Optical Communication Flight Systems

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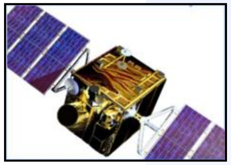
Optical Comm Demonstrations and Systems

< 2002 | 2002 | 2004 | 2006 | 2008 | 2010 | 2012 | 2014 | 2015+

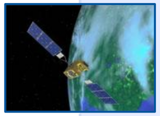
LCE (Japan)
GEO-Ground
1995

ALEX (MITLL)
Air-GEO
2002



GEOLITE (MITLL)
GEO-Ground
2001

SILEX (ESA)
50 Mbps LEO-GEO
2001

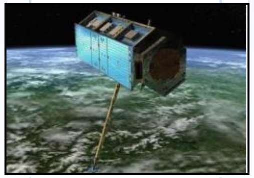


OICETS (Japan)
LEO-GEO 50 Mbps
LEO-Ground
2005

LOLA (France)
50 Mbps
2006

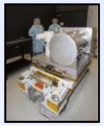
FOCAL (SAF/MITLL)
Air-Ground 2.5 Gbps
2009

FALCON (AFRL)
Air-Ground 2.5 Gbps
2010



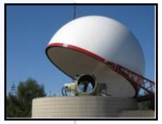
NFIRE/TerraSar
(ESA/FRG/MDA)
LEO-LEO 5.6 Gbps
2008

LLCD (NASA/MITLL)
Moon-Ground 622 Mbps
2013

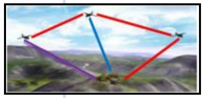


OPALS (NASA/JPL)
2014

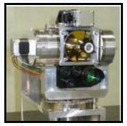
Alphasat (ESA)
GEO-LEO 1.8 Gbps
2013-14



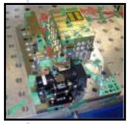
HY-2 (China)
LEO-Ground, 504 Mbps



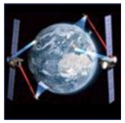
FOENEX (DARPA)
Air-Air 10 Gbps
Air-Ground
2012



SOTA (Japan)
2014

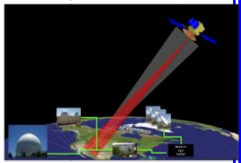


OSIRIS (DLR)
2016



EDRS/Sentinal (ESA)
2015

LCRD (NASA)
2019



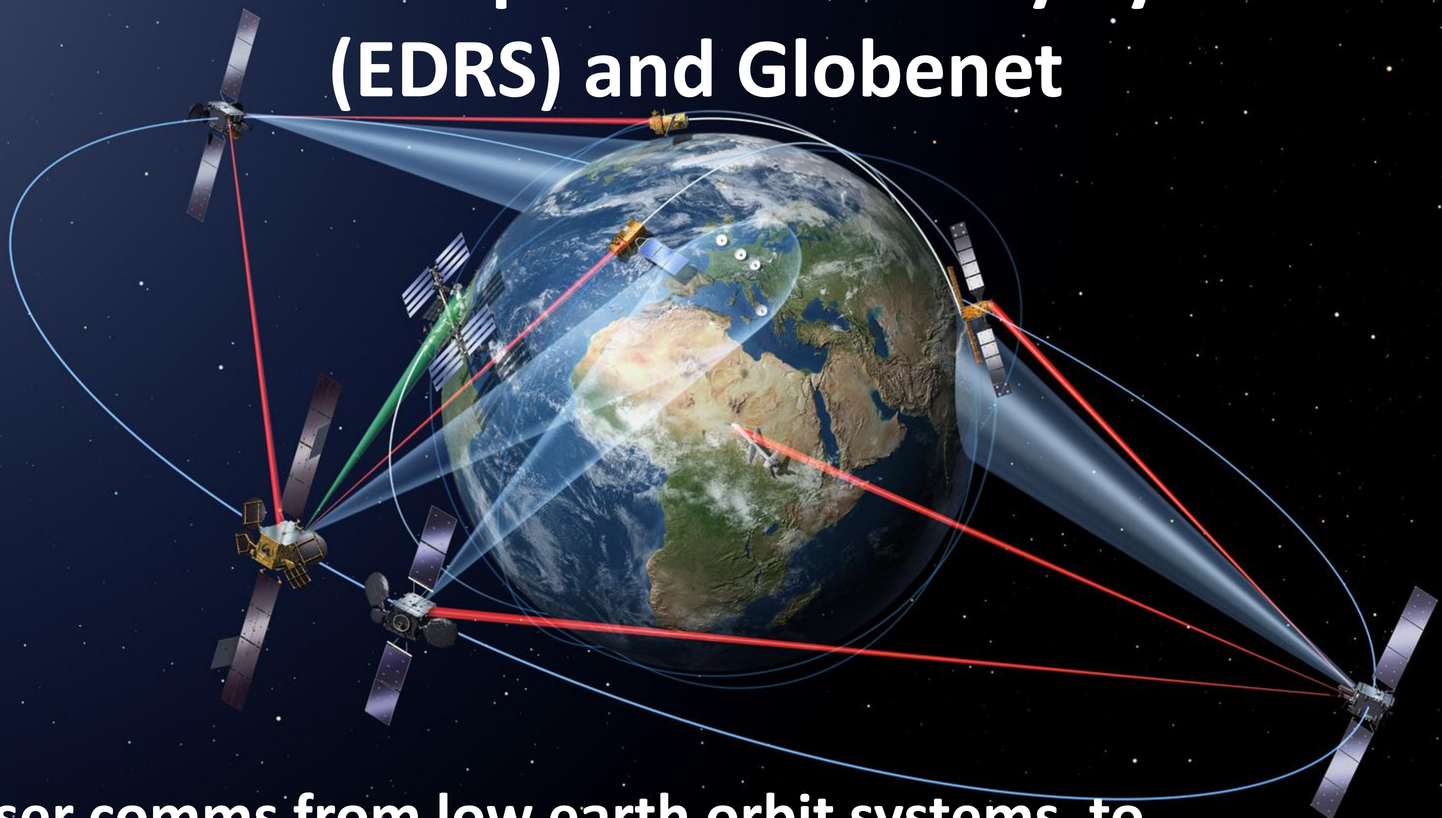
DSOC (NASA)
2021

Outline

- **Near-Earth lasercom systems**
  - **Charts provided by Frank Heine, TESAT**

- **Deep space lasercom systems**

European Data Relay System (EDRS) and Globenet



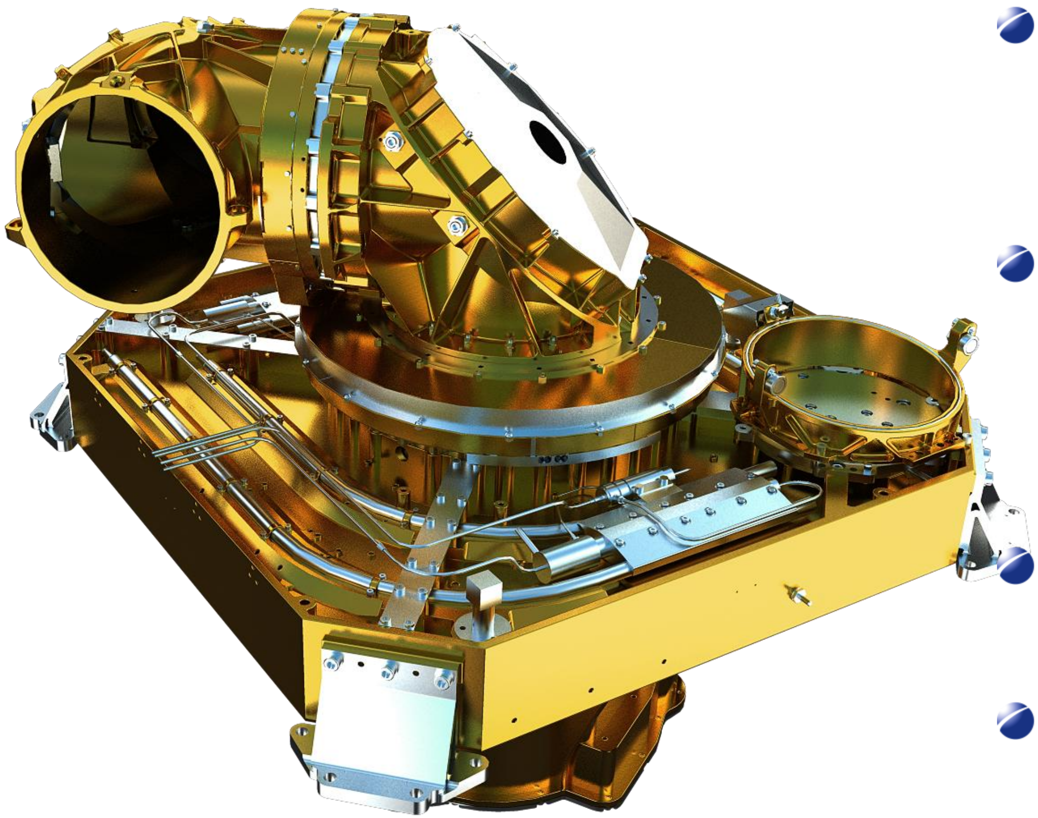
ESA

Laser comms from low earth orbit systems to geostationary platforms, RF links to ground

11 LCTs up to now

5 already operational in space

The TESAT Laser Communication Terminal LCT



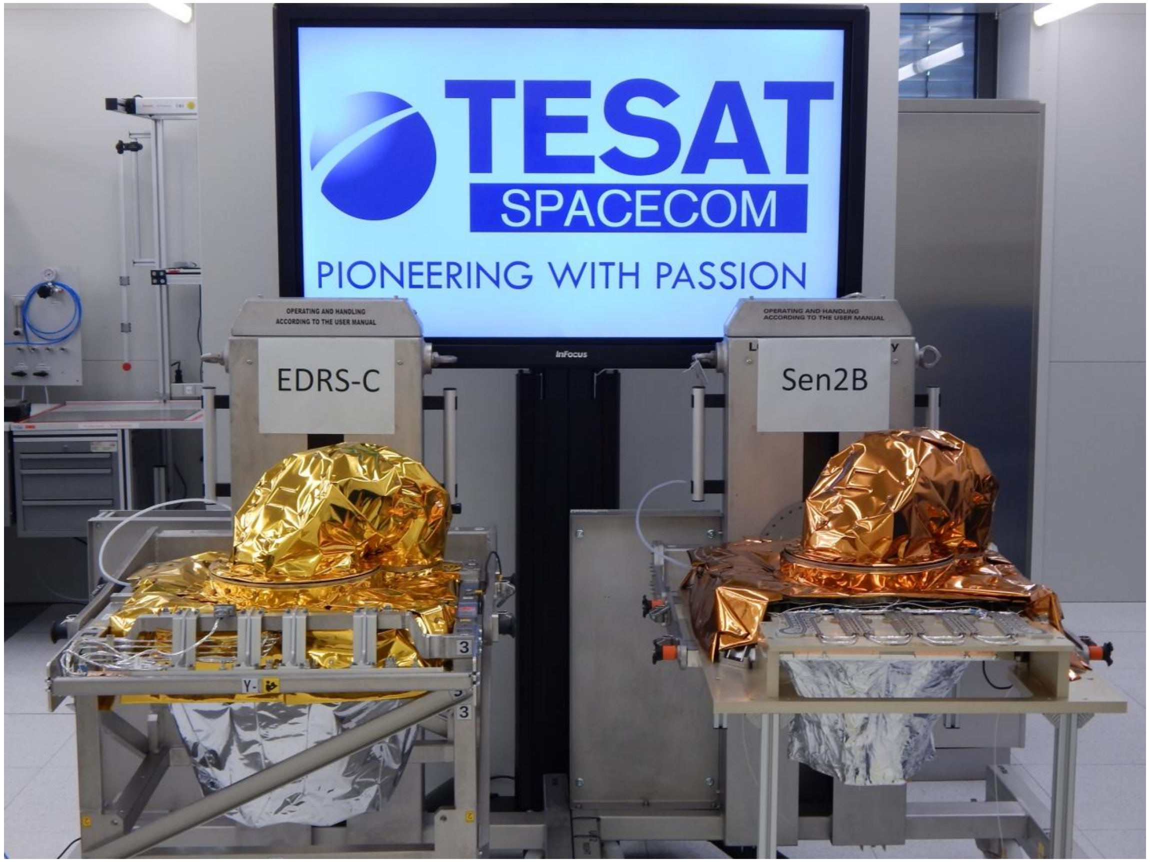
- **High Data Rate full-duplex**
  - 1.8 Gbit/s user data rate
  - 2.8 Gbit/s optical data rate
- **Homodyne BPSK**

  1064nm

  => Single frequency laser (NPRO Byer /Kane)
- **Beacon-Less spatial acquisition**
- **Single unit, SWaP**
  - 60*60*60 cm
  - 50kg
  - 160W max 120 W av.

LCT types

- GEO and LEO (photo April 2016)



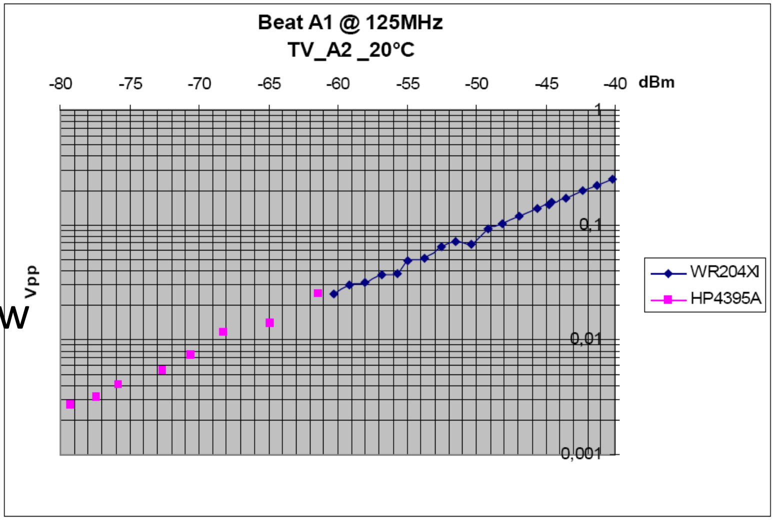
TESAT SPACECOM

Coherent Detection and BPSK

- Received light is mixed with a phase locked **single frequency** source on a photo diode, transfer of data from 300THz carrier to baseband

$$i_H = D\left\{\frac{1}{2}A_c^{\,2} + \frac{1}{2}A_o^{\,2} + A_c\,A_o\cos(\varphi_o - \varphi_c)\right\}$$

- Photocurrent has DC and AC part, AC part is the information
- Basically the RX light amplitude is multiplied by the strong local oscillator
- Phase locking builds an interferometer over link distance (> 45000 km)
- Receiver is shot noise limited (mW of local oscillator optical power on photo diode)
- Broad band background (Sun) is suppressed, penalty is less than 0.5d dB if Sun is in field of view
- Can detect single photons
- Most efficient system without bandwidth expansion (coding)
- PPM outperforms coherent detection with coding



Questions?

Frank Heine

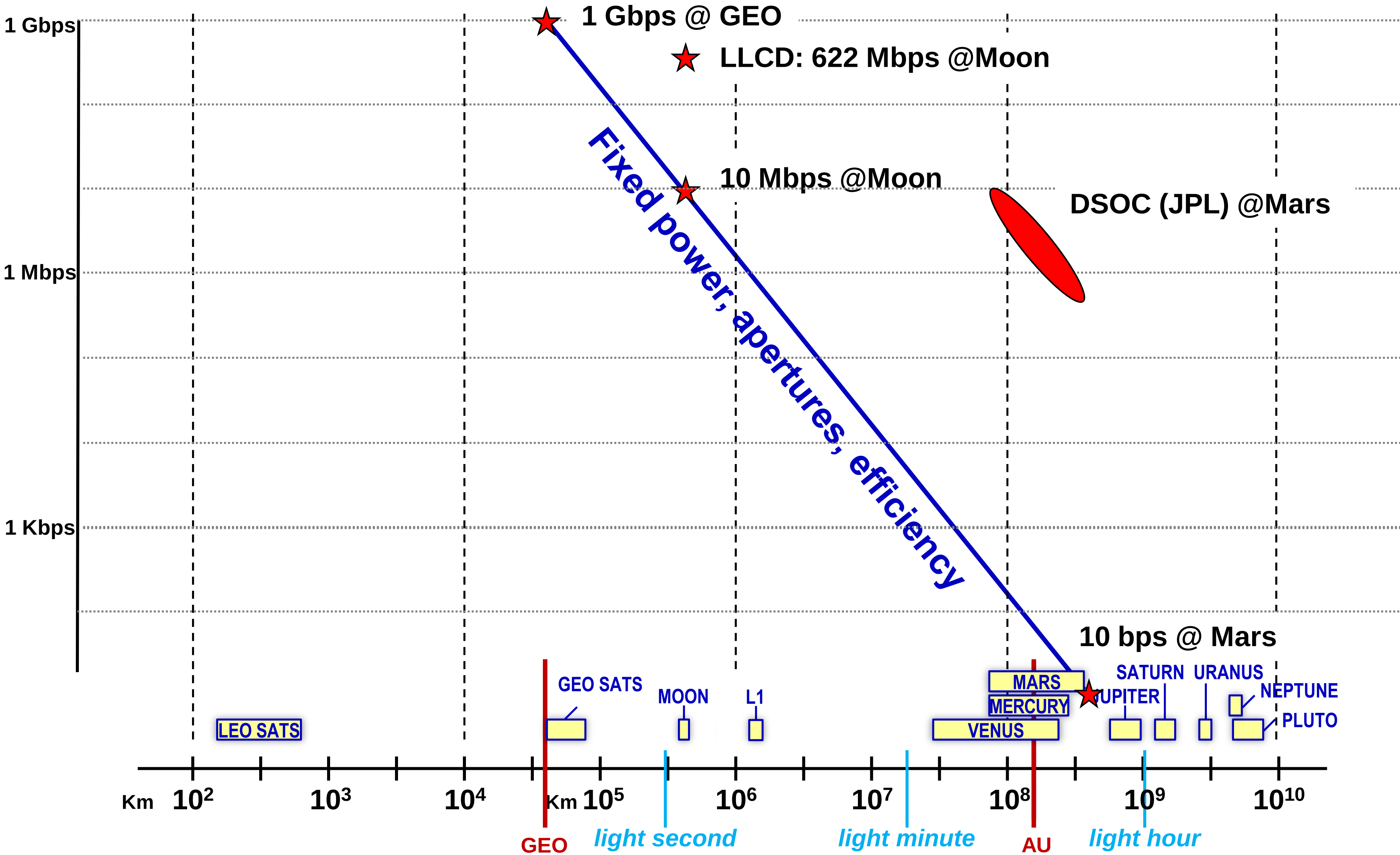
Head of LCT System Engineering
Frank.Heine@tesat.de

Outline

- **Near-Earth lasercom systems**
  - **Charts provided by Frank Heine, TESAT**

➡ **Deep space lasercom systems**

Optical Comm for Deep Space



Deep Space Communications Links

Space Terminal Aperture Gain

$$P_R = L_R A_R \frac{1}{4\pi R^2}\left(\frac{4\pi A_T}{\lambda^2}\right) L_T P_T$$

$$\text{DataRate [bits / sec]} = \frac{1}{\eta}\frac{P_R}{h\nu}$$

$P_{T/R}$ = Transmitted/Received Power

$L_{T/R}$ = Transmitter/Receiver Loss

$A_{T/R}$ = Transmitter/Receiver Aperture Area

R = Range

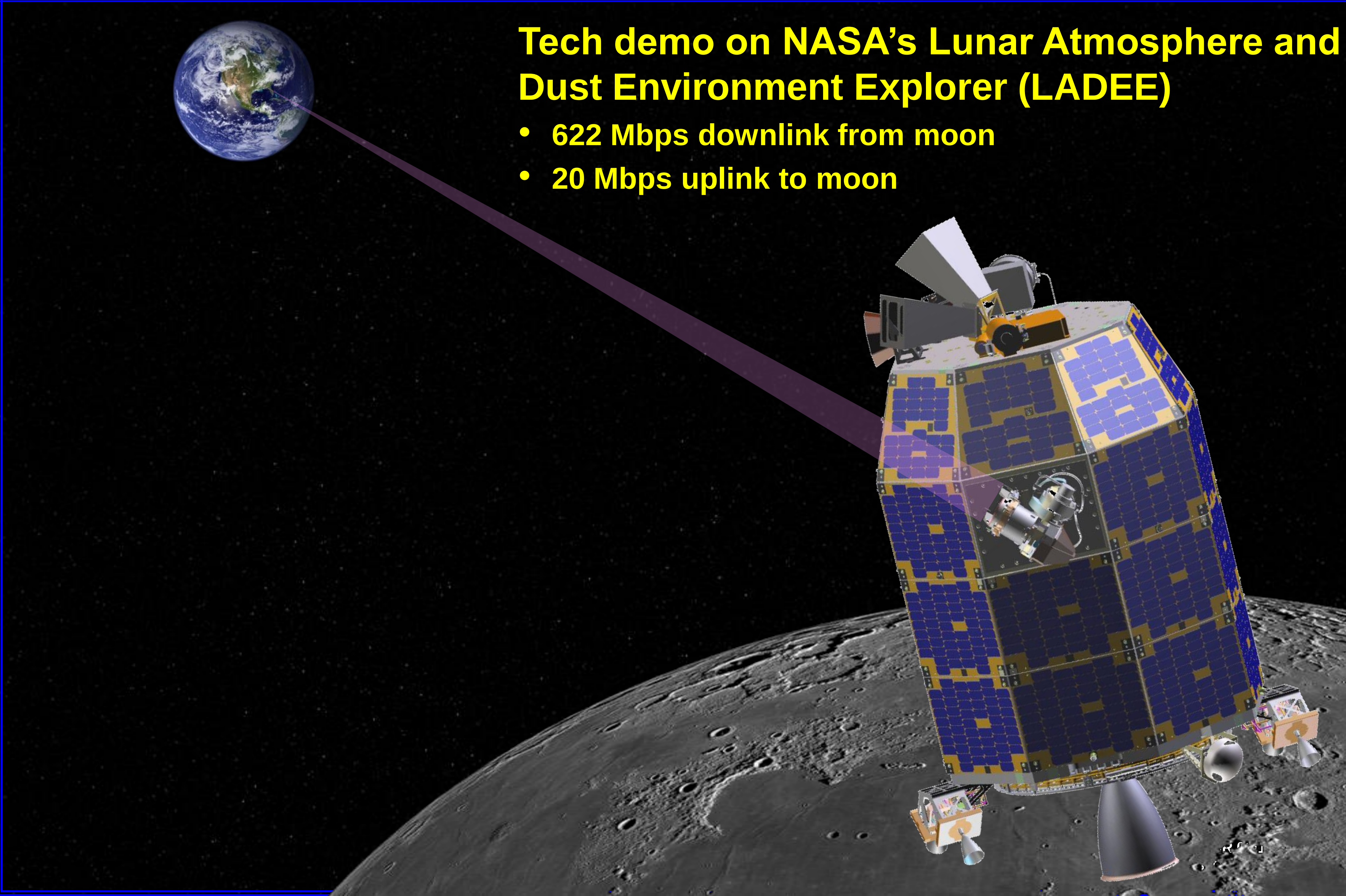
λ = Carrier Wavelength

ν = Carrier Frequency

Lunar Laser Communication Demonstration

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

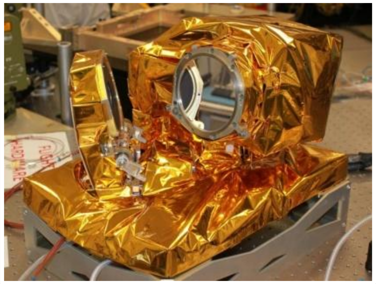
- 622 Mbps downlink from moon
- 20 Mbps uplink to moon



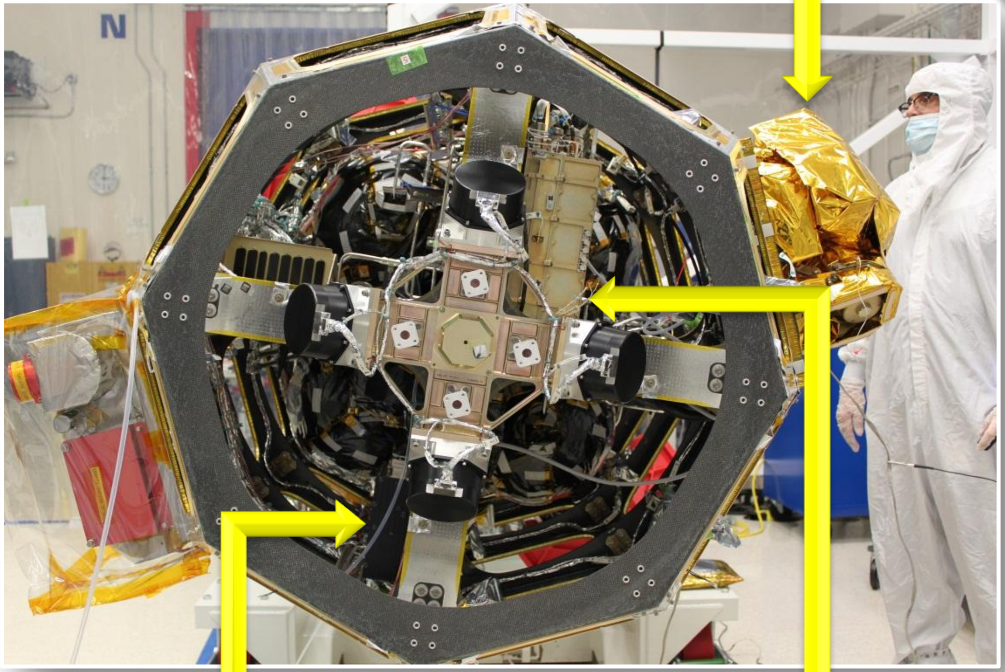
LLCD Space Terminal on LADEE

Modular design allowed for balanced placement in small spacecraft

LLCD Optical Module



0.5-W transmitter
4-inch telescope
Fully-gimballed
Inertial stabilization

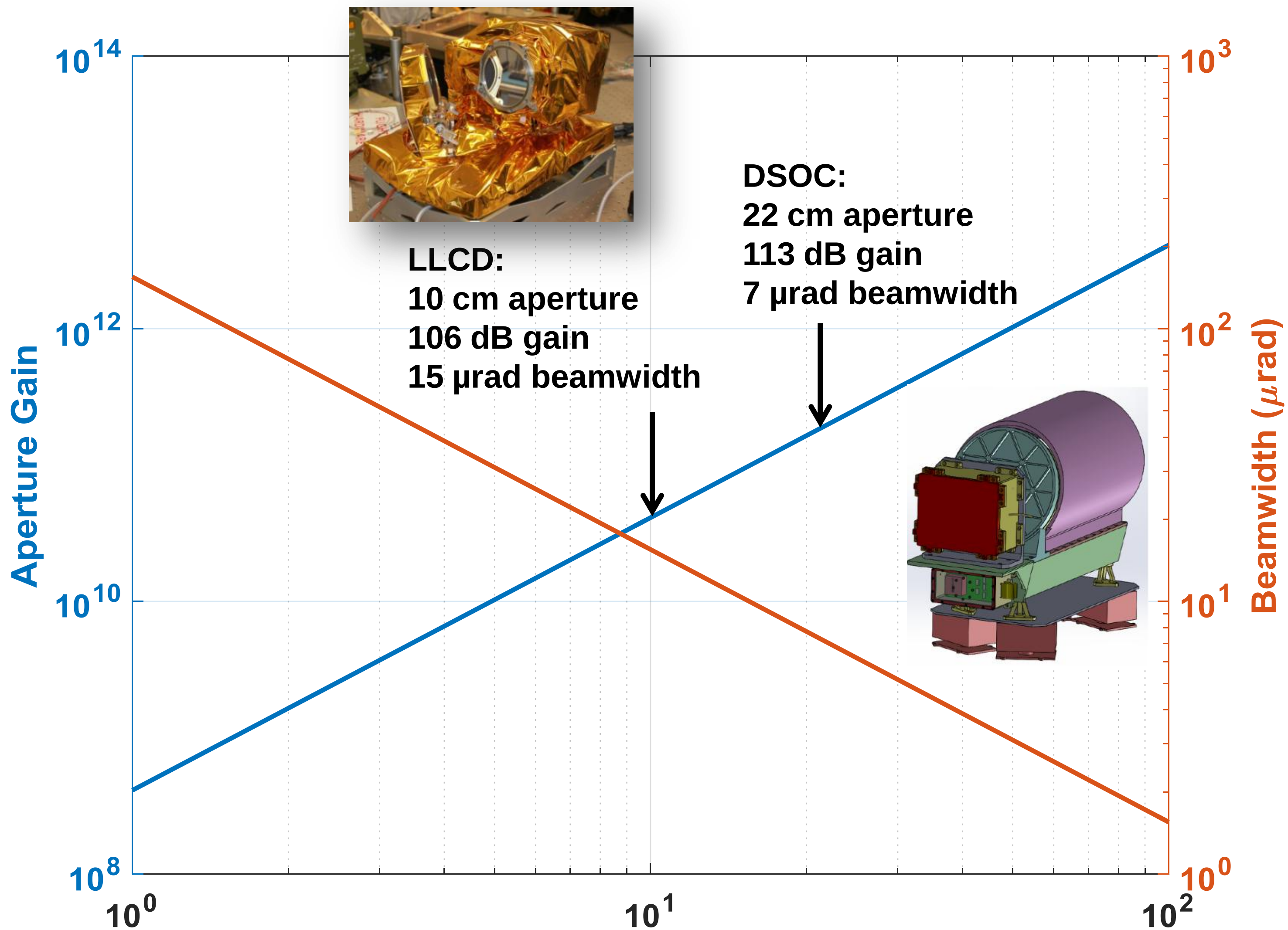


LLCD Controller Module

LLCD Modem Module

Space Terminal mass ~ 30 kg
Space Terminal power ~ 90 W

Transmit Aperture Gain



* At 1550 nm

Beam Size From Moon

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

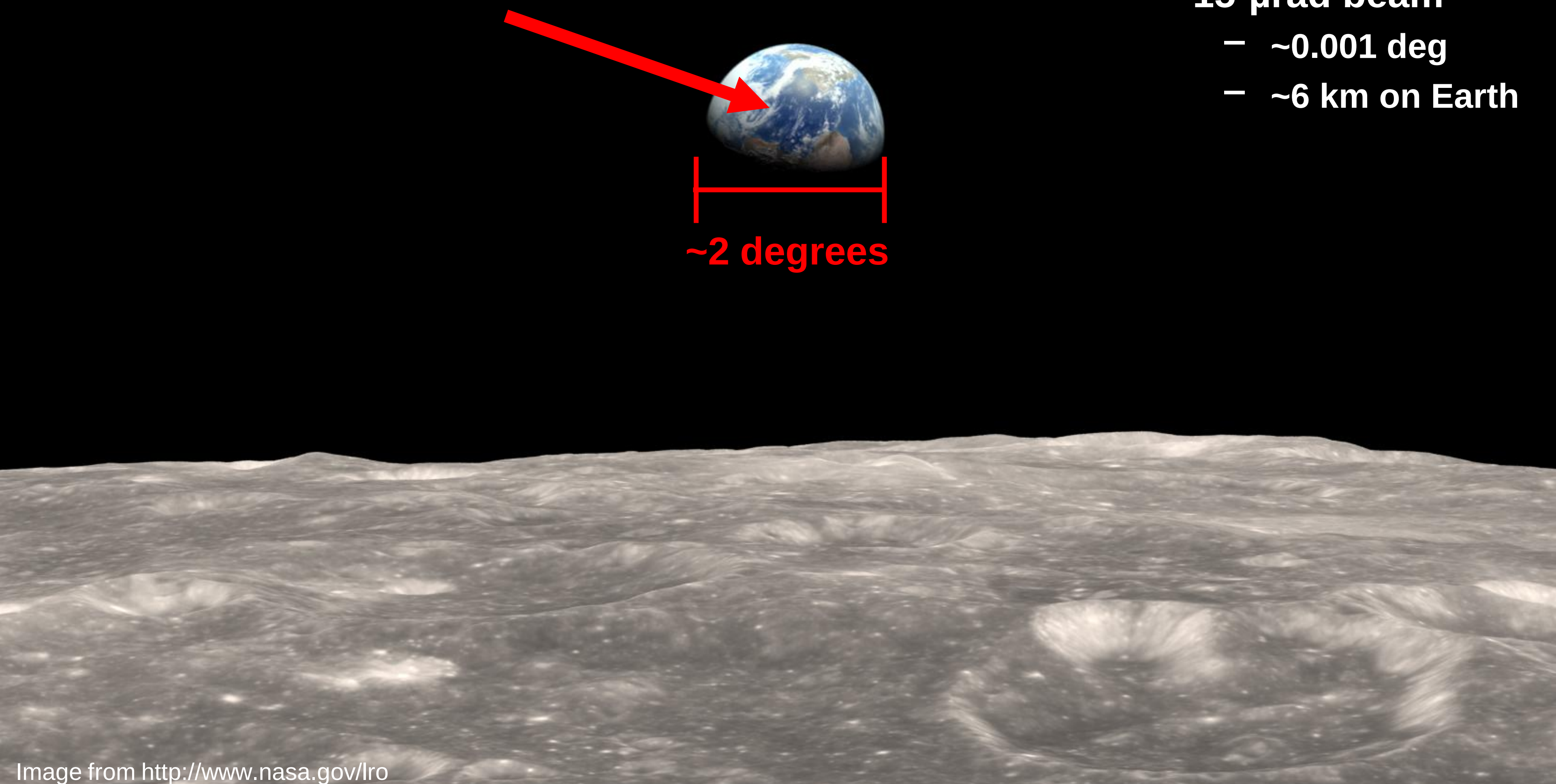
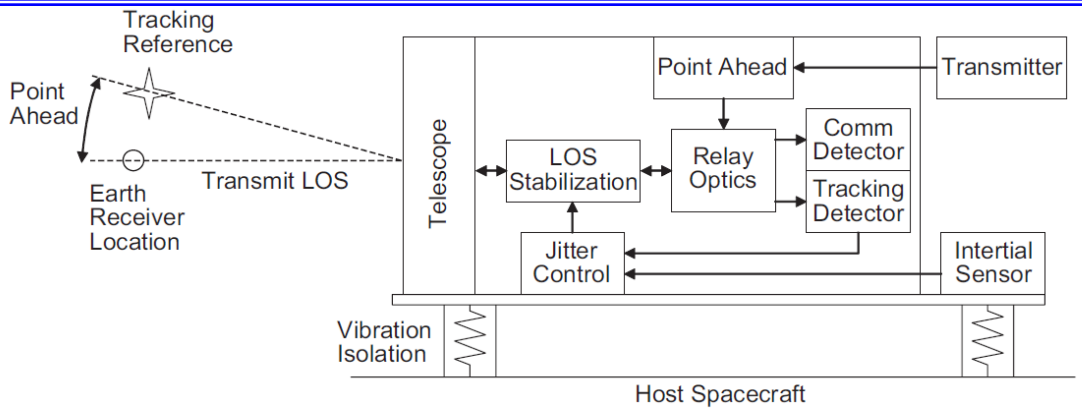


Image from http://www.nasa.gov/lro

Beam Stabilization



* Figure from “Deep Space Optical Communicaitons”, H. Hemmati, ed.

Disturbances

Terminal distortions | **Spacecraft and target motions** | **Platform vibrations**

0.1 — **1** — **10** — **100** — **1000**

Frequency (Hz) →

Stabilization Methods

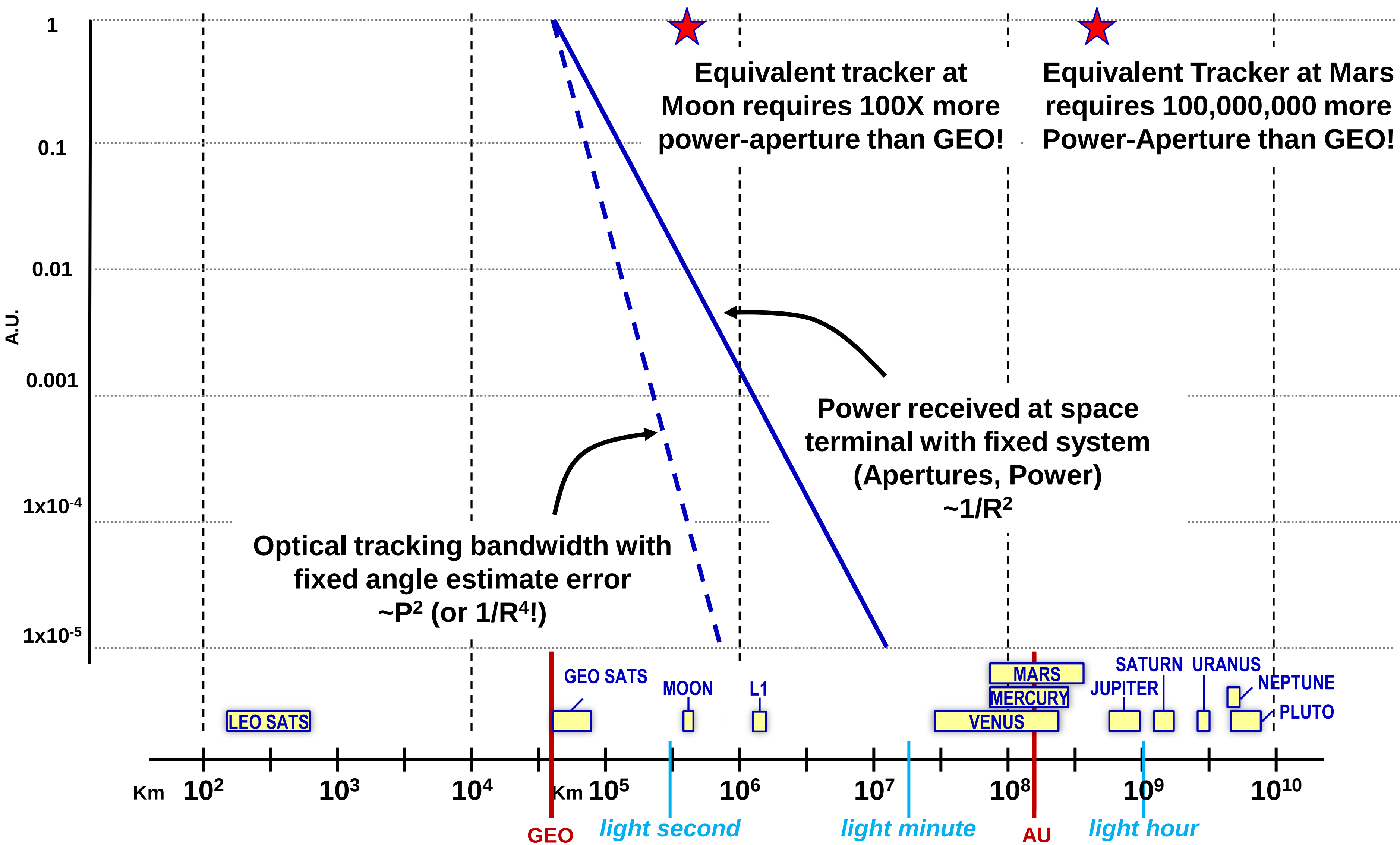
Passive Isolation

High BW tracking with beacon

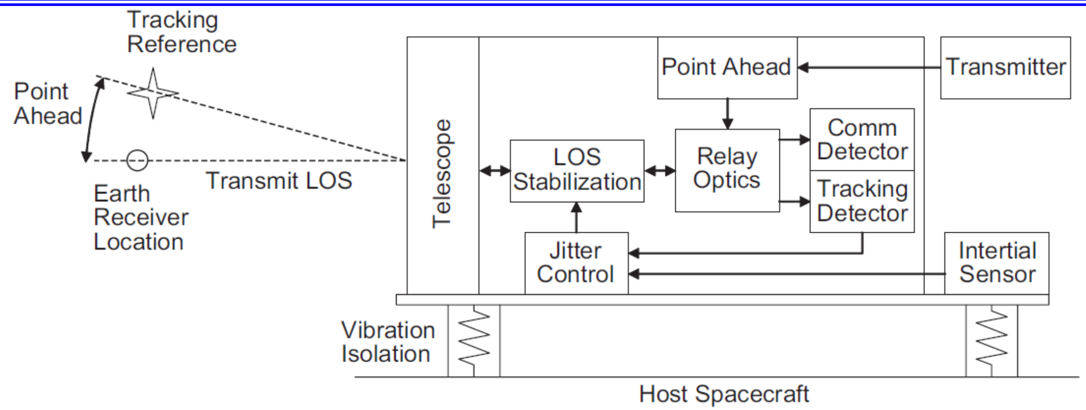
LLCD Approach

BW = Bandwidth

Tracking for Deep Space Optical Comm



Beam Stabilization



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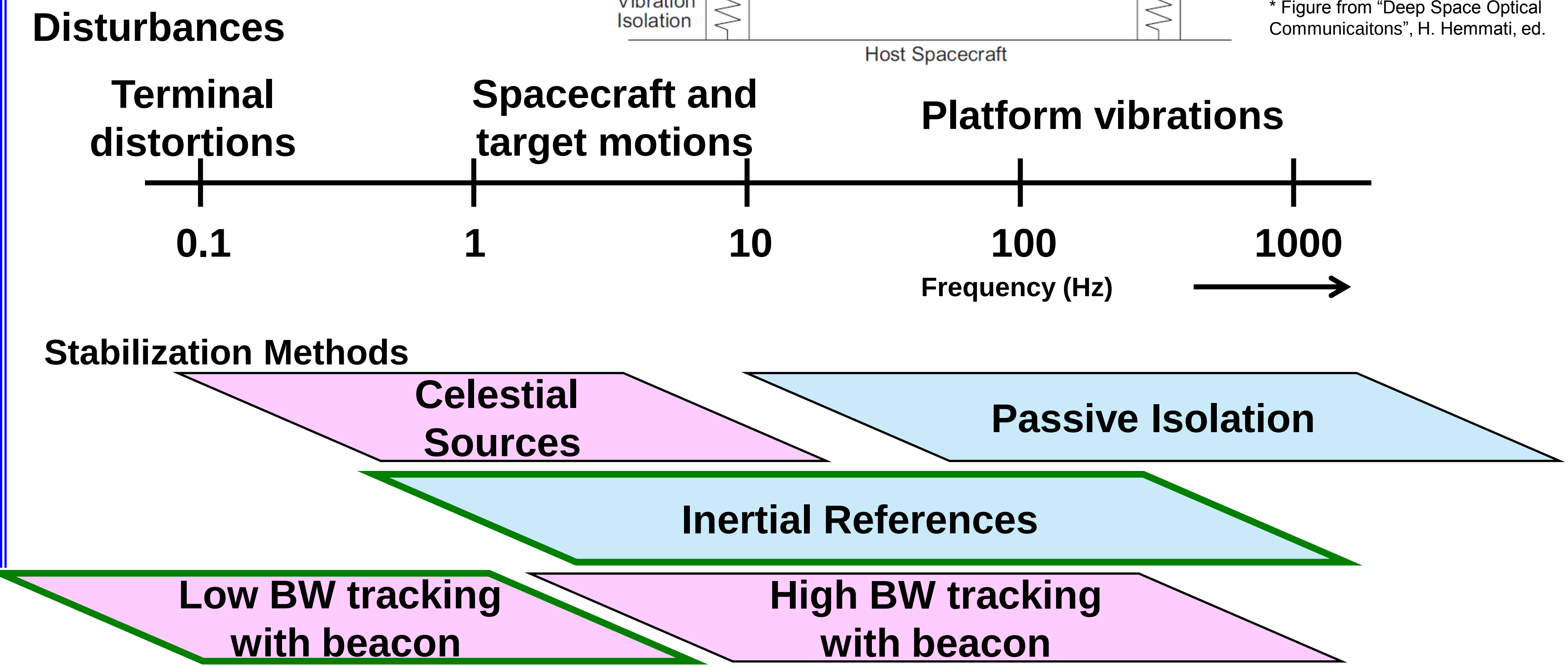
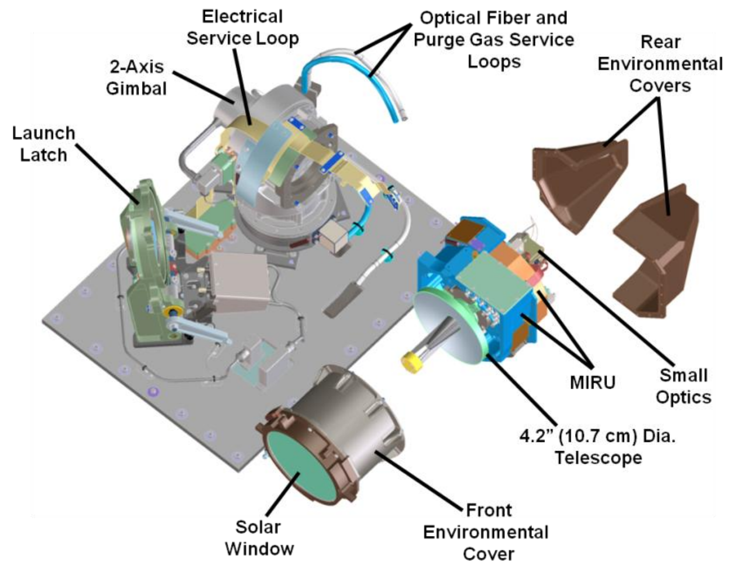
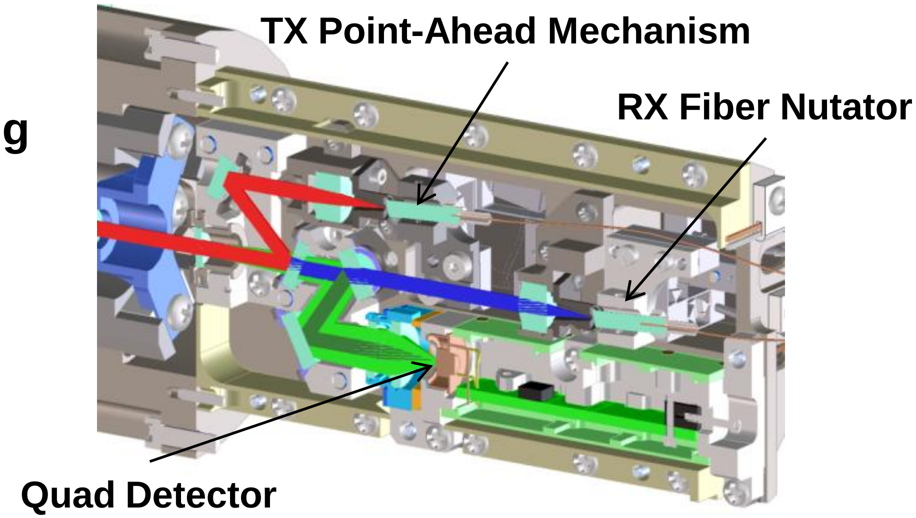


LLCD Approach

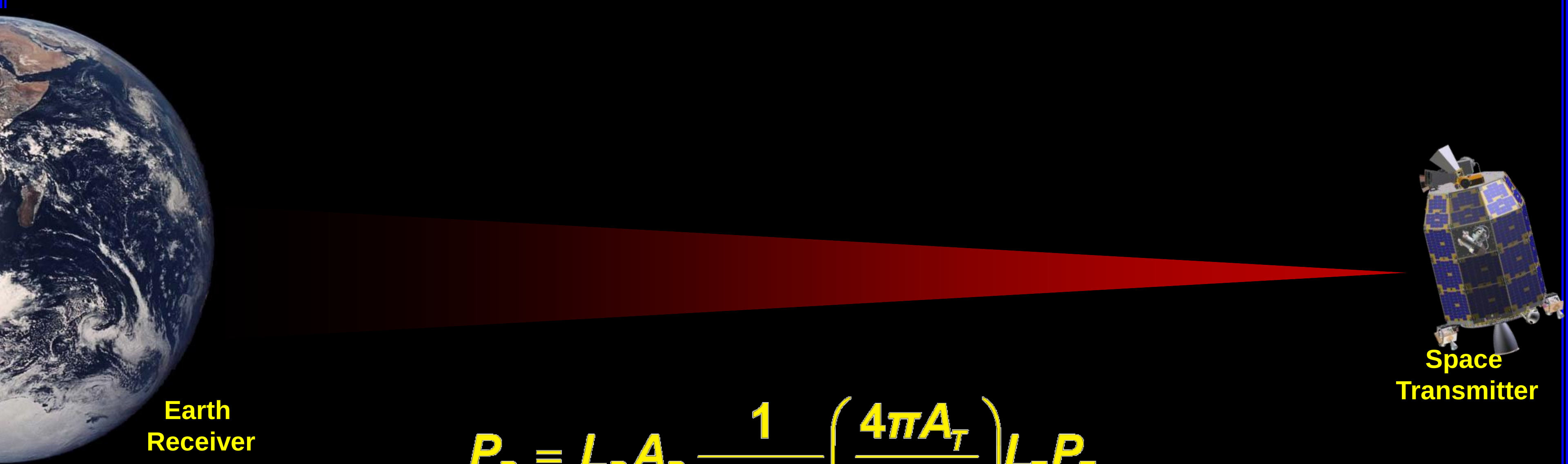
LLCD Space Pointing Systems

- **2-axis gimbal**
  - Provides coarse pointing
  - 55 deg az, +/- 10 deg el
- **Magnetohydrodynamic Inertial Reference Unit (MIRU)**
  - 2-axis angle rate sensors and voice-coil actuators
  - Rejects high-frequency (> ~few Hz) disturbances
- **Piezo-electric actuators**
  - Transmit fiber point-ahead mechanism
  - Receive fiber nutator for tracking uplink comm signal
- **Quadrant detector**
  - Detects uplink beacon
  - Coarse tracking during acquisition





Deep Space Communications Links



$$P_R = L_R A_R \frac{1}{4\pi R^2}\left(\frac{4\pi A_T}{\lambda^2}\right) L_T P_T$$

$$\text{DataRate [bits / sec]} = \frac{1}{\eta}\frac{P_R}{h\nu}$$

Receiver Efficiency (photons / bit)

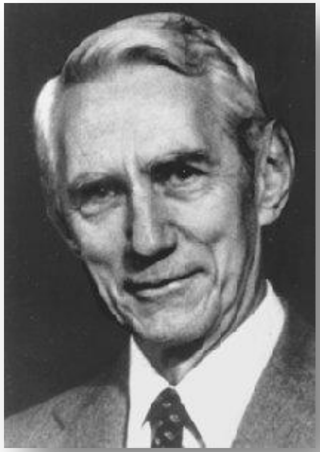
$P_{T/R}$ = Transmitted/Received Power
$L_{T/R}$ = Transmitter/Receiver Loss
$A_{T/R}$ = Transmitter/Receiver Aperture Area
R = Range
λ = Carrier Wavelength
ν = Carrier Frequency

Shannon Capacity for AWGN Channel

MIT Lincoln Laboratory

- The channel capacity, C, for a AWGN channel with bandwidth, W, received power, P_R, and noise variance $N_0/2$ is:

$$C = W \log_2\left(1 + \frac{P_R}{N_0 W}\right) [\text{bits}/\text{s}]$$



Claude Shannon

- For reliable data transfer, the data rate, R, over a channel must be less than C

$$R < W \log_2\left(1 + \frac{E_b R}{N_0 W}\right)$$

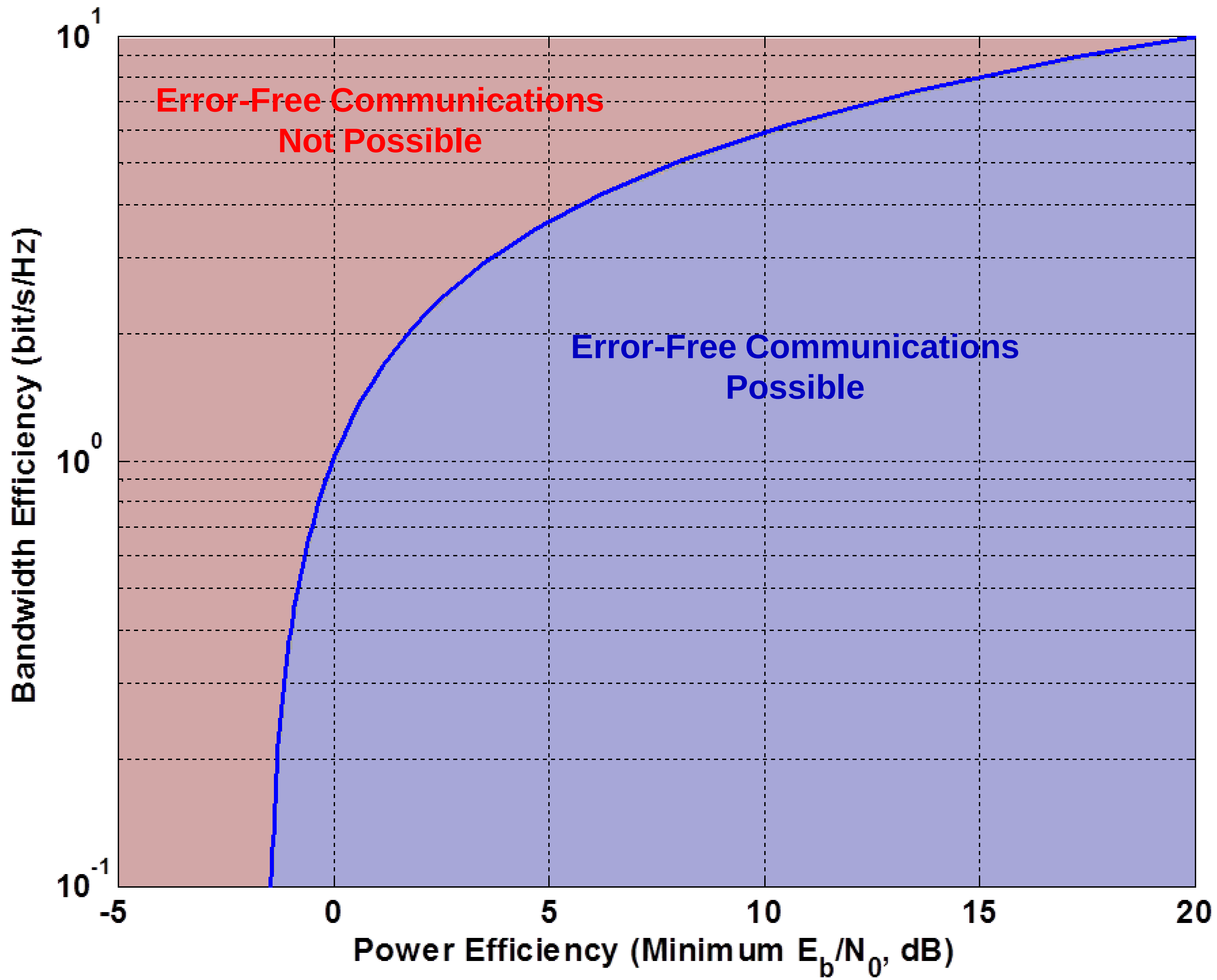
$$\Rightarrow \frac{E_b}{N_0} > \frac{2^{\frac{R}{W}} - 1}{\frac{R}{W}}$$

Power Efficiency (E_b/N_0)

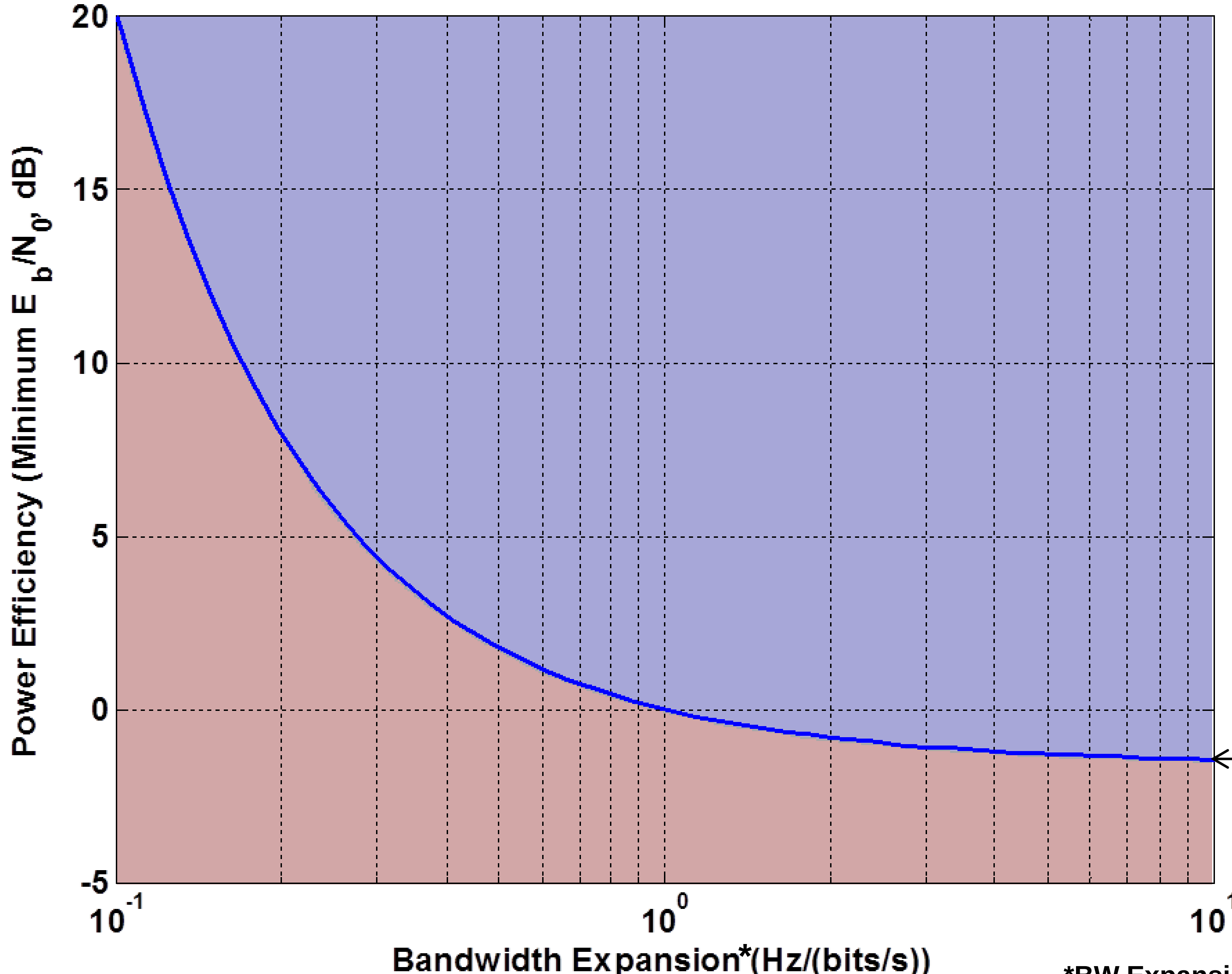
Bandwidth Efficiency (R/W) = Data Rate / Channel Bandwidth

AWGN = Additive White Gaussian Noise

Shannon Capacity for AWGN Channel



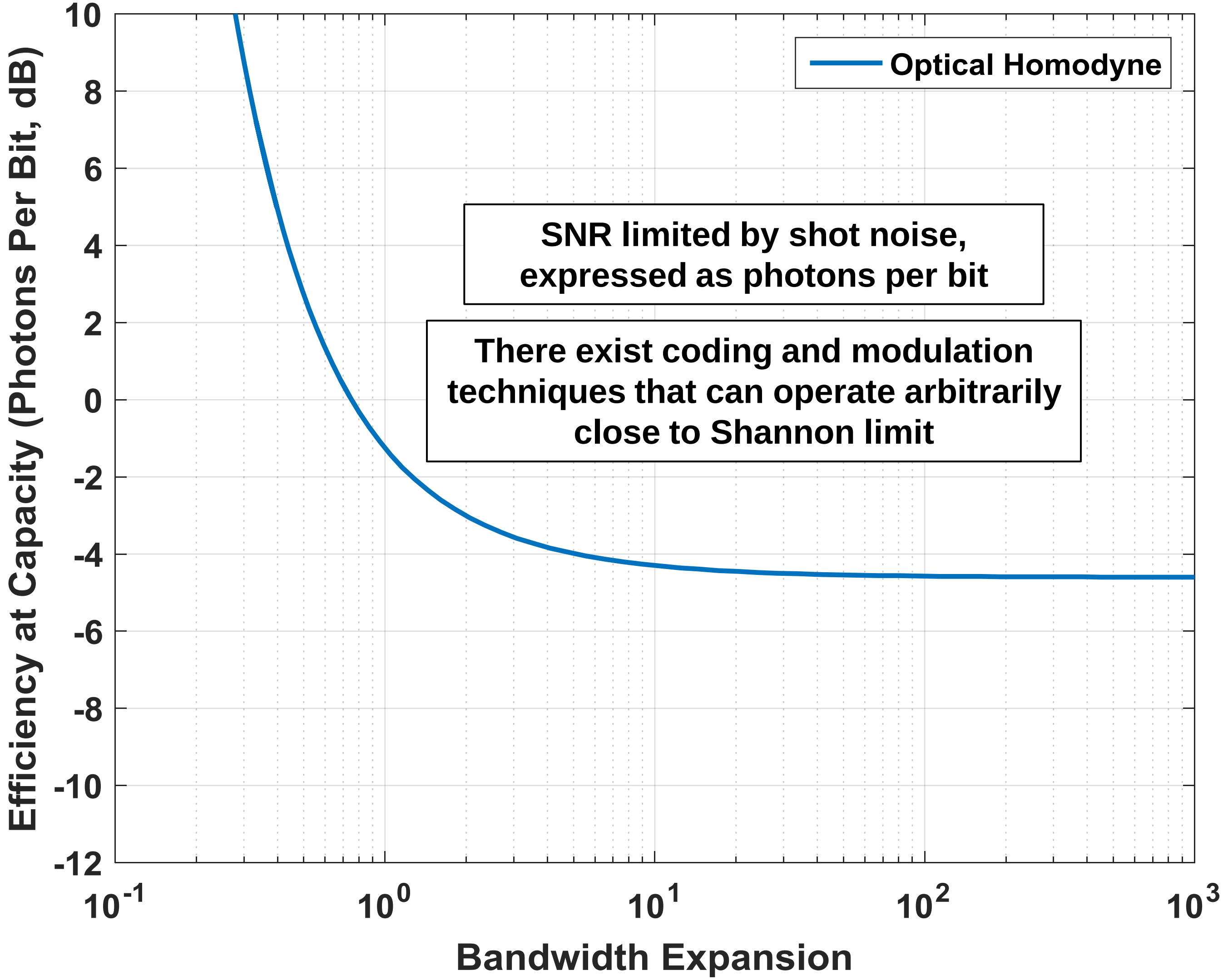
Shannon Capacity for AWGN Channel



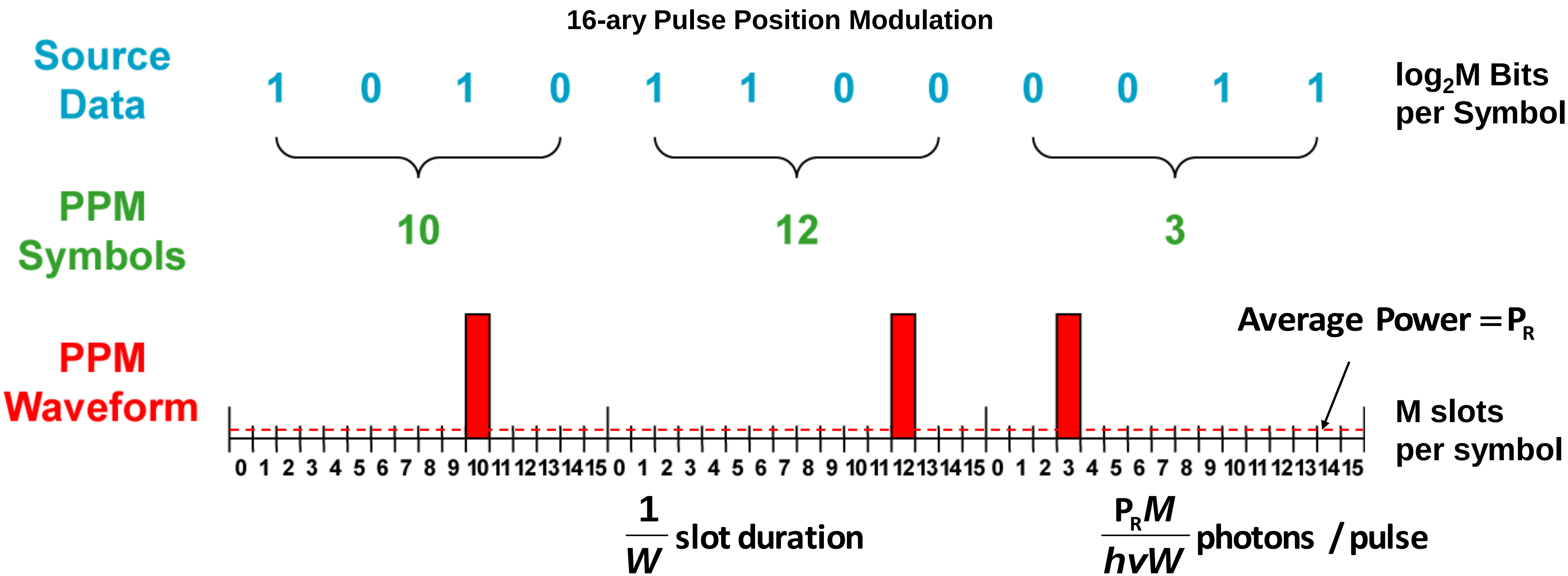
Limit of -1.6 dB for large bandwidth expansion

*BW Expansion = 1 / BW Efficiency

Optical Comm Efficiency



Pulse Position Modulation (PPM)



- In the absence of background, single photon detection provides $\log_2 M$ bits of information
- For single-photon detector, pulse detection probability is

$$1 - \exp\left(-\frac{P_R M}{h\nu W}\right)$$

PPM Channel Capacity

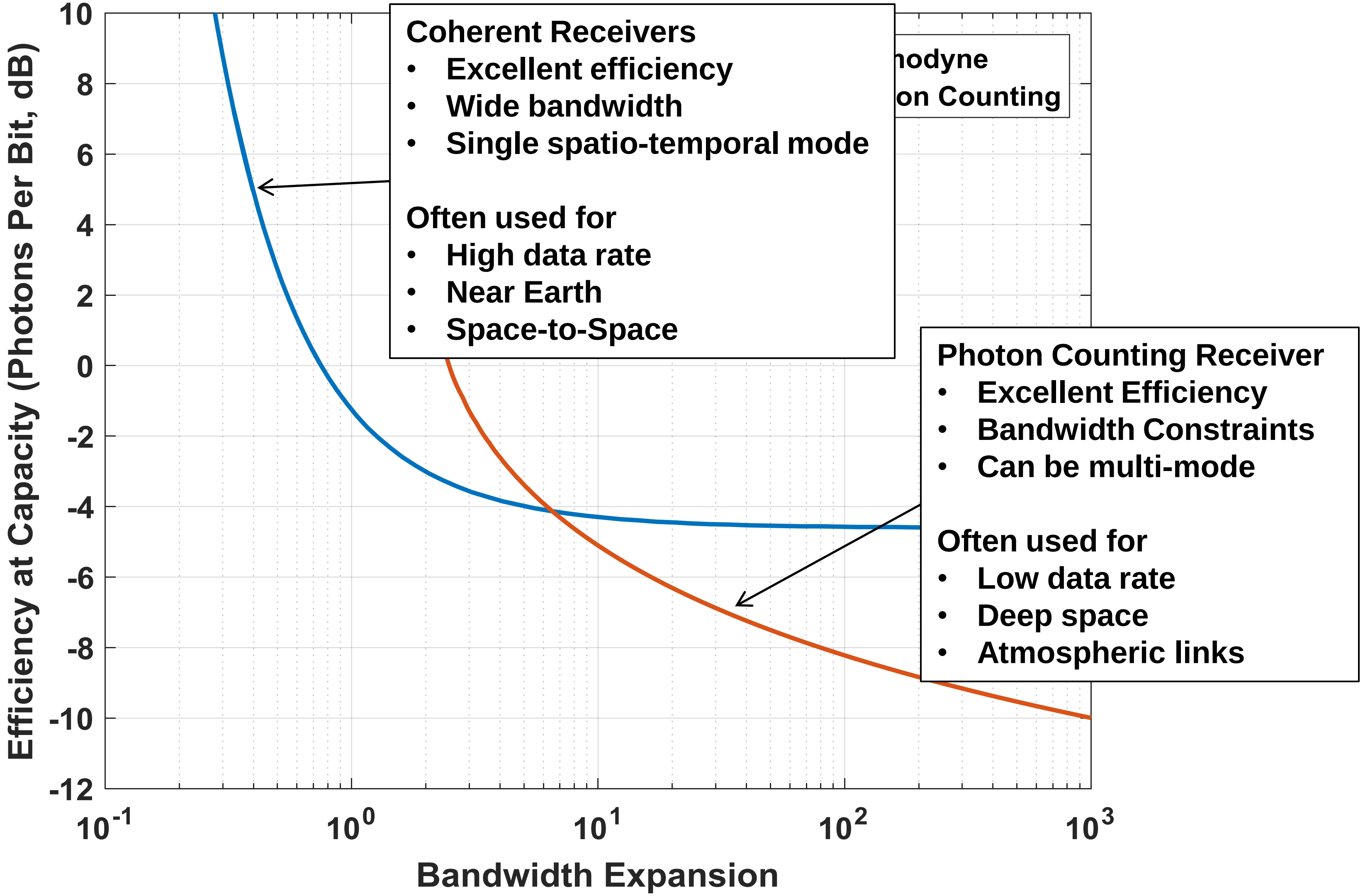
- Background-free photon-counting PPM channel capacity is

$$C = \left[\frac{W}{M}\right]\left[1 - \exp\left(-\frac{P_R M}{h\nu W}\right)\right]\log_2 M \quad \text{[bits / second]}$$

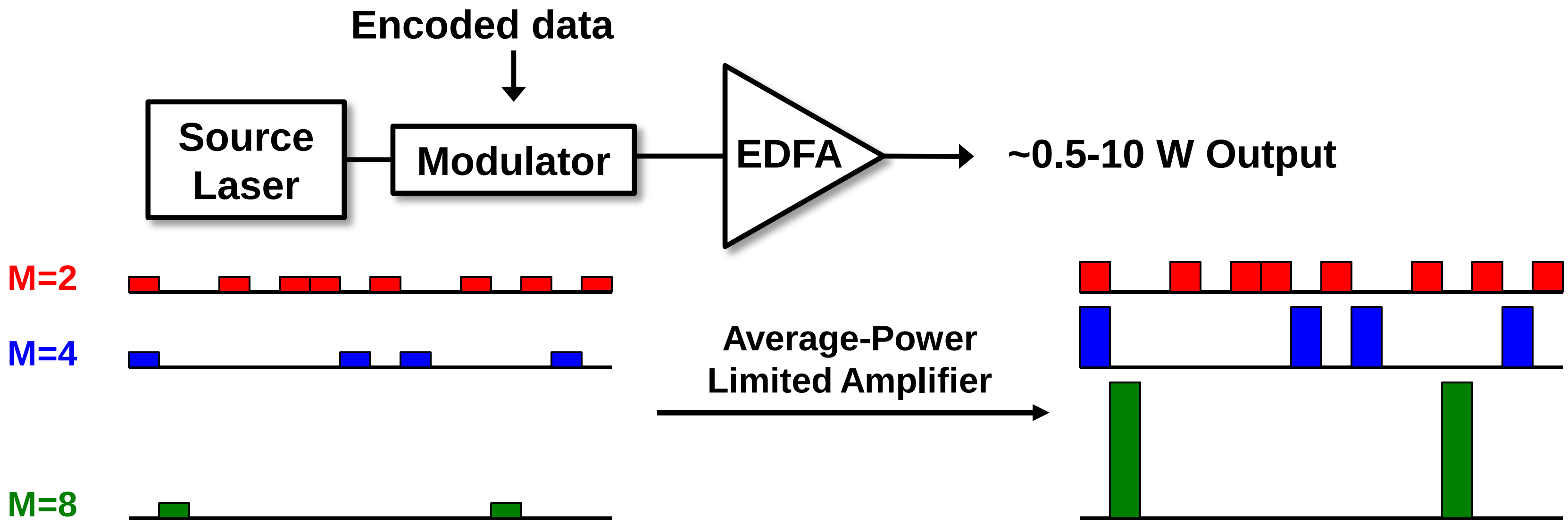
- Constraint for photon efficiency $\left(\eta \equiv \frac{P_R}{h\nu R}\right)$ as a function of bandwidth expansion $\left(\beta \equiv \frac{W}{R}\right)$ is

$$\eta > -\frac{\beta}{M}\ln\left(1 - \frac{M}{\beta \log_2 M}\right)$$

Optical Comm Efficiency

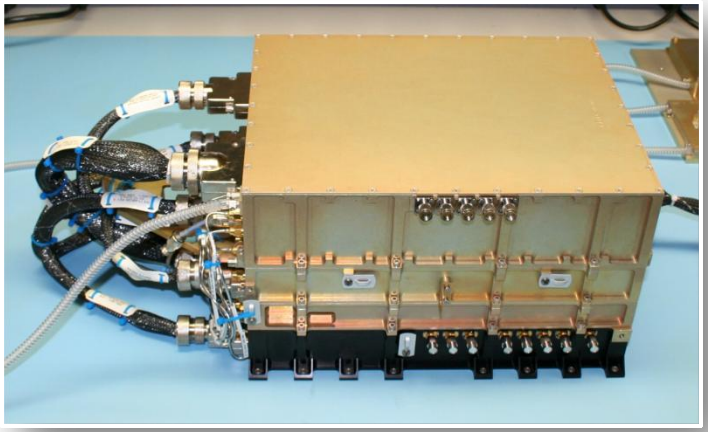


Downlink Optical Transmitter



LLCD Space terminal modem functions

- ***40-620 Mbps downlink***
  - ***½-rate FEC encode***
  - ***16PPM modulator***
  - ***0.5-W Erbium-doped fiber amplifier***
- ***10-20 Mbps uplink receiver***



LLCD Modem

EDFA = Erbium-Doped Fiber Amplifier

Lunar Lasercom Ground Terminal

Novel Transportable Design

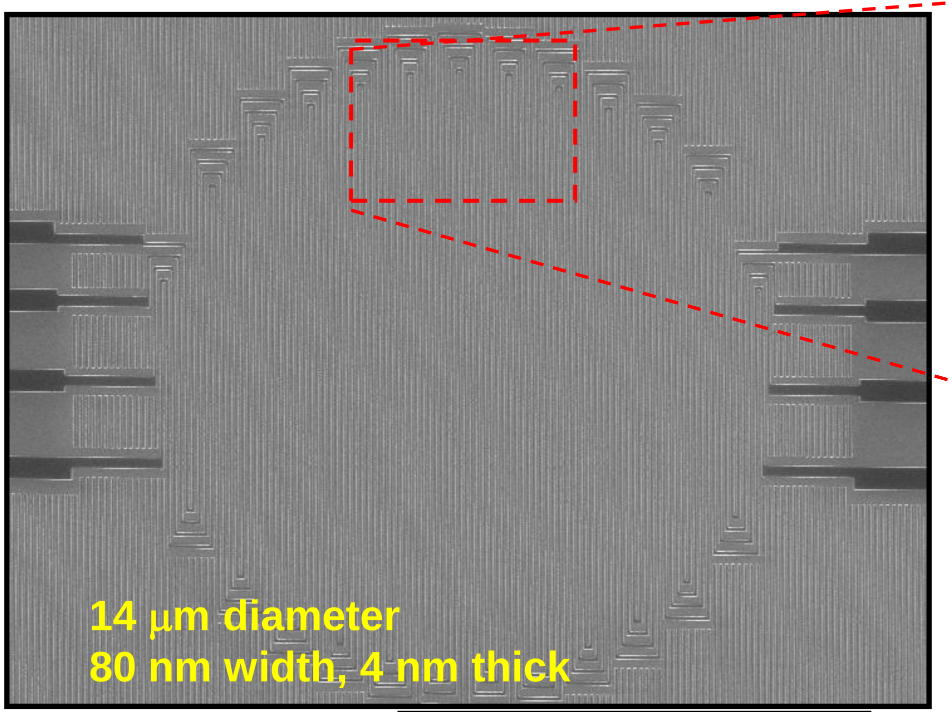
- Single gimbal
- Four 16-inch receive telescopes
- Four 6-inch transmit telescopes
- All fiber-coupled
- Air-conditioned globe for optics
- Clamshell dome for weather protection

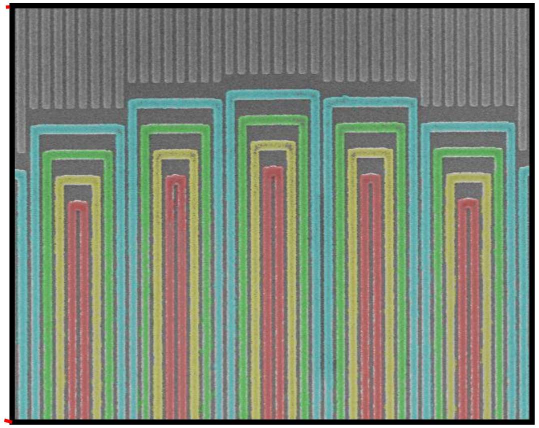
- Shipping container houses modem, computers, office
- Developed at MITLL, transported to White Sands NASA site for operations

LLCD Photon Counting Detectors

NbN Superconducting Nanowire Arrays

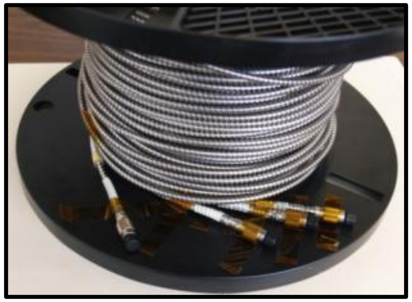
NbN nanowire on SiO_2 patterned in "meander" shape

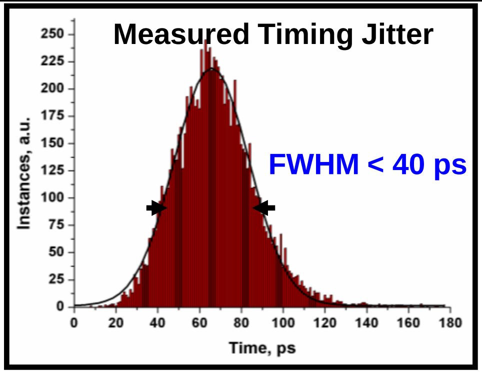




Interleaving multiple detectors results in shorter equivalent reset time

PM multi-mode fiber

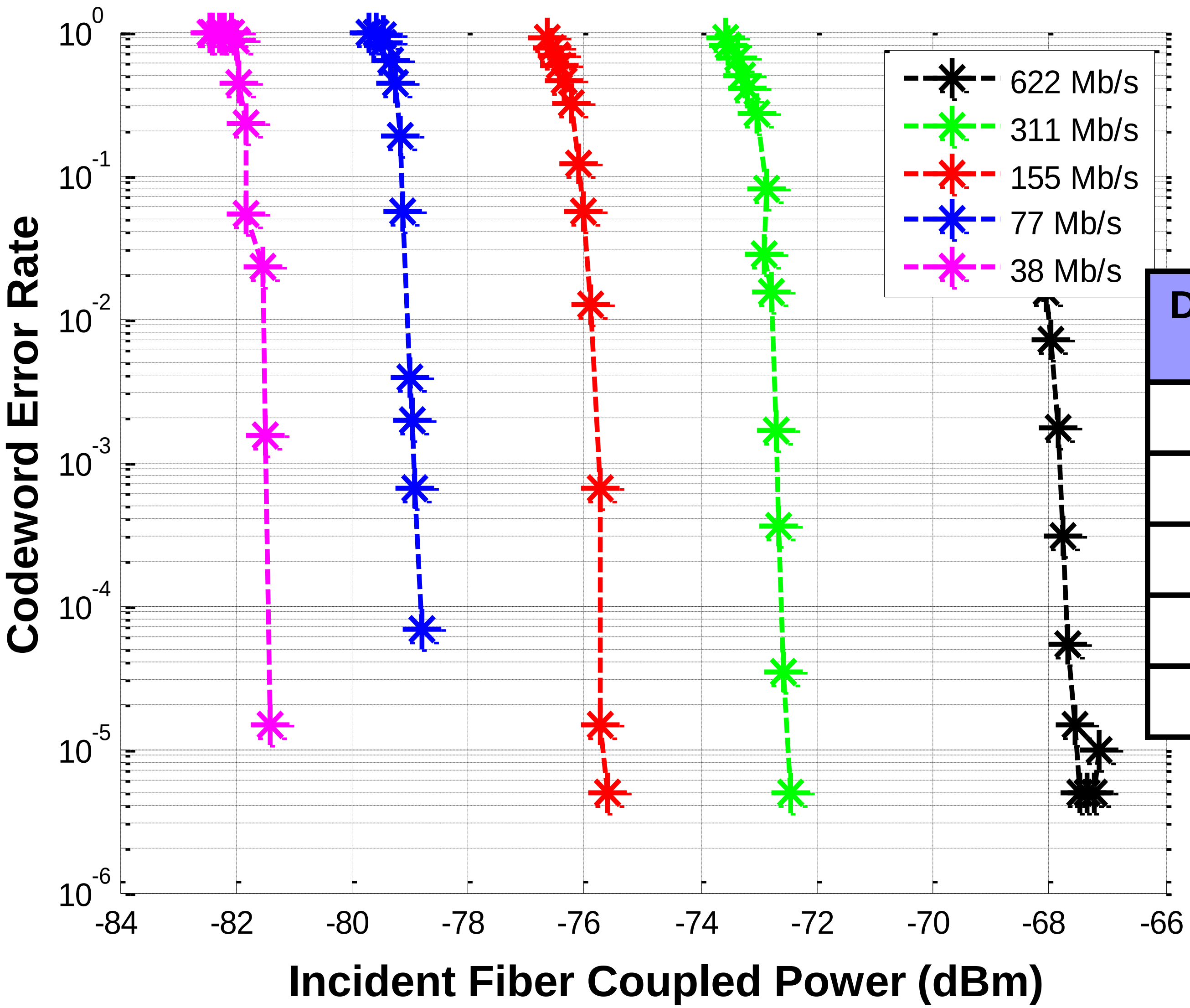




High detection efficiency	**>70%**
Fast reset time	**< 10 ns**
Low timing jitter	**< 40 ps**
Extremely low noise	

Receiver achieves ~ 2 bits per detected photon

Measured Performance of LLCD Primary Receiver



Data Rate, Mb/s	*Sensitivity, photons/bit
38	1.49
77	1.52
155	1.68
311	1.93
622	3.48

*Sensitivity measures detection efficiency of photons in the fiber

Summary

- **Operational near-Earth optical communications systems are being deployed today**
  - **European Data Relay System**

- **Optical comm for can enable high data volume delivery from deep space**
  - **Because of the large transmission distances, alternatives to optical tracking for beam stabilization must be employed**
    - **Passive isolation**
    - **Inertial references**
    - **Celestial sources**
  - **In some cases, photon-counting optical comm can outperform traditional coherent receiver performance**
    - **Coherent receivers are typically useful for high-rate / near-Earth links**
    - **Photon-counting receivers can be useful for medium- to low-rate / deep space links**