking, passive jitter rejection
Atmosphere Interactions	Rain can degrade > 20 GHz	Clouds can block lasers; turbulence must be considered
Regulatory / Permissions	Spectrum is regulated and licensed	Unregulated; need care with sensor satellites / aircraft

From: Khatri & Robinson, "Operational Considerations for Future Laser Communications Systems," *AIAA Improving Space Operations Workshop*, Pasadena, CA, May 5-6, 2015.

Block Diagram of Free-Space Comm System: RF



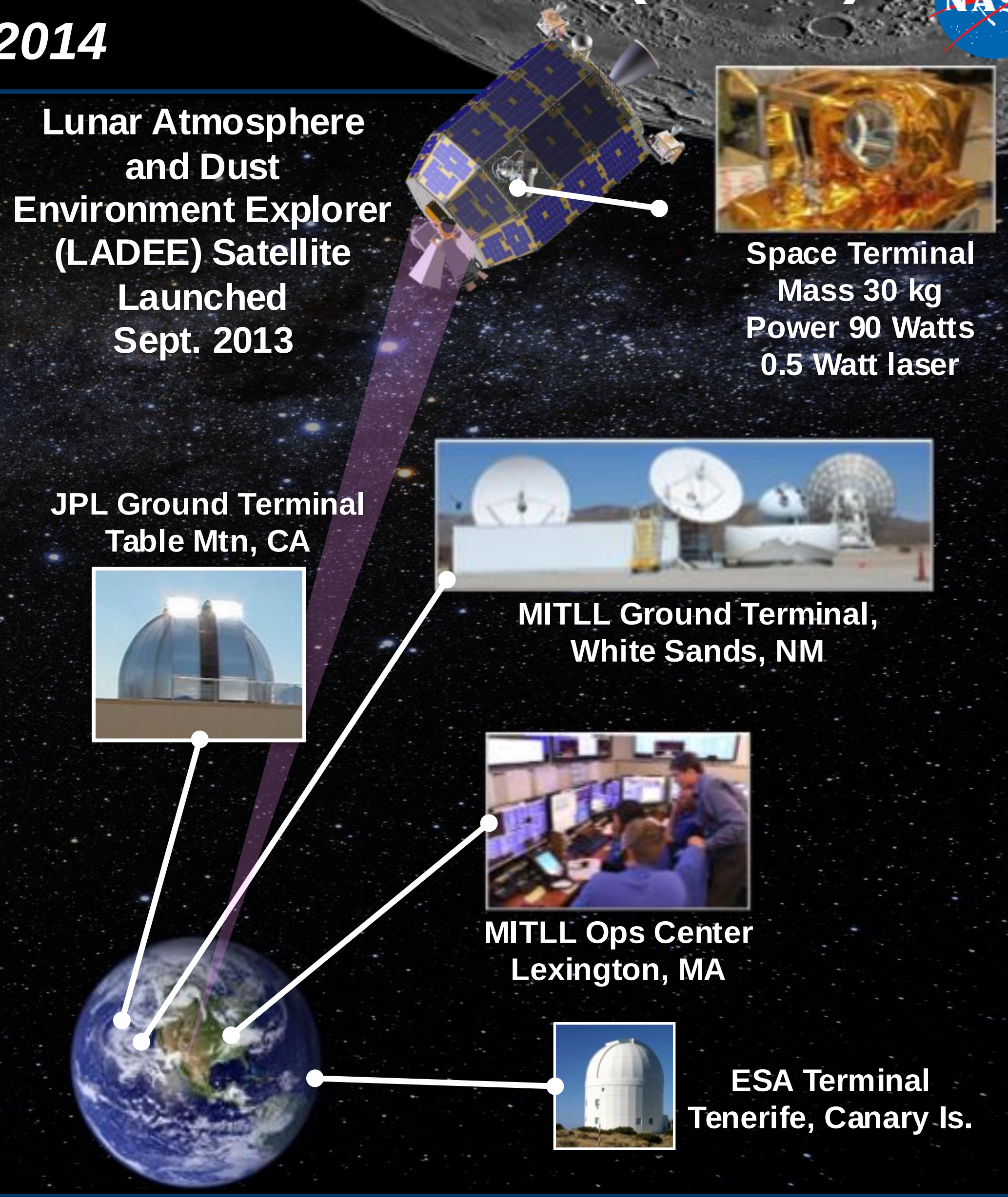
Block Diagram of Free-Space Comm System: Optical



Lunar Laser Communication Demonstration (LLCD)

2013–2014

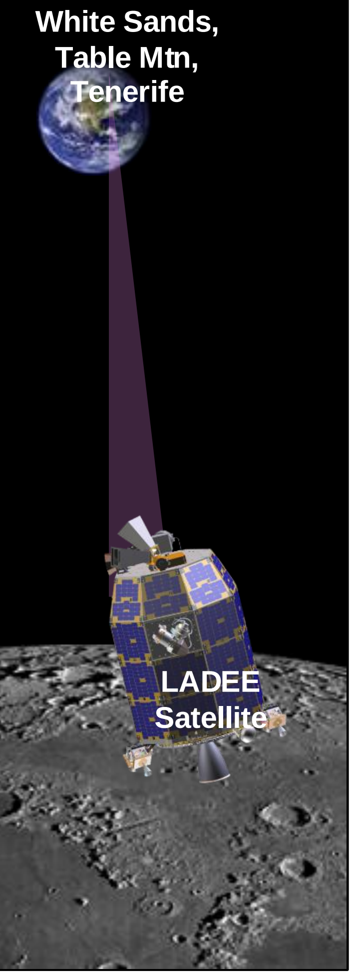
- **Complete lasercom system designed, built, and operated by MIT Lincoln Laboratory**
- **622 Mbps downlink and 20 Mbps uplink demonstrated**
  - ✓ Pointing and acquisition of narrow optical beams
  - ✓ Error-free link operation through atmosphere
  - ✓ Daily download of 1 GB spacecraft buffer
  - ✓ Multiple simultaneous HD video streams up and down (live and pre-recorded, looped back)
  - ✓ Delay tolerant network
  - ✓ Time of flight measurement for ranging/navigation
- **Technology transitioned back to NASA to support Laser Comm Relay Demonstration (LCRD)**



LLCD*: A Successful Operational Lasercom Demo

*Lunar Laser Communication Demonstration

- In 2013, NASA's LLCD showed operational utility of lasercom
  - 622 Mbps downlink, 20 Mbps uplink
  - Automated point/acq/track of 15 μrad beam
  - Daily downlink of entire 1 GB s/c buffer
  - File transfers up / down
- Demonstrated reliable data delivery over lasercom links through Earth atmosphere:
  - Link worked through thin cirrus clouds
  - Multiple ground sites and higher layer data protocols to combat clouds
  - Data interleaving and multiple apertures to mitigate turbulence
  - Aircraft/sensor sat avoidance easily achieved

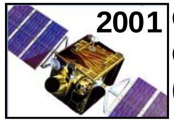


OPTICAL – NOW KNOWN!	
Narrow beam (<0.006º)	✓
Is space craft position information good enough to point?	✓
Is it possible to stabilize if space craft jitter is >> beam?	✓
Can clouds, weather, and turbulence be managed?	✓
Can sensor satellites / aircraft be easily avoided and not disruptive to link?	✓
Can lasercom ever be routine and automated?	✓

From: Khatri & Robinson, "Operational Considerations for Future Laser Communications Systems," *AIAA Improving Space Operations Workshop*, Pasadena, CA, May 5-6, 2015.

A Sampling of Space Lasercom Activities to Date

≤ 2009 | 2010 | 2012 | 2014 | 2016 | 2021 | 2023 | 2025+

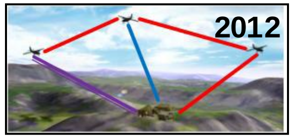


GEOLITE
GEO-Ground
(MITLL)

ALEX
Air-GEO
(MITLL)

FALCON
Air-Ground
(AFRL)

FOCAL
Air-Ground
(SAF/MITLL)



FOENEX
Air-Air, -Ground
(DARPA)

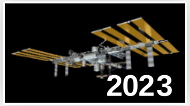
LLCD
Moon-Ground
(NASA/MITLL)

OPALS
(NASA/JPL)

LCRD
GEO-Ground
(NASA)

Orion EM-2
Moon-Ground
(NASA/MITLL)

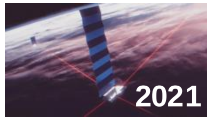

TBIRD
LEO-Ground
(NASA/MITLL)

ILLUMA-T
LEO-GEO
(NASA/MITLL)

DSOC
Deep Space-Ground
(NASA/JPL)

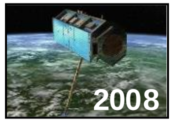
Mandrake
LEO-LEO
(DARPA)

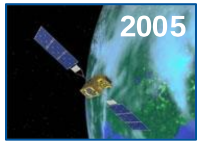
Starlink
LEO-LEO
(SpaceX)

SILEX
LEO-GEO
(ESA)

LOLA
(France)

NFIRE/TerraSar
LEO-LEO
(ESA/FRG/MDA)

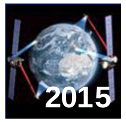


OICETS
LEO-GEO
LEO-Ground
(Japan)

HY-2
LEO-Ground
(China)

Alphasat
GEO-LEO
(ESA)

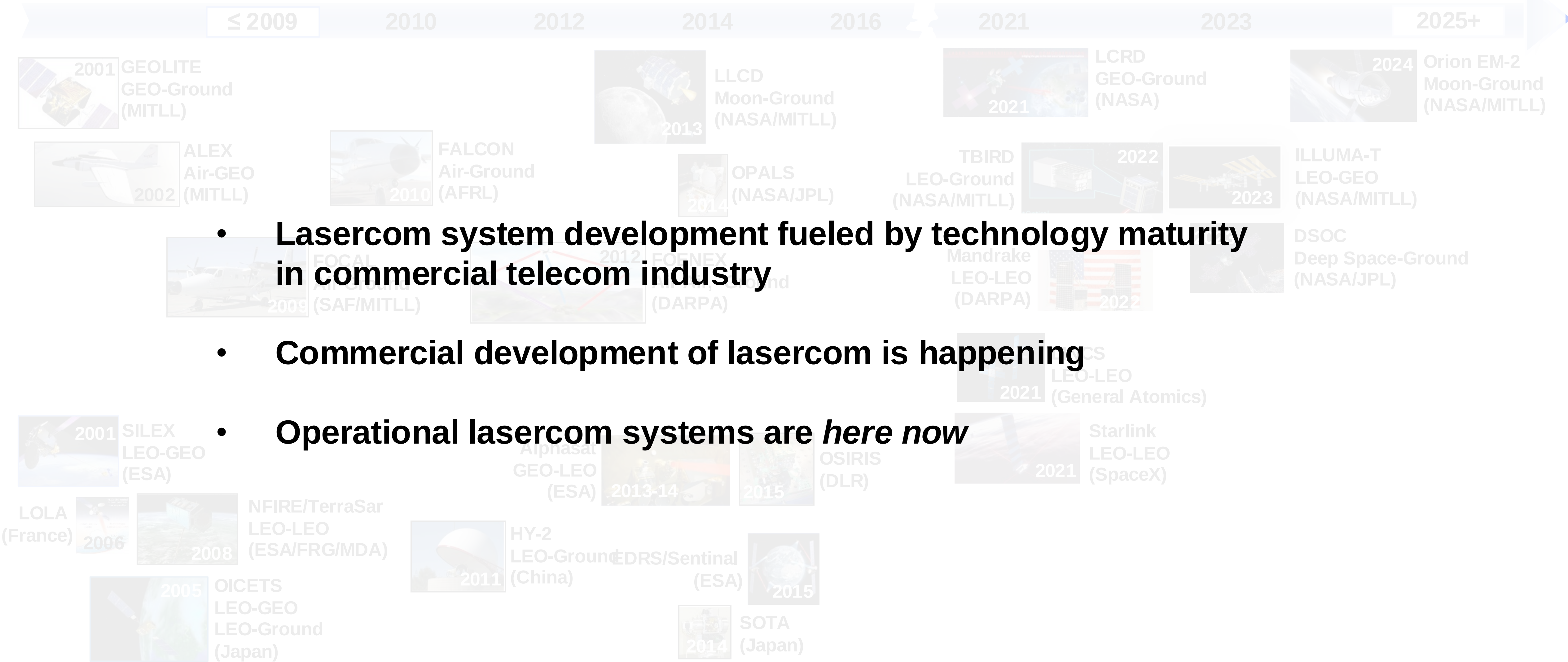

OSIRIS
(DLR)

EDRS/Sent
inal
(ESA)


SOTA
(Japan)

Adapted from D.M. Boroson, "Laser Communications," ICSSC 2014 Colloquium.

A Sampling of Space Lasercom Activities to Date

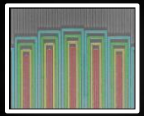


- **Lasercom system development fueled by technology maturity in commercial telecom industry**
- **Commercial development of lasercom is happening**
- **Operational lasercom systems are *here now***

Adapted from D.M. Boroson, "Laser Communications," ICSSC 2014 Colloquium.

Commercialization of Lasercom

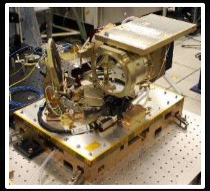
Components



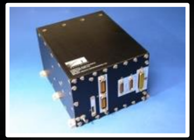
SNDA

Space Modules and Sub-Modules

Modem



Optical Module



Controller

Ground Terminals

Standards

SDA

Systems and services

ILLUMA-T

Examples of Industries with ties to lasercom technologies

Photon Spot, CACI, MOOG, L3, Single Quantum, Quantum Opus, Fibertek, Inc., SE, TESAT, Scontel, IDQ, RT Logic (A Kratos Company), mynaric, BlueHalo, BridgeSat Inc., Sea West Observatories, cailabs, Officina Stellare, Work Microwave, MDA, SpaceX, Sony, Kepler, Telesat, Northrop Grumman, Lockheed Martin, Ball Aerospace & Technologies Corp., amazon project kuiper

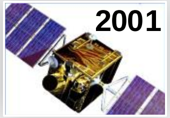
- Technologies and end-to-end systems demonstrated by LLCD mission are commercially available and lasercom standards have emerged
- Lasercom systems are offering network services now

Free Space Lasercom Projected Market Growth

Global Free space lasercom market:

2013	2021-2023	2030-2034
$33M $42M	$0.5-1.6B	$3.6-15B

Early Demos

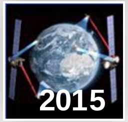


GEOLITE
GEO-Gnd
(MITLL)

LLCD
Moon-Gnd
(NASA/MITLL)

Alphasat
(ESA)

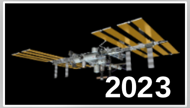
OSIRIS
(DLR)



EDRS/
Sentinel
(ESA)

Mature Demos & Operational Systems

LCRD
GEO-Gnd
(NASA)



ILLUMA-T
LEO-GEO
(NASA/MITLL)

Orion EM-2
Moon-Gnd
(NASA/MITLL)

TBIRD
LEO-Gnd
(NASA/MITLL)

DSOC
Deep Space-Gnd
(NASA/JPL)

Mandrake
LEO-LEO
(DARPA)

Service Providers

Starlink
LEO-LEO

SPACEX

TELESAT

SDA

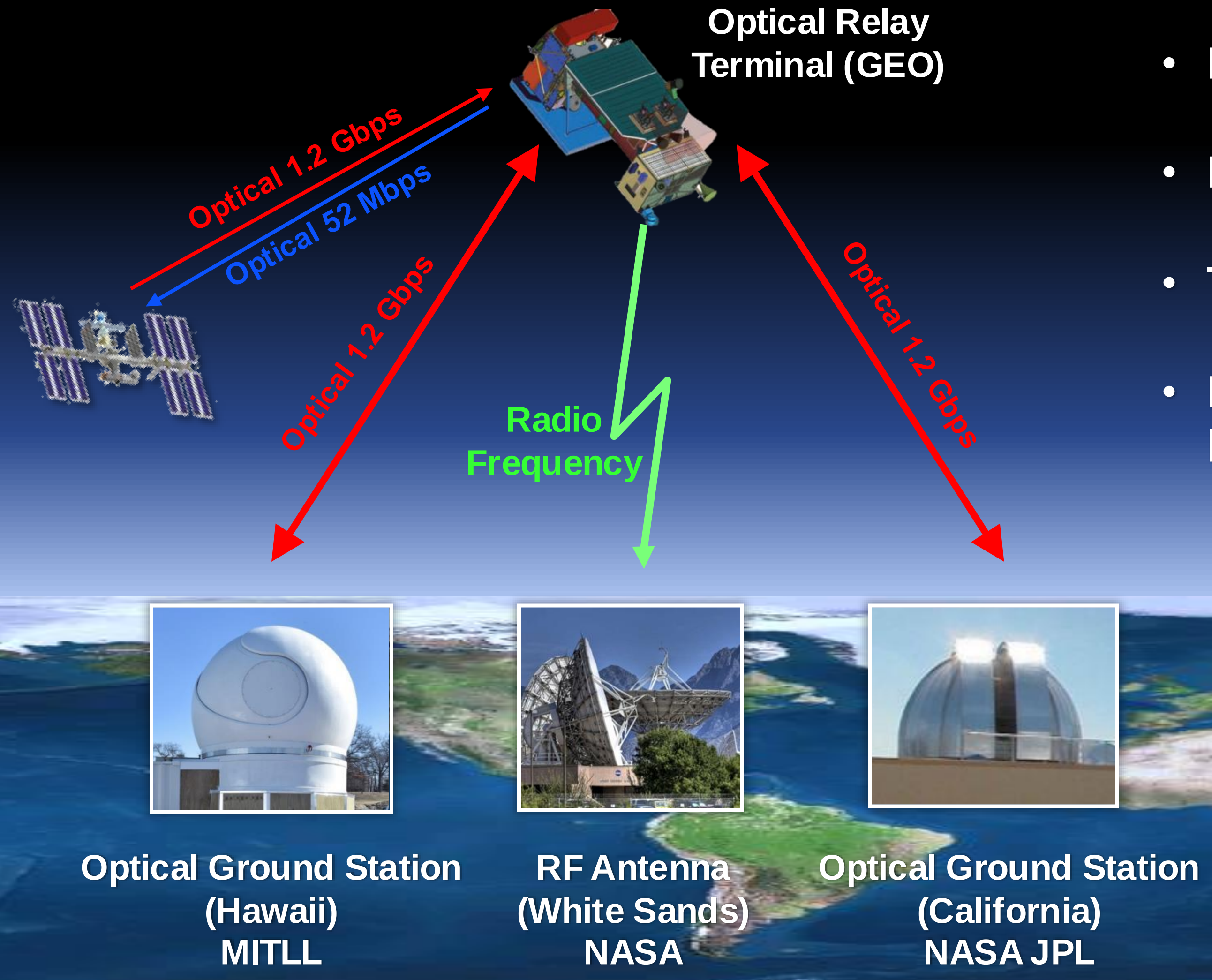
amazon project kuiper

- Zion Market Research: $1.6B (2022) → $10.2B (2030), CAGR 26.2%
- Straits Research: $11.1B (2032), CAGR 25.7% (2024-2032)
- Visiongain: $1.6B (2023), CAGR 13.6% (2024-2034)
- Global Market Insights: $0.7B (2023) → $15B (2032), CAGR 40% (2024-2032)
- Astute Analytica: $0.5B (2021) → $3.6B (2030), CAGR 24.2%

NASA Lasercom Development

Laser Communications Relay Demonstration

2021-Present

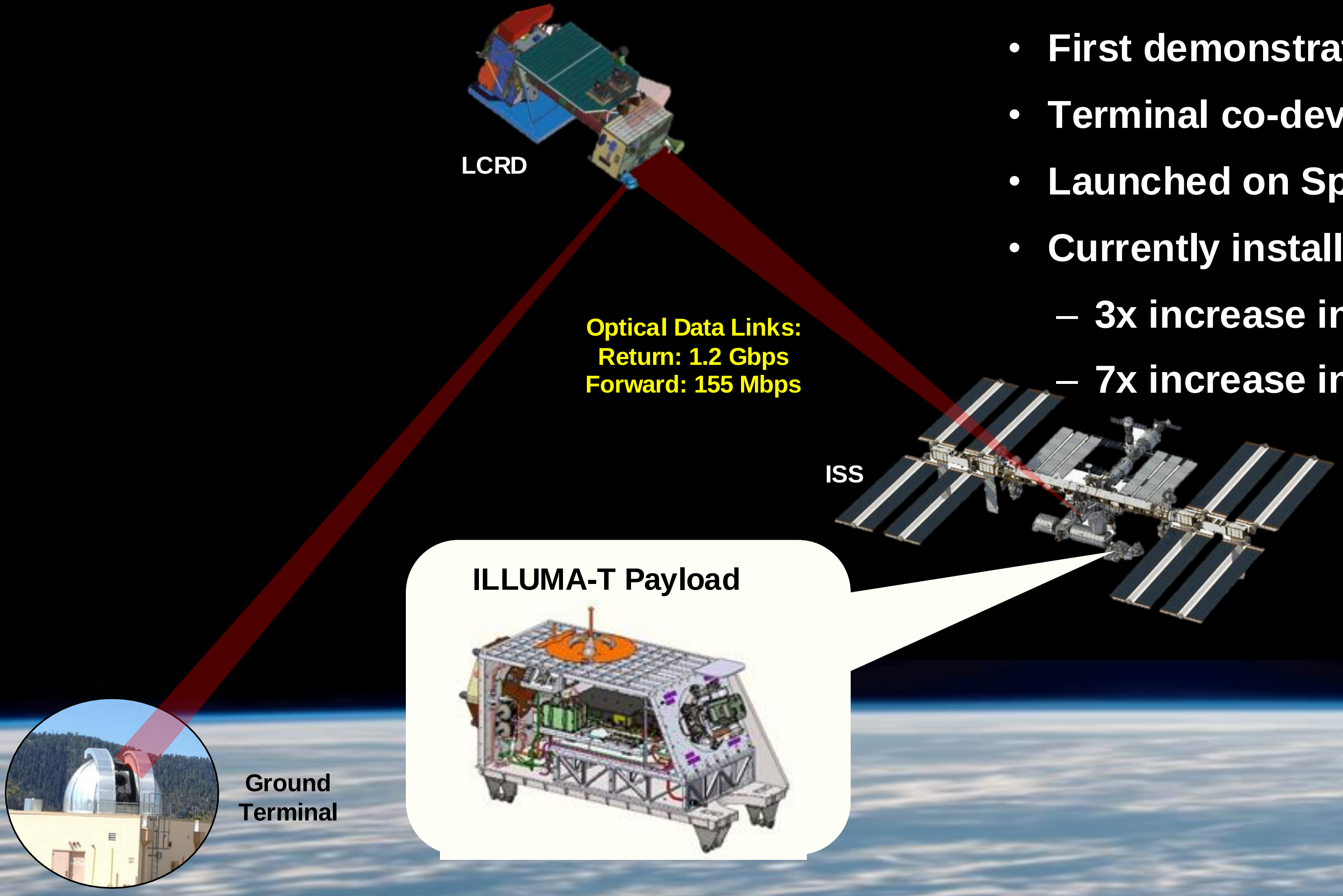


- **Follow on to Lunar Lasercom Demo**
- **Relay demo / operational pathfinder**
- **Tech transfer to NASA Goddard & Industry**
- **Follow on mission ILLUMA-T provides space-based user platform on ISS (launched in 2023)**

ILLUMA-T: Integrated LCRD LEO User Modem and Amplifier Terminal
LCRD: Laser Communications Relay Demonstration
LEO: Low Earth Orbit
GEO: Geosynchronous Earth Orbit
ISS: International Space Station

International Space Station Lasercom (ILLUMA-T)

2023-Present



- **First demonstration optical relay from user to ground**
- **Terminal co-developed with MIT LL, NASA, industry**
- **Launched on SpaceX Dragon, November 2023**
- **Currently installed and operating on ISS**
  - **3x increase in ISS downlink data rate**
  - **7x increase in ISS uplink data rate**

ILLUMA-T: Integrated LCRD LEO User Modem and Amplifier Terminal
LCRD: Laser Communications Relay Demonstration
LEO: Low Earth Orbit
ISS: International Space Station

ILLUMA-T Operational Statistics

193
Days
18 Dec 2023 – 27 June 2024

307
Links established

134 hours
Total experiment time

~5000 minutes
Active communications

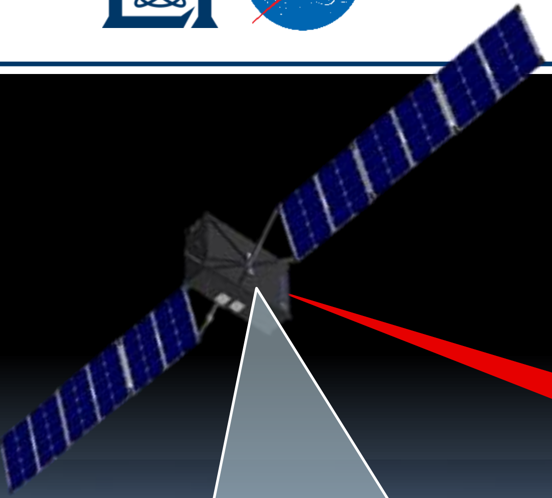
~375 Tbytes
Data from the ISS

~45 TBytes
Data to the ISS

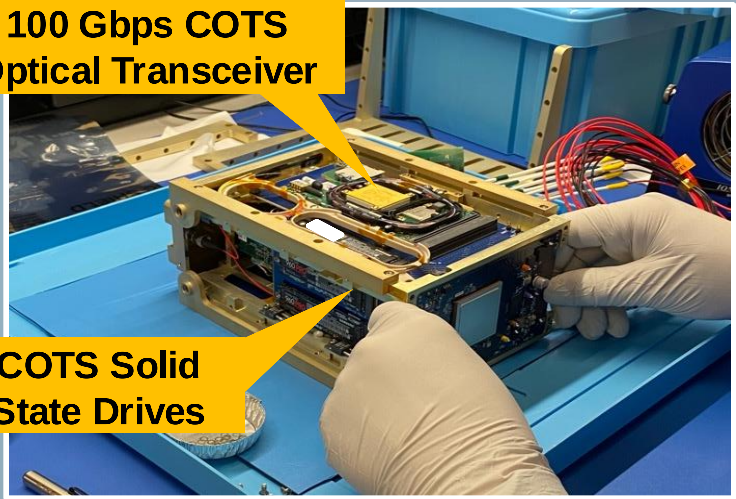
First successful laser communications terminal for human spaceflight!

TeraByte InfraRed Delivery (TBIRD)

2022-2024



- **Launched May 2022 on NASA-provided 6U CubeSat**
- **Provides 200-Gbps Space-to-Ground optical link– >1000X higher than typical small sat radio links**
- **Demonstrated delivery of 5 TB of data in single ~5-minute pass over ground station**



3U CubeSat Payload Design

COTS: Commercial Off The Shelf

JPL Ground Terminal
Table Mtn, CA

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Lasercom on Orion Artemis II

September 2025 Launch

- Artemis is NASA's mission for human exploration of Moon and Mars
- Artemis I un-crewed mission completed in 2022
  - S-band radio comm downlink of 6 Mbps at lunar ranges– data stored and retrieved after Orion return
  - Stressed capacity of shared Deep Space Network resources
- Artemis II crewed mission to add lasercom capability to provide
  - Up to 260 Mbps downlink and 20 Mbps uplink from Lunar vicinity
  - Downlink of all data collected during mission, including real-time mission video

Ground stations:

JPL Ground Terminal
Table Mtn, CA

MIT LL Ground Terminal,
White Sands, NM

Optical terminal installed on Orion, NASA KSC

NASA

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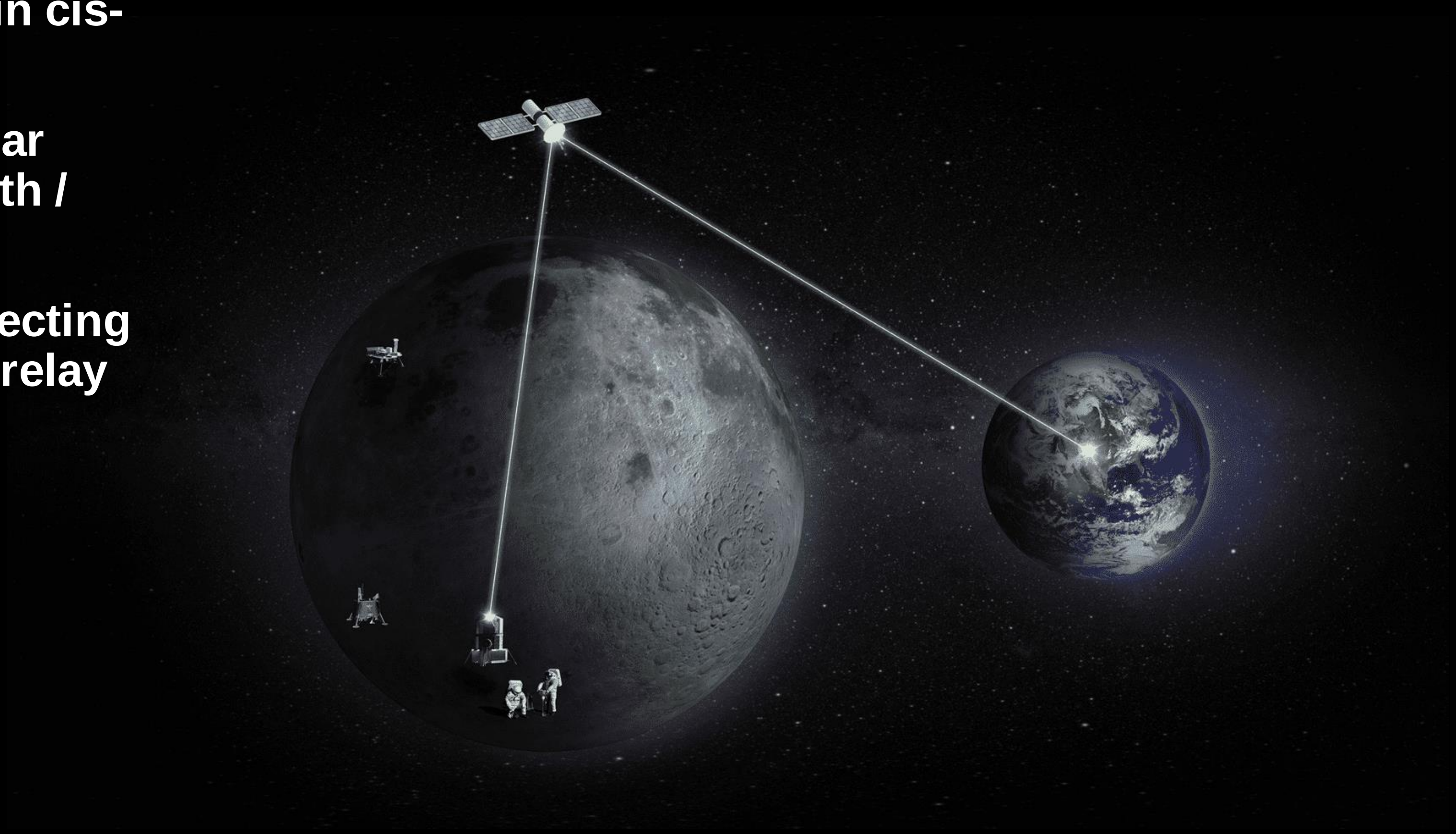
The Future: Lunar Relay

Potential applications of lasercom in cis-Lunar space:

- **High rate trunking to connect lunar assets / near-Lunar assets to Earth / near-Earth assets**
- **Lunar proximity operations connecting lunar surface / orbiting assets to relay backbone services**

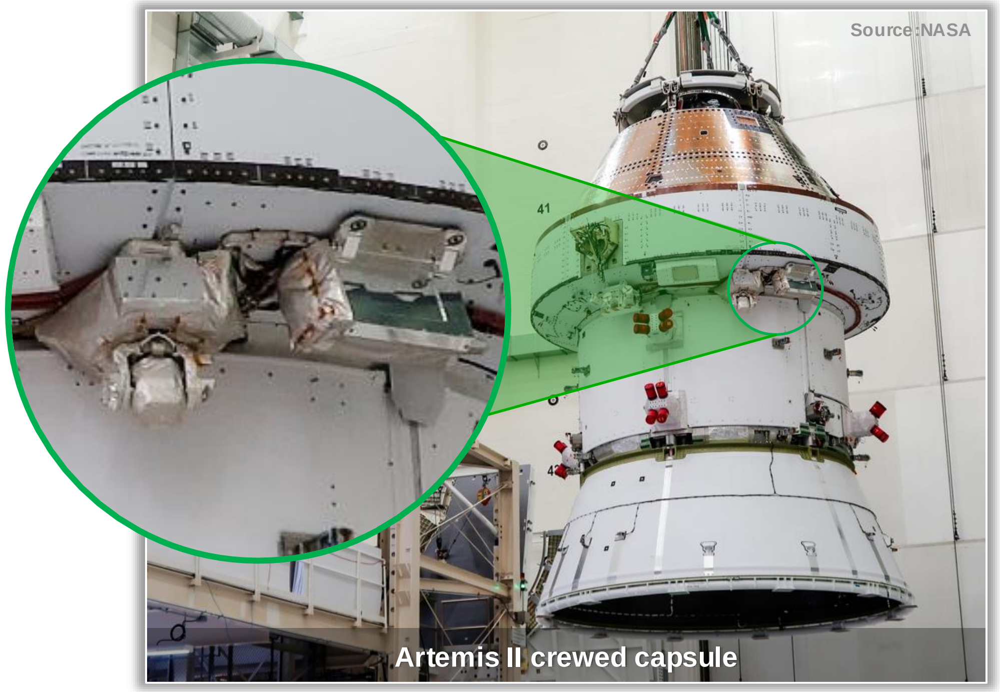


Summary

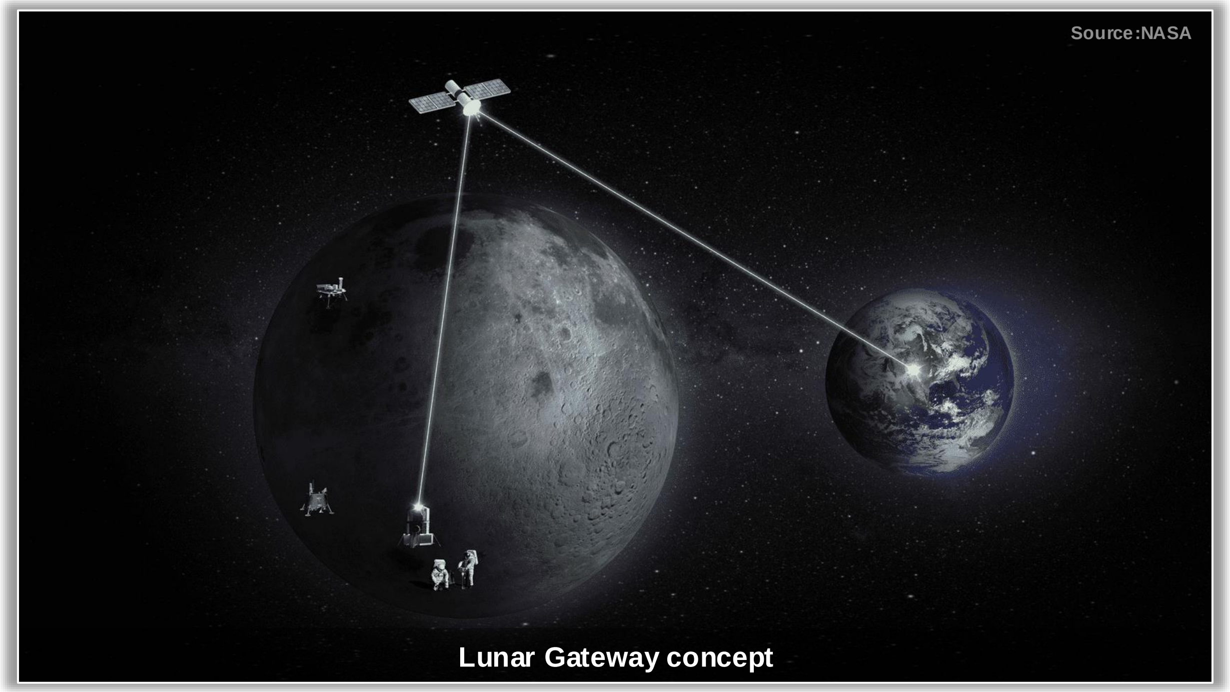
- **Lasercom can revolutionize space missions by providing much higher bandwidth than traditional radio frequency comm**

- **NASA and MITLL have worked collaboratively over the past decade+ to advance lasercom from demonstration-class to operational systems**

What's Next: Lunar



Artemis II crewed capsule



Lunar Gateway concept

Similar hardware currently installed on Artemis II crewed capsule

- **Incorporated lessons learned from ILLUMA-T**
- **9-day mission supporting human spaceflight in lunar environment**
- **Launch planned for Dec 2025**

Last known picture of ILLUMA-T, courtesy of Alan Hylton, GSFC

Backup

Moon to Mars Architecture Segments

Human Lunar Return

Foundational Exploration

Sustained Lunar Evolution

Humans to Mars

This chart provided by NASA (J. Free, Cislunar Security Conference 2024)