ILLUMA-T: Laser Communications from the International Space Station

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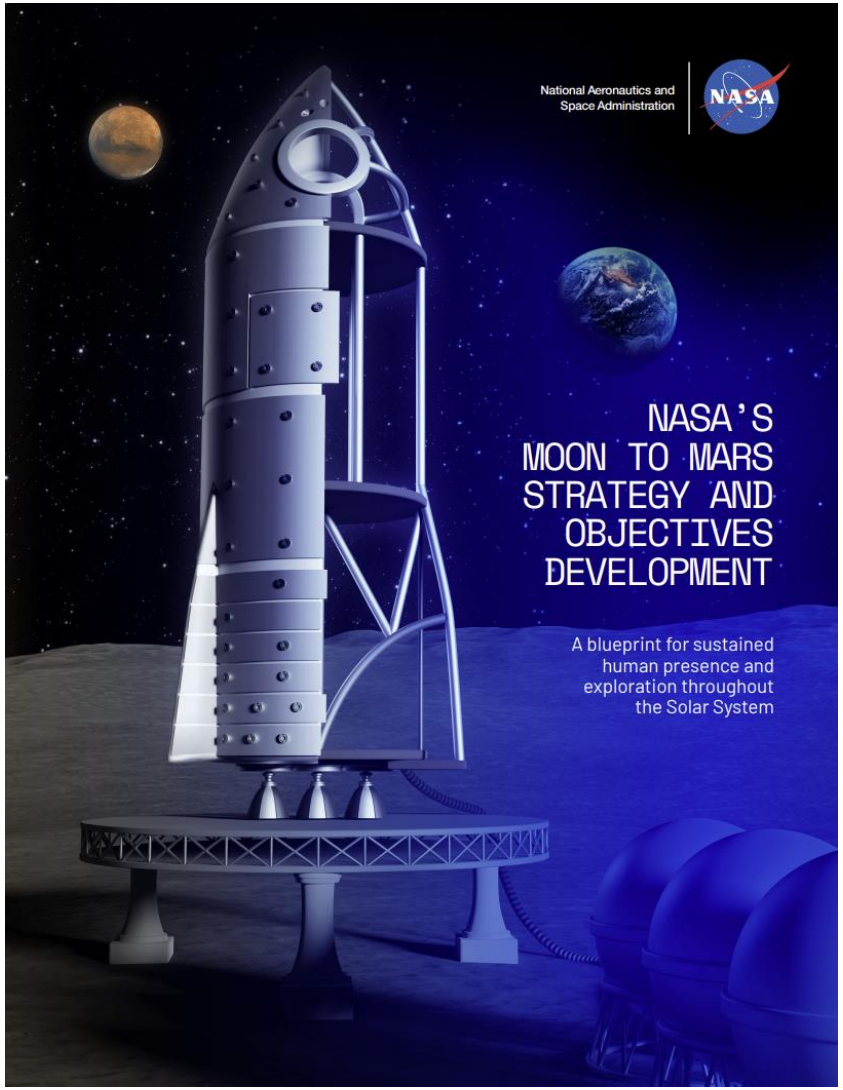
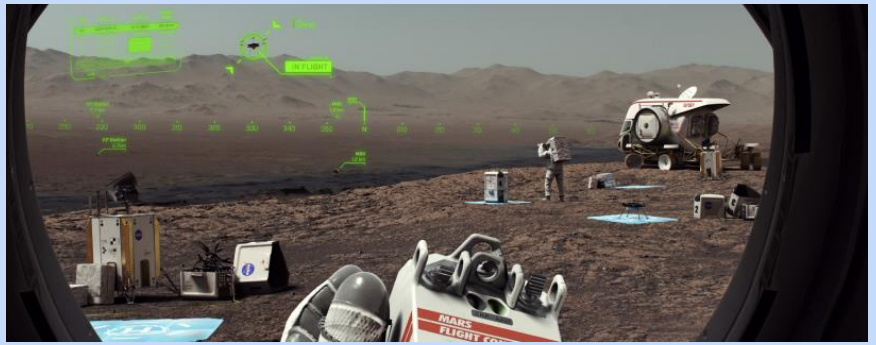
NASA Human Exploration

Communications for Human Space Exploration



https://www.nasa.gov/wp-content/uploads/2023/04/m2m_strategy_and_objectives_development.pdf

Monitor and maintain crew health



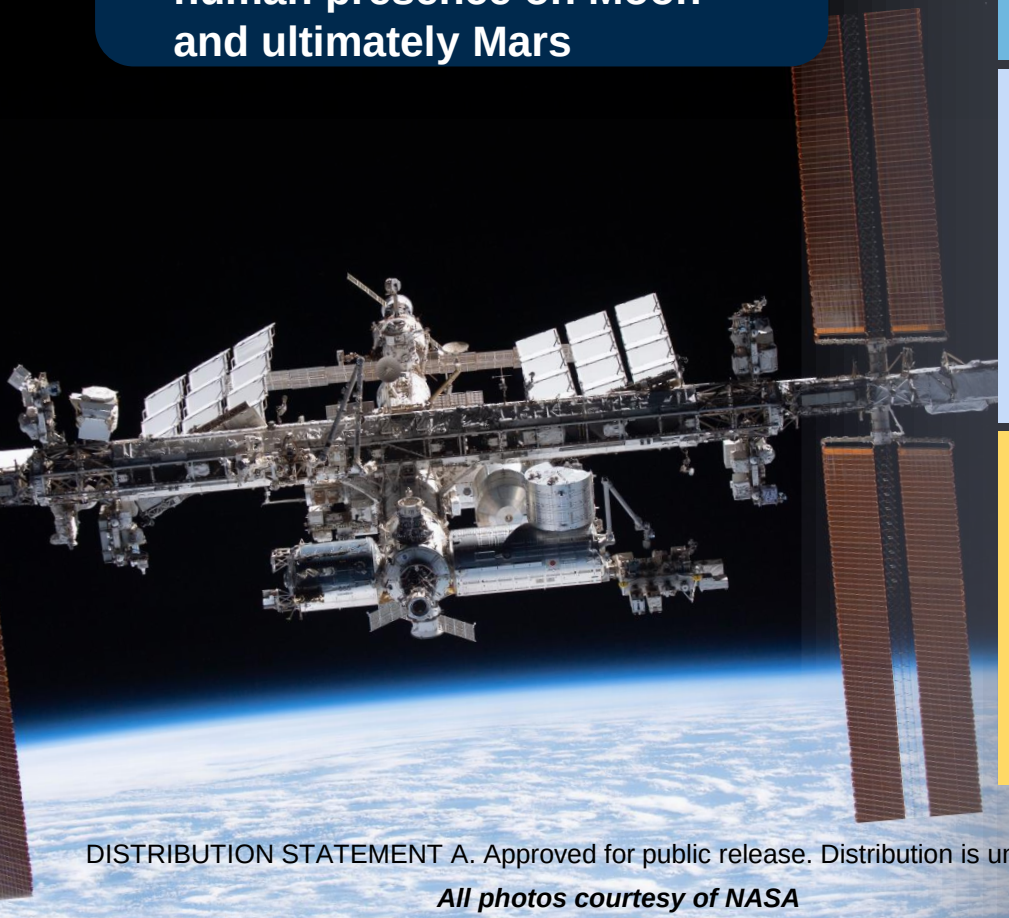
Characterize and monitor space and surface environments

Remote support of astronaut and science missions

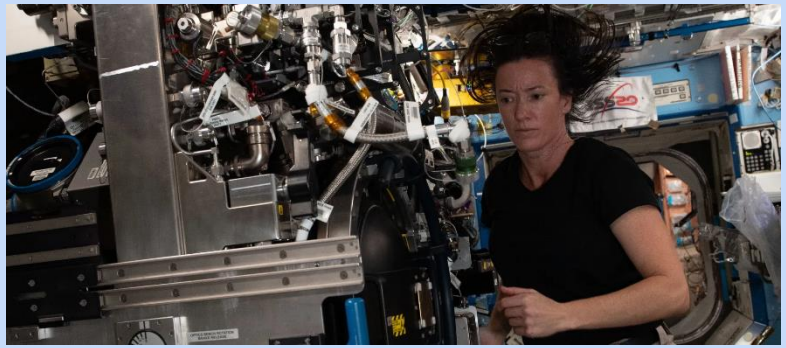
International Space Station (ISS):

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

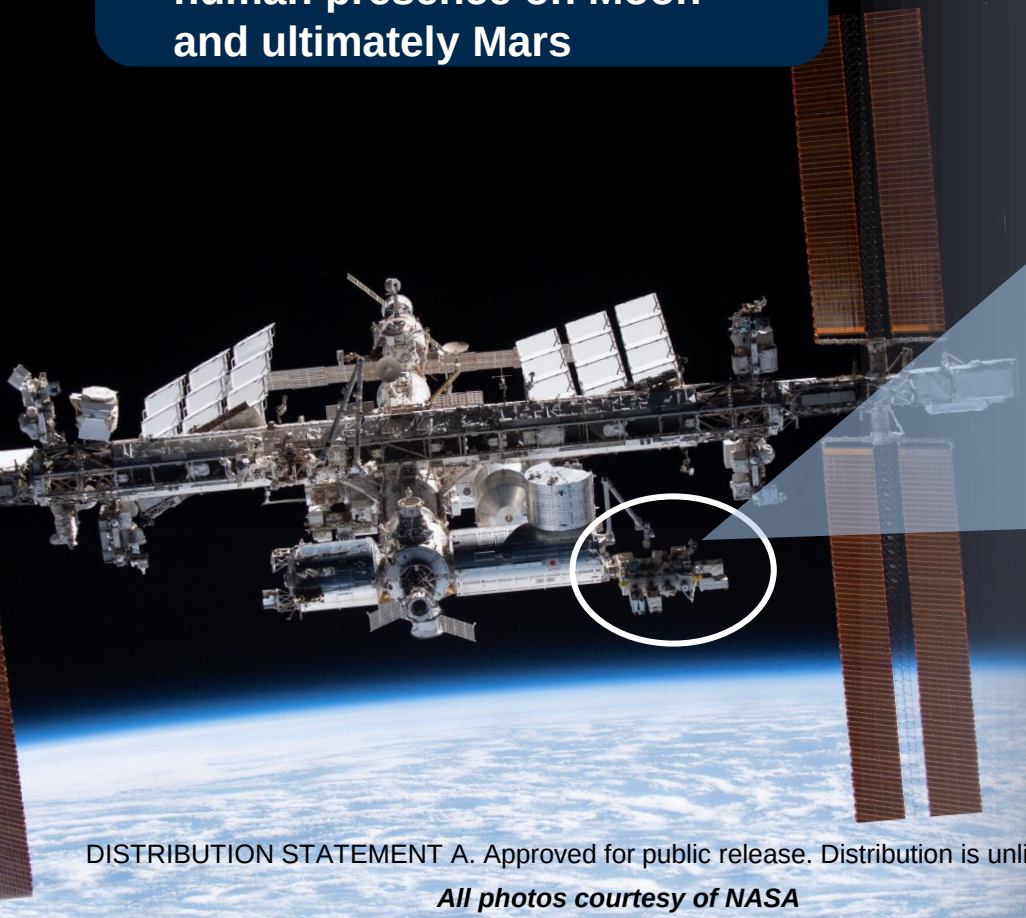
8K HD Video

All photos courtesy of NASA

International Space Station (ISS)

Continued human presence in space since Nov 2, 2000

Critical proving ground for human presence on Moon and ultimately Mars



ILLUMA-T: First lasercom user terminal for human exploration

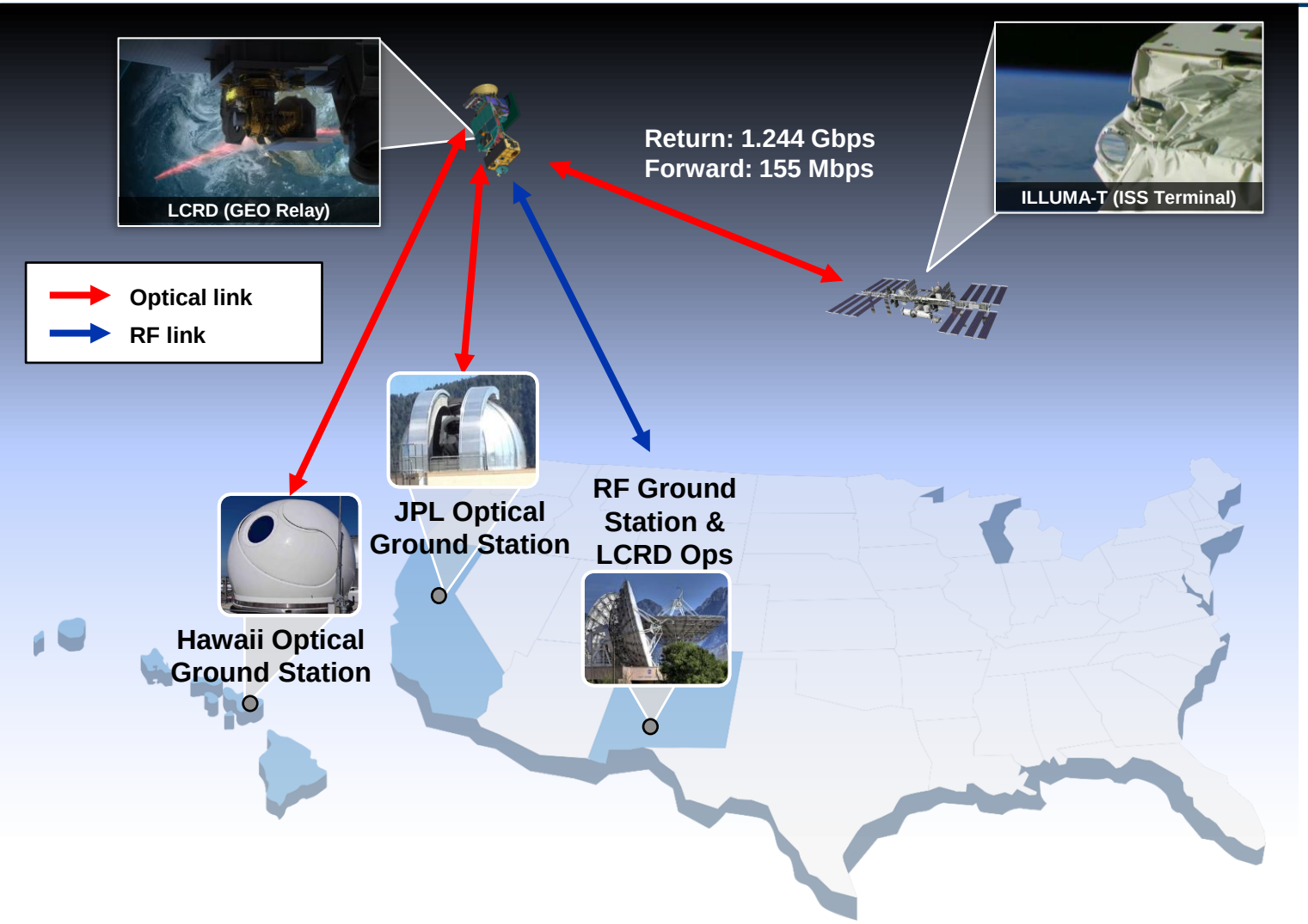
ILLUMA-T: Integrated LCRD LEO User Modem and Amplifier Terminal

All photos courtesy of NASA

Outline

- Motivation
- **ILLUMA-T**
- **On-Orbit Performance**
- **Summary**

ILLUMA-T



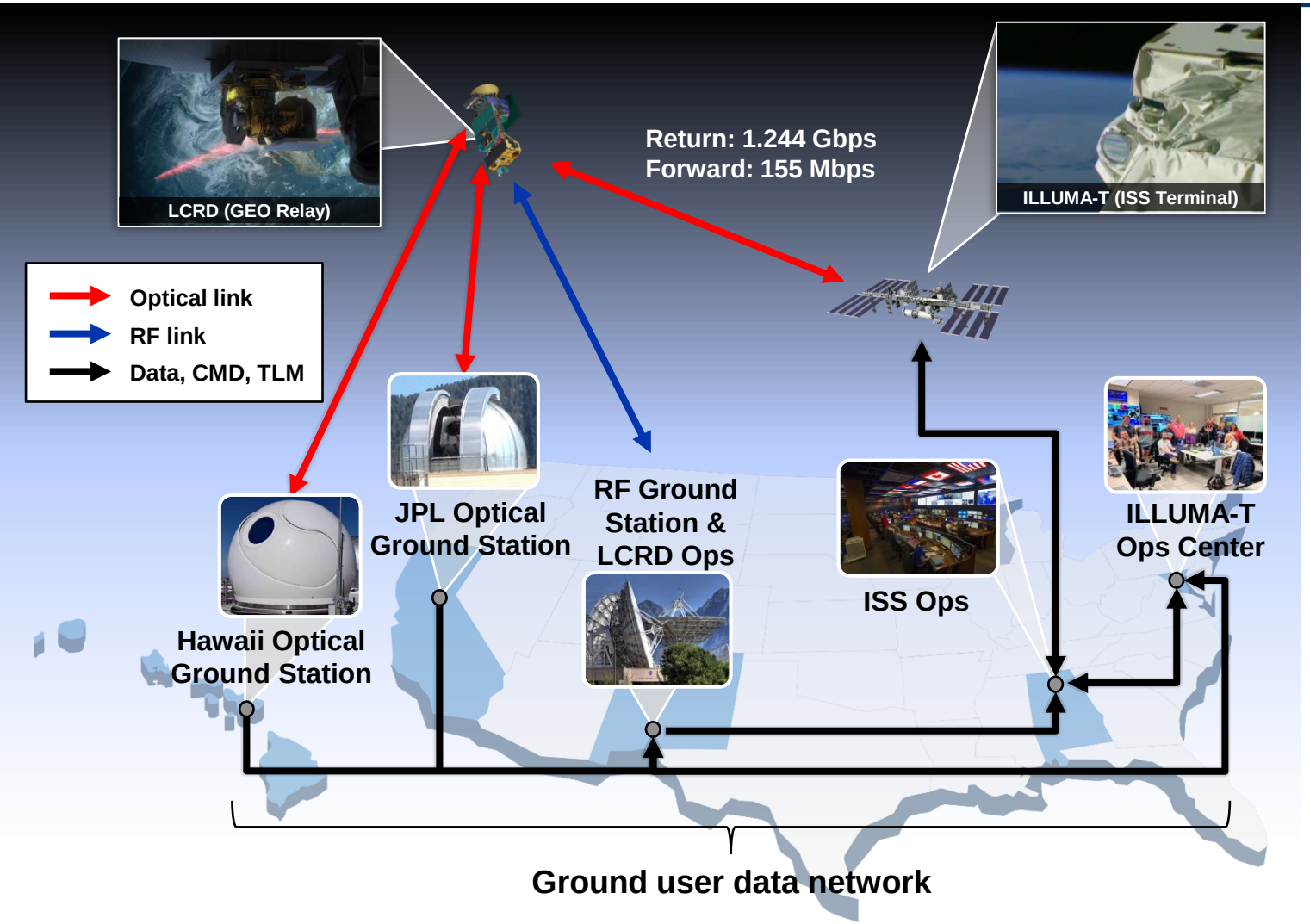
Develop an optical communications user terminal to demonstrate data transfer between low Earth orbit and the ground through a geosynchronous relay

- **Mature lasercom systems as precursor to optical relays at the moon and Mars**
- **Foster development of lasercom industry through tech transfer**
- **Provide high rate forward and return links for human spaceflight on ISS to alleviate existing bandwidth bottlenecks**
- **Provide bi-directional Ethernet data connection to ISS**

ILLUMA-T: Integrated LCRD LEO User Modem and Amplifier Terminal

LCRD: Laser Communications Relay Demo
JPL: Jet Propulsion Laboratory (NASA)
ISS: International Space Station
RF: Radio Frequency
GEO: Geosynchronous Earth Orbit

Maturing Lasercom Systems



- Expanding beyond point-to-point technology demonstrations
- Relay architecture with multiple space nodes & multiple ground stations
- Data delivery beyond "physical layer" considerations
- Operations and coordination including relay, ISS (host), payload, and multiple ground stations

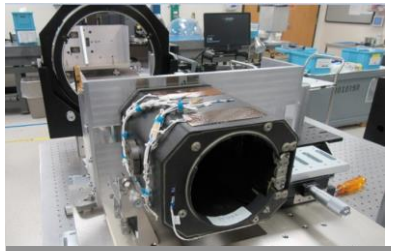
ILLUMA-T: Integrated LCRD LEO User Modem and Amplifier Terminal

LCRD: Laser Communications Relay Demo
JPL: Jet Propulsion Laboratory (NASA)
ISS: International Space Station
RF: Radio Frequency
GEO: Geosynchronous Earth Orbit
CMD & TLM: Command & Telemetry

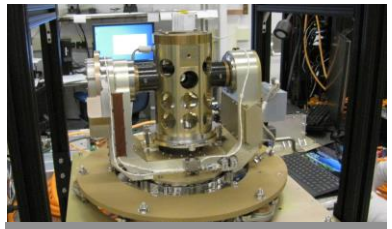
ILLUMA-T: ISS Space Terminal

ILLUMA-T Space Terminal

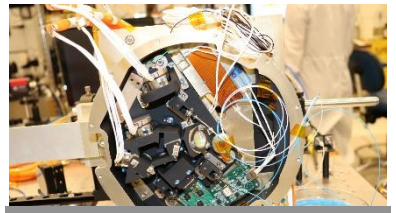
Modular, Agile, Scalable Optical Terminal (MAScOT)



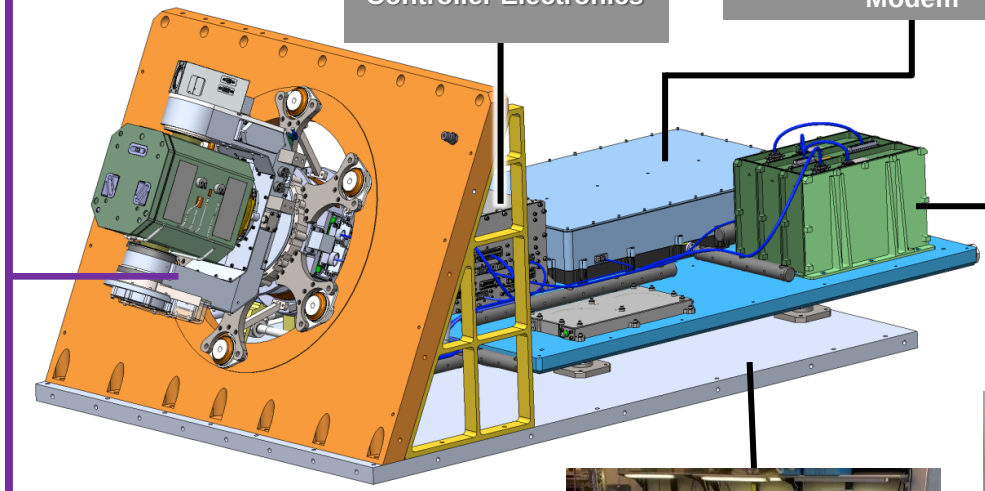
Telescope and Relay



Latch and Gimbal

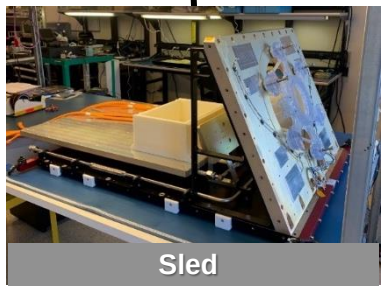


Backend Optics

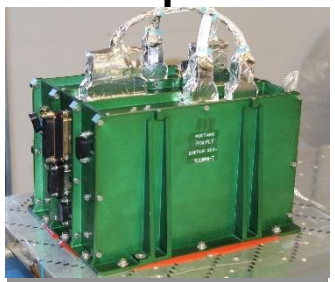


Controller Electronics

Modem



Sled



Power Converter

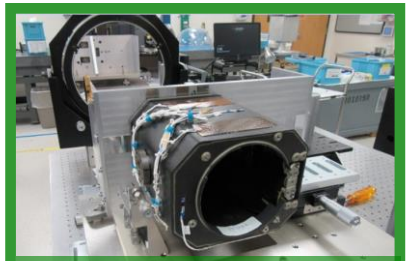
ILLUMA-T: ISS Space Terminal

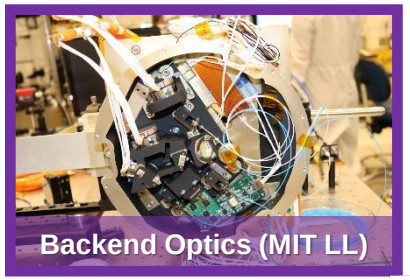
ILLUMA-T Space Terminal

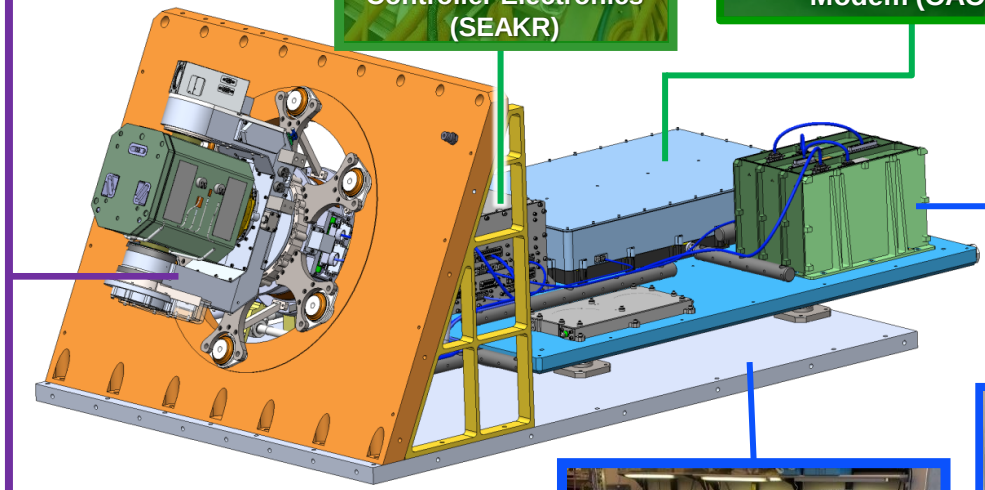
Industry
NASA GSFC
MIT LL

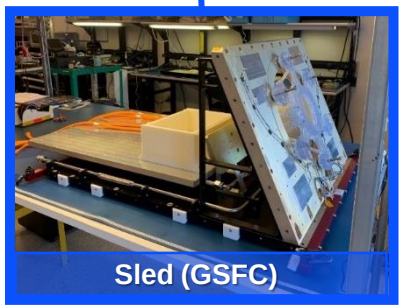
GSFC: Goddard Space Flight Center
ISS: International Space Station

Modular, Agile, Scalable Optical Terminal (MAScOT)

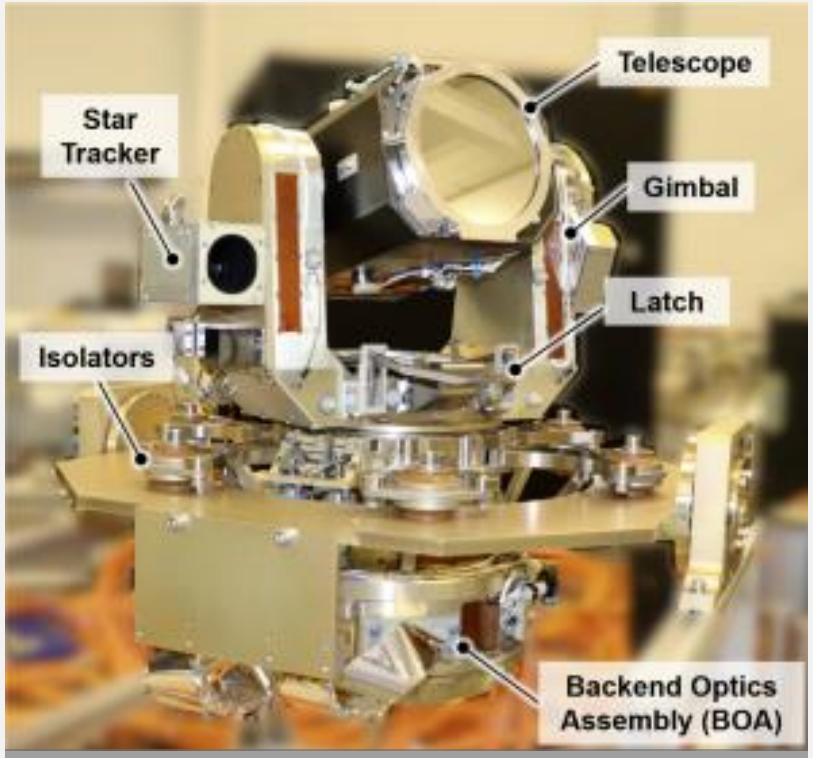






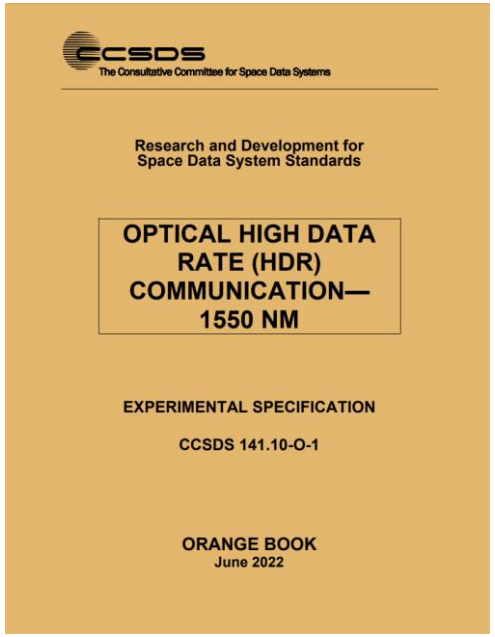


Supporting Lasercom Proliferation



MAScOT: a multi-mission optical head design

- Near-hemispherical field of regard
- Modular design
- Customizable



Multi-rate high data rate communications

- Multi-rate communications to accommodatea range of link distances, support multiple users, and provide fall-back modes
- Development of standards to foster competitive industry base

LCRD: Laser Communications Relay Demonstration
ILLUMA-T: Integrated LCRD LEO User Modem and Amplifier Terminal

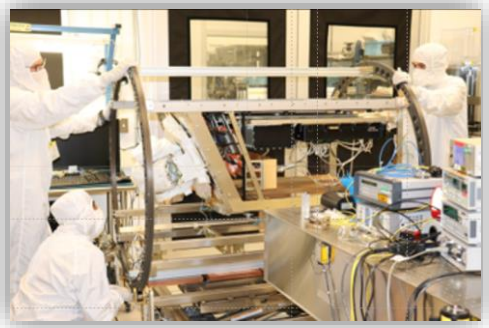
MAScOT: Modular, Agile, Scalable Optical Terminal

ILLUMA-T Timeline

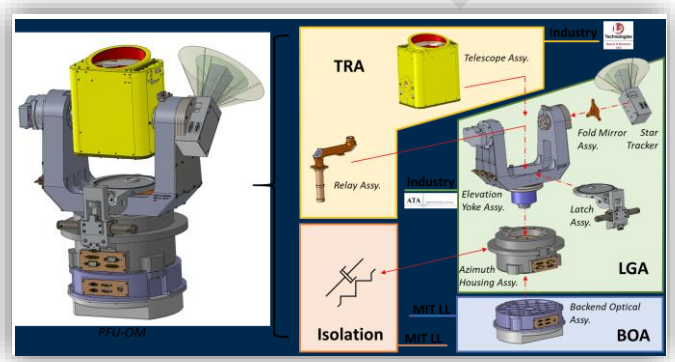
System Req't Review 2017

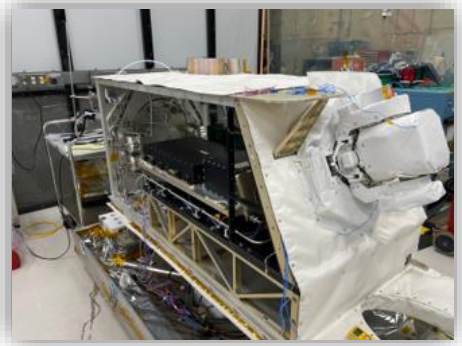
Preliminary Design Review 2018

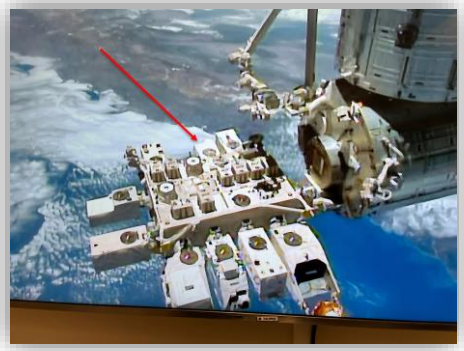
Critical Design Review 2019



ILLUMA-T Kickoff	Industry Build	Assembly, Integration and Test at MIT LL	Payload Integration and Test at NASA	Launch	ISS Docking and Transfer	Commissioning	Experiments
2017	2018–2021	2021–2022	2022	11/9/2023	11/11/2023	11/2023	12/2023–6/2024







5 photos courtesy of NASA

MAScOT: Modular, Agile Scalable Optical Terminal
BOA: Backend Optical Assembly
LGA: Latch and Gimbal Assembly
TRA: Telescope and Relay Assembly

Outline

- Motivation
- ILLUMA-T
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ILLUMA-T Launch, Installation, and Commissioning

Payload on Canada Arm


Payload inside SpaceX Dragon


MAScOT checkout

Installation and all initial checkouts successful!

All photos courtesy of NASA

LCRD = Laser Communications Relay Demonstration
GSFC=Goddard Space Flight Center

On-Orbit Experiments

Lasercom Link Engineering	Lasercom as Network Service	Operational Use
Pointing, Acquisition, Tracking Communications (physical layer)	Applications (file transfer, streaming video) Handovers Delay tolerant networking	Routine establishment of links Reliable application performance User experience Autonomy

DEC 2023

S	M	T	W	R	F	S
					1	2
3	4	5	6	7	8	9
10	11	12	13	14	15	16
17	18	19	20	21	22	23
24/31	25	26	27	28	29	30

JAN 2024

S	M	T	W	R	F	S
	1	2	3	4	5	6
7	8	9	10	11	12	13
14	15	16	17	18	19	20
21	22	23	24	25	26	27
28	29	30	31			

FEB 2024

S	M	T	W	R	F	S
				1	2	3
4	5	6	7	8	9	10
11	12	13	14	15	16	17
18	19	20	21	22	23	24
25	26	27	28	29		

First Light
ISS unavailable
LCRD unavailable
ILLUMA-T Software Update
ILLUMA-T jettison

MAR 2024

S	M	T	W	R	F	S
					1	2
3	4	5	6	7	8	9
10	11	12	13	14	15	16
17	18	19	20	21	22	23
24/31	25	26	27	28	29	30

APR 2024

S	M	T	W	R	F	S
	1	2	3	4	5	6
7	8	9	10	11	12	13
14	15	16	17	18	19	20
21	22	23	24	25	26	27
28	29	30				

MAY 2024

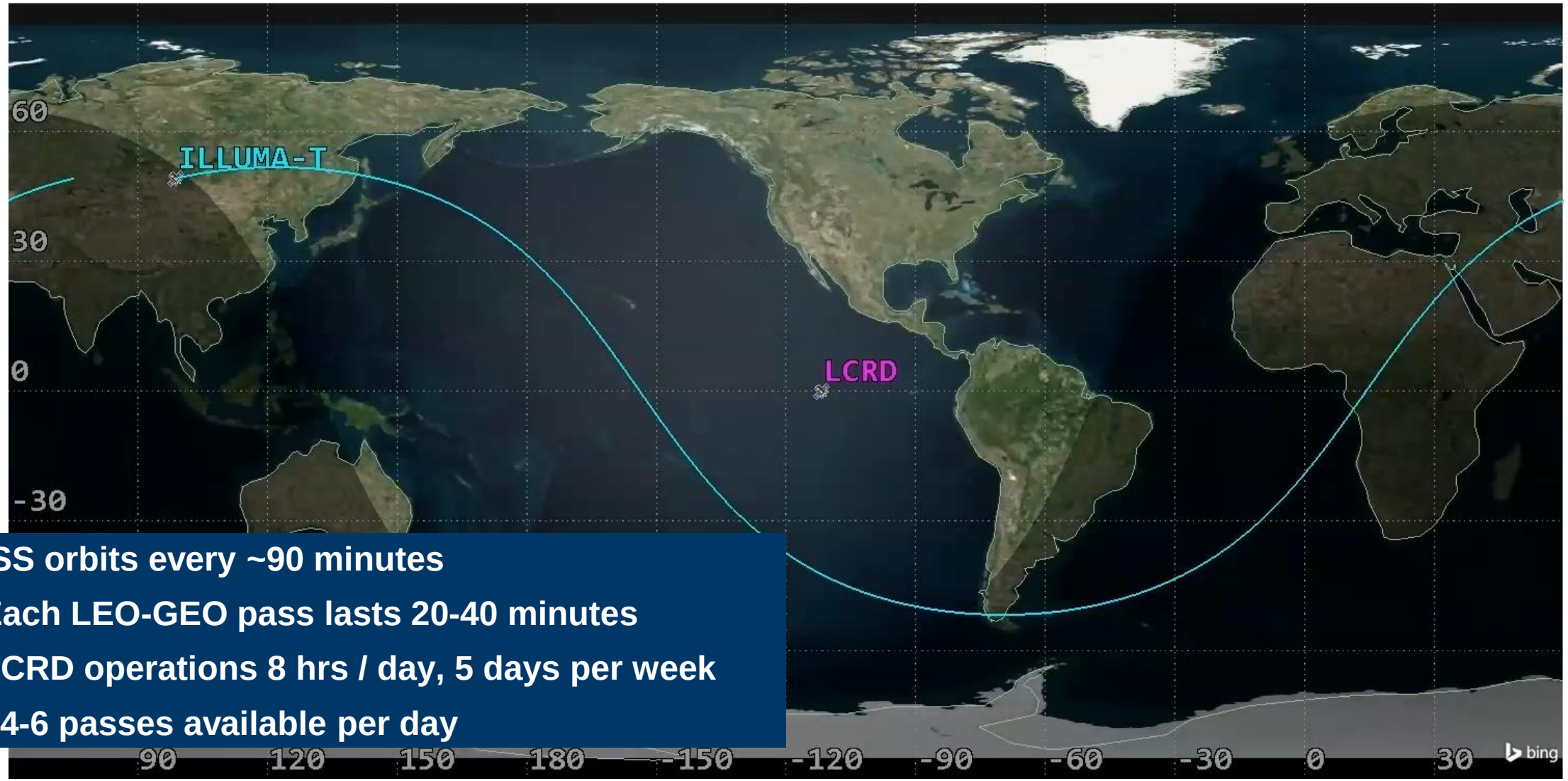
S	M	T	W	R	F	S
			1	2	3	4
5	6	7	8	9	10	11
12	13	14	15	16	17	18
19	20	21	22	23	24	25
26	27	28	29	30	31	

JUN 2024

S	M	T	W	R	F	S
						1
2	3	4	5	6	7	8
9	10	11	12	13	14	15
16	17	18	19	20	21	22
23/30	24	25	26	27	28	29

Successful completion of 36 experiments

Orbit Visualization



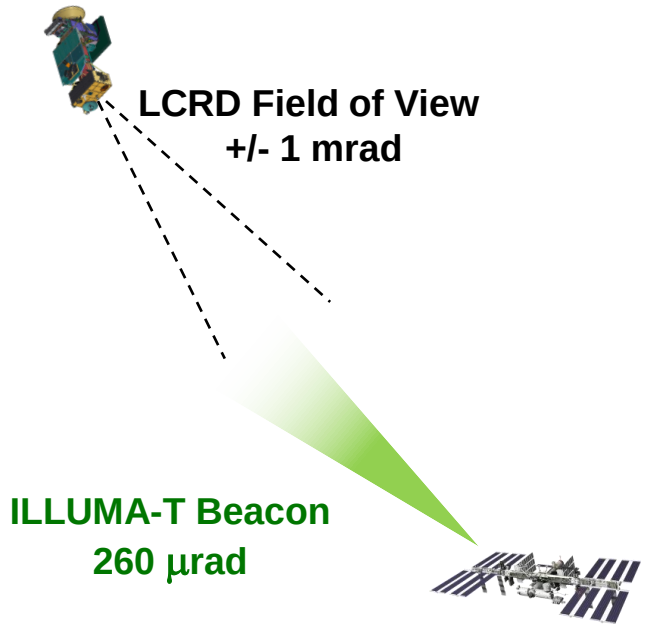
- ISS orbits every ~90 minutes
- Each LEO-GEO pass lasts 20-40 minutes
- LCRD operations 8 hrs / day, 5 days per week
- ~4-6 passes available per day

Outline

- Motivation
- ILLUMA-T
- **On-Orbit Performance**
  - **ILLUMA-T Pass Overview**
    - **Lasercom Link Engineering**
    - **Lasercom as Network Service**
- **Summary**

ILLUMA-T Pass Overview

Pointing → Acquisition → Tracking → Communications



- **Receive initial knowledge of ephemeris of LCRD and ISS**
  - **This tells the lasercom systems where to initialize pointing**
- **ILLUMA-T orientation calibrated to ISS**
- **Appropriate configurations on all segments for selected experiments**

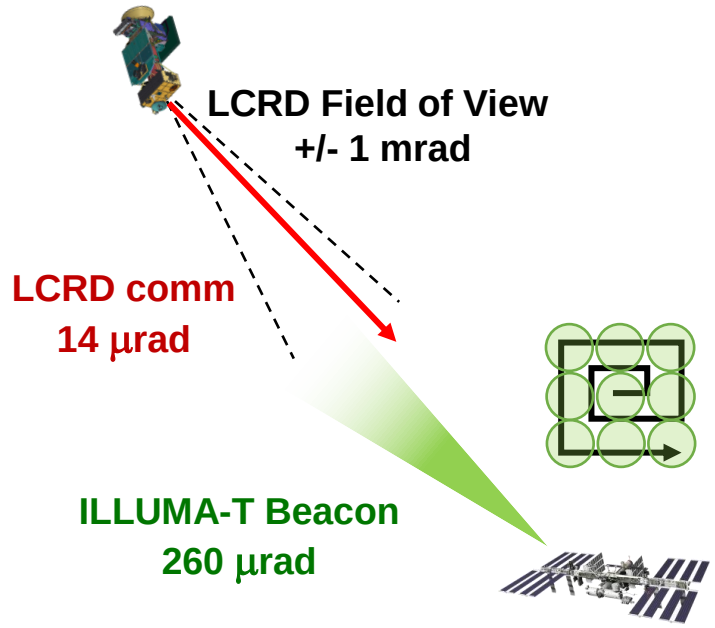
Lasercom Beam Examples

Quarter from across a football field
218 µrad
0.012 degrees

ISS as seen from Earth:
275 µrad
0.015 degrees

ILLUMA-T Pass Overview

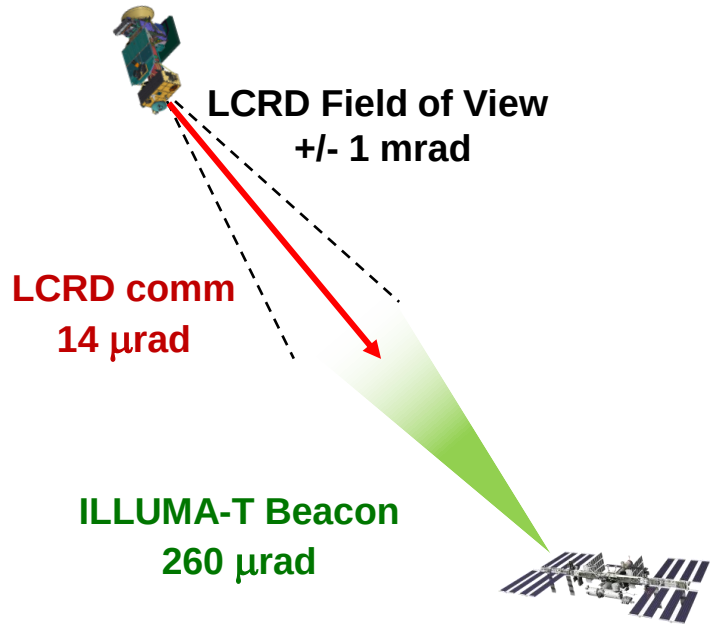
Pointing → **Acquisition** → Tracking → Communications



- **ILLUMA-T beacon** scans in a spiral pattern
- LCRD stares at expected location while transmitting **forward comm beam**

ILLUMA-T Pass Overview

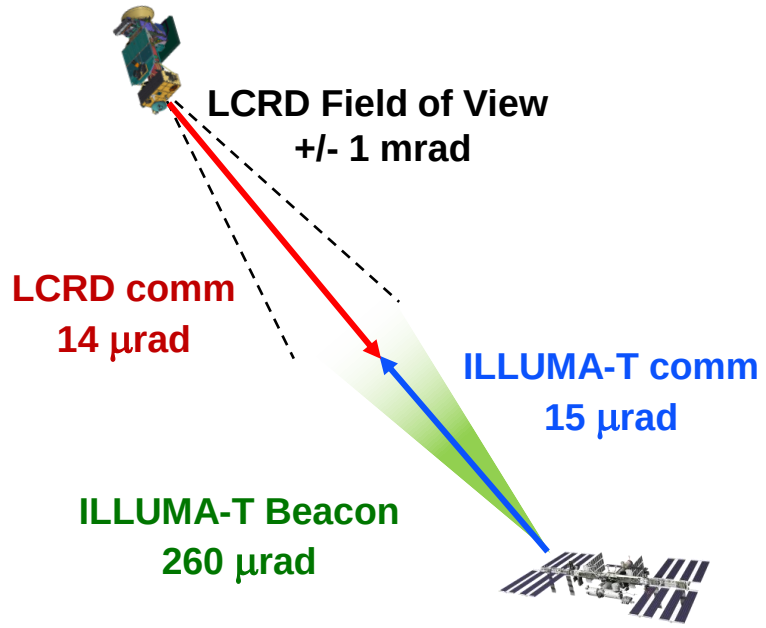
Pointing → Acquisition → **Tracking** → Communications



- ILLUMA-T beacon scans in a spiral pattern
- LCRD stares at expected location while transmitting forward comm beam
- **Once LCRD detects ILLUMA-T beacon, it can track on the beacon and maintain the forward comm beam in the correct direction**

ILLUMA-T Pass Overview

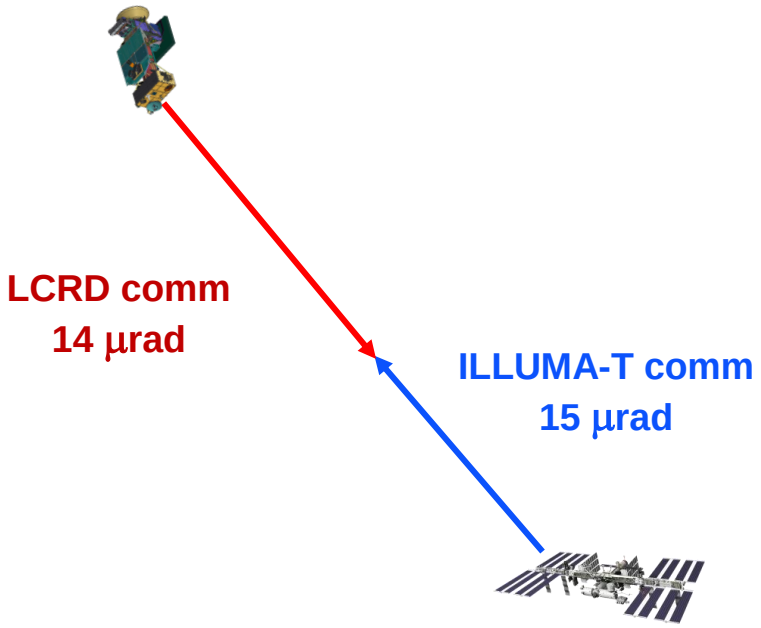
Pointing → Acquisition → **Tracking** → Communications



- ILLUMA-T beacon scans in a spiral pattern
- LCRD stares at expected location while transmitting forward comm beam
- Once LCRD detects ILLUMA-T beacon, it can track on the beacon and maintain the forward comm beam in the correct direction
- **Once ILLUMA-T sees the forward comm beam, it can track on it and maintain the return comm beam back to LCRD**
- **LCRD can then use the return comm beam to refine its tracking**

ILLUMA-T Pass Overview

Pointing → Acquisition → Tracking → Communications



- **LCRD & ILLUMA-T can maintain tracking using comm beams**
- **Multiple comm modes available**
  - **Return: 155 Mbps, 311 Mbps, 622 Mbps, 1.244 Gbps**
  - **Forward: 51 Mbps, 155 Mbps**
- **Each LEO-GEO pass lasts 20-40 min**

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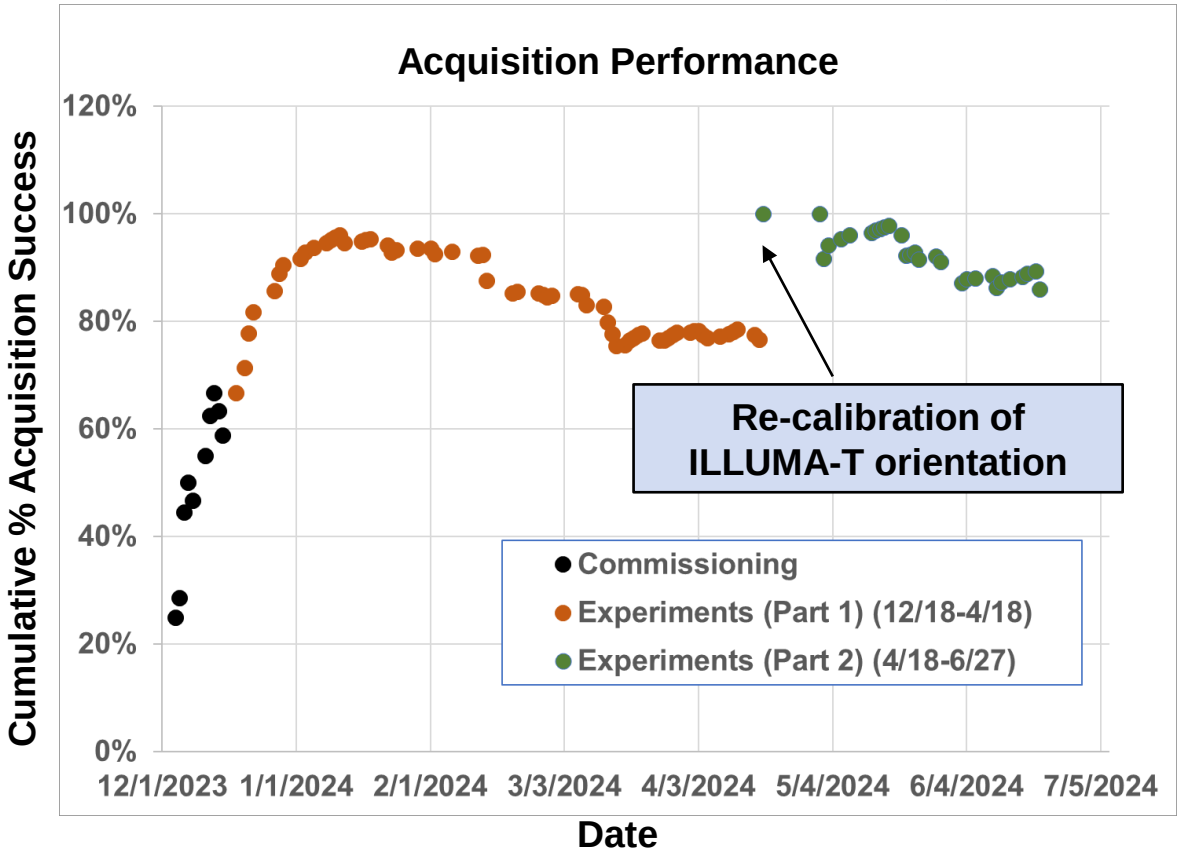
Results: Pointing & Acquisition

Pointing → Acquisition → Tracking → Communications



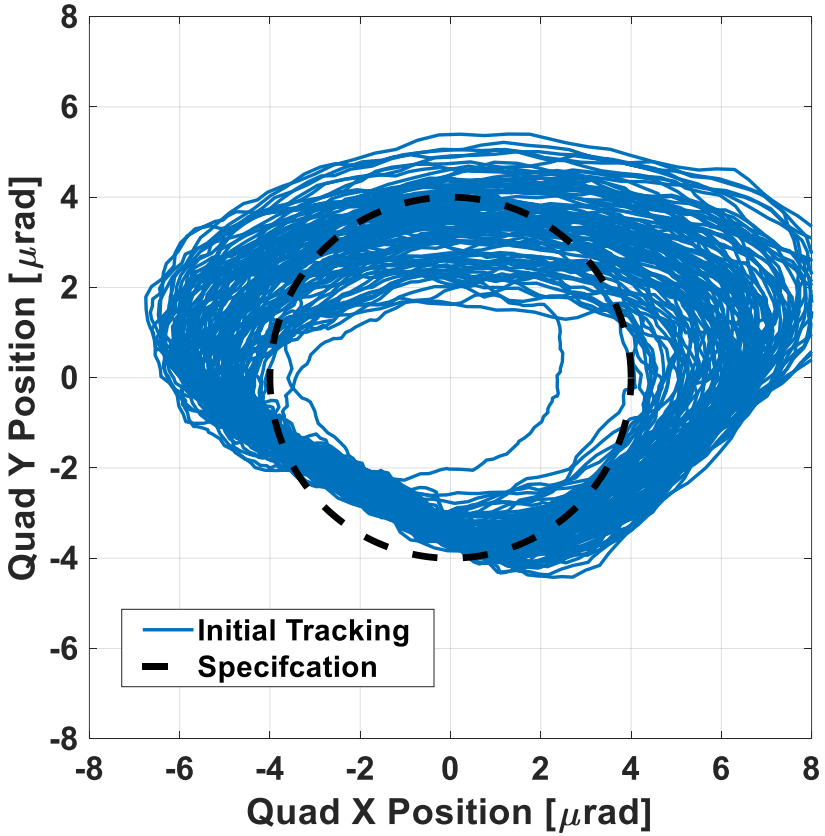
- **Acquisition relies on initial ephemeris**
  - Initial acquisitions were not reliable due to multiple GEO relay maneuvers and stale ISS ephemeris
- **Multiple improvements made during experiments**
  - Better updates of ISS ephemeris
  - Re-calibrate orientation between ISS and ILLUMA-T
- **Additional time needed to improve acquisition success rates**
  - Evidence of slow mechanical orientation drift between ISS & ILLUMA-T
  - Solar weather may impact acquisition success

Successful acquisition rate of ~90%

Results: Tracking

Pointing | Acquisition | **Tracking** | Communications

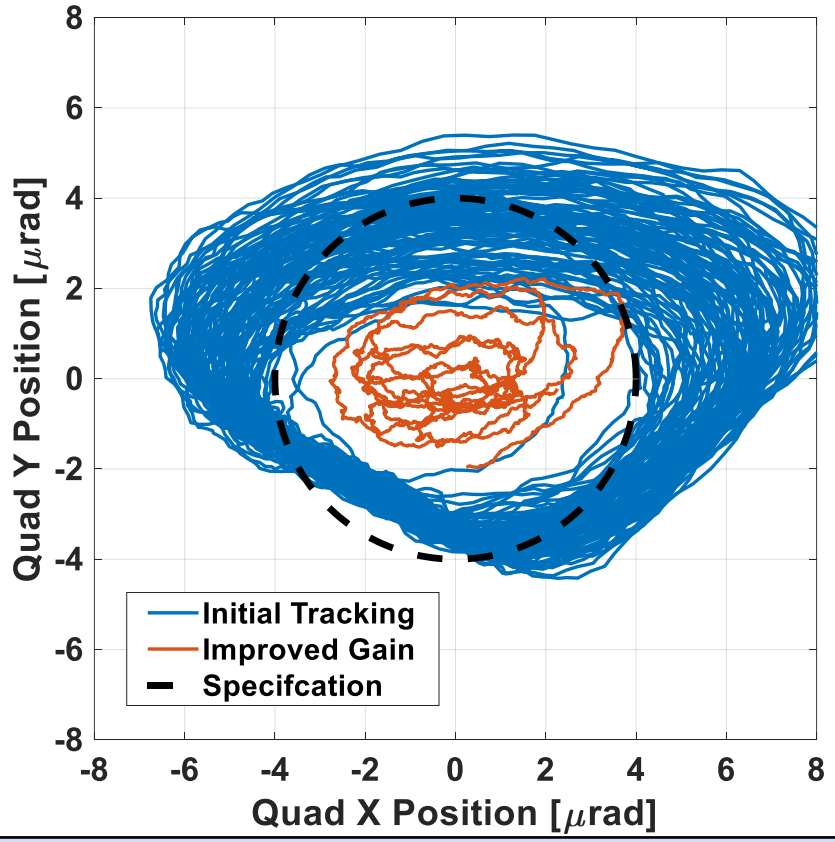
- **Tracking maintains beam alignment on fiber**
- **Initial performance exceeded requirement of ~4 urad on quad sensor**



Results: Tracking

Pointing | Acquisition | **Tracking** | Communications

- **Tracking maintains beam alignment on fiber**
- **Initial performance exceeded requirement of ~4 urad on quad sensor**
- **Reduced bandwidth to improve rejection of noise**
  - **Conservative design robust against high platform disturbances**
  - **On-orbit adjustment of parameters**

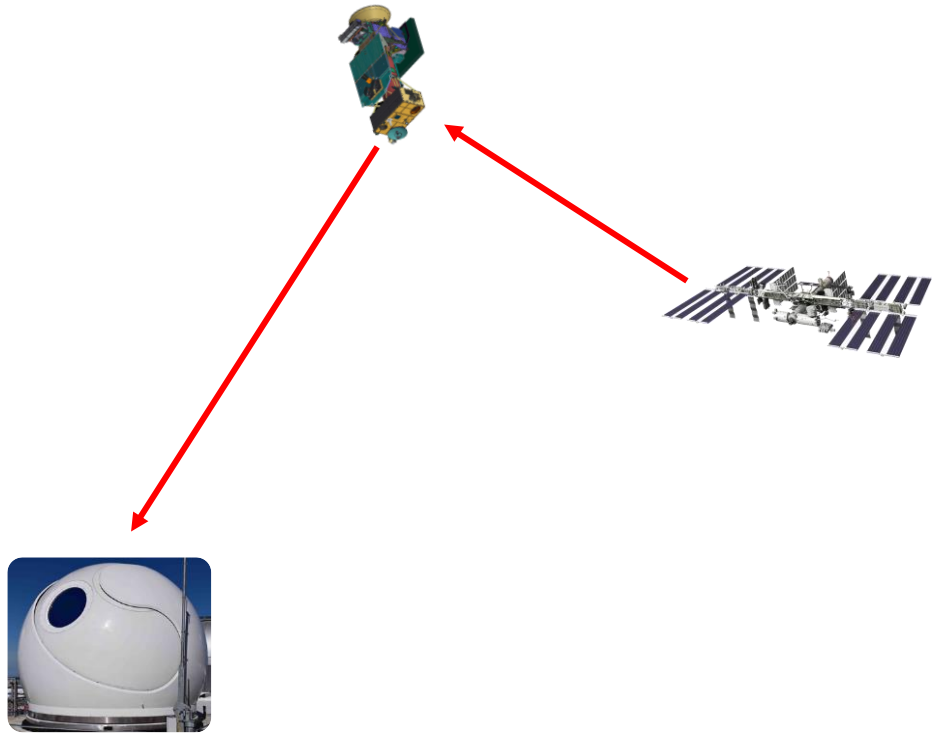


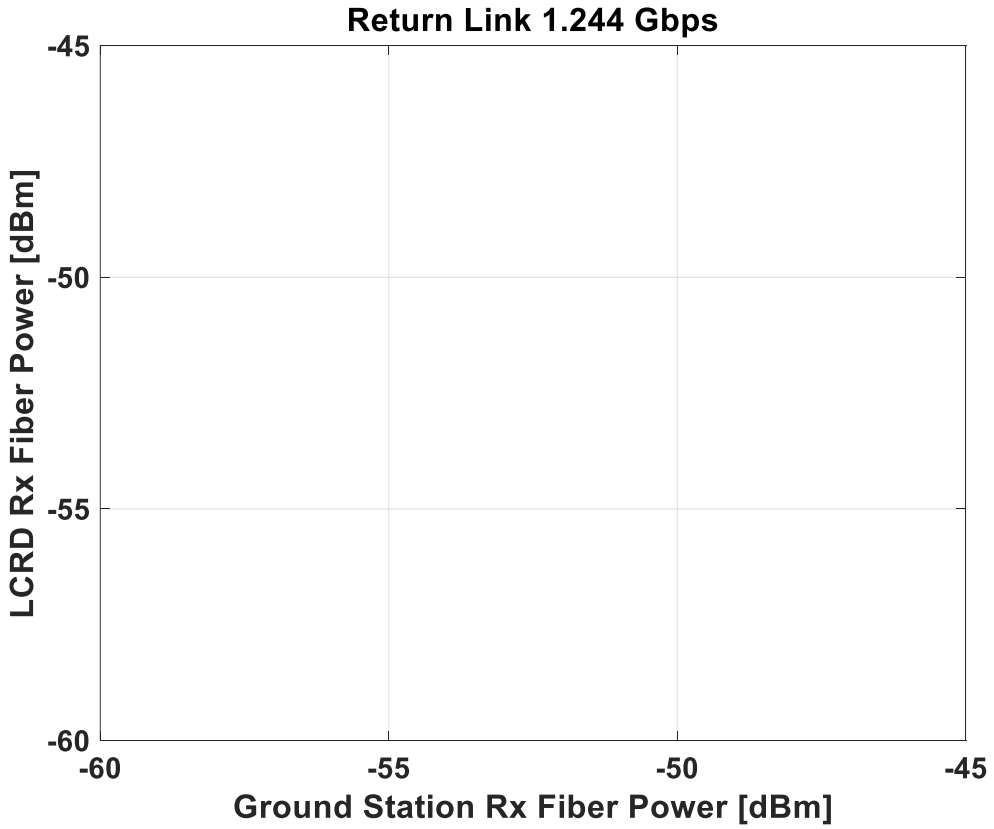
On-orbit tracking performed better than required

Results: Communications

Pointing → Acquisition → Tracking → Communications

- **Return Link: 1.244 Gbps**

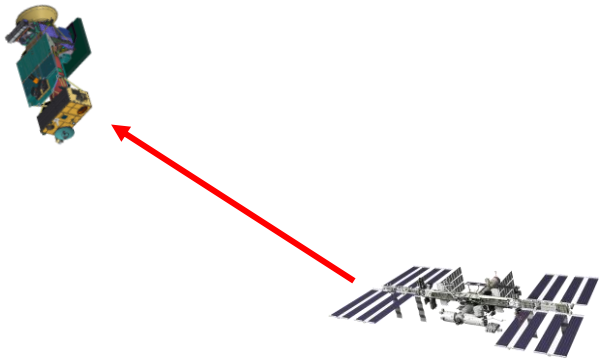


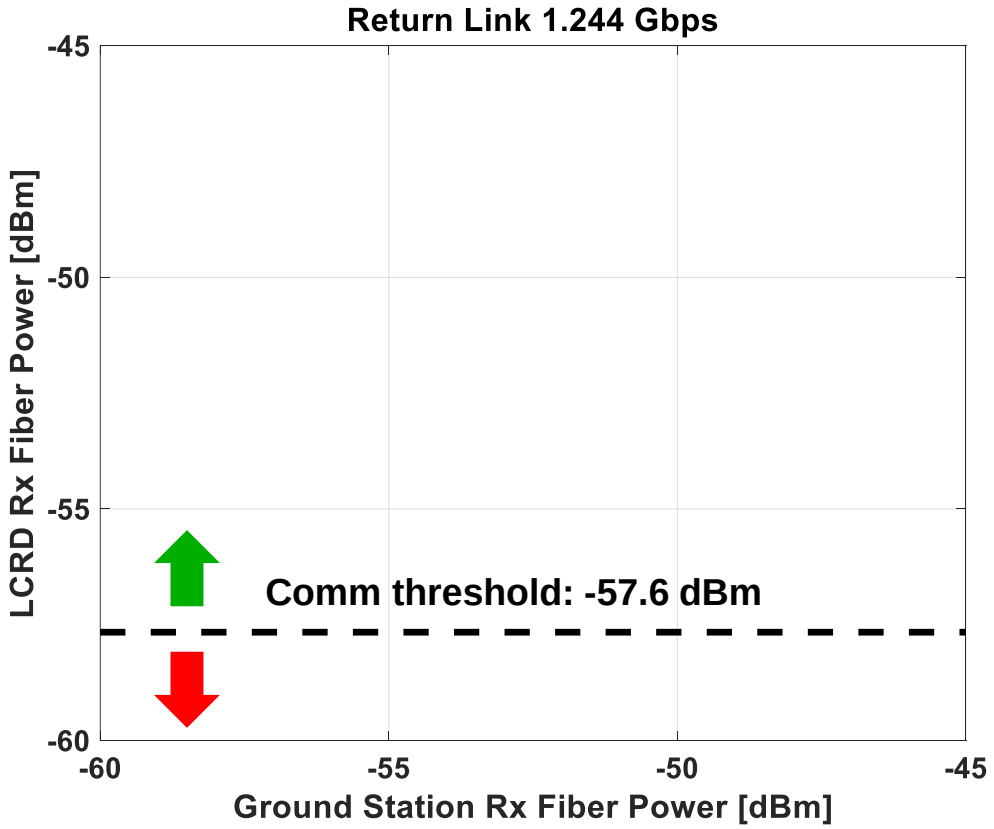


Results: Communications

Pointing → Acquisition → Tracking → Communications

- **Return Link: 1.244 Gbps**

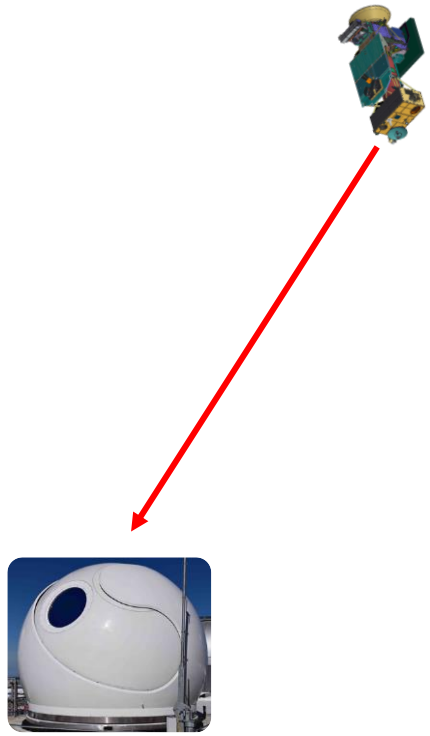


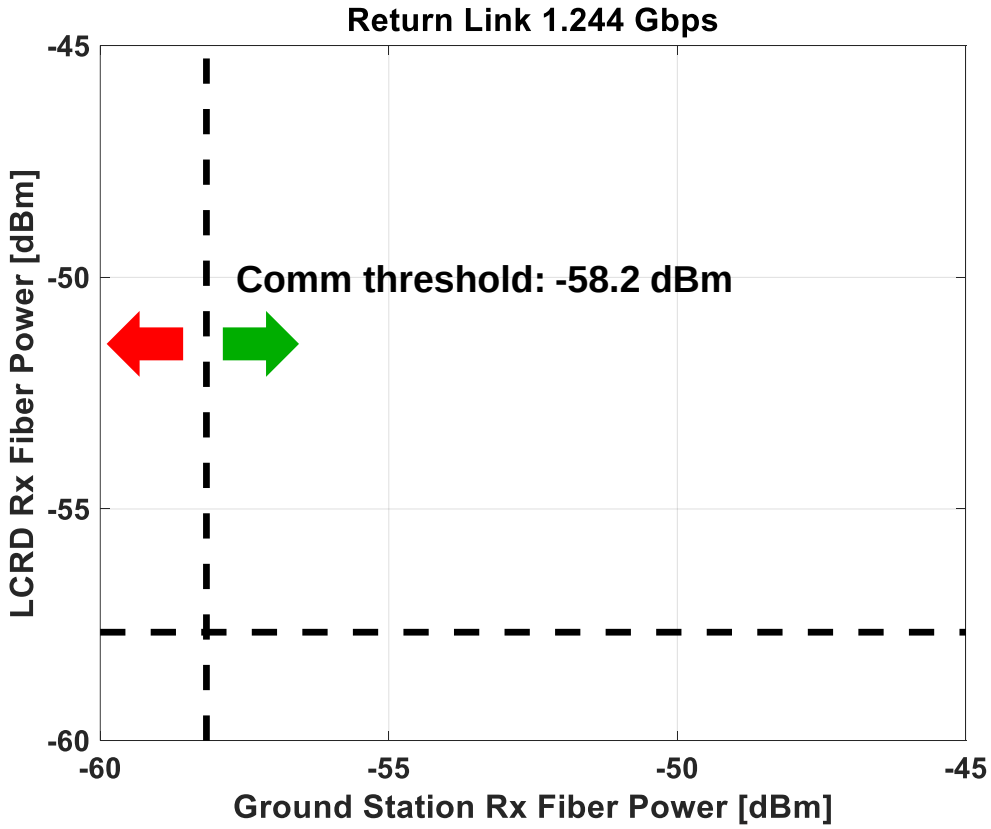


Communications at 1.244 Gbps

Pointing → Acquisition → Tracking → Communications

- **Return Link: 1.244 Gbps**

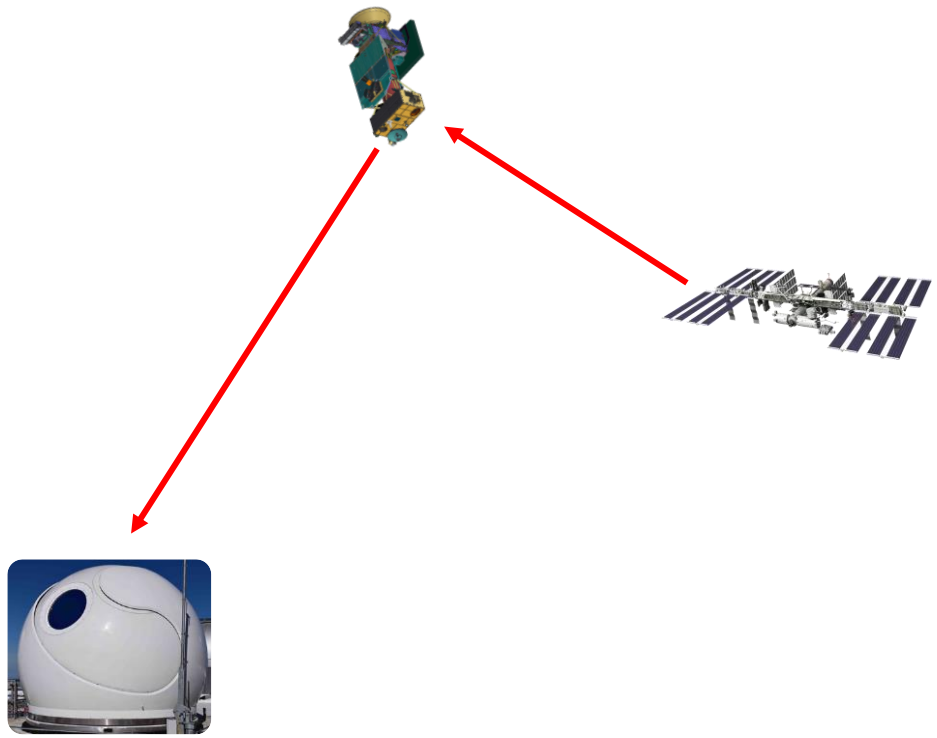


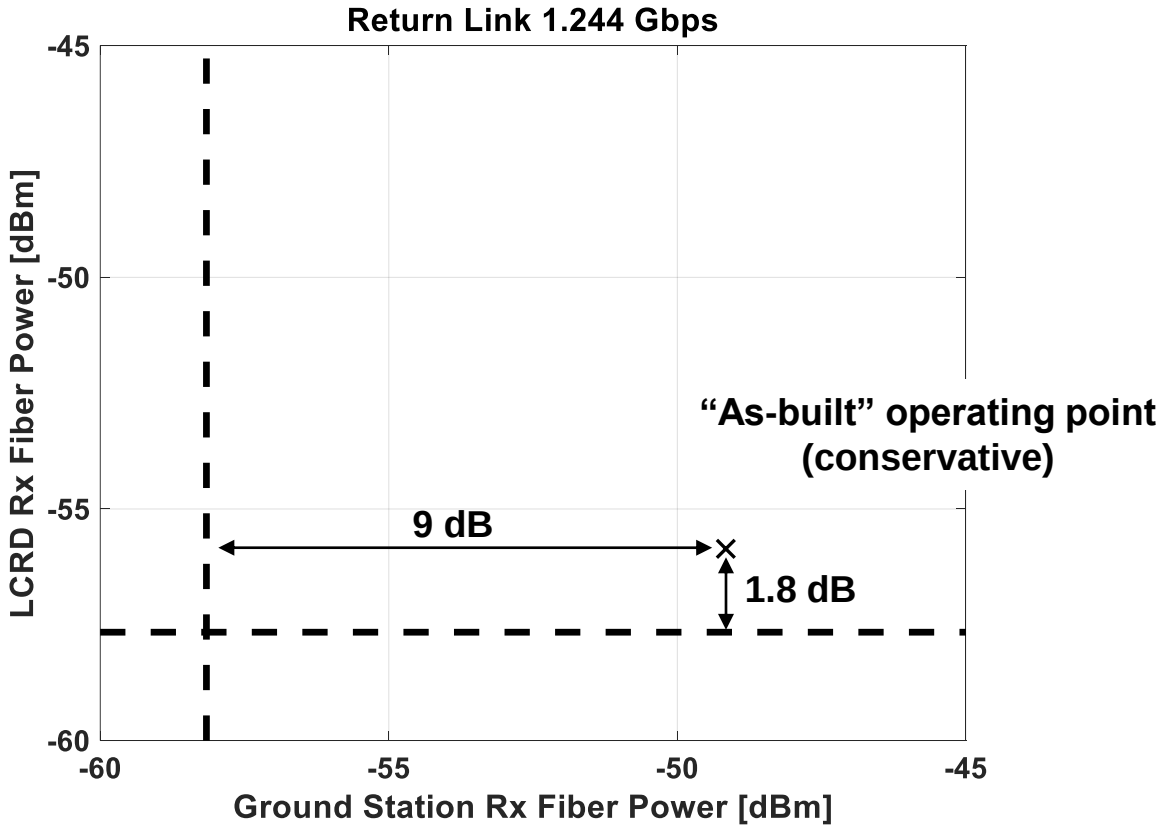


Communications at 1.244 Gbps

Pointing → Acquisition → Tracking → Communications

- **Return Link: 1.244 Gbps**





Communications at 1.244 Gbps

Pointing → Acquisition → Tracking → Communications

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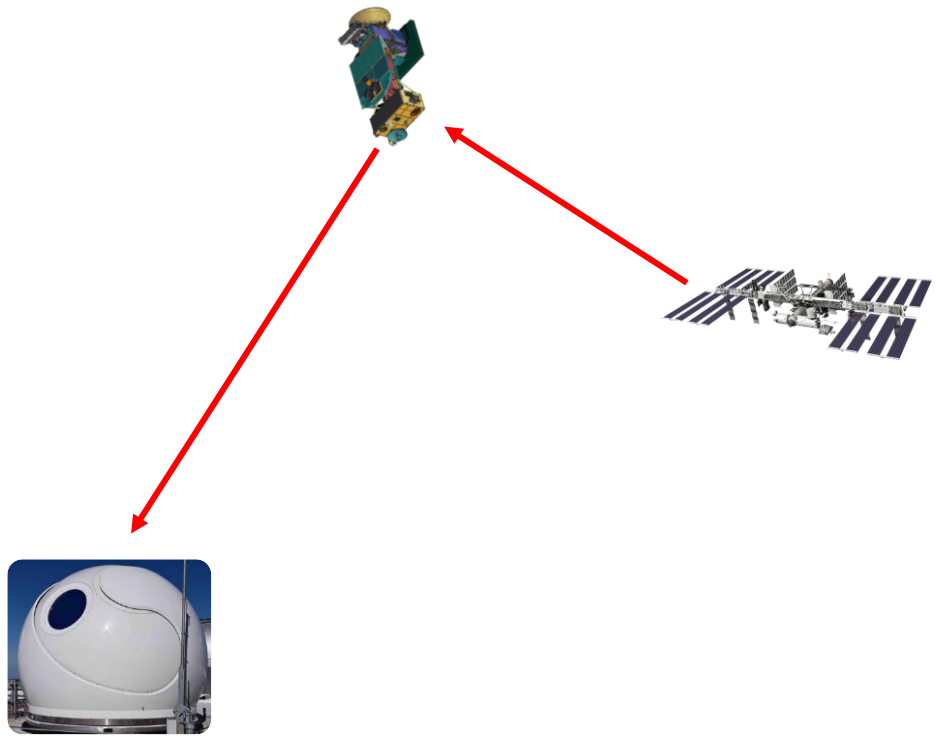
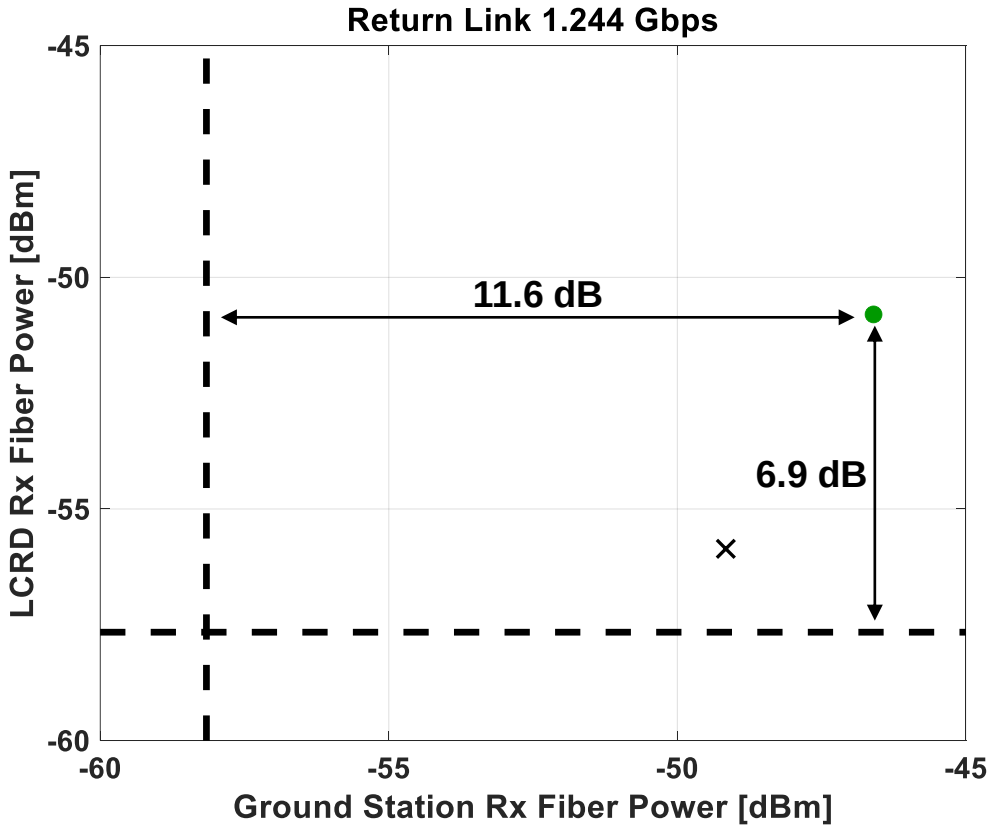


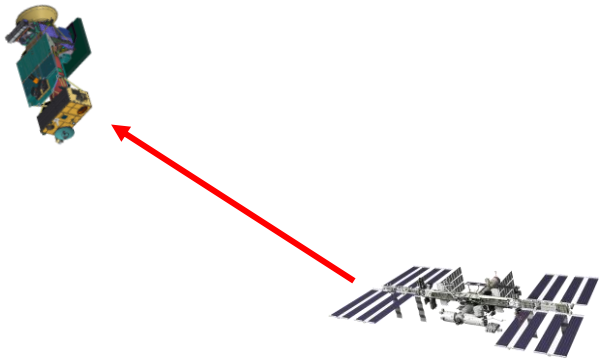


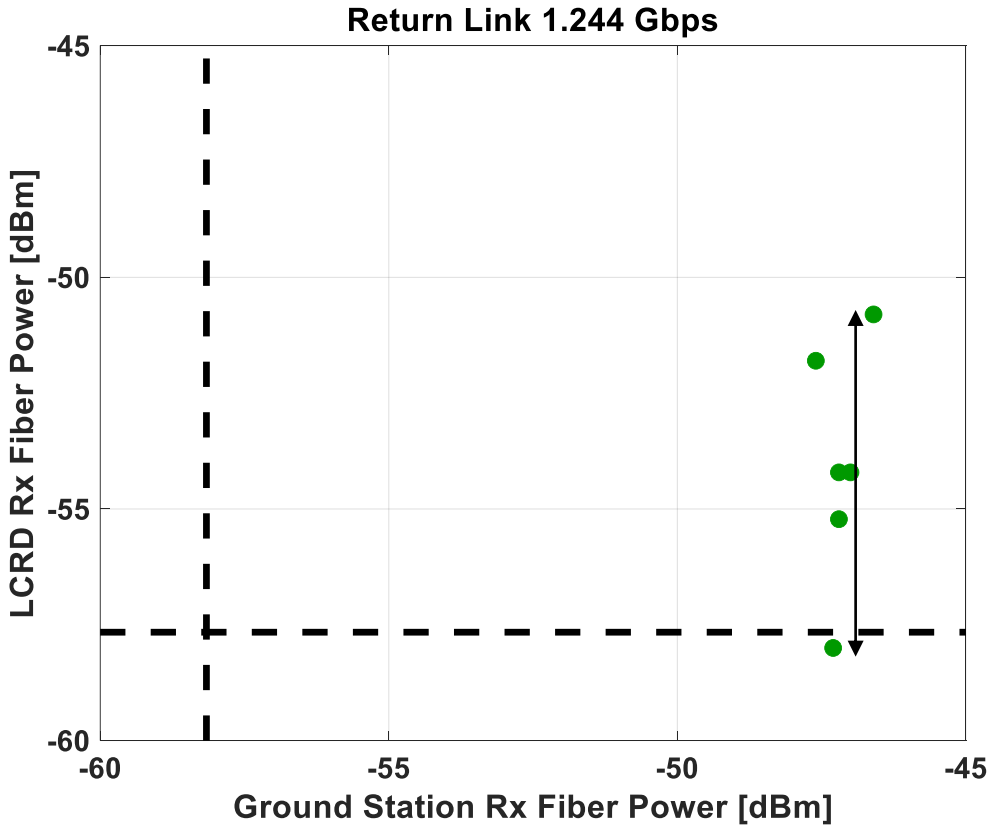
On-orbit link performed substantially better than (conservative) design

Communications at 1.244 Gbps

Pointing → Acquisition → Tracking → Communications

- **Return Link: 1.244 Gbps**



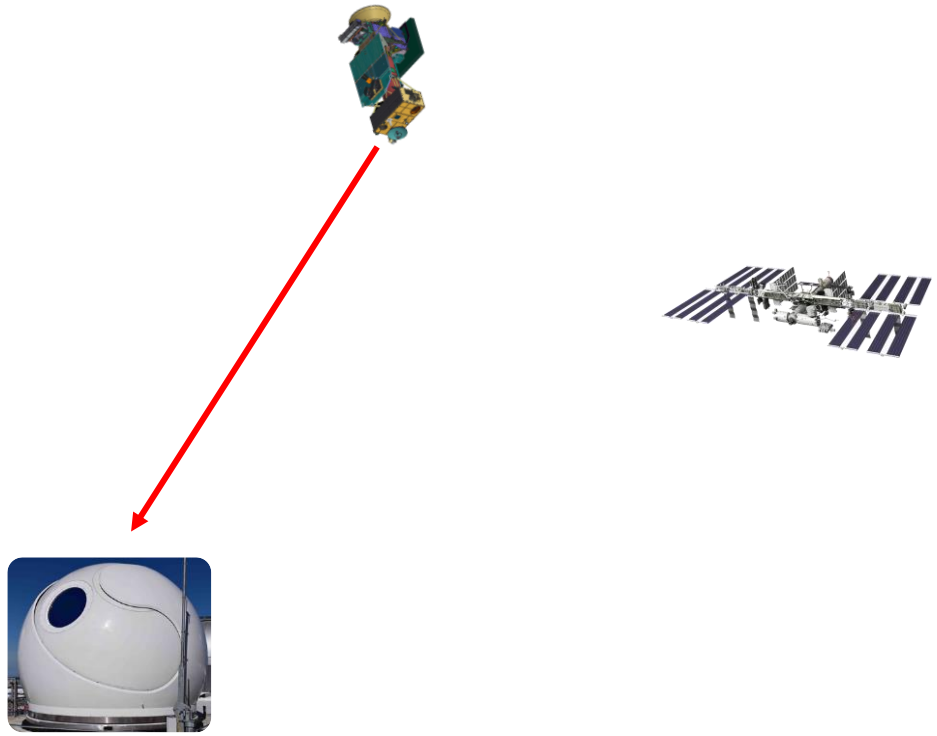


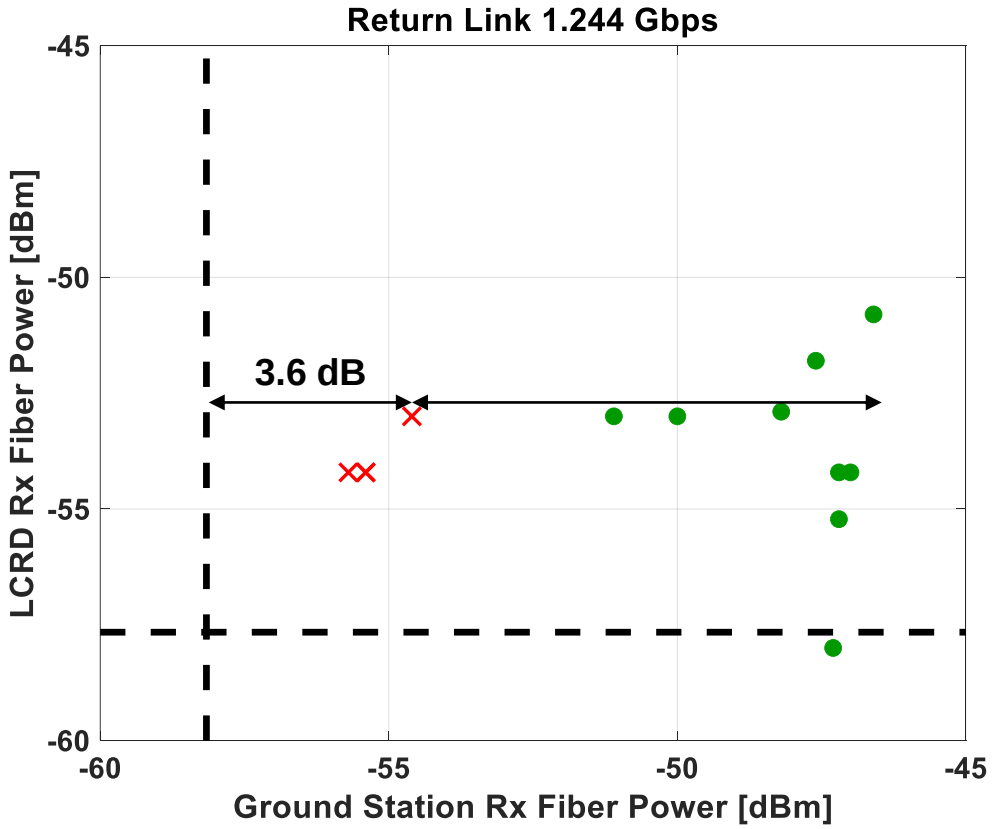
Space-to-space link performed at least as well as expected

Communications at 1.244 Gbps

Pointing → Acquisition → Tracking → Communications

- **Return Link: 1.244 Gbps**



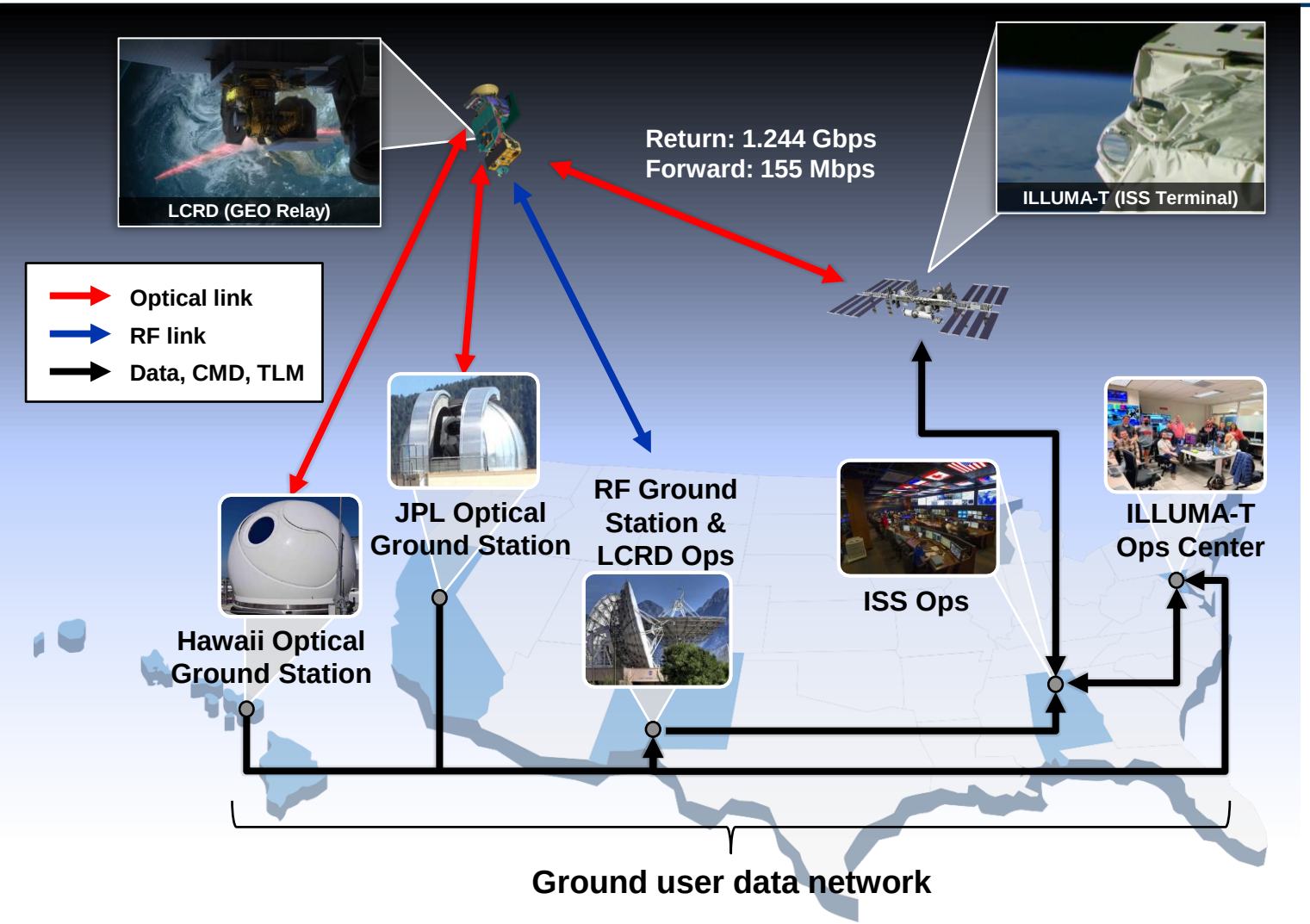


Space to Ground link (through atmosphere) had errors above expected threshold
Additional data needed to fully characterize

Outline

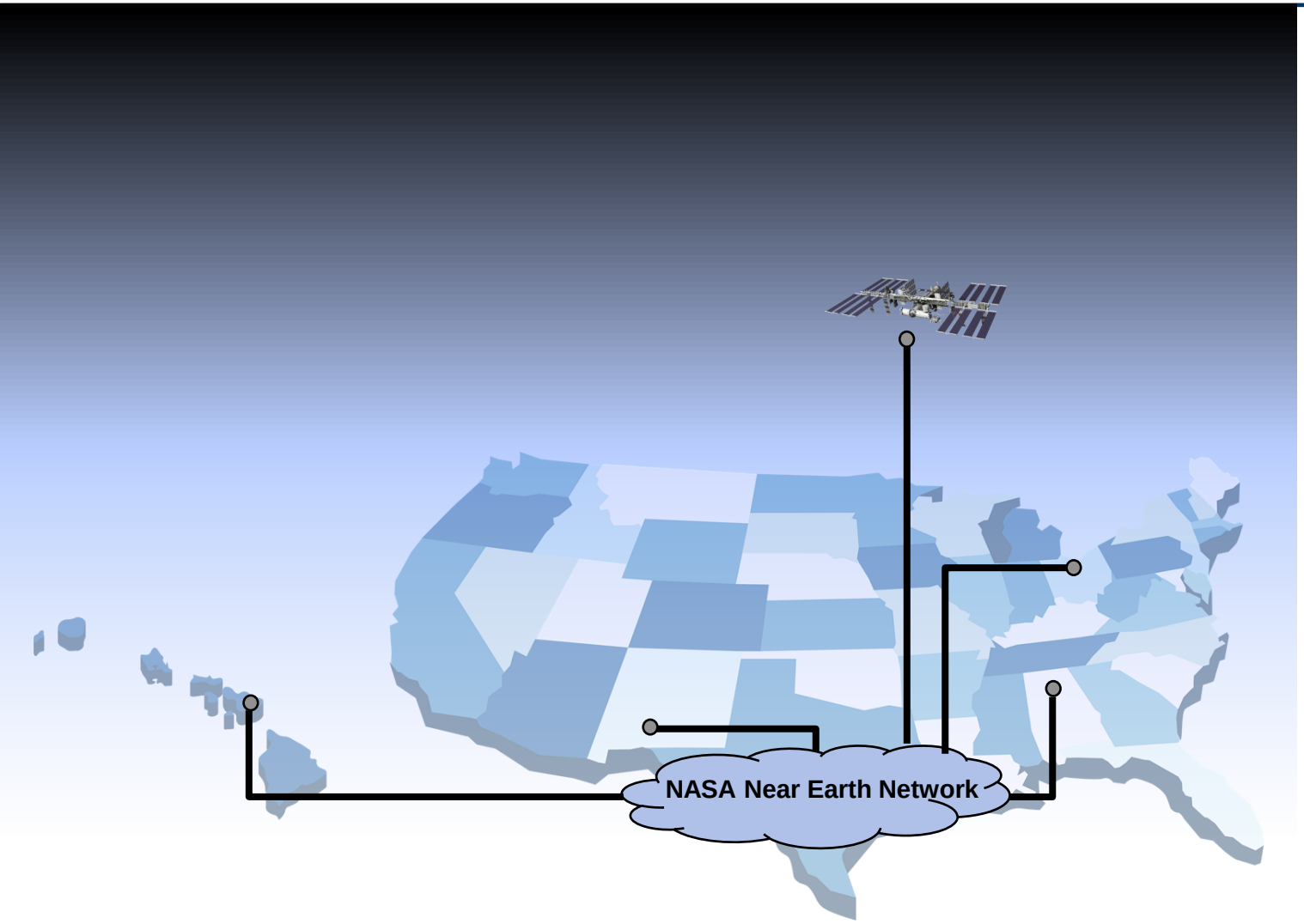
- Motivation
- ILLUMA-T
- On-Orbit Performance
  - ILLUMA-T Pass Overview
  - Lasercom Link Engineering
- **Lasercom as Network Service**
- **Summary**

Lasercom as Network Service



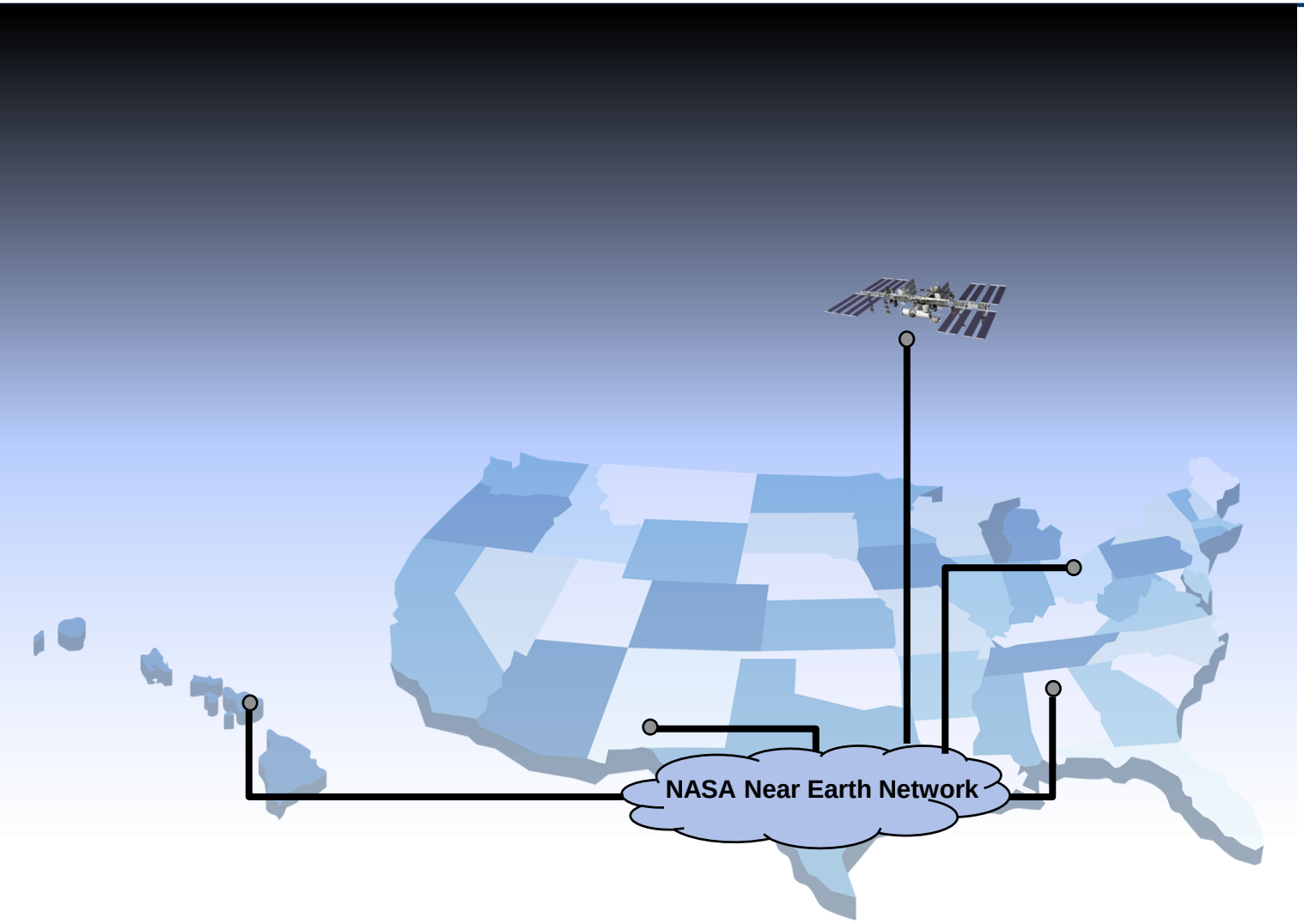
LCRD: Laser Communications Relay Demo
JPL: Jet Propulsion Laboratory (NASA)
ISS: International Space Station
RF: Radio Frequency
GEO: Geosynchronous Earth Orbit
CMD & TLM: Command & Telemetry

Lasercom as Network Service



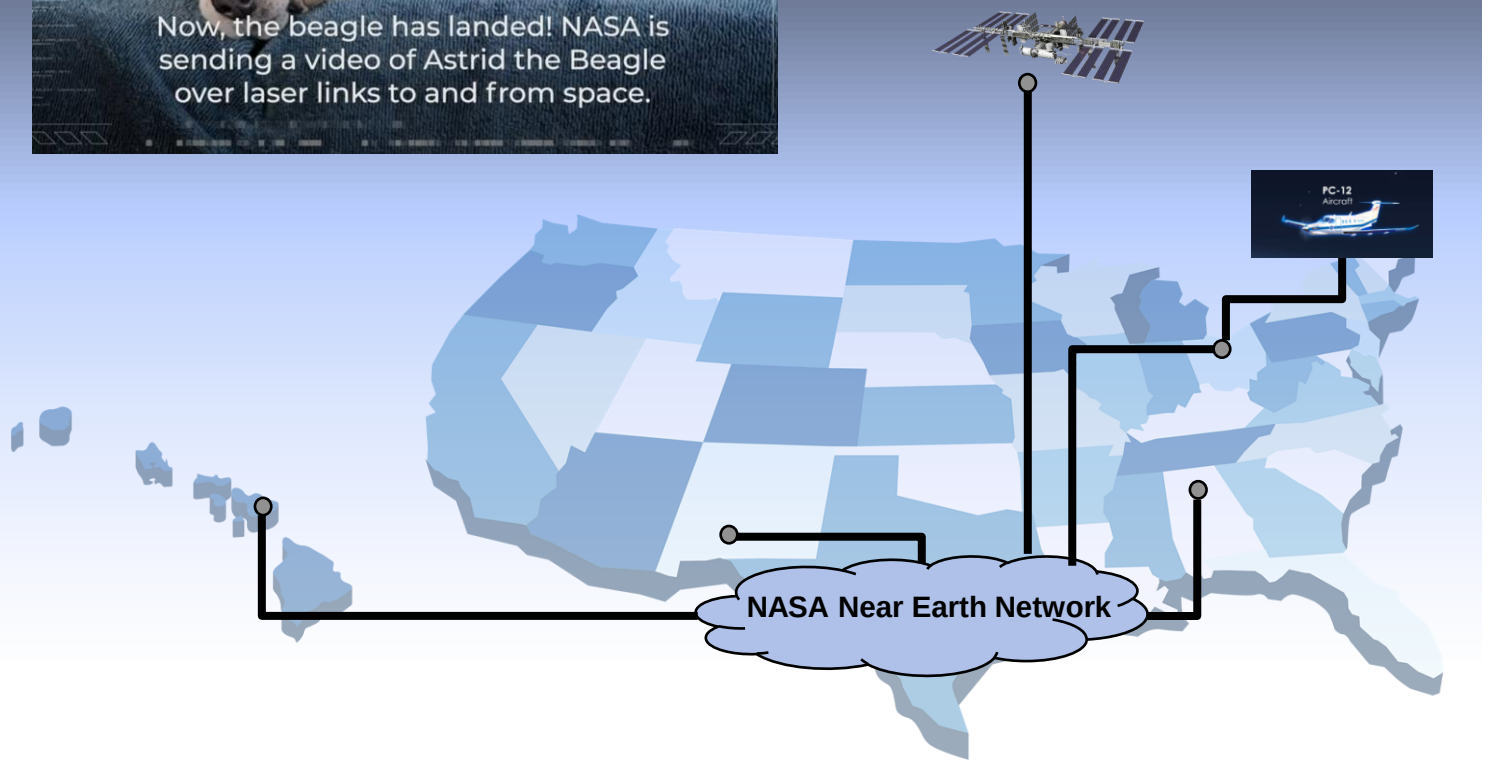
- **Network connectivity instead of link connectivity**
- **User applications**

Lasercom as Network Service



- Network connectivity instead of link connectivity
- User applications
- Handovers between ground stations
- Automation of ILLUMA-T pass operations
- Data transfers between ISS & ground
- 4K streaming from ISS to ground
- 4K streaming from ground to ISS
- Demonstration of Delay Tolerant Networking (DTN) data custody between multiple nodes
- Connectivity of ISS to aircraft through NASA network

Lasercom as Network Service



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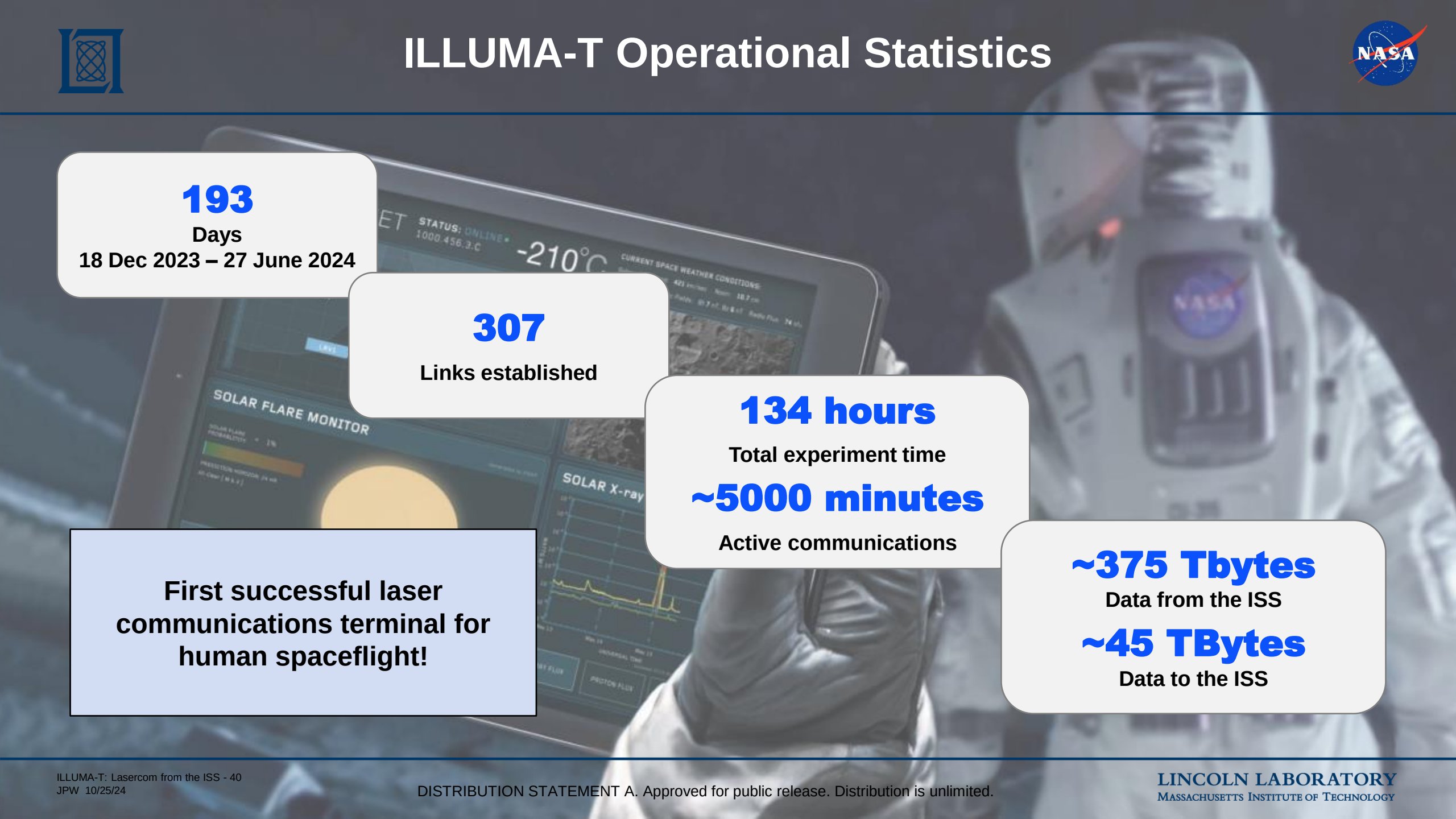
ILLUMA-T Operational Statistics



193
Days
18 Dec 2023 – 27 June 2024

307
Links established

134 hours
Total experiment time

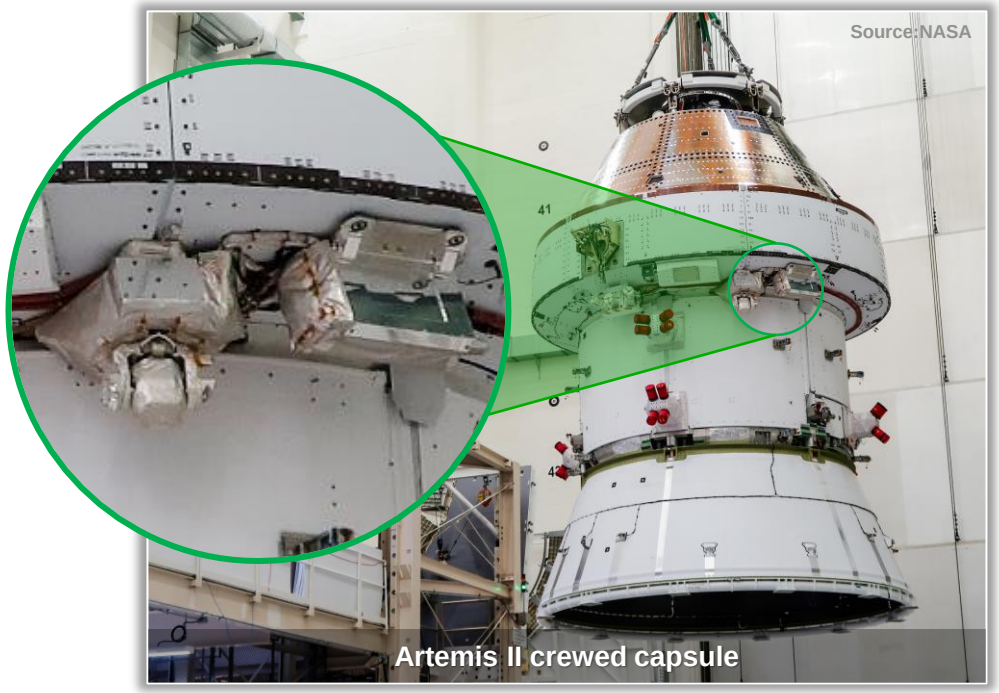
~5000 minutes
Active communications

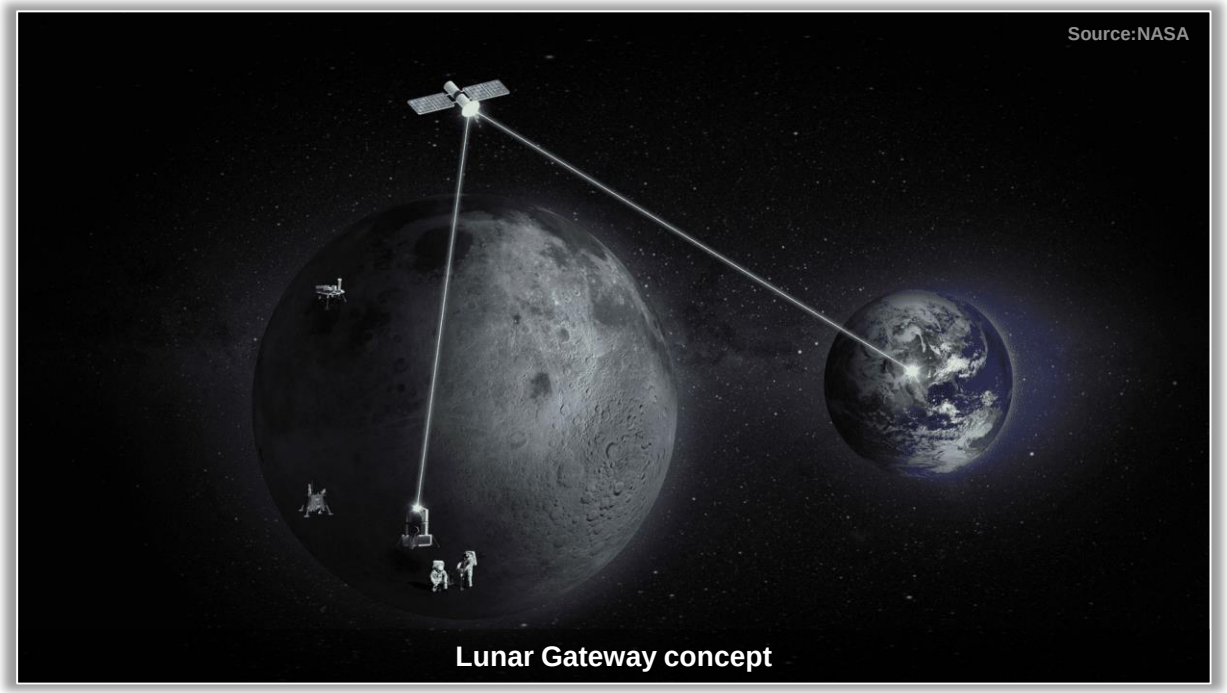
~375 Tbytes
Data from the ISS

~45 TBytes
Data to the ISS

First successful laser communications terminal for human spaceflight!

What's Next: Lunar





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**

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DENNIS ALTOBELLI
PETER ANDERSON
JAMES ANDRE
KENNETH AQUINO
ROY ARTHUR
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BRYAN ROBINSON
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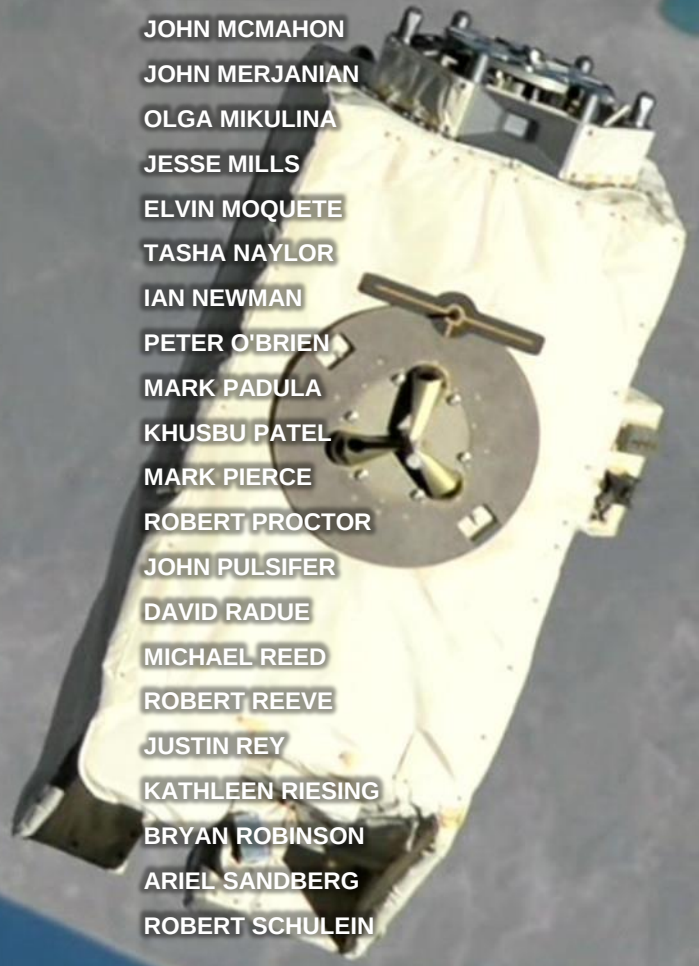

RAJDEEP SHARMA
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CORRIE SMEATON
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NEAL SPELLMEYER
MARK STEVENS
GERHARD STOECKEL
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CRAIG THOMAS
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BRIAN TWEED
JASON VEEREN
TROY VETH
JADE WANG
JOSEPH WARFEL
TERRI WELCH
JOHN WELLMAN
MATTHEW WILLIS
TIMOTHY YARNALL
MICHAEL ZERVAS

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

Summary

ILLUMA-T had substantial accomplishments in short ~6 month mission

- **Successfully validated optical communications relay performance for human spaceflight operations**
- **Provided “routine” operations of optical communications links**
- **Matured processes for operational success**
- **Identified areas of improvement needed for human operational use**