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# **Space-Based Laser Communications for NASA**

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**AIAA Meeting**

**7 November 2017**



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# Outline



- **Background**
- **New lasercom missions**
- **Summary**

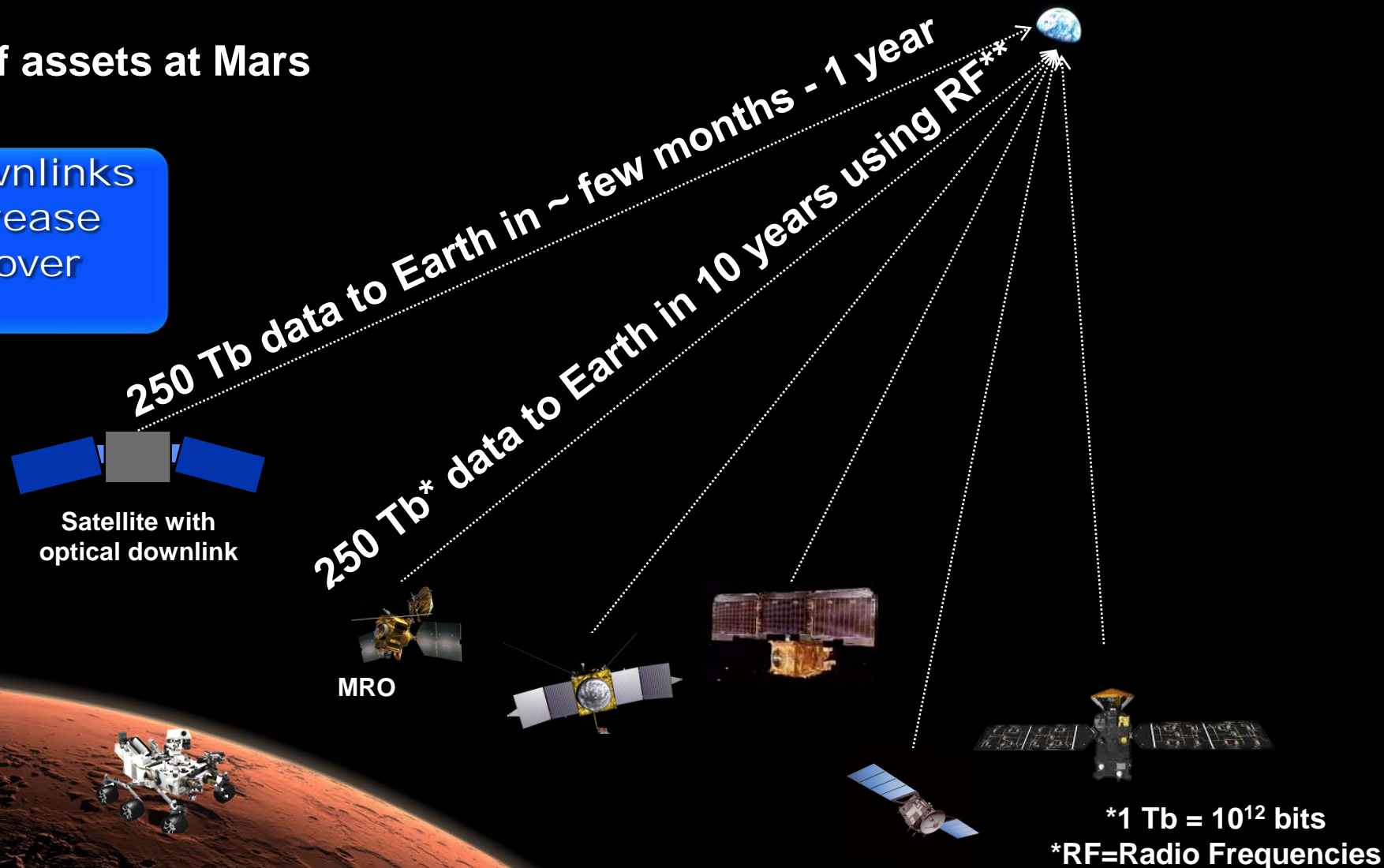


# A Potential Deep-Space Lasercom Application



- Today, >\$7B<sup>1</sup> worth of assets at Mars

Lasercom-enabled downlinks  
can significantly increase  
data return volume over  
mission lifetime



<sup>1</sup>2015 dollars, includes ESA ExoMars Trace Gas Orbiter

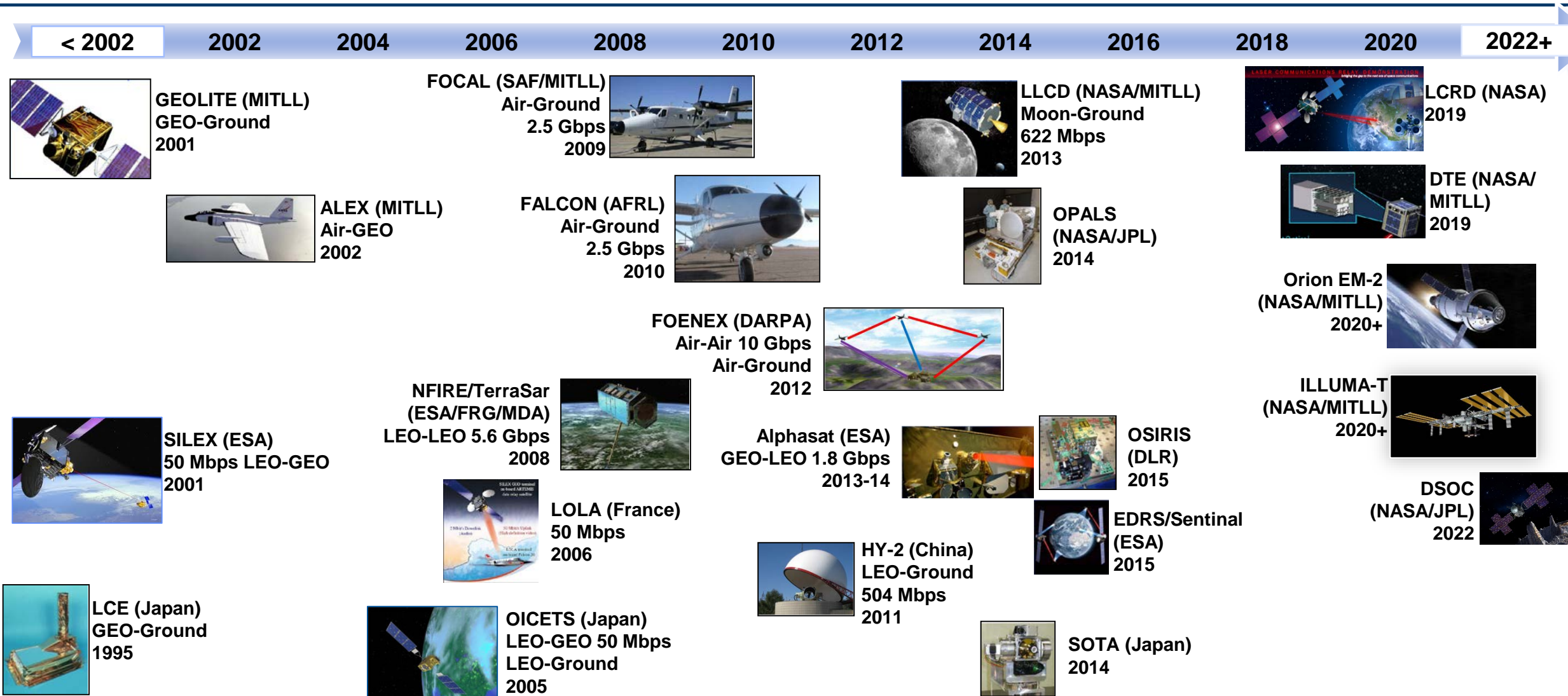
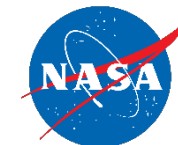
<sup>2</sup><http://mars.nasa.gov/mro/>

<sup>3</sup><http://scienceandtechnology.jpl.nasa.gov/research/ResearchTopics/topicdetails/?ID=67>

<sup>4</sup>JPL proposal for Deep space Optical Terminal (DOT).

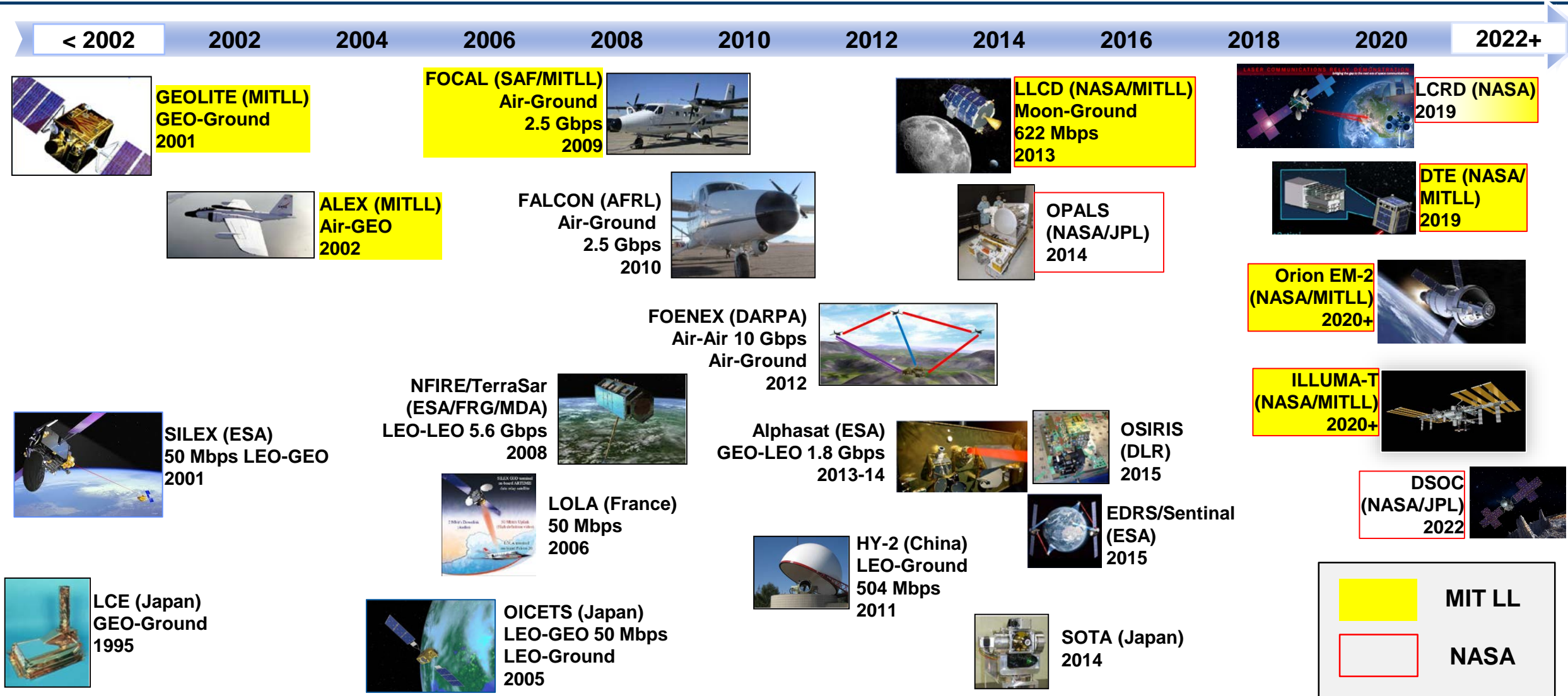


# Space Lasercom Activities to Date





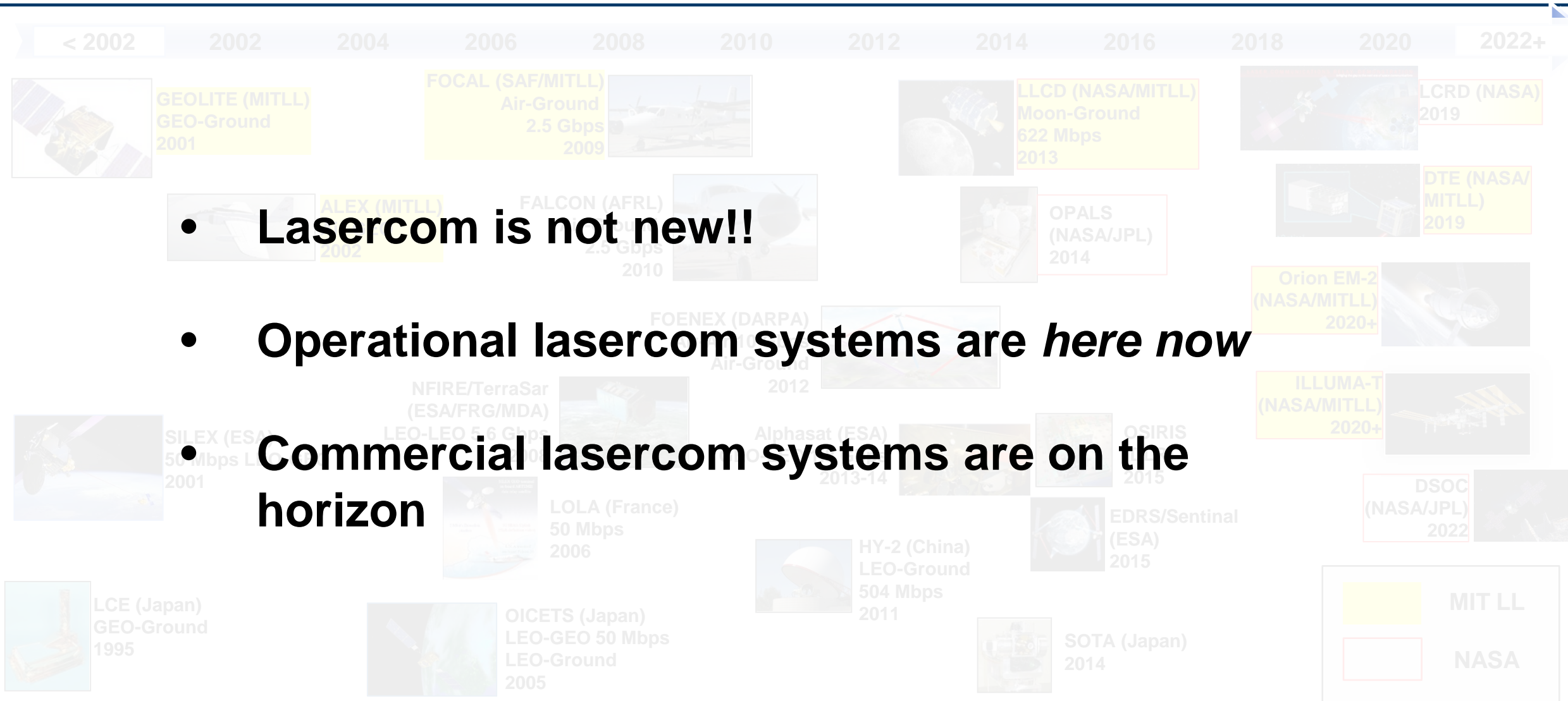
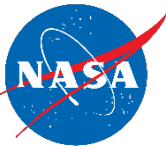
# Space Lasercom Activities to Date







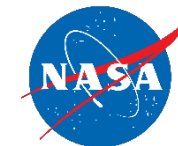
# Space Lasercom Activities to Date



- **Lasercom is not new!!**
- **Operational lasercom systems are *here now***
- **Commercial lasercom systems are on the horizon**



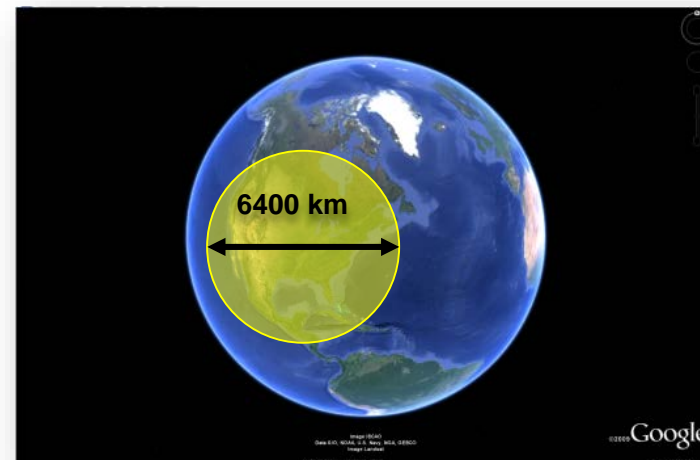
# Benefits of Optical Communications for Deep Space Missions



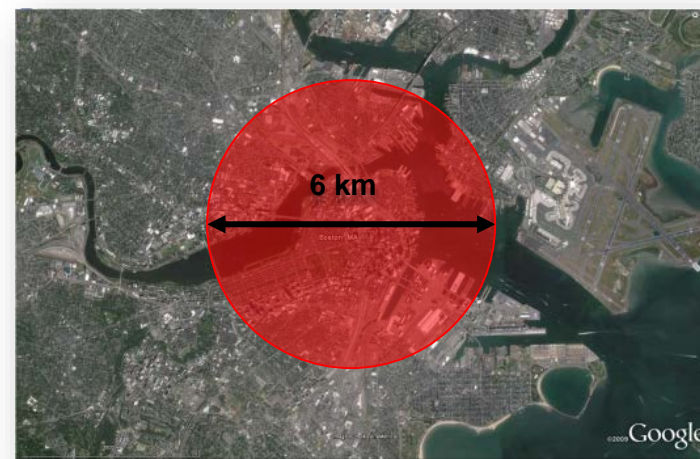
- **Extremely narrow beams with small apertures → small, low power terminals**
  - More science instruments / memory
  - Save fuel costs
  - Reduce mission duration
- **High data rates (downlink and uplink)**
  - Mbps to Gbps to ???
  - Supports growing need for in-flight software upgrades
- **Unlimited, unregulated spectrum**
  - Less paperwork, more science

Lower cost, higher value missions

Beam Size From Moon



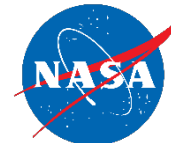
RF  
75-cm Antenna  
→ 6400 km Spot



Optical  
10-cm Antenna  
→ 6 km Spot



# Potential Operational Differences between RF & Optical



	RADIO - KNOWN	OPTICAL – PREVIOUSLY UNKNOWN
Beam width	0.5 - 30°	Narrow beam (<0.006°)
Point / Acquire Beam	Open loop	Is space craft position information good enough to point?
Stabilize / Track Beam	N/A	Is it possible to stabilize if space craft jitter is >> beam?
Atmosphere Interactions	Rain can degrade > 20 GHz, but can work through atmosphere	Can clouds, weather, and turbulence be managed?
Regulatory / Permissions	Spectrum is regulated and licensed; process in place	Can sensor satellites / aircraft be easily avoided and not disruptive to link?
Operations	Routine and automated for space systems since 1950's!!	Can lasercom ever be routine and automated?





# LLCD\*: A Successful Operational Lasercom Demonstration



- In 2013, NASA's LLCD showed operational utility of lasercom
  - 622 Mbps downlink, 20 Mbps uplink
  - Automated point/acq/track of 15  $\mu$ rad 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
  - Interleaving and multiple apertures to mitigate turbulence
  - Aircraft/sensor sat avoidance easily achieved

White Sands,  
Table Mtn,  
Tenerife



LADEE  
Satellite

## OPTICAL – NOW KNOWN!

Narrow beam ( $<0.006^\circ$ )



Is space craft position information good enough to point?



Is it possible to stabilize if space craft jitter is  $\gg$  beam?



Can clouds, weather, and turbulence be managed?



Can sensor satellites / aircraft be easily avoided and not disruptive to link?



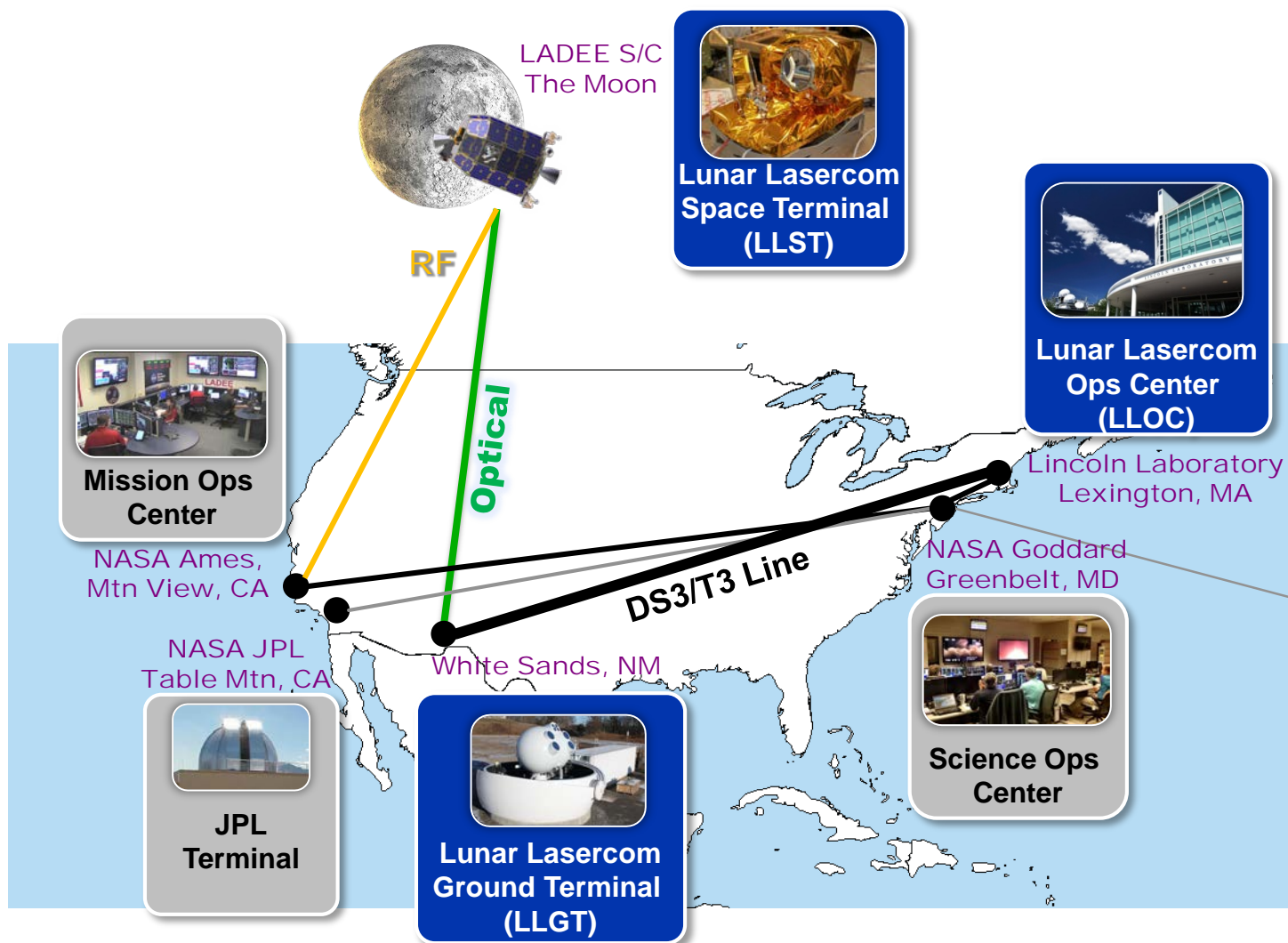
Can lasercom ever be routine and automated?



\*Lunar Laser Communication Demonstration



# LLCD Architecture

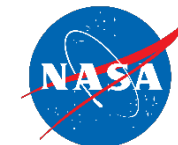


2 existing terminals  
retro-fitted to

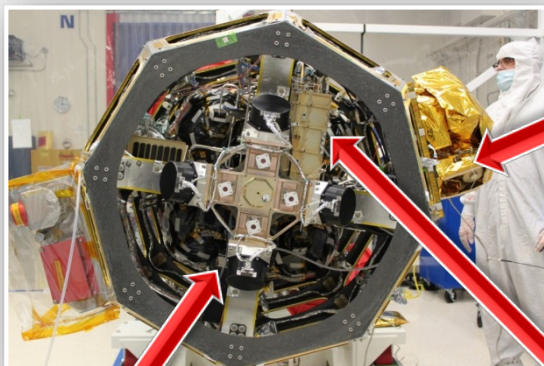
- Provide cloud robustness
- Increase possible ops time



# LLCD Space and Ground Terminals



## Lasercom Space Terminal



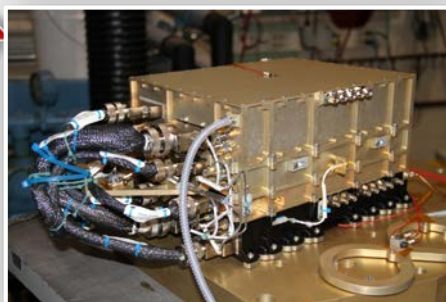
Optical Module

- 10 cm
- 2-axis gimbal
- Inertially stabilized



Controller Electronics

- Point, acq, track control
- S/C data interface



Modem Module

- Uplink Rx
- Downlink 0.5-W Tx
- Fiber-coupled

**Total Weight: 30 kg, Power: 90 W**

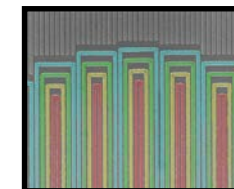
## Lasercom Ground Terminal



4 x 15-cm Tx Telescopes



4 x 40 cm Rx Telescopes



**Superconducting nanowire Rx Detectors**

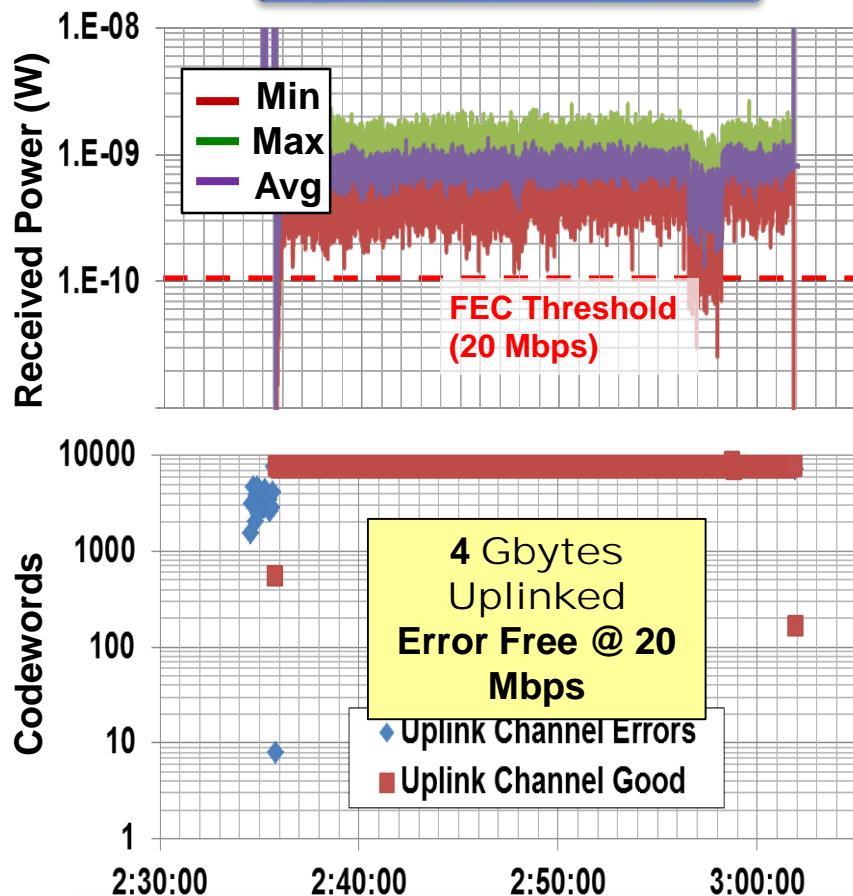


# On-Orbit Performance

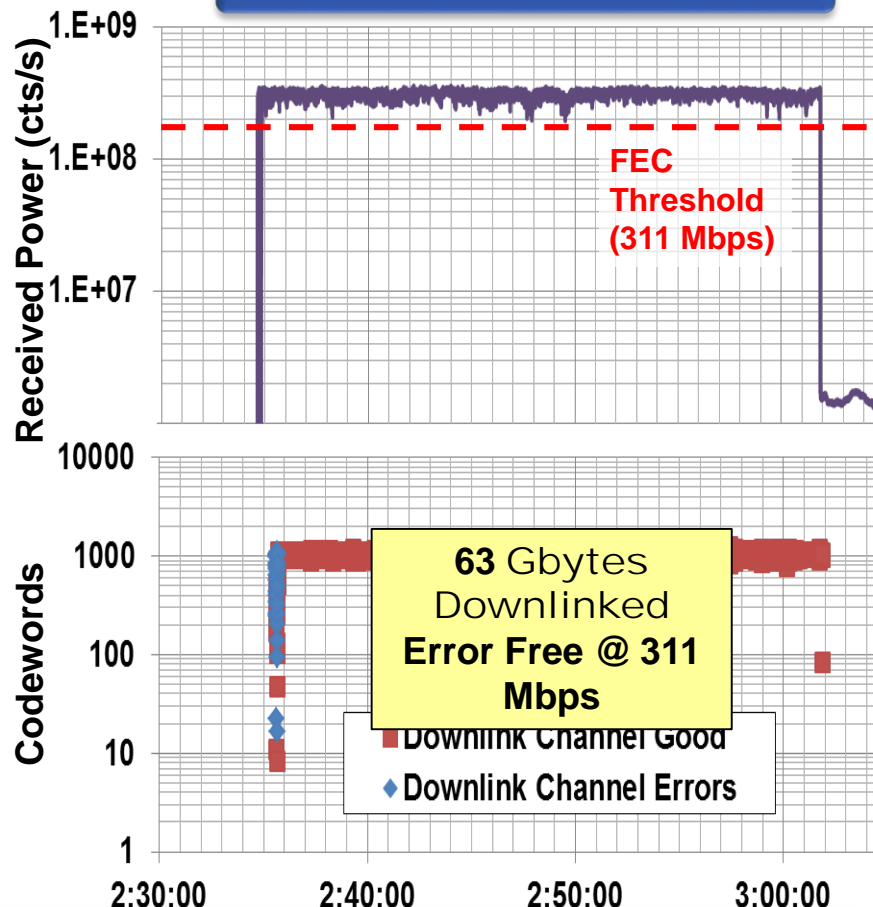
DOY 322, Pass 4, Clear Sky, < 20° Elevation



Uplink Performance



Downlink Performance



Uplink: 4-ary Pulse  
Position Modulation;  
311 MHz Clock,  
Variable Dead time.

Downlink: 16-ary Pulse  
Position Modulation;  
311-4977 MHz Clock.

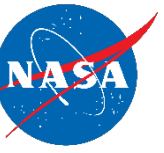
Both:  
SC PPM rate  $\frac{1}{2}$  code  
and  
Powerful Interleaving

Because of channel interleaver, performance depends only on *average power*, not dynamic fading!





# LLCD is a Success!



Demonstrated reliable, *record-breaking* data delivery over lasercom links through the Earth's atmosphere!

- Up to 622 Mbps downlink and 20 Mbps uplink
- Daily downlinks of entire LADEE science data buffer (1 GB)
- File transfers, up and down
- All optical link (command / control / data)
- Downlink of space terminal high rate telemetry
- Loopback of multiple simultaneous HDTV streams
- Time of flight measurements resulting in cm-class ranging

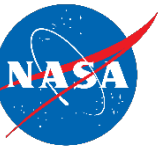
The project was a complete success







# Outline



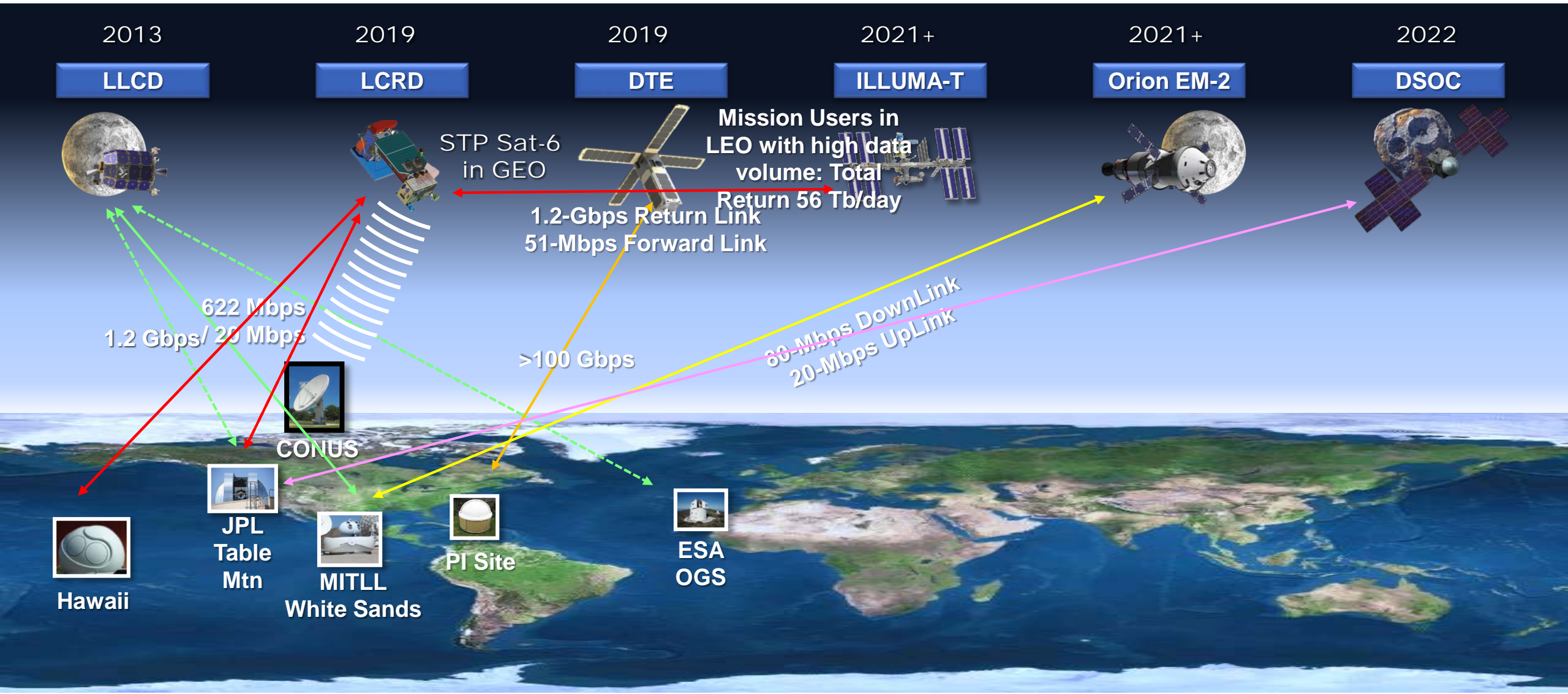
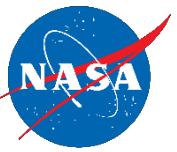
- Background

- ➡ • New lasercom missions

- Summary



# NASA's Next Generation Near-Earth Space Comm and Nav Network



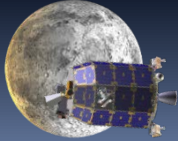


# NASA's Next Generation Near-Earth Space Comm and Nav Network



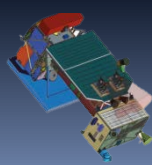
2013

LLCD



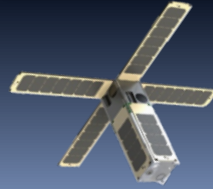
2019

LCRD



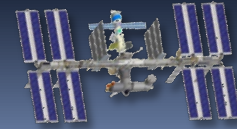
2019

DTE



2021+

ILLUMA-T



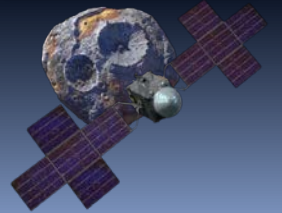
2021+

Orion EM-2



2022

DSOC



CONUS



JPL  
Table  
Mtn



MITLL  
White Sands



PI Site



ESA  
OGS

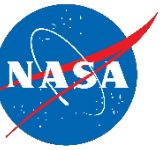


Hawaii

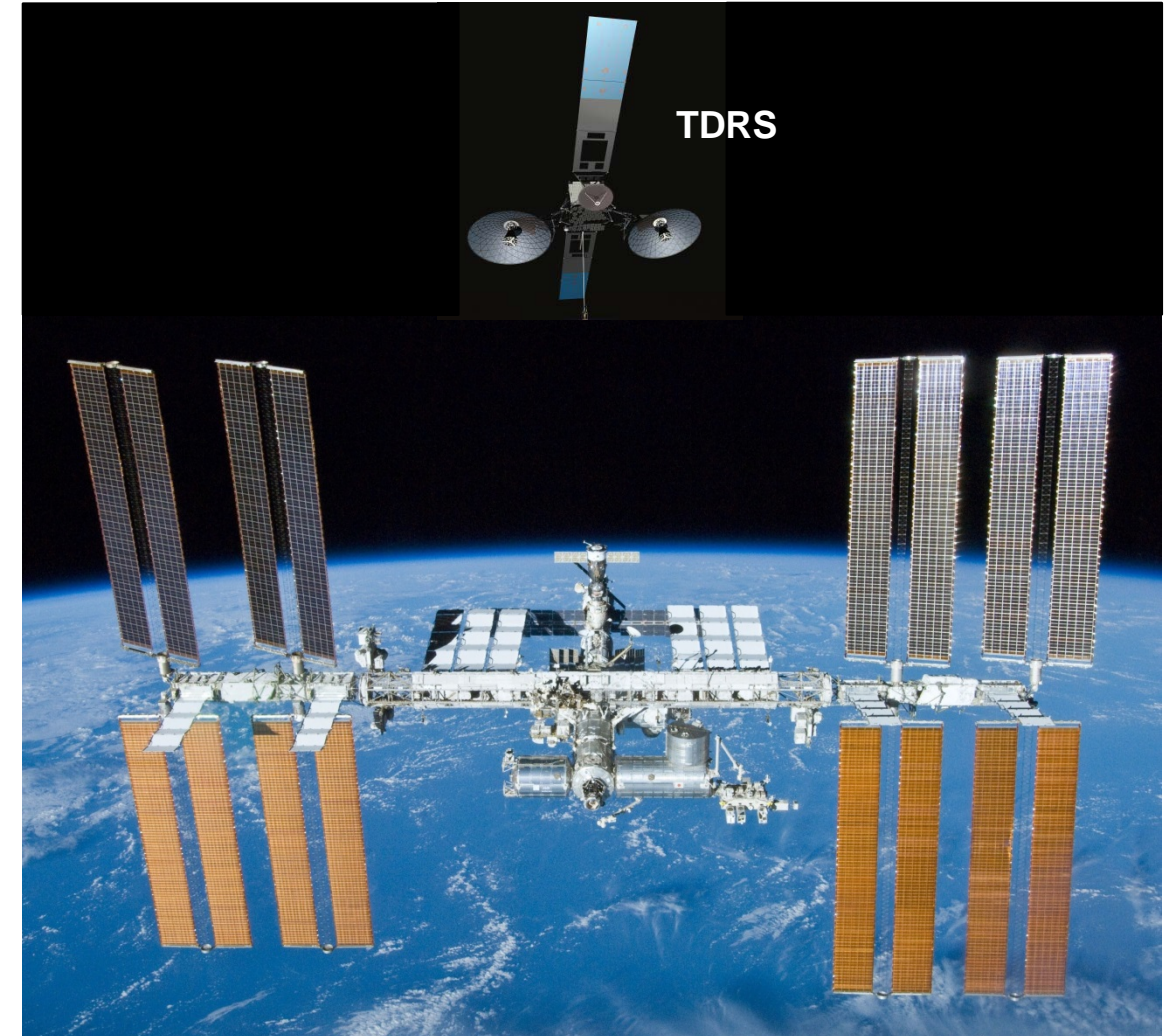




# ISS Mission

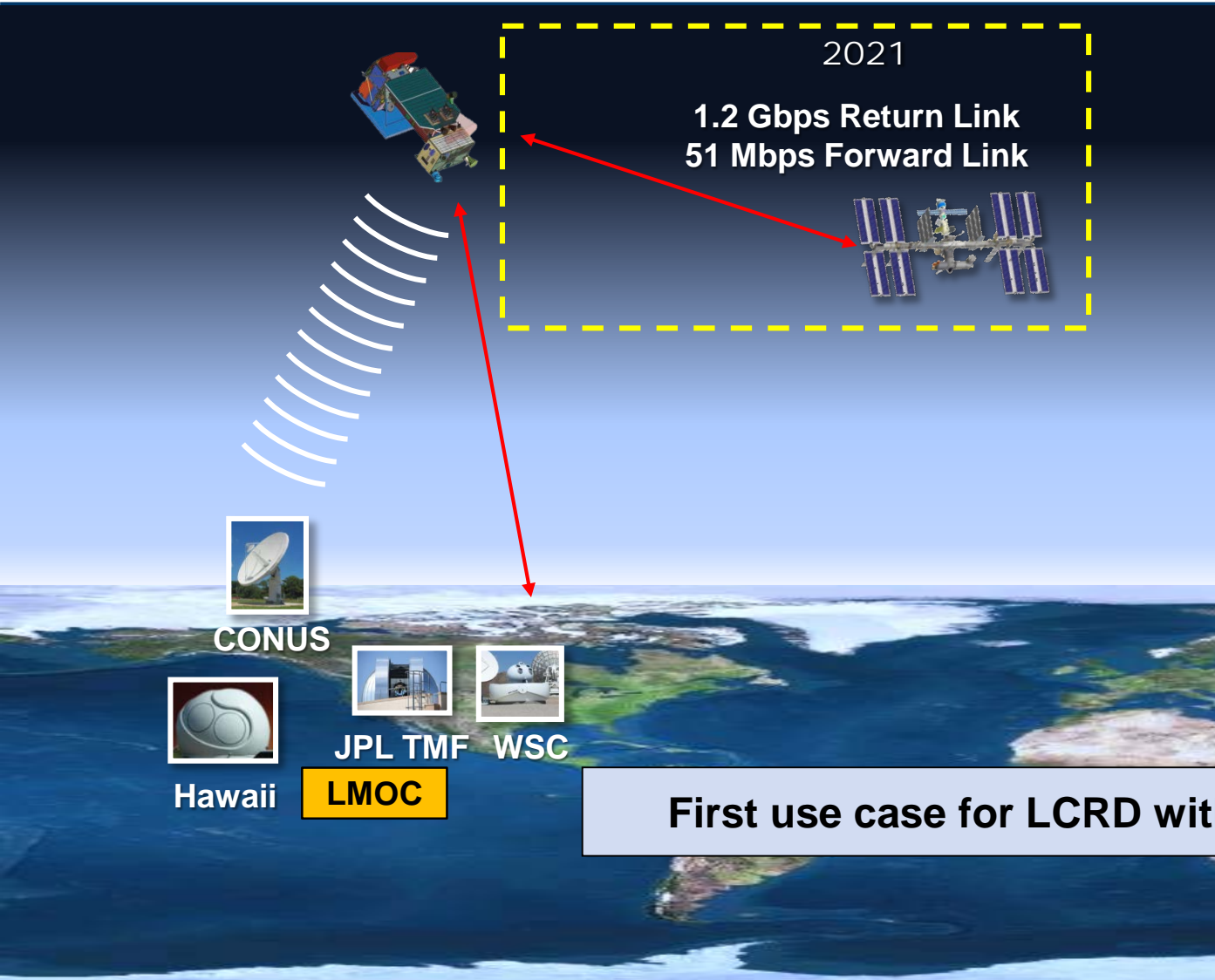
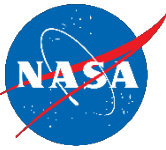


- ISS currently uses Ku-band data downlink via NASA's Tracking and Data Relay System (TDRS) at 300 Mbps
- Supports 6 video channels, 4 space-to-ground voice channels, and 64 payload experiment channels
- Optical comm via the Lasercom Relay Demonstration (LCRD) will increase the ISS downlink data rate to 1.2 Gbps





# ISS as User Terminal for LCRD\*



- Program kicked off in FY 2017
- Industry-built proto-flight lasercom space terminal
- MIT LL to perform system I&T
- Payload manifested on SpaceX Dragon and to be installed on ISS

**First use case for LCRD with a LEO user terminal!**

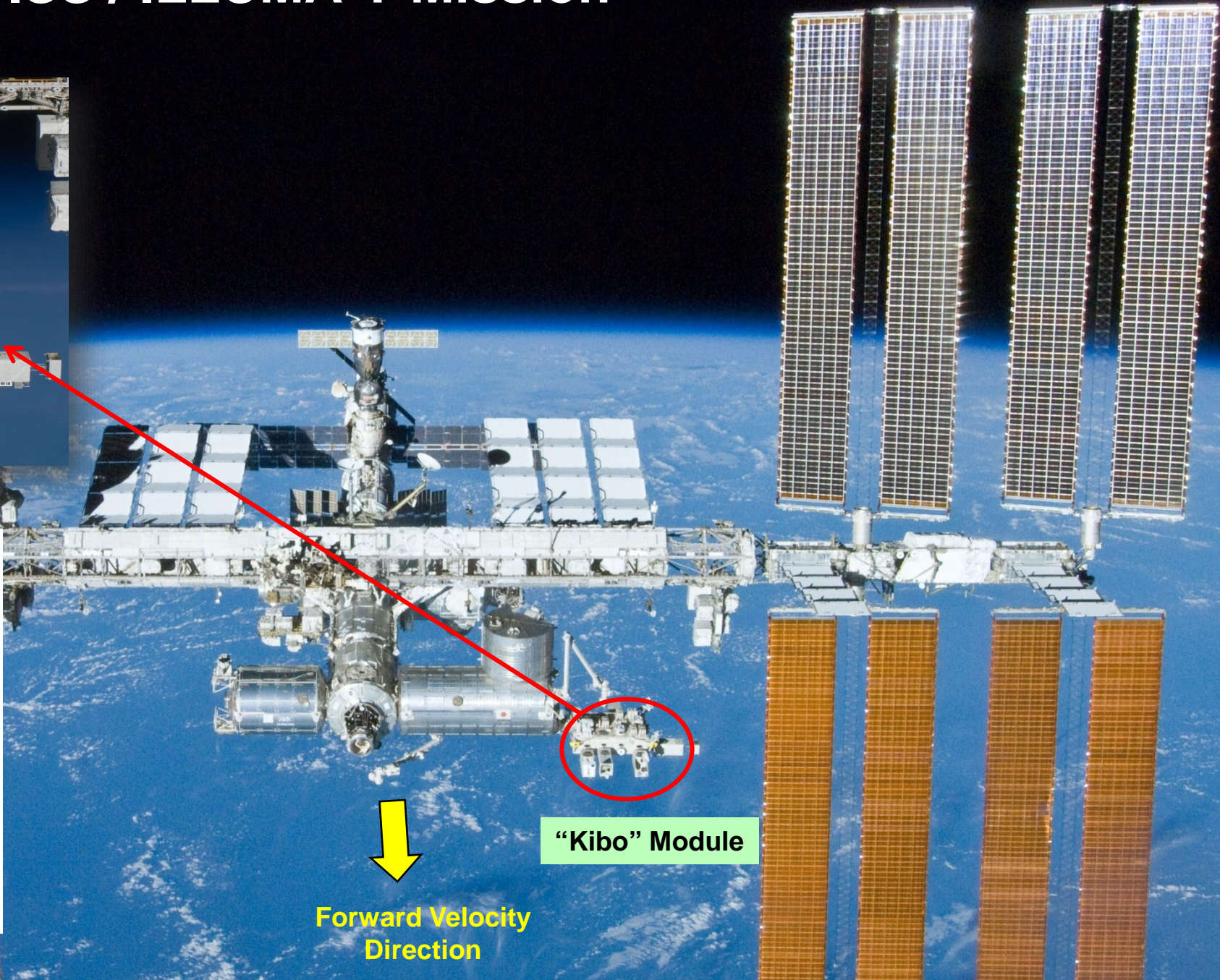
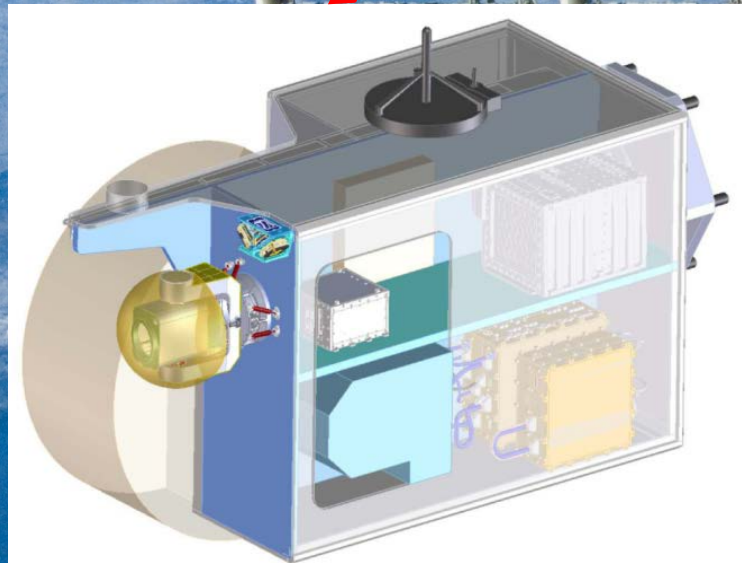
\* Also known as ILLUMA-T, Integrated LCRD LEO User Modem and Amplifier Terminal



# ISS / ILLUMA-T Mission



Experimental Facility 3



“Kibo” Module

Forward Velocity  
Direction





# Orion EM-1, EM-2... Missions

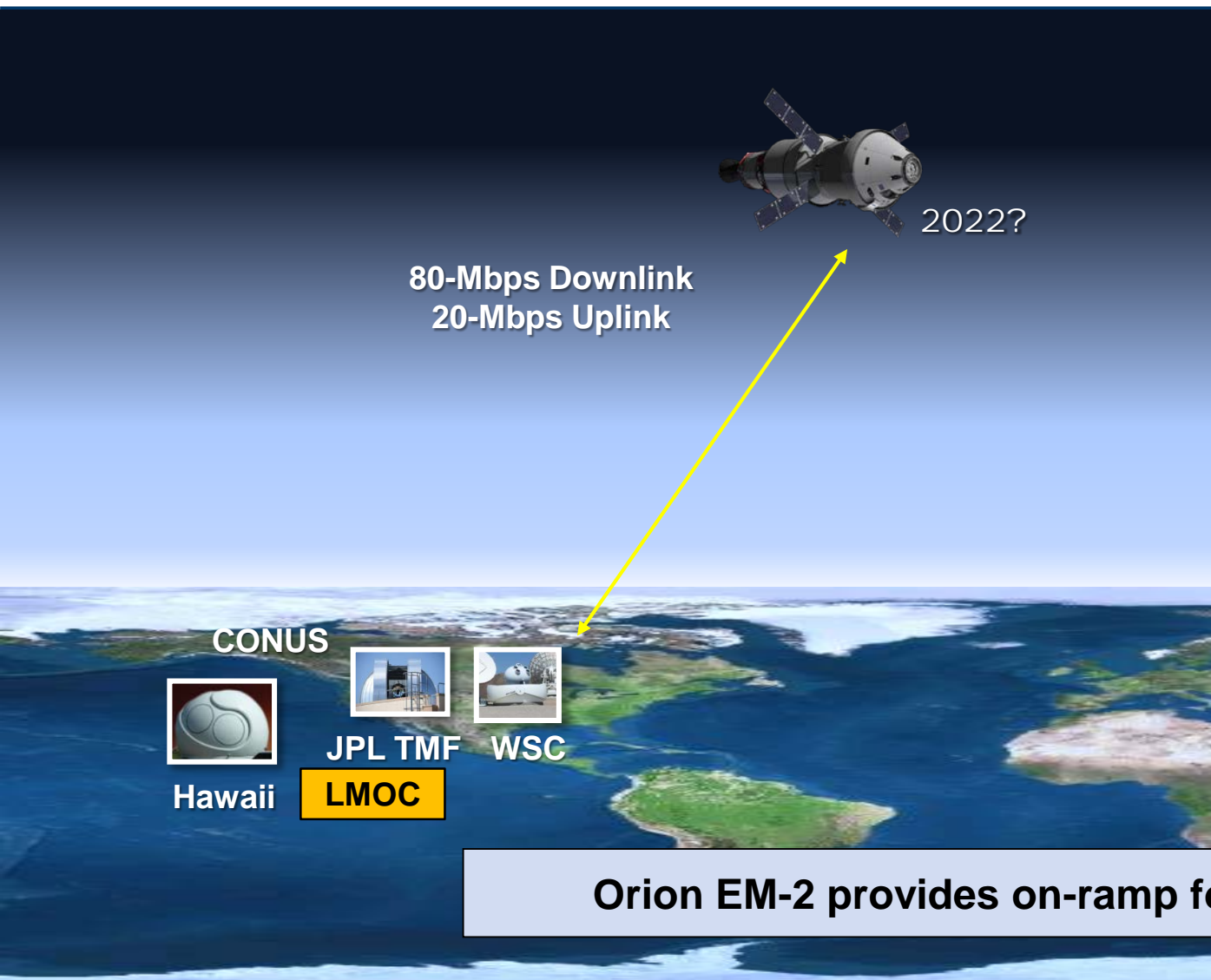
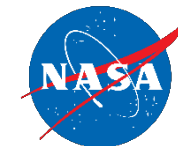


- **Orion Mission is NASA's platform for their Journey to Mars**
  - Orion EM-1 uncrewed mission to fly in 2019
  - Orion EM-2 crewed mission to fly in 2022?
- **Primary comm link for EM-1 is S-band phased array radio**
  - 192 Kbps data rate at lunar ranges
- **X/Ka band high gain antenna (10 Mbps at lunar ranges) was eliminated in 2008 due to mass constraints!**
- **Optical comm will increase the ISS downlink data rate to 80 Mbps and provide high res streaming video**





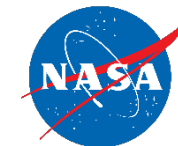
# Lasercom for Orion EM-2 Mission



- Development Test Objective (DTO)
- Industry-built proto-flight lasercom space terminal
- MIT LL perform system I&T
- Terminal installed on Orion EM-2 Spacecraft, first of many...



# Orion EM-2 Lasercom Ground Terminal Options



**LLCD Ground Terminal  
4 @ 40-cm receivers  
Transportable  
Design could be replicated**

- Presently disassembled, in storage
- Downlink at 80 Mbps only requires single 40-cm collector with photon counting receiver
- Can be re-installed at White Sands or relocated to new location
- Other terminals can be added for additional availability
  - OCTL / JPL
  - LCRD
  - Firepond / MIT LL
  - Foreign
  - Many others



**0.6-meter LCRD design  
Hawaii**



**1-meter LCRD design  
Table Mountain**



# NGT on Orion EM-2

Outer diameter = 5 m (16.5')

Next Gen Terminal  
Optical Module  
(~270°)

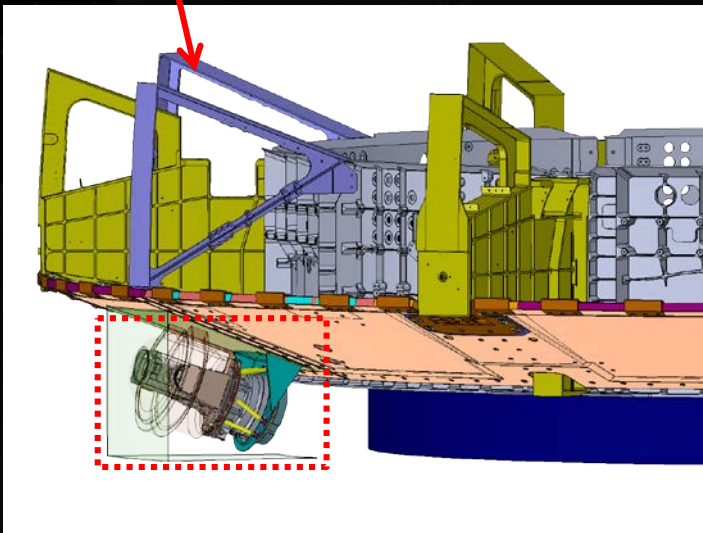
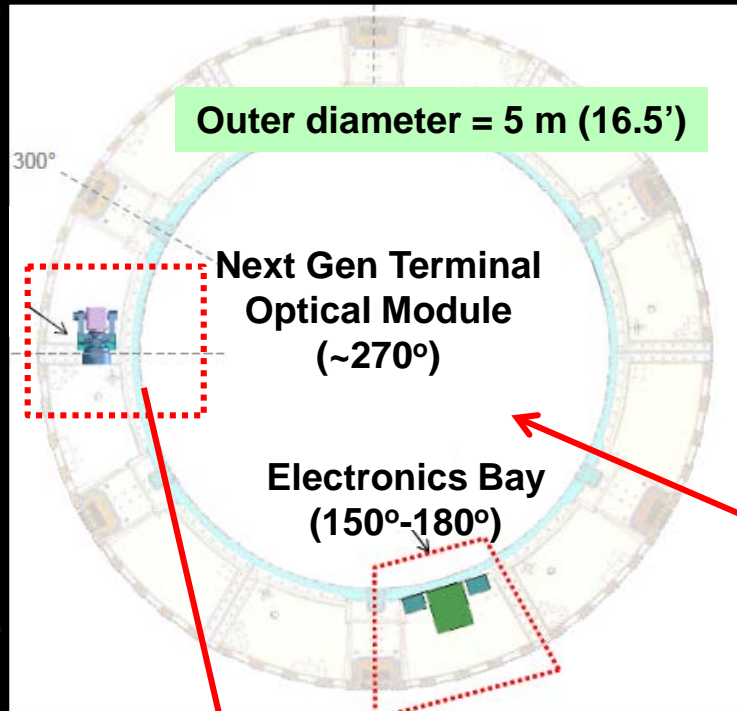
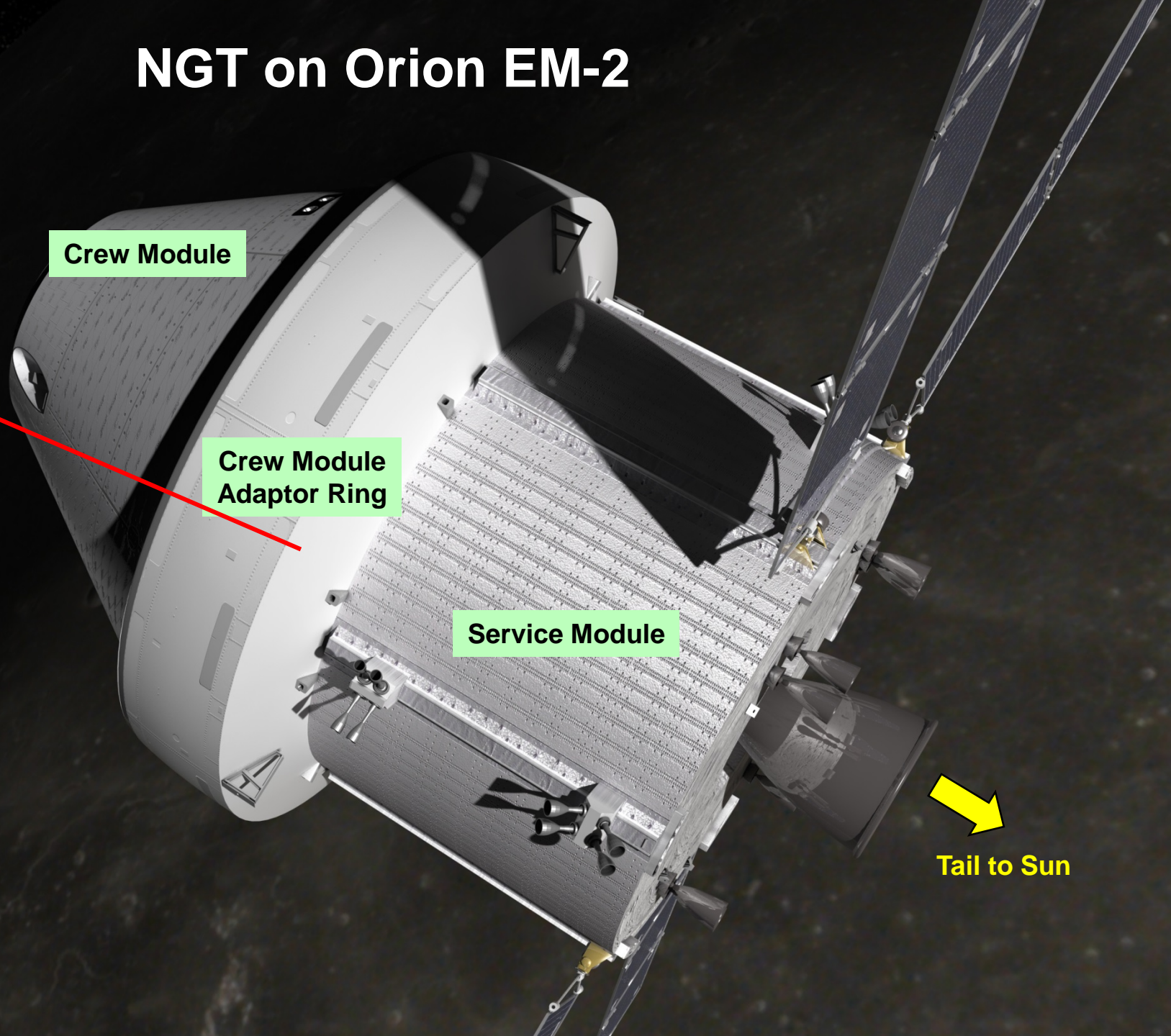
Electronics Bay  
(150°-180°)

Crew Module

Crew Module  
Adaptor Ring

Service Module

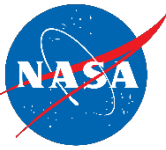
Tail to Sun







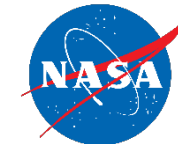
# MITLL Lasercom Terminal Key Differences



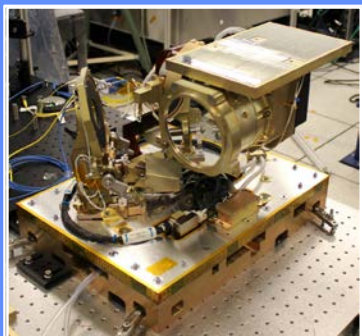
	ISS Lasercom	Orion EM-2 Lasercom
Remote/Receive terminal	Adheres to LCRD ICD and $\lambda$ 's	Adheres to CCSDS High Photon Efficiency spec
Modulation format	Differential Phase Shift Keying (DPSK)	Pulse Position Modulation (PPM)
Link range	40,000 km	500,000 km
Point, Acq, Track Architecture	User Terminal "Goes first" External beacon	"Goes second"
Launch vehicle	SpaceX Dragon	SLS
Spacecraft	ISS	Orion EM-2
Launch date (tentative)	2021+	2021+



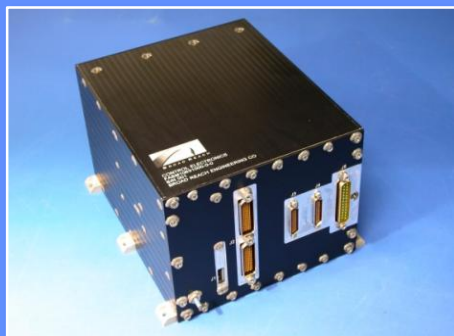
# Modular Space Terminal Architecture



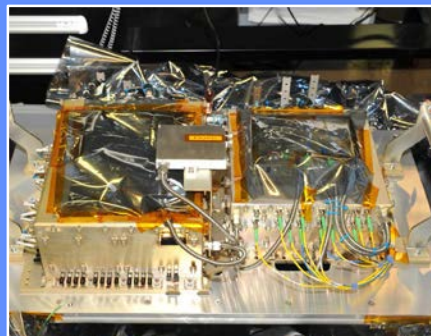
## Lasercom Space Terminal



LCRD Optical  
Module (2011–present)



Controller  
Electronics



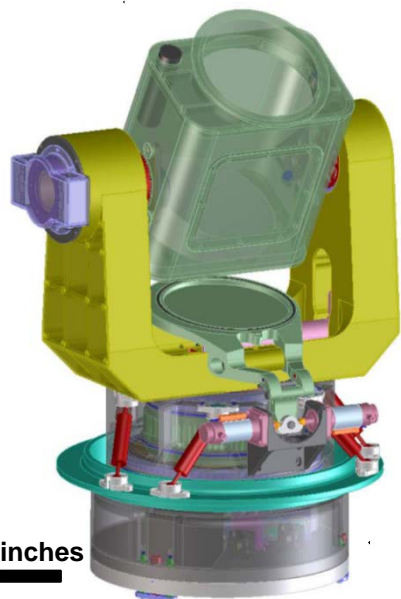
LCRD Modem  
Module (2011–present)

Module	LLCD (2009-14)
OM	MIT LL
CE	Industry
MM	MIT LL
LST I&T	MIT LL

- OM has gimbal, telescope, and back end optics
- CE does command / telemetry and runs pointing algorithms
- MM has electro-optics, modulation and coding, data interface
- For LLCD, MIT LL built OM and MM; payload flew on LADEE in 2013–2014
- For LCRD, GSFC modified and updated MIT LL design to be compatible with LCRD requirements; payloads to fly on STPSat-6 in 2019



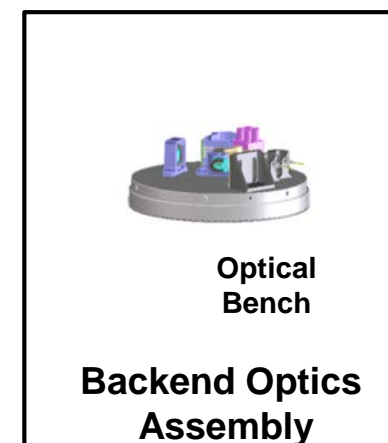
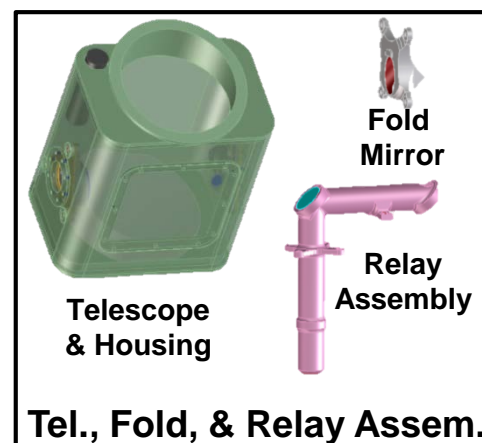
# Next Generation Terminal (NGT) Optical Module



NextGen Terminal (NGT)  
estimated 13 kg mass

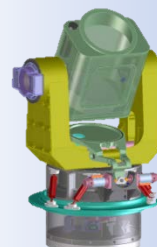
- ✓ Modular
- ✓ Scalable
- ✓ Leverages heritage programs

MODULAR

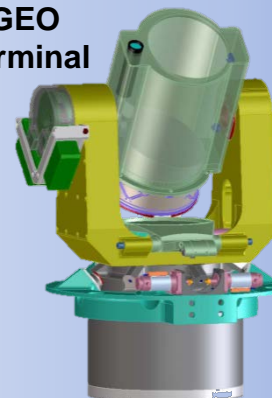


SCALABLE

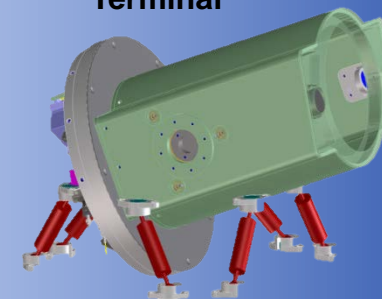
LEO  
Terminal



GEO  
Terminal



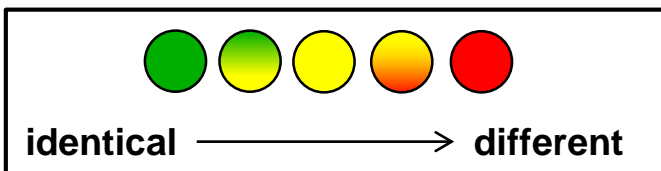
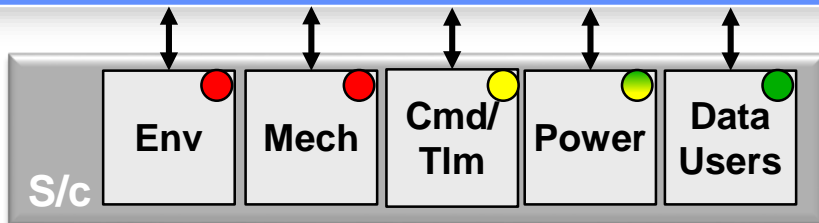
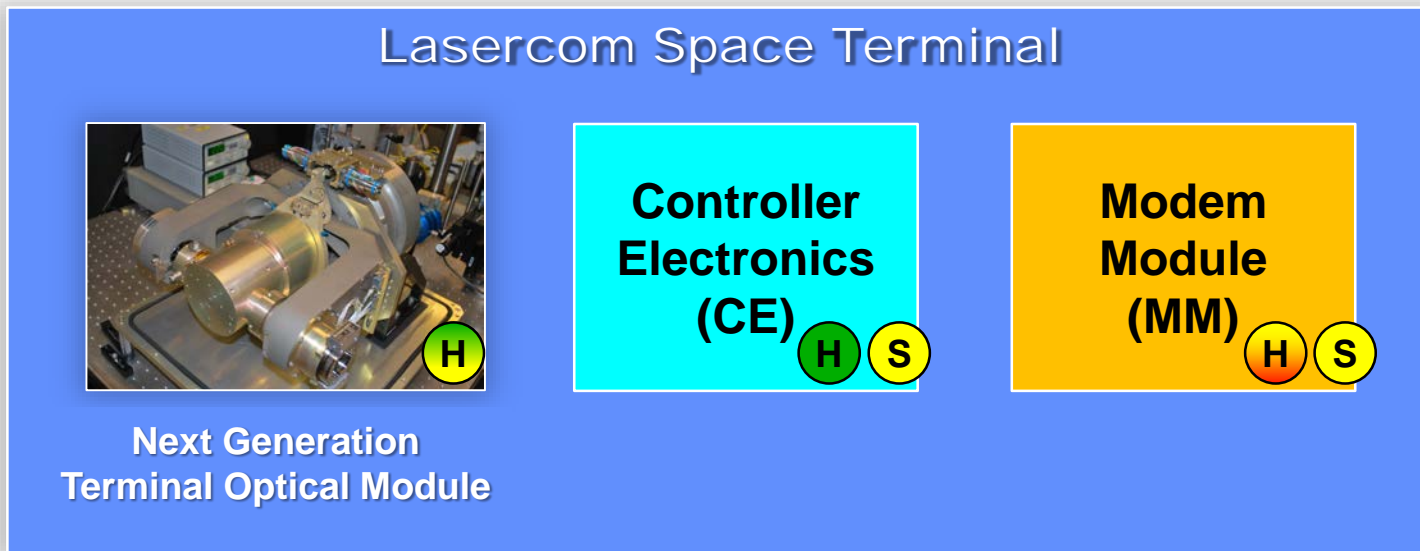
Deep Space  
Terminal



Modularity and scalability of NGT design facilitates future upgrades and tech transfer



# ISS / Orion Space Terminal Comparison



H=Hardware  
S=Software

Module	ISS (2016- )	Orion (2017- )
OM	Industry	Industry
CE	Industry	Industry
MM	Industry*	Industry
LST I&T	MIT LL	MIT LL

\* Procured by GSFC

## Physical/Hardware that differs:

- Optical wavelengths
- Launch loads, vibration/thermal env
- Modem vendors
- PAT/beacon

## Software that differs:

- PAT sequence
- Control software

**Modular terminal architecture easily handles these differences!**



# Summary



- **NASA and MIT LL have been working to advance lasercom systems from “demo” to “operational”**
- **MITLL actively facilitating lasercom transition from government to industry**
- **NASA/MITLL to perform several new operational demos in 2021+**
  - ISS user terminal
  - Orion lasercom DTO\*



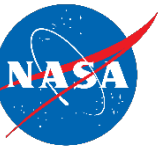
\* DTO=Development Test Objective



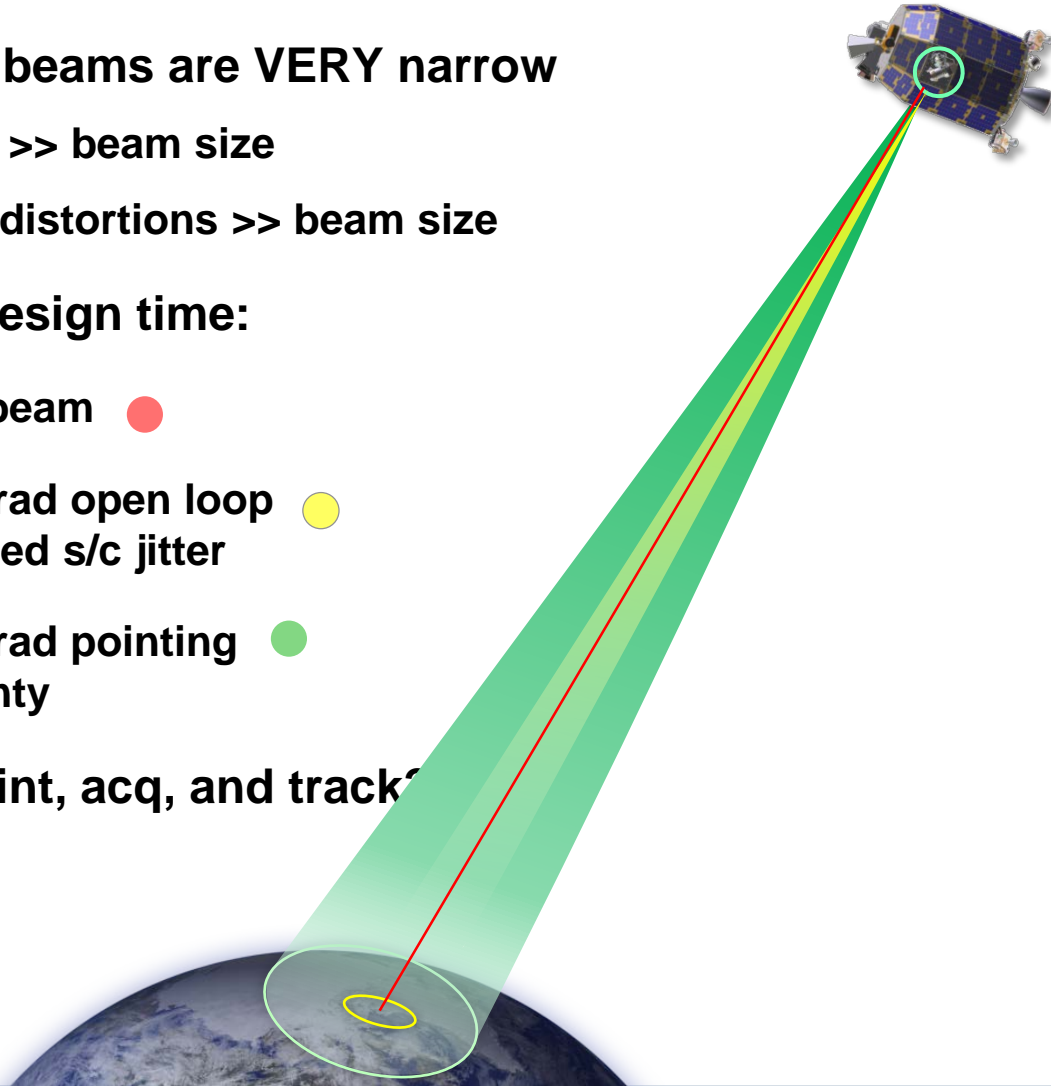




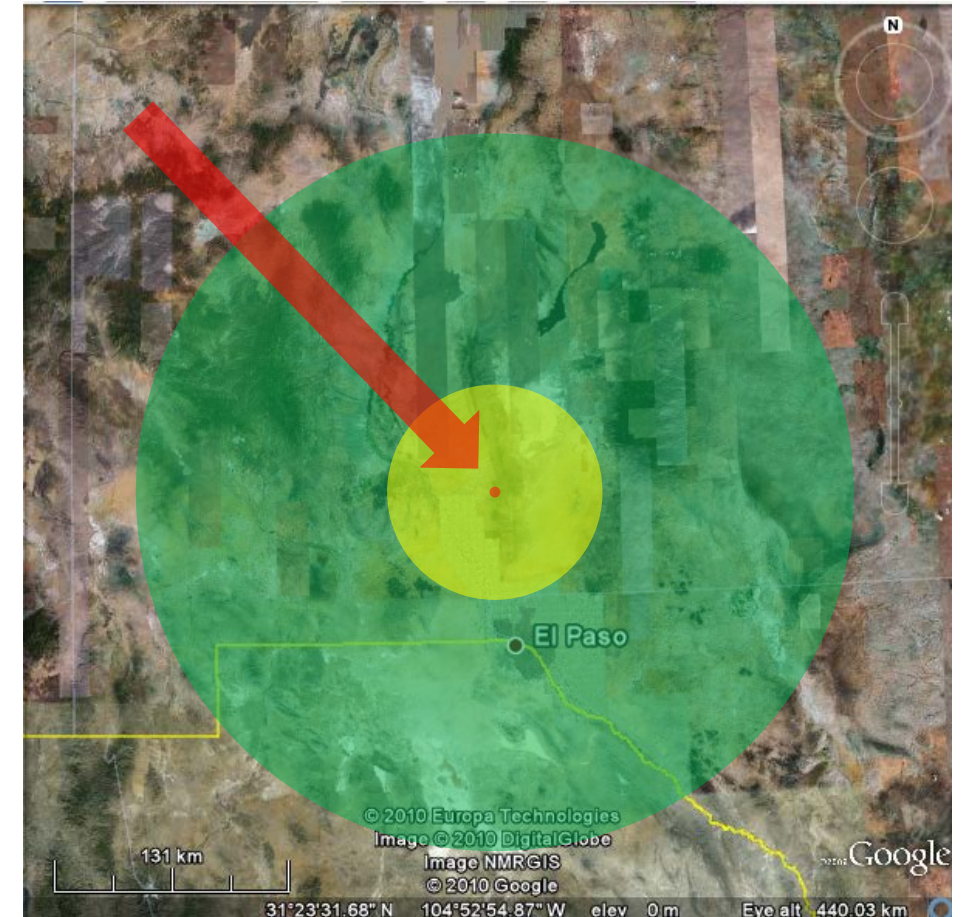
# How Narrow are Lasercom Beams?



- Lasercom beams are VERY narrow
  - S/C jitter >> beam size
  - Thermal distortions >> beam size
- At LLCD design time:
  - 15  $\mu$ rad beam ●
  - +/- 150  $\mu$ rad open loop un-rejected s/c jitter ●
  - +/- 500  $\mu$ rad pointing uncertainty ●
- How to point, acq, and track?



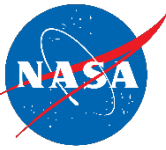
LLCD beam received at White Sands



~ 500 km



# PAT Techniques for Lasercom Systems



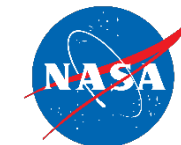
- Onboard star tracker provides ~mrad knowledge of s/c position (typical)
- Lasercom terminal employs a ~mrad FOV acquisition detector
- Lasercom terminal uses ephemeris data with periodic s/c attitude updates to point
- Lasercom terminal is inertially stabilized
- Ground terminal uses s/c position knowledge (e.g. ~10's of km at Moon)
- Ground terminal employs star calibration as needed to update telescope mount model
- Acquisition is cooperative
- Ground and/or space terminal can diverge (spread) beam and/or scan if needed

**LLCD experience: acquisition during 56 of 56 passes to White Sands Ground Terminal were successful (and automatic)**

**Lasercom PAT is solved by design – no longer an operations problem;  
No special pointing hardware required on s/c!**



# Lasercom Operations in the Presence of Clouds



Thin Cirrus Clouds

- **Reduce data rate**
  - Downlink data rates from 39 to 622 Mbps
  - Uplink data rates 10/20 Mbps



Intermittent Clouds

- **Mid-pass handover between ground stations**
- **Delay / disruption tolerant network**

*Goddard*  
SPACE FLIGHT CENTER



Thick Cloud Cover

- **Use alternate ground station!**

LLCD Oct–Nov Ops

Day	Block 1				Block 2				Block 3				Block 4			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
1	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█
2	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█
3	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█
4	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█
5	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█
6	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█
7	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█
8	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█
9	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█

- █ Operations
- █ Clouded out
- Not available

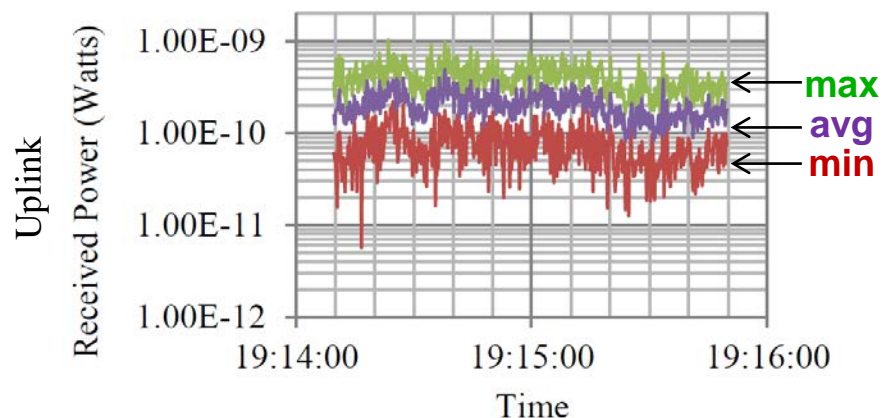
- **10% passes clouded out**
- **11% alternate ground station used**

**All solutions were demonstrated during LLCD**





# Data Delivery through the Earth's Atmosphere: Turbulence



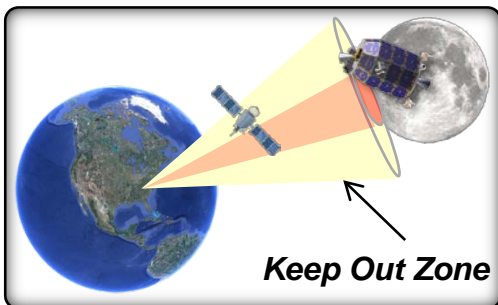
- Earth's atmosphere causes msec-class fading on optical channel
- 20-dB fades are possible!

Solution	Comments
Interleaving with powerful error correcting codes	Adds latency; demonstrated during LLCD
Erasure correcting codes	Expected complexity compares to interleaving/coding; could be implemented in higher level application (app specific)
Automated Repeat Request (ARQ)	Can work well with shorter links (e.g. near-earth); latency of feedback; demonstrated in FOENEX air-air demo

**Lasercom provides reliable, error-free data transmission through Earth's atmosphere!!**



# Regulatory / Permissions



- U.S. Air Force's Laser Clearing House regulates laser use to protect space assets (Predictive Avoidance - PA)
- U.S. Federal Aviation Agency (FAA) regulates potential laser-aircraft interactions
- PA data provided 24-hrs in advance; aircraft data is in real-time
- Uplink beams may need to be disabled during these events (power dependent)

Solution	Comments
Employ active aircraft avoidance system for high power uplinks	Demonstrated during LLCD (JPL's OCTL facility has aircraft avoidance system); near earth system have low uplink powers
Locate terminals in no-fly zone to avoid aircraft avoidance	Demonstrated in LLCD (primary ground terminal at White Sands)
Plan for PA event by selecting alternate ground terminal or planning for outage and re-acquisition	Demonstrated in LLCD; in future, outage durations may reduce to precise pointing capabilities of ground terminals
For near earth, employ low power uplink	No need to turn off for airplane or satellite

**Regulatory / permissions mitigated with *minimal* effort!**