Overview on Lasercom (from an MIT-LL Perspective)

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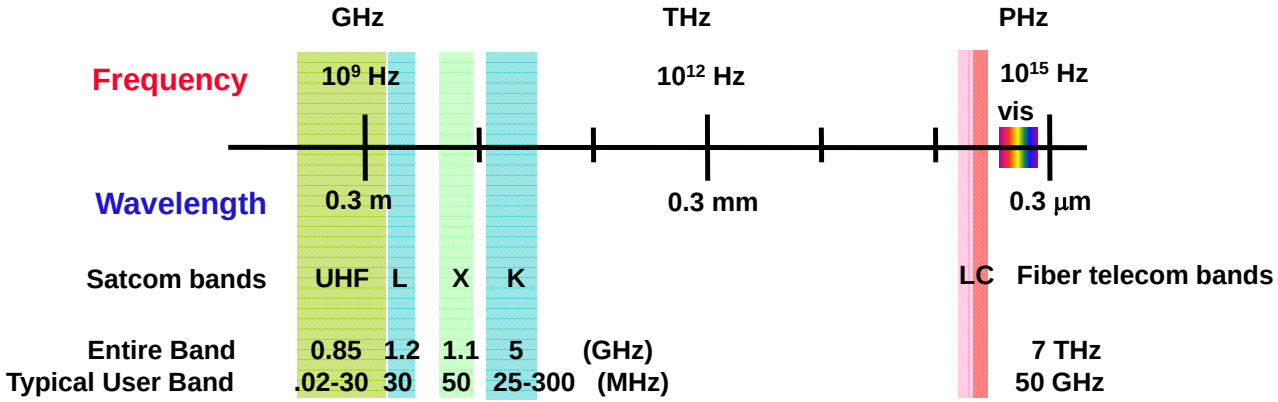
Presented to: **Workshop on Free Space Optical Networks**

13-14 July 2017

LINCOLN LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Why Free-Space Optical Communications?



High Carrier Frequency

- **Extremely Wide Bandwidth**

Short Wavelength

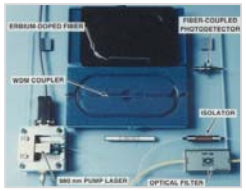
- **High Beam Directionality (~ λ/D)**

System benefits

- **High data rates in *unregulated* bands**
- **Efficient power delivery for low SWaP**
- **Security through narrow beams (LPD/LPI)**

MIT-LL Lasercom Flight Demonstrations

Technology Development (80's-90's)



High-power and Low-noise Optical Amps (pre-industry)

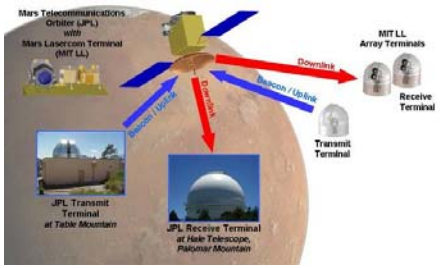
First Space-qualified >1 Khz Tracking Mirror

Lasercom Terminal Integration and Full-functional Testing

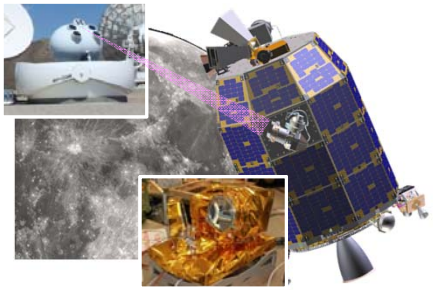
GeoLITE (2001)

ALEX (2002)

Mars Lasercom Demo (2003-05)



Lunar Lasercom Demo (2008-14)



Lasercom Relay Demo (2011-19)

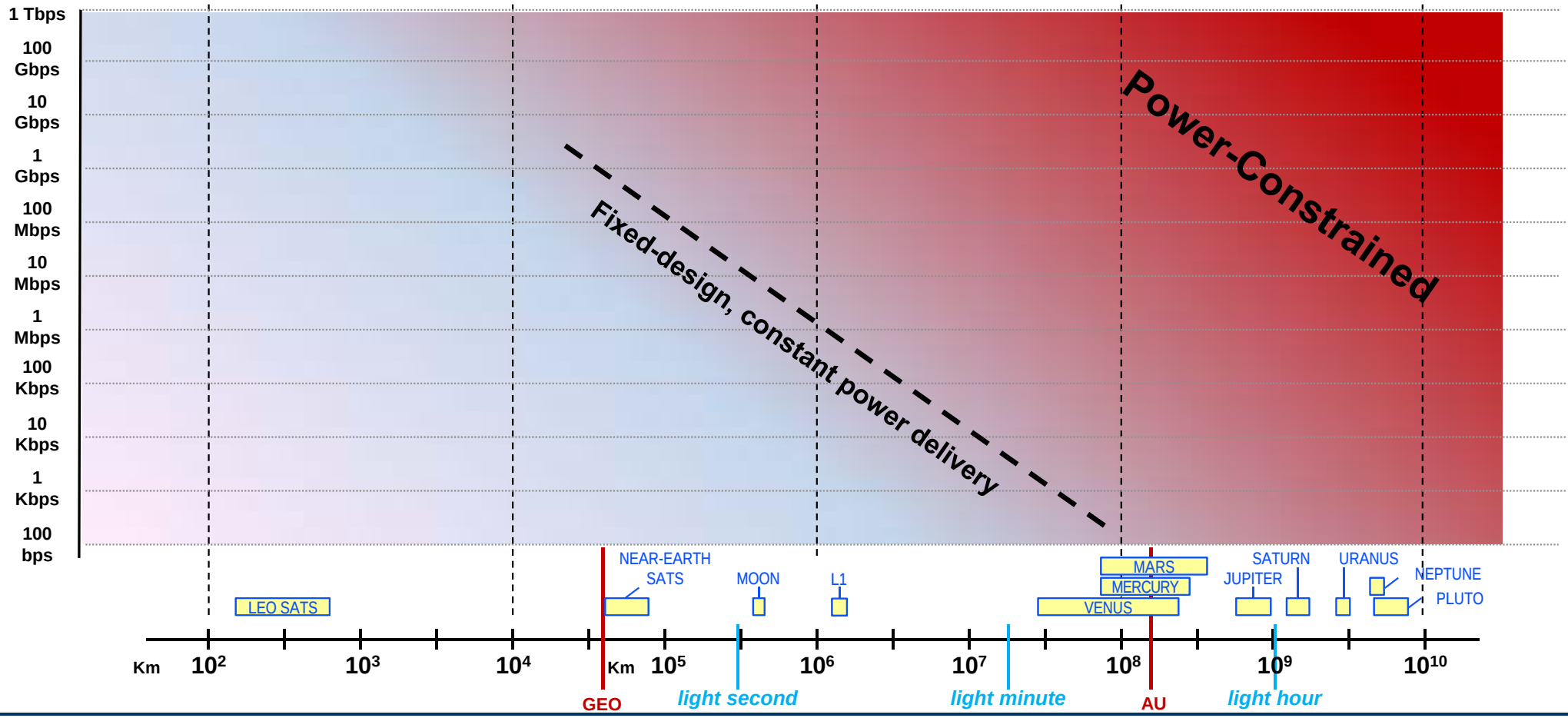
2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019

Free-space Optical Comm Airborne Link (2008-10)

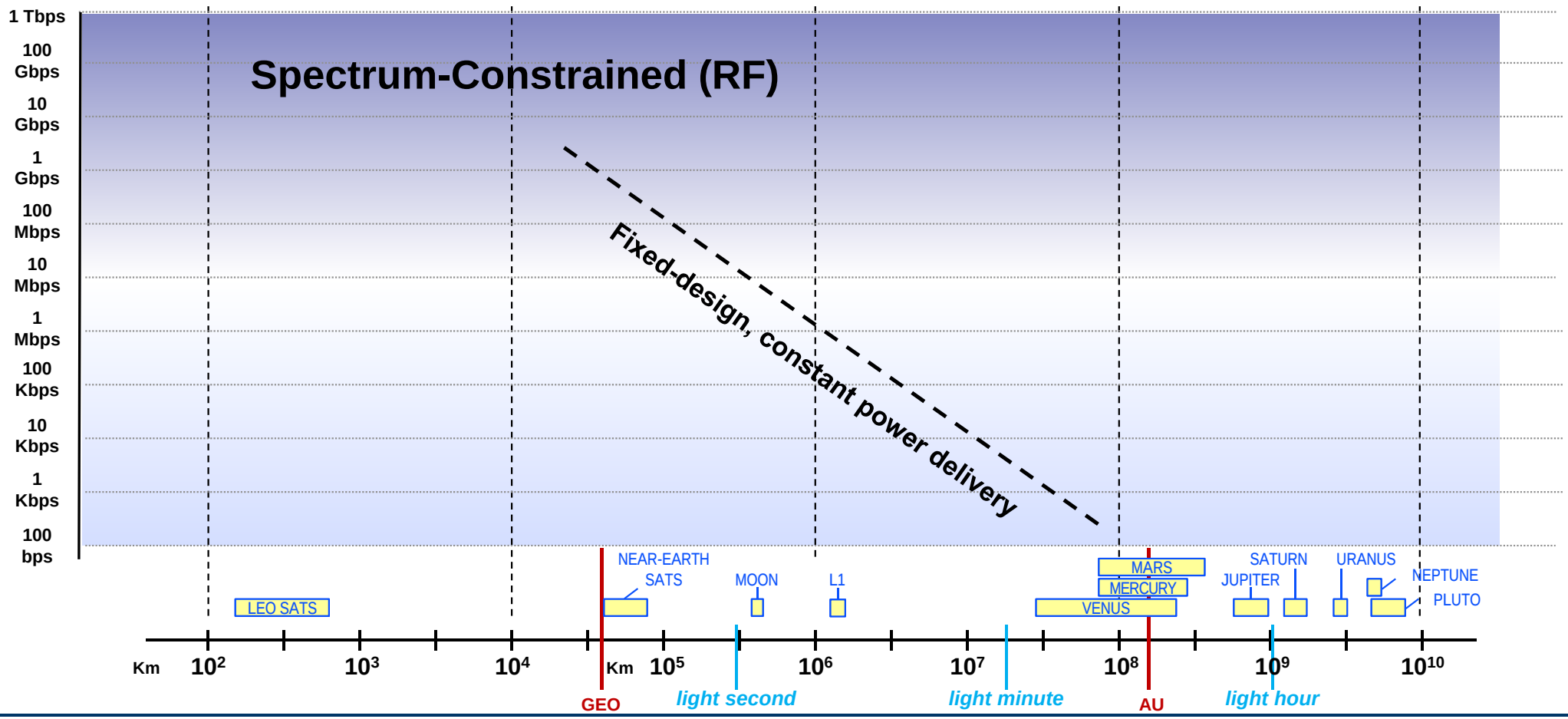
Compact Laser Transmitter (2009-14)

Perceived lasercom technical challenges have been solved

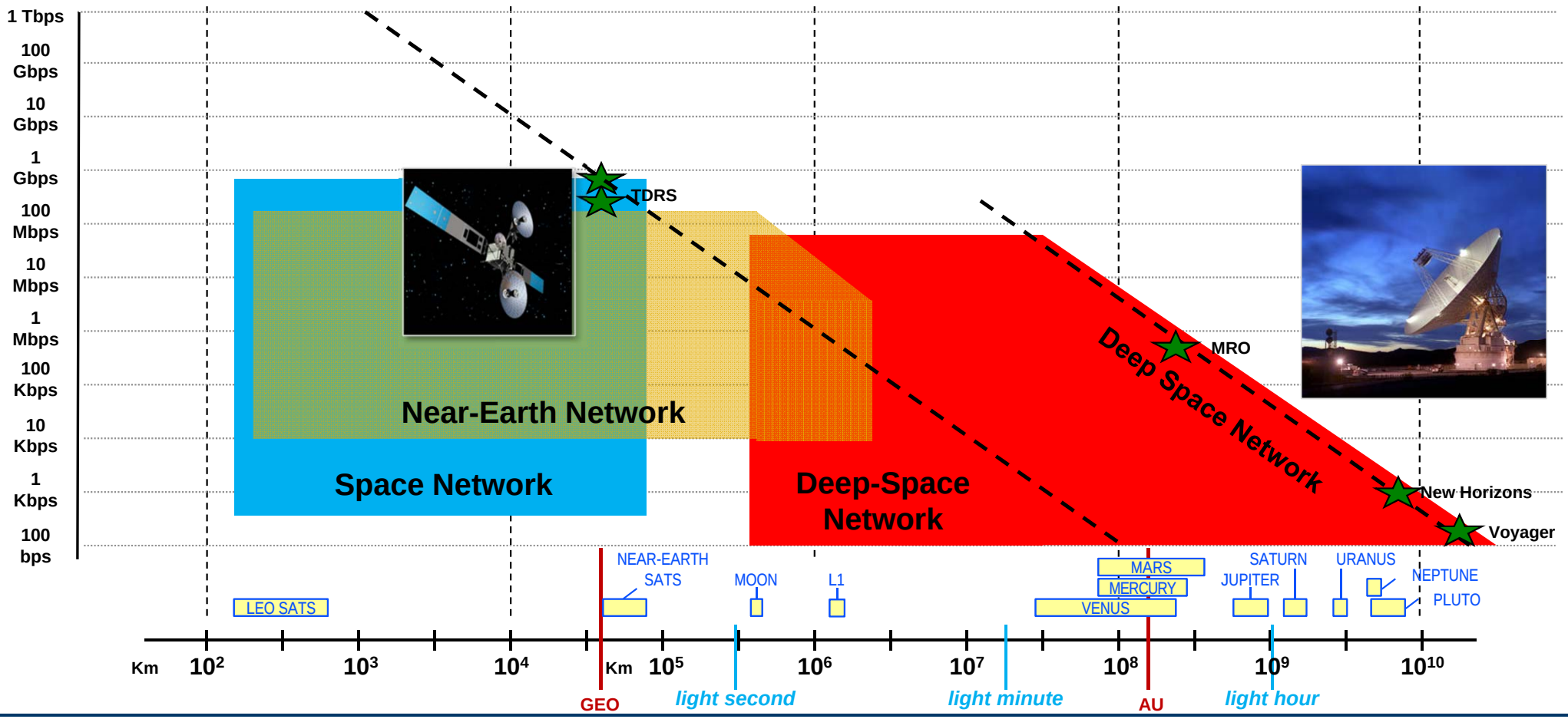
NASA Space Communication Challenges



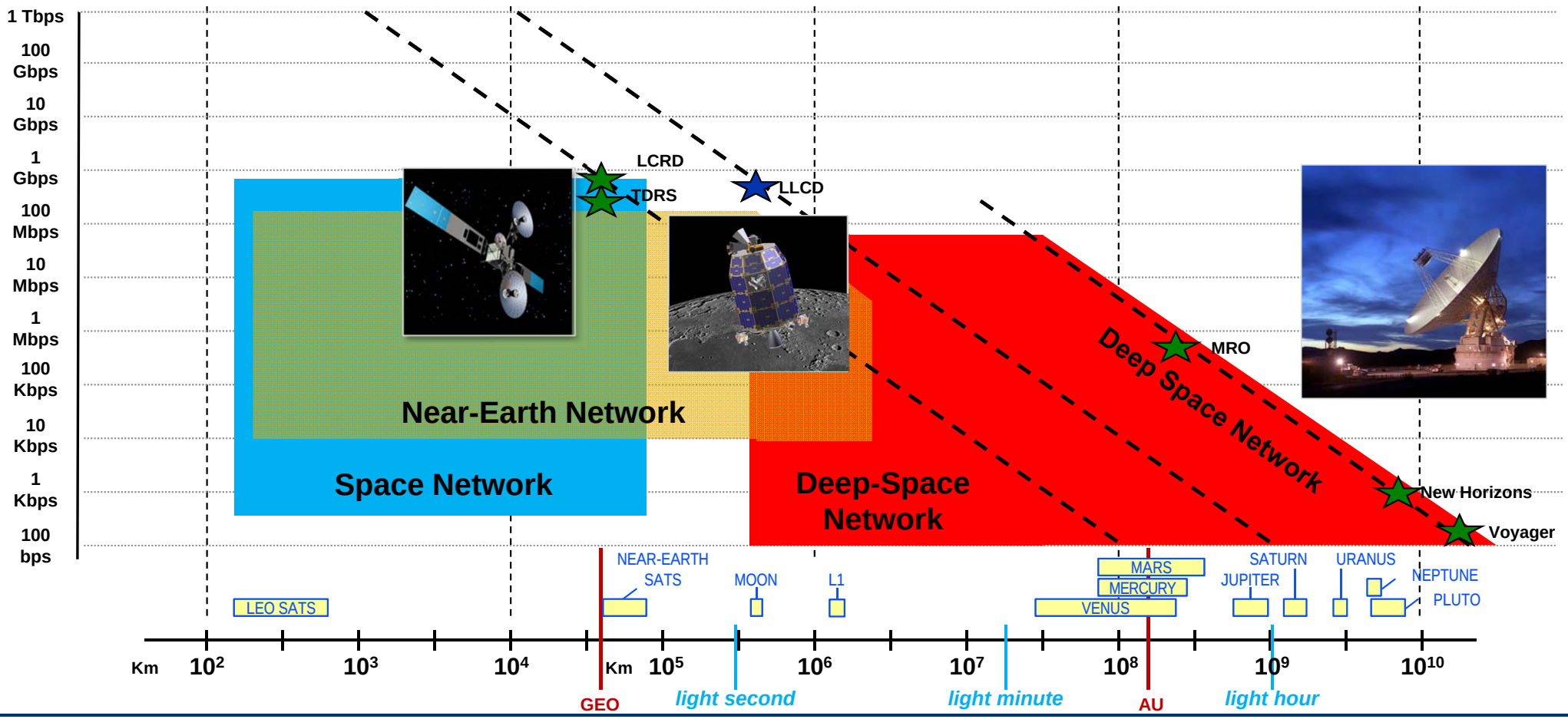
NASA Space Communication Challenges



NASA Space Communication Challenges



NASA Space Communication Challenges

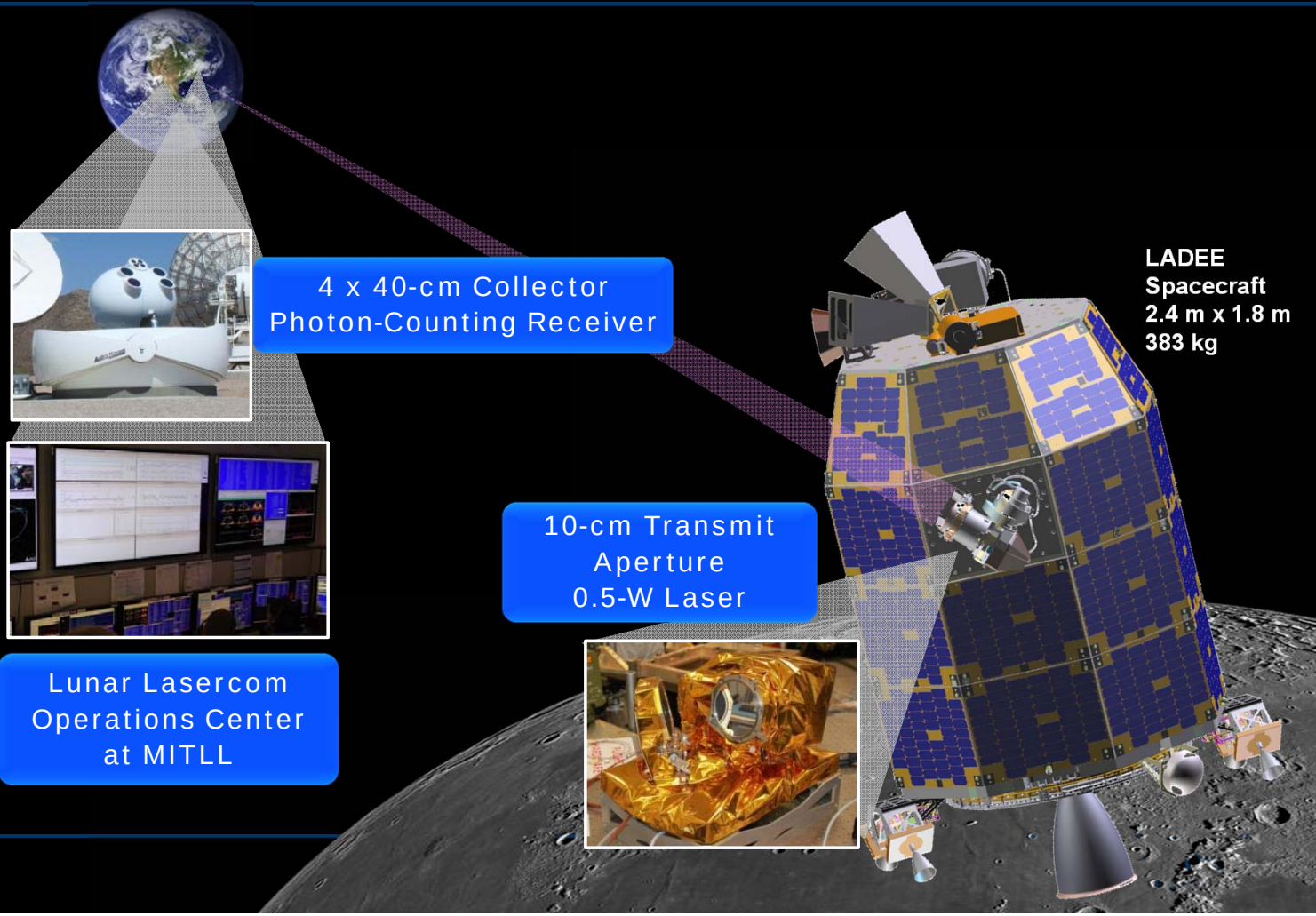


Lunar Laser Communication Demonstration

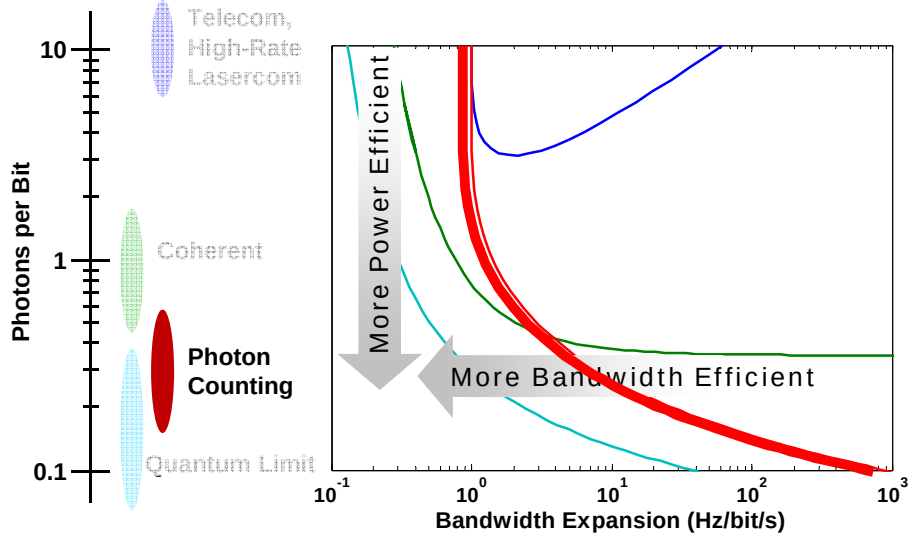
NASA's First Lasercom Demonstration (2013-2014)

Technology demo on NASA's Lunar Atmosphere and Dust Environment Explorer (LADEE)

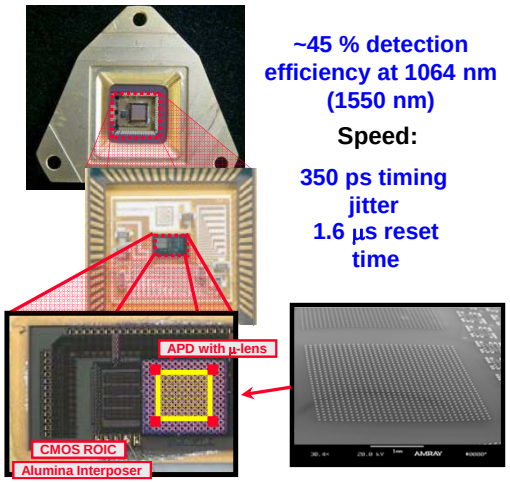
- **622 Mbps downlink from moon**
- **20 Mbps uplink to moon**
- **Longest lasercom link ever demonstrated**



LLCD Key System Parameters and Design Choices (1/4)



MIT-LL Geiger-Mode Avalanche Photodiode Arrays

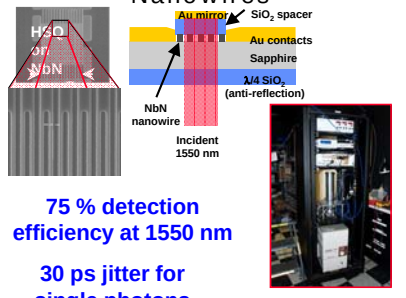


~45 % detection efficiency at 1064 nm (1550 nm)

Speed:

350 ps timing jitter
1.6 μs reset time

MIT-LL Superconducting Nanowires



75 % detection efficiency at 1550 nm

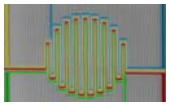
30 ps jitter for single photons

3 ns reset time for 3 μm square device

Radiation hard

Response from UV to Mid-IR

Closed-cycle Cryo-cooler

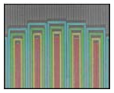


4-element SNSPD Array

Key System Parameters

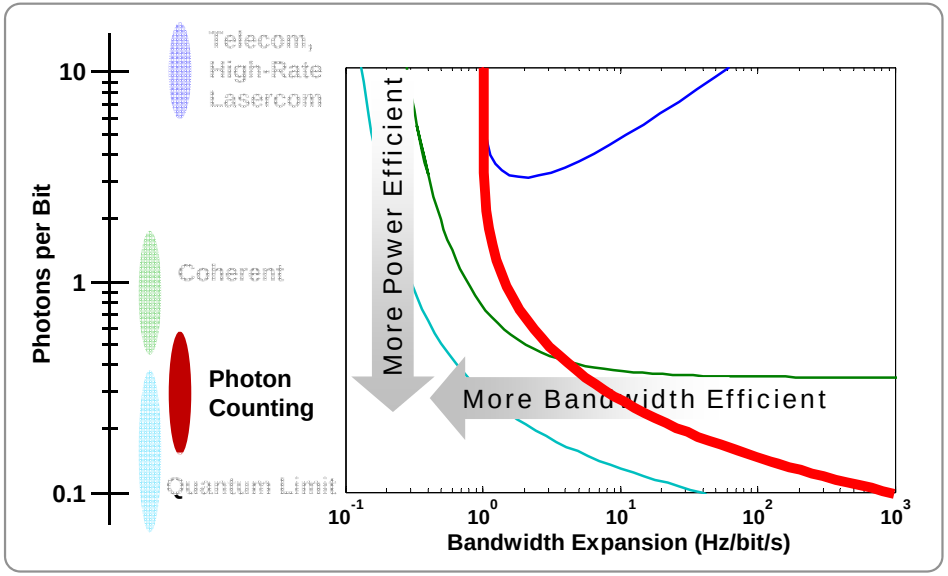
Receiver Selection | **Modulation** | **Coding & Interleaving** | **Ground Terminal Design**

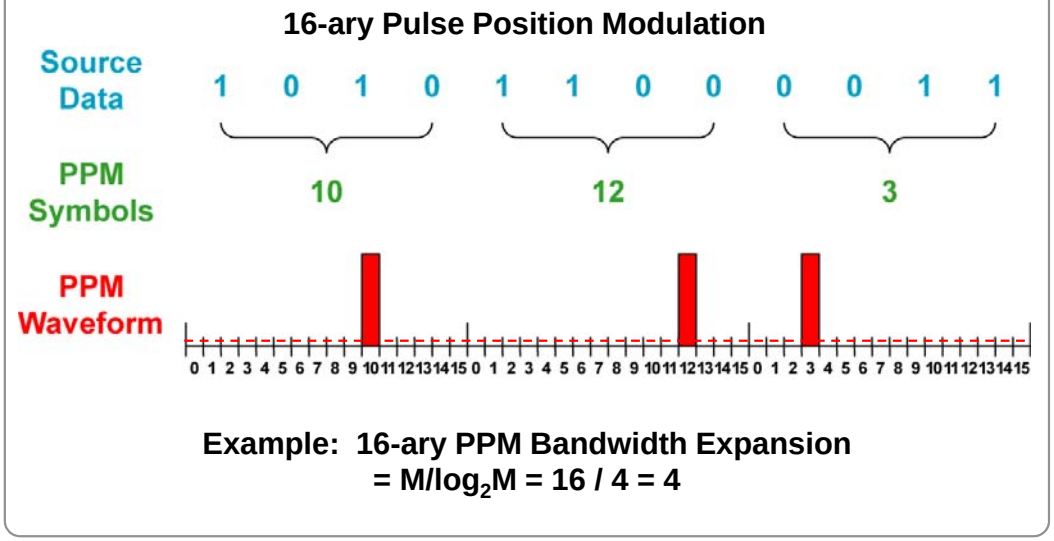
LLCD Design Choices



Superconducting Nanowire Arrays

LLCD Key System Parameters and Design Choices (2/4)



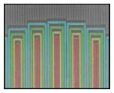


Example: 16-ary PPM Bandwidth Expansion
$= M/\log_2 M = 16 / 4 = 4$

Key System Parameters

Receiver Selection | **Modulation** | **Coding & Interleaving** | **Ground Terminal Design**

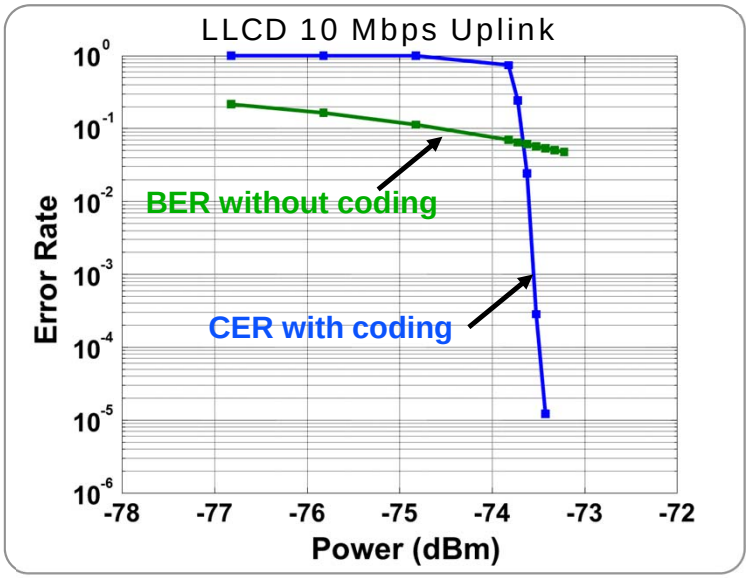
LLCD Design Choices

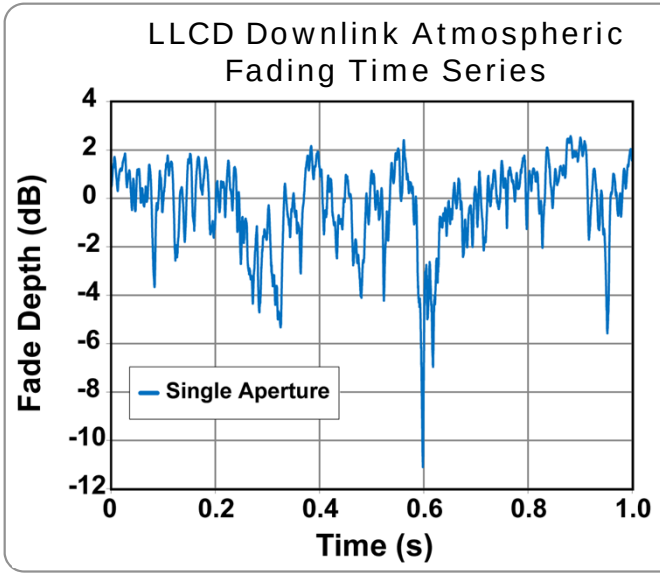


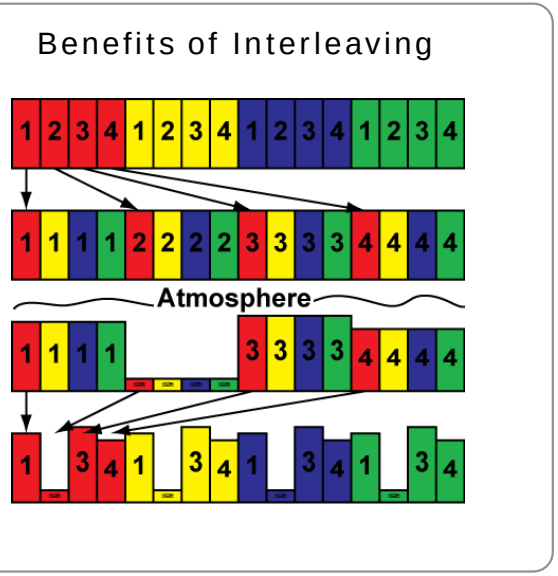
Superconducting Nanowire Arrays

- **Pulse Position Modulation**

LLCD Key System Parameters and Design Choices (3/4)



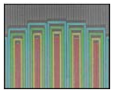




Key System Parameters

Receiver Selection | **Modulation and Coding** | **Coding & Interleaving** | **Ground Terminal Design**

LLCD Design Choices

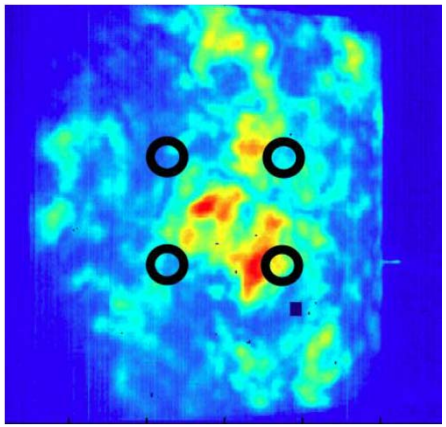


Superconducting Nanowire Arrays

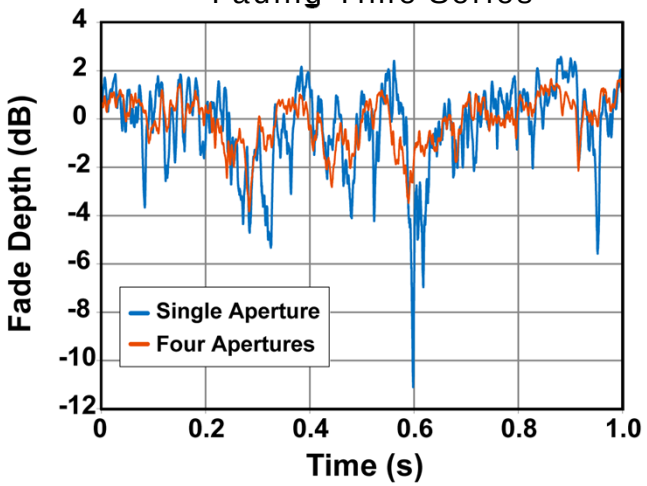
- **Pulse Position Modulation**
- **½ rate Serially Concatenated Pulse Position Modulation (SCPPM)** JPL
- **1 sec interleaver**

LLCD Key System Parameters and Design Choices (4/4)

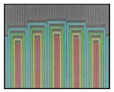
Multiple Aperture Receiver Spatial Diversity



LLCD Downlink Atmospheric Fading Time Series



Ground-Based Telescope Array (LLCD)

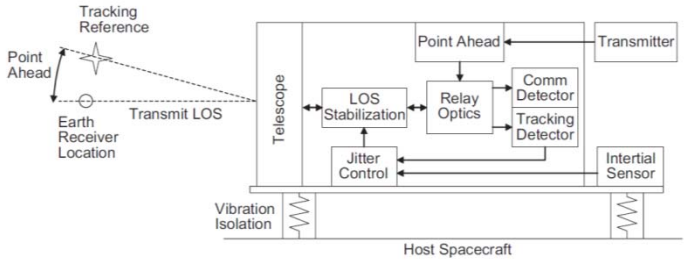
Key System Parameters	Receiver Selection	Modulation	Coding & Interleaver	Ground Terminal Design
LLCD Design Choices	 **Superconducting Nanowire Arrays**	• **Pulse Position Modulation**	• **1 sec interleaver** • **Serially Concatenated Pulse Position Modulation (SCPPM)**	• **Scalable** • **Transportable** • **Array 4 x 40 cm**

JPL

Beam Size from Moon

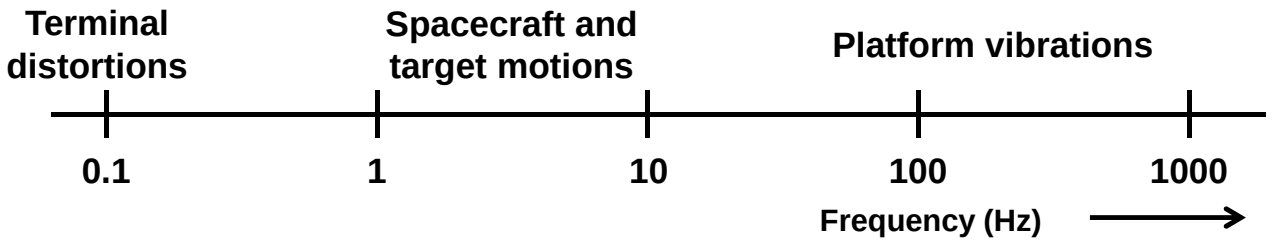
- 10-cm transmit aperture
- 15 μrad beam
  - ~0.001 deg
  - ~6 km on Earth

Beam Stabilization



* Figure from "Deep Space Optical Communications", H. Hemmati, ed.

Disturbances



Vibration Isolator

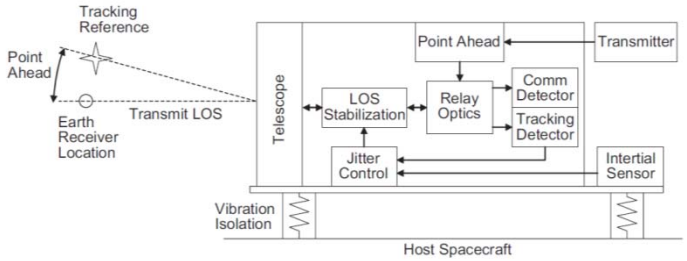
Stabilization Methods

Passive Isolation

High BW Tracking with Beacon

Electro-Optic Nutator with scan

Beam Stabilization



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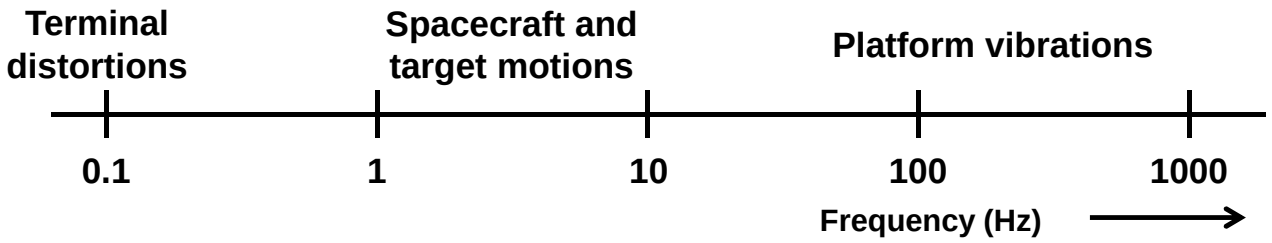
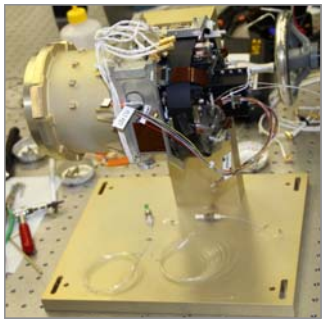
Disturbances

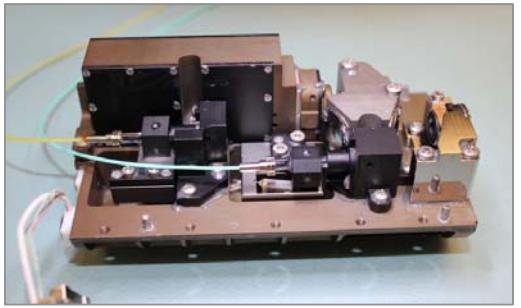


Stabilization Methods

- Celestial Sources
- Passive Isolation
- Inertial References
- Low BW Tracking with Beacon
- High BW Tracking with Beacon



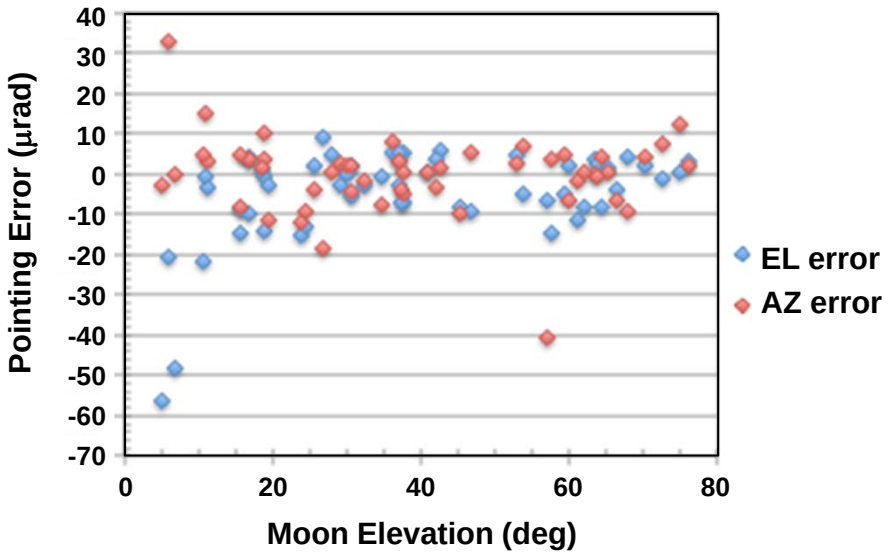
Inertially-Stabilized Terminal



Small Optics with Piezo Nutator

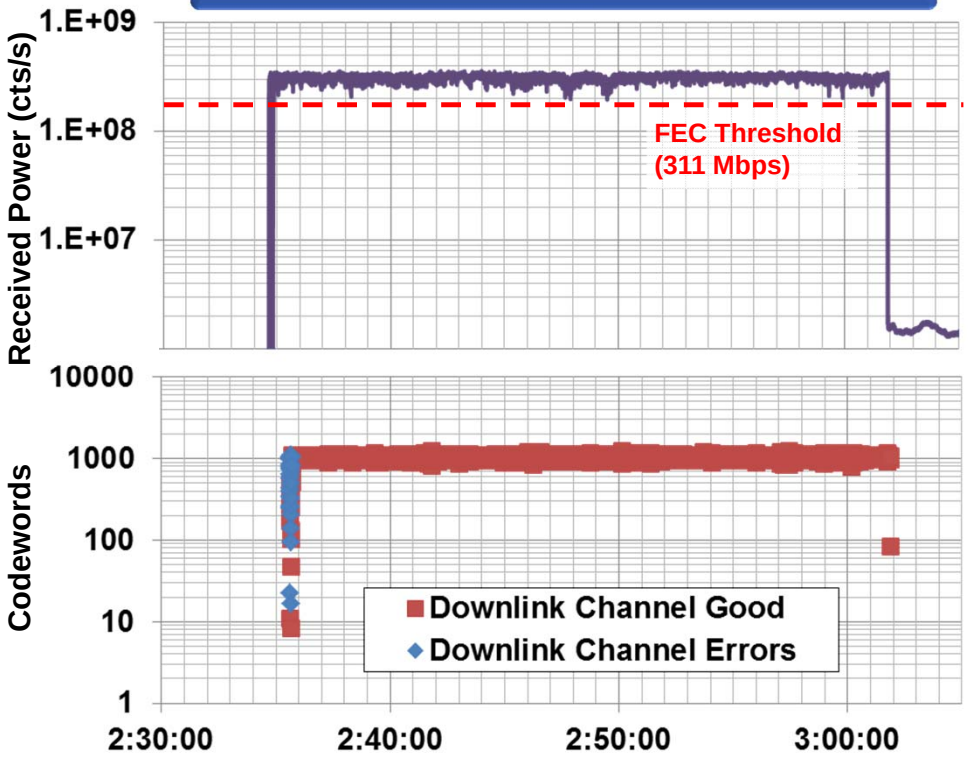
Acquisition and Downlink Communication Performance

LLGT Initial Pointing Error at Acquisition



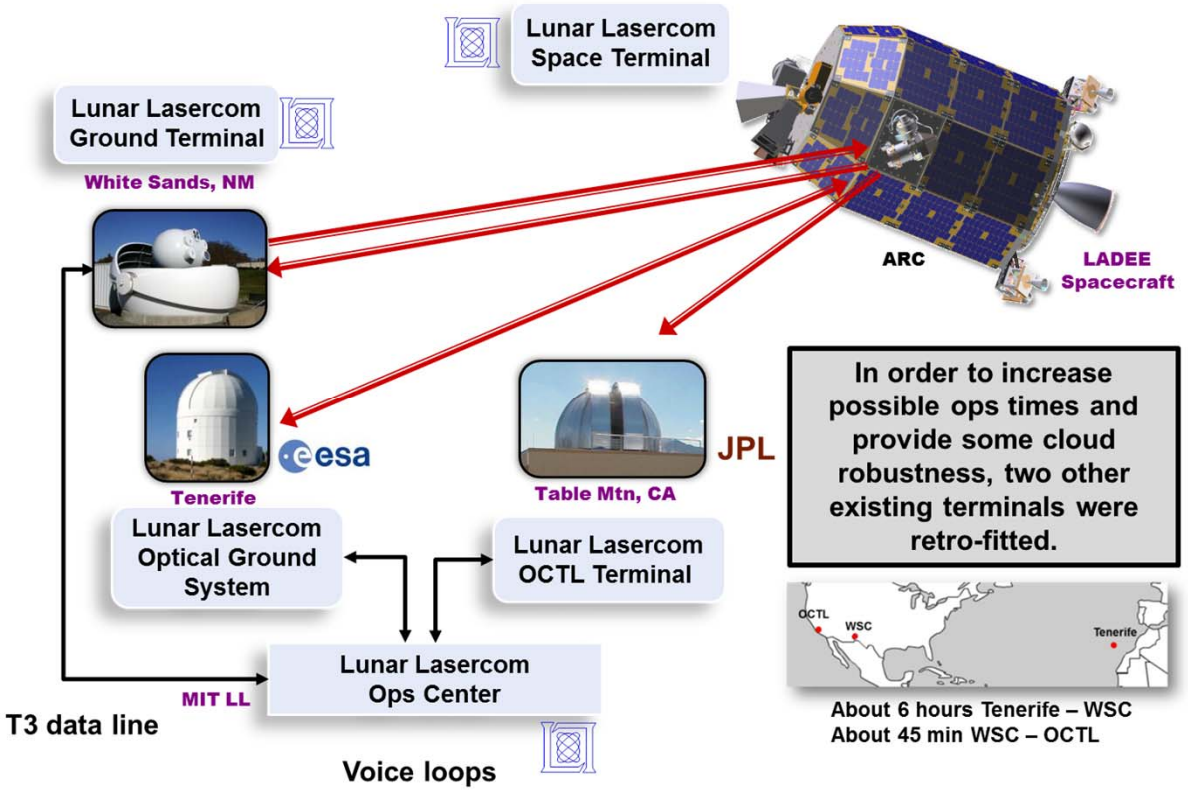
2-axis pointing error for elevation > 7 deg = 11.2 μrad rms

Downlink Comm Performance



Error-free communication achieved

LLCD System



International community understands how to build interoperable ground terminals

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

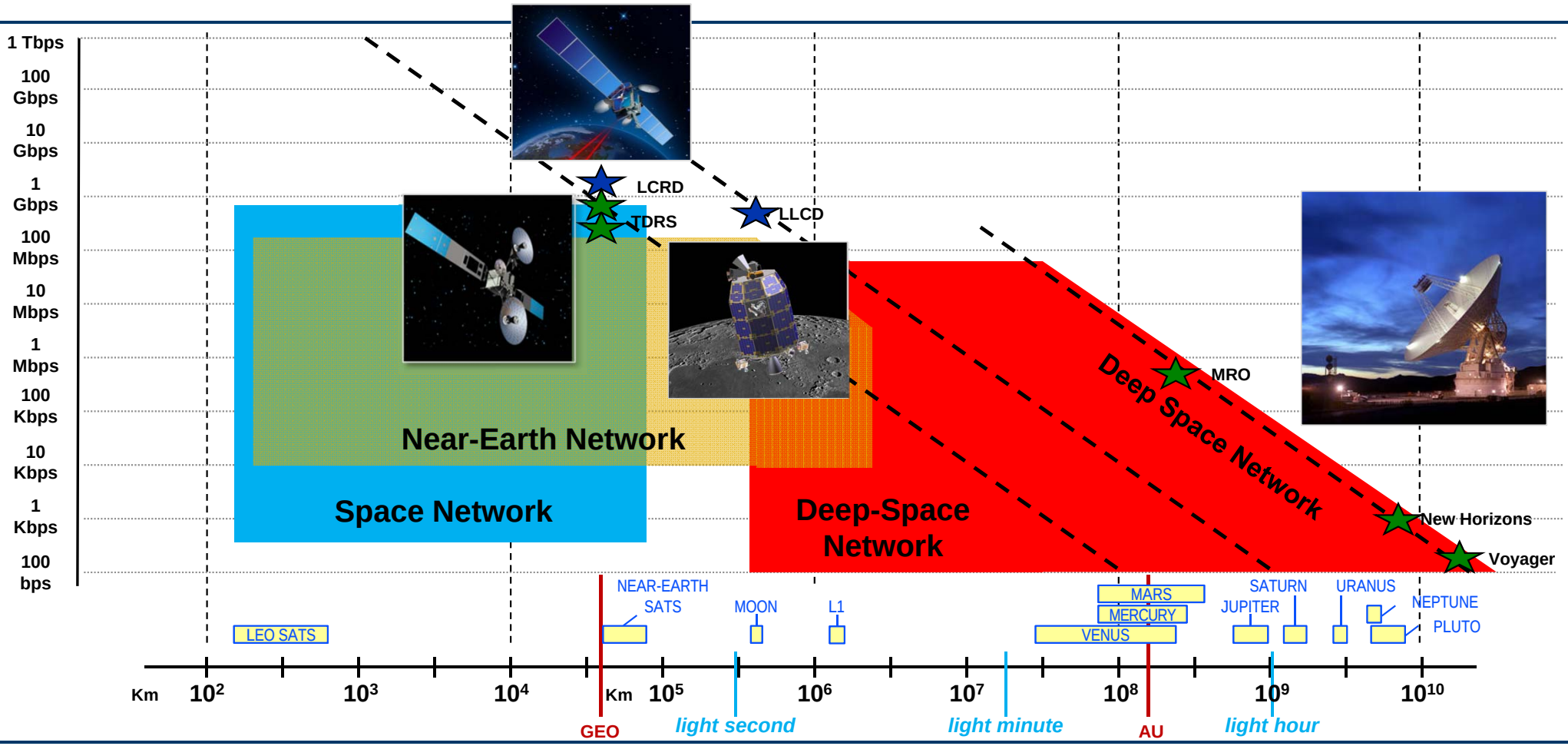
	Block 1				Block 2				Block 3				Block 4		
Day	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3
1															
2															
3															
4															
5															
6															
7															
8															
9															

Operations
Clouded out
Not available

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

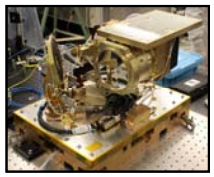
All solutions were demonstrated during LLCD

NASA Space Communication Challenges

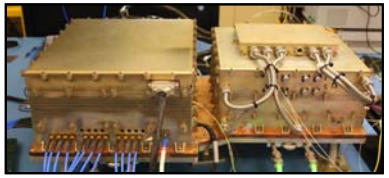


Space Lasercom Operational Pathfinder

Qualified Subsystems being Integrated at MIT-LL

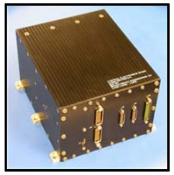


Optical Module

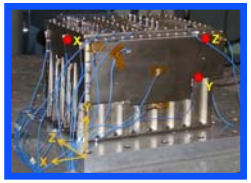


Multi-Rate Modem

Qualified Subsystems being Procured from Industry

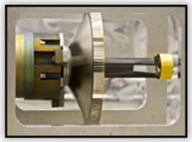


Pointing Processor
(Moog BRE)

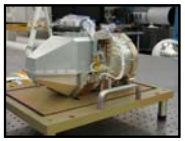


Digital Processor
(SEAKR Eng., Inc)

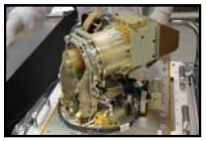
Modem Electronics
(Aeroflex Cobham)



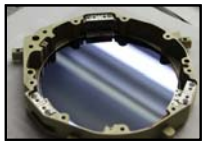
Optical
Subassembly
(ITT-Exelis)



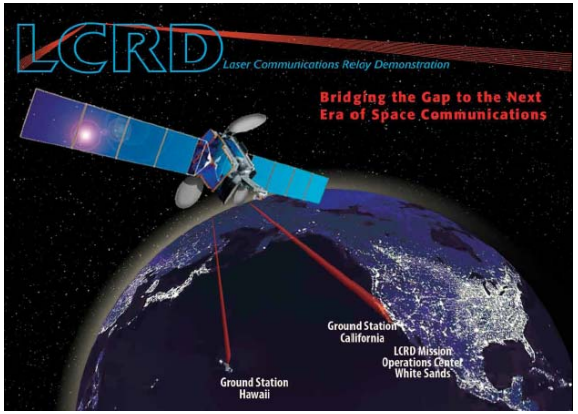
Inertially-Stable
Platform
(ATA)



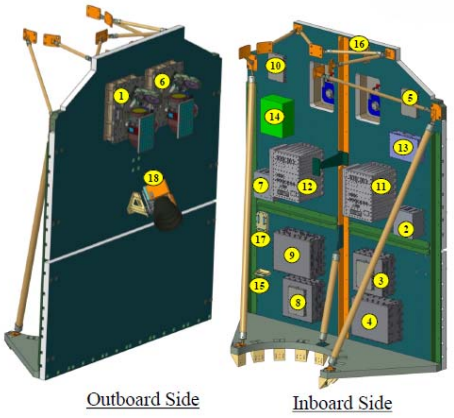
Gimbal & Latch
(Sierra Nevada
Corp)



Solar Window
Assembly
(L3-SSG)

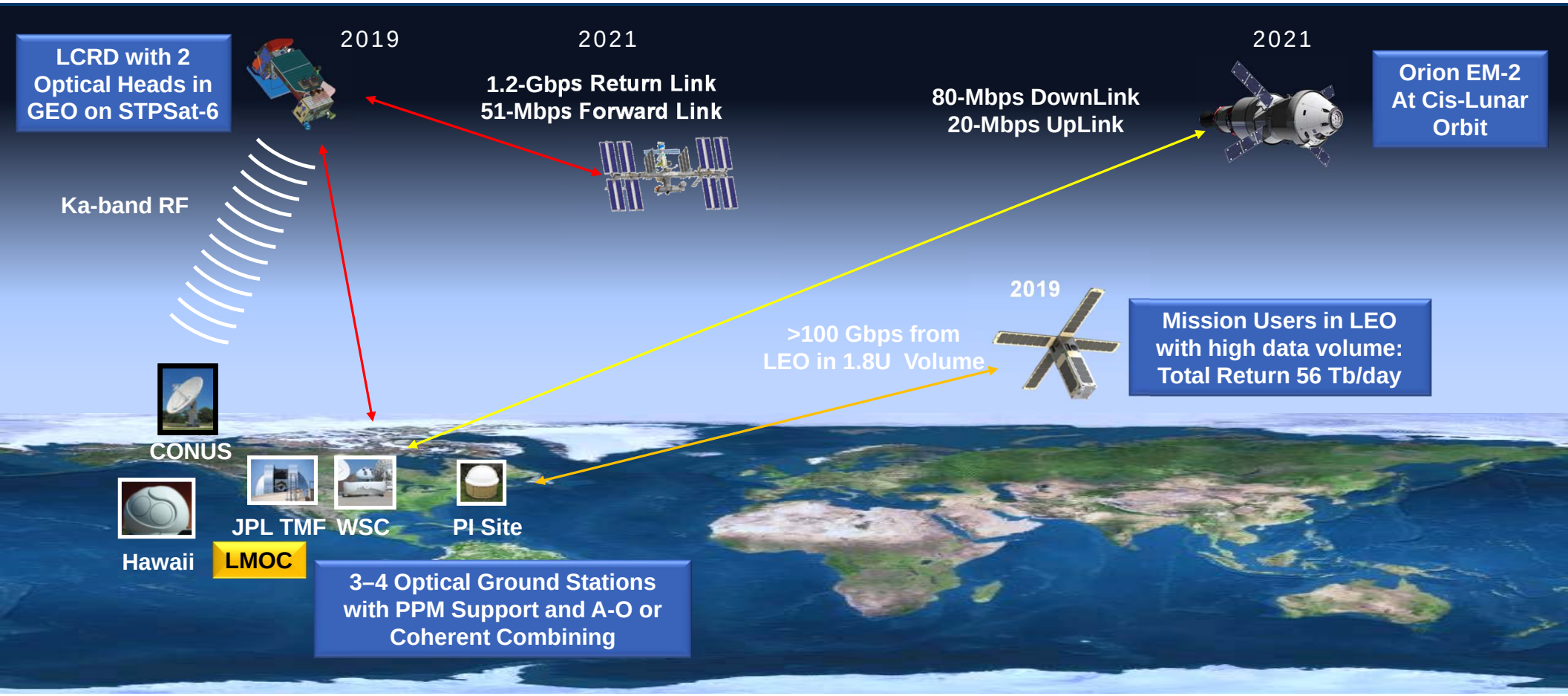


Payload Configuration

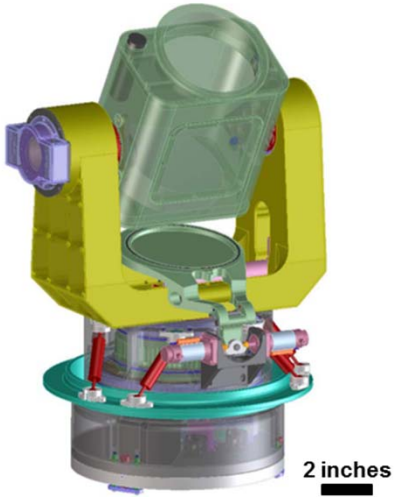


International Standards

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

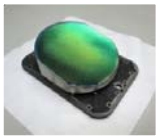


Next Generation Terminal (NGT) Optical Module



NextGen Terminal (NGT)
estimated 13 kg mass
- ☑ **Modular**
- ☑ **Scalable**
- ☑ **Leverages heritage programs**

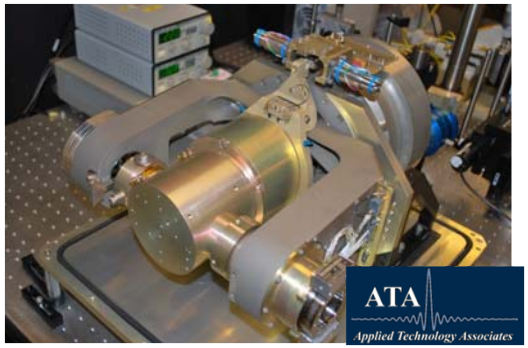
MODULAR

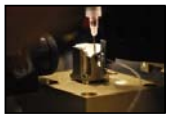


Telescope and Relay

Redstone Aerospace

Latch and Gimbals



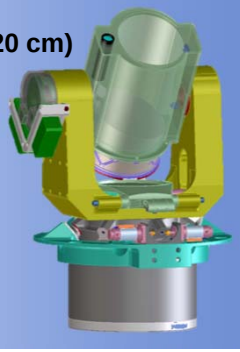


Optical Bench

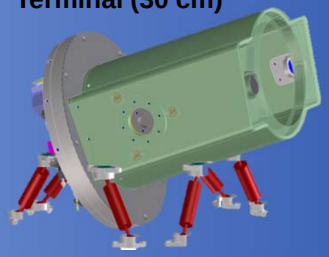
SCALABLE

LEO User Terminal (10 cm)

GEO Terminal (20 cm)

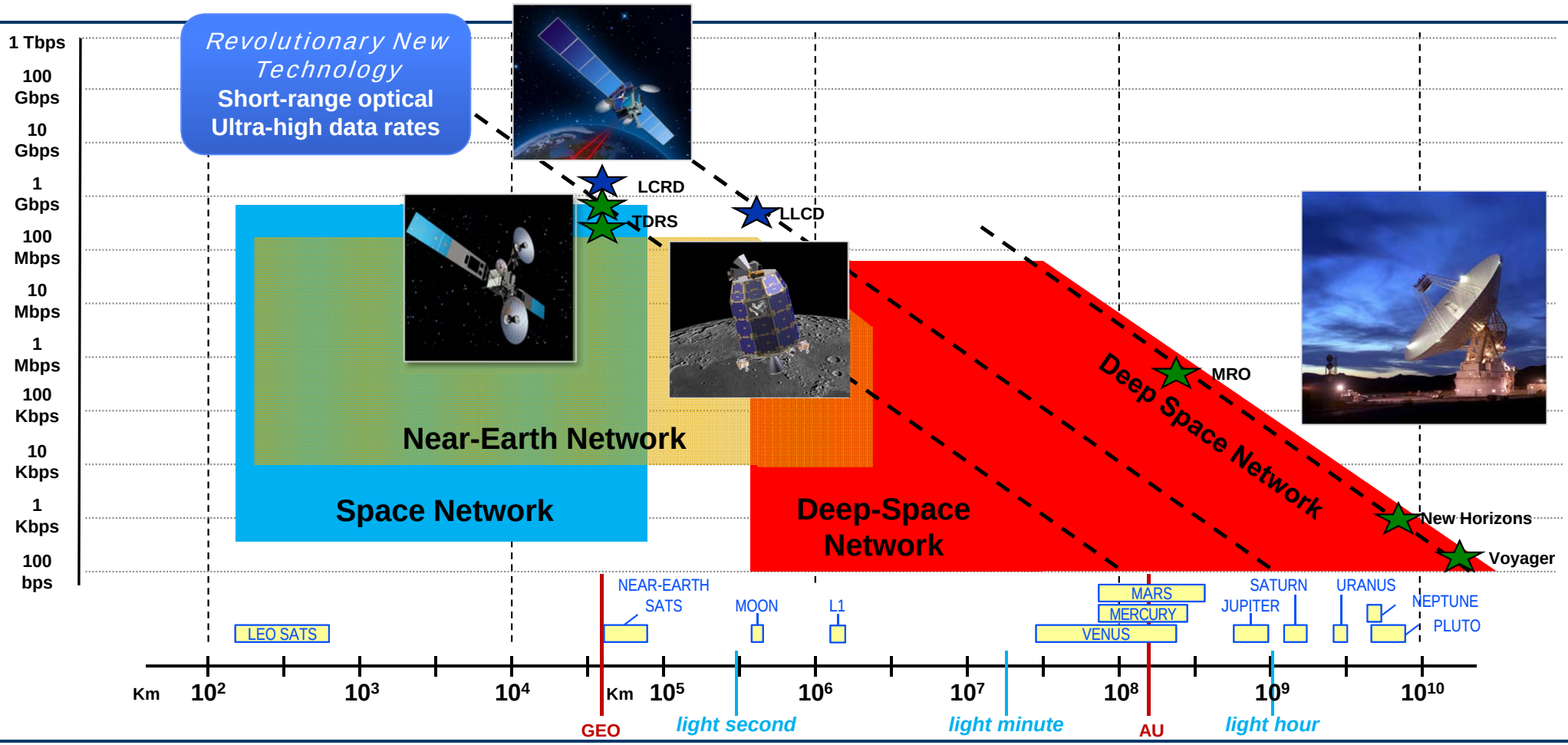


Deep Space Terminal (30 cm)



Subassemblies for initial NGT prototype are being developed by industry

NASA Space Communication Challenges

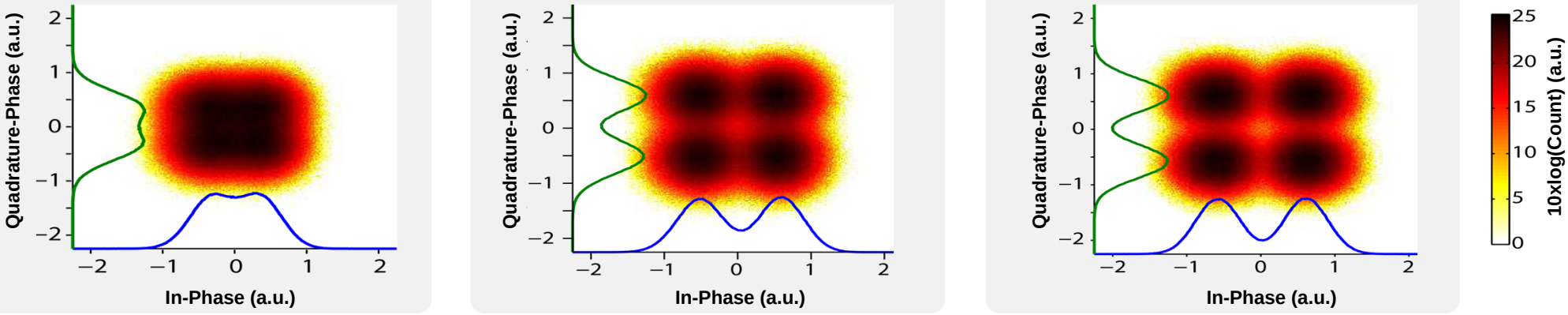


Coherent Optical Receiver Technology

25 Gbps QPSK
25 GHz Symbol Clock
Rate-1/2 FEC

40 Gbps QPSK
25 GHz Symbol Clock
Rate-4/5 FEC

45 Gbps QPSK
25 GHz Symbol Clock
Rate-9/10 FEC



- **High-sensitivity scalable multi-aperture receivers**
- **High data-rate communications leveraging fiber-optic communications technology**

MIT-LL is developing high-rate efficient coherent modem technologies for lasercom applications

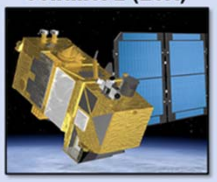
Low-Earth Orbit Direct-to-Earth Optical Links

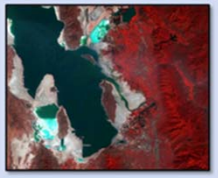
Transmitter
0.5 W,
2-cm Telescope

- **Large data volume – many Terabytes per day!**
- **Small space terminal – CubeSat scale!**
- **Small, low-cost ground terminal – widely deployable!**

200 Gbps Downlink from LEO can deliver 7 Terabytes per day to single ground station

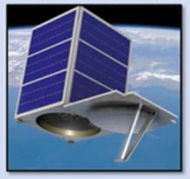
Sentinel-2 (ESA) **Environmental Monitoring**





- Multispectral imaging, 10-60m resolution
- Generates ~450 Mbps (compressed)
- Downlinks ~0.5 Terabytes per day via geosynchronous relay
- Continuous operation would generate ~4.9 Terabytes per day

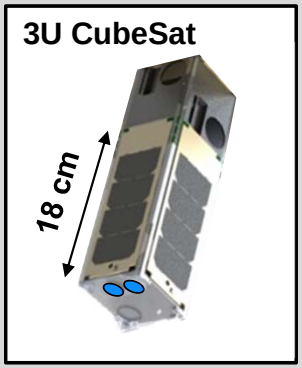
SkySat (SkyBox) **Still Image from HD Video**



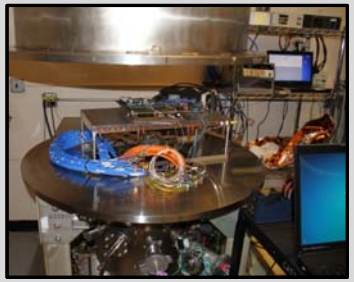
- 1080p HD video, 1m resolution
- Generates ~100 Mbps (compressed)
- Downlinks ~0.2 Terabytes per day direct to Earth
- Continuous operation would generate ~1.1 Terabytes per day

Receiver
40-cm
Telescope

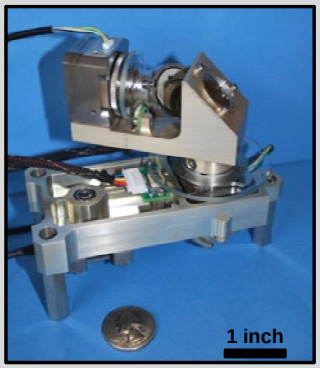
DTE Risk Reduction Efforts



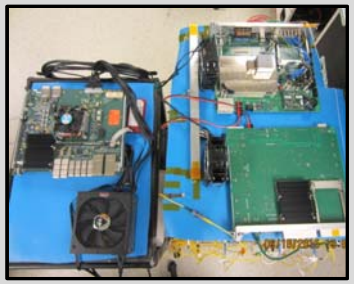
- Concept for 1.8U lasercom payload being developed with NASA SCaN
  - Working with NASA STMD to procure a CubeSat



- Space qualification of COTS components
  - Vacuum
  - Thermal
  - Vibration
  - Radiation

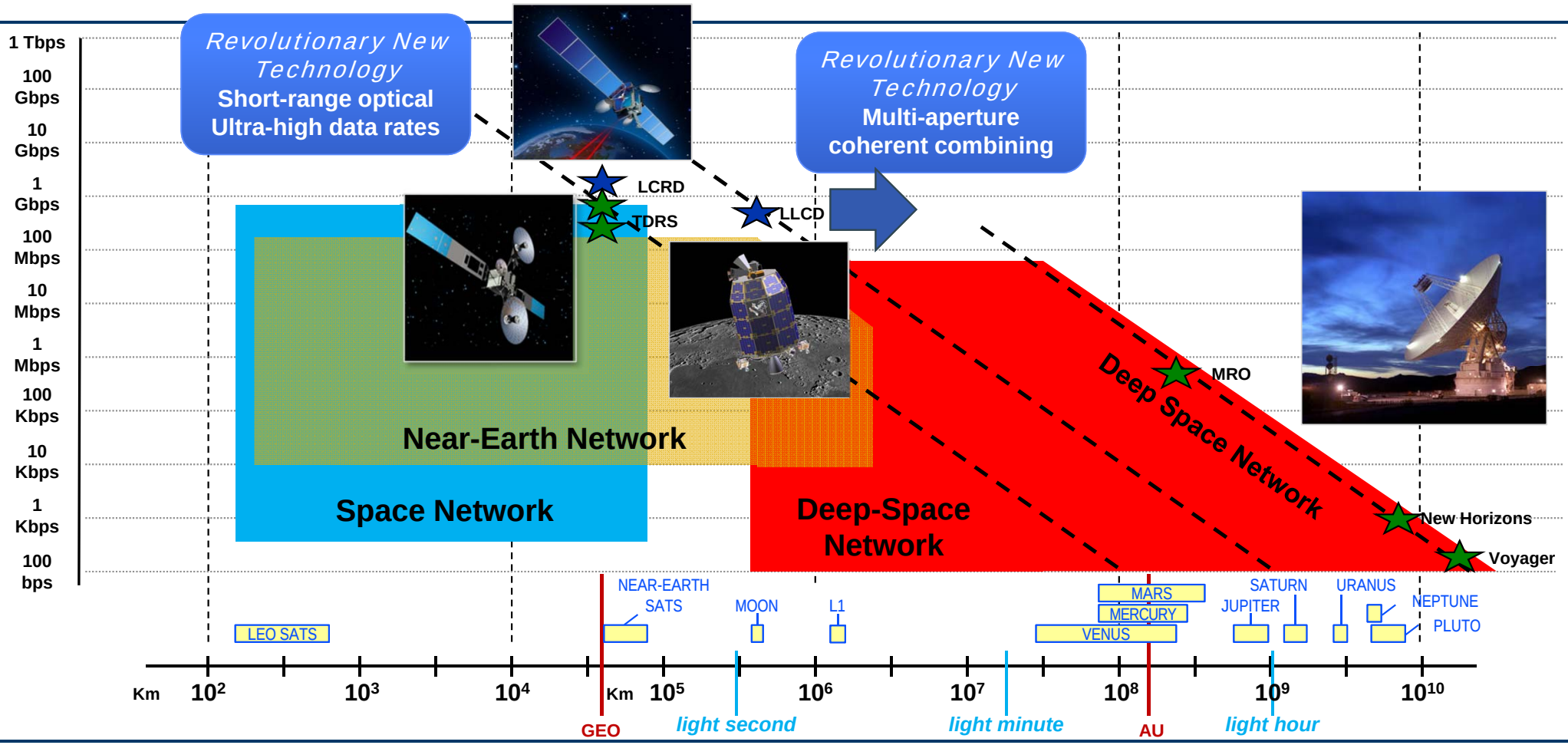


- Compact Beam Director
  - 1-2 cm aperture
  - 0.5 kg
  - Hemispherical field of regard



- End-to-end comm testbed
  - Fading channel emulator
  - High-bandwidth data buffer

NASA Space Communication Challenges

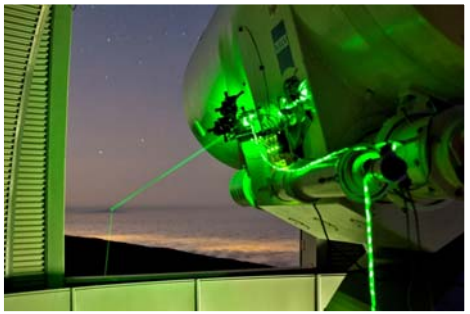


Large Scientific-Class Ground Terminals

- Historically require fixed-site high-cost installations
- Typically utilize large >1-m telescope apertures
  - Coupled via coudé path to laboratory class optical tables
- Examples include:
  - JPL's Mount Palomar Hale 5.1-m Telescope
  - JPL's 1-m Optical Communication Telescope Laboratory (OCTL)
  - ESA's 1-m Teide Observatory in Tenerife, Spain

Mt. Palomar 5.1-m Hale Telescope

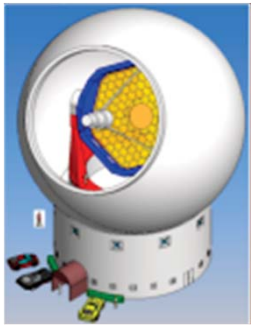
Table Mountain 1-m OCTL Telescope



Teide Observatory 1-m Telescope

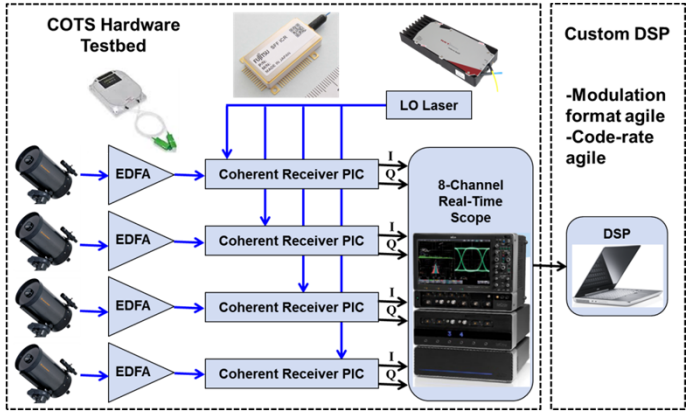
Next-Generation Optical Gateway Concepts

- **Which solution is best for large area optical ground stations?**
  - **Cost for equivalent performance**
  - **Daytime operation and pointing near the sun**

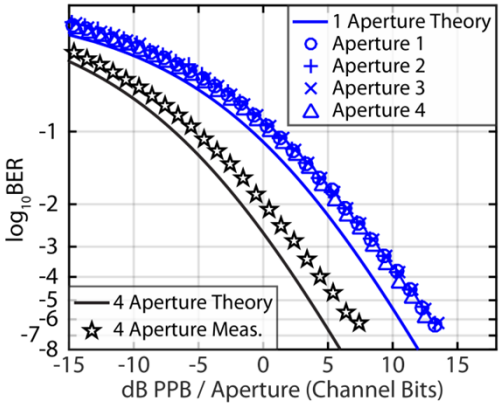


NASA Integrated Telescope

- **12-m aperture diameter**
- **~100 Hexagonal segmented mirrors**
- **Dedicated for optical communications**



Lossless Coherent Combining



Coherent Multi-Aperture Array

- **Leverage COTS telescopes and telecom components**
- **Develop custom DSP algorithms to support multi-aperture arrays for next generation optical ground terminals**

Summary

Findings:

- Lasercom offers higher rates and reduced SWaP for space communications
  - Requires cloud-free line-of-sight
- Lasercom has been matured to at least TRL-6 and is ready for transition to operations
- Space-to-air/space and space-to-ground has been matured to TRL-6 or beyond
- Lasercom is an enabling technology for other important links
  - Air-to-air, LEO and deep-space

Recommendations:

- Insert lasercom into program-of-record, e.g. relay
- Invest in manufacturability
- Continue R&D on other links

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