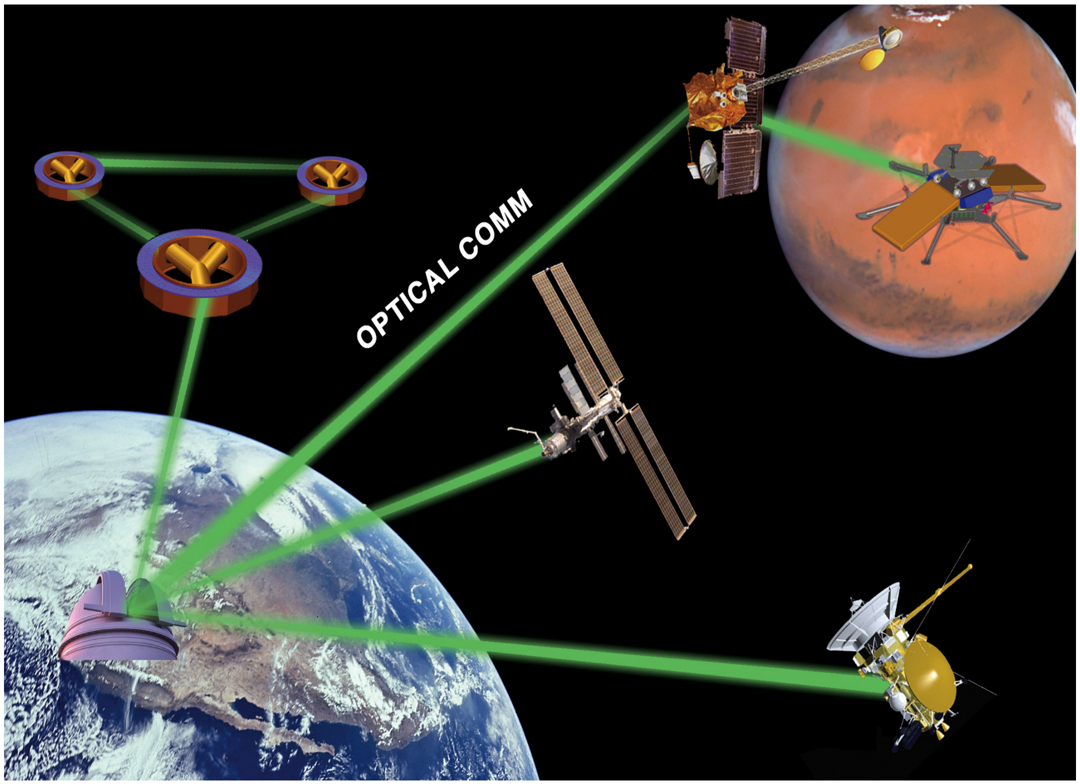
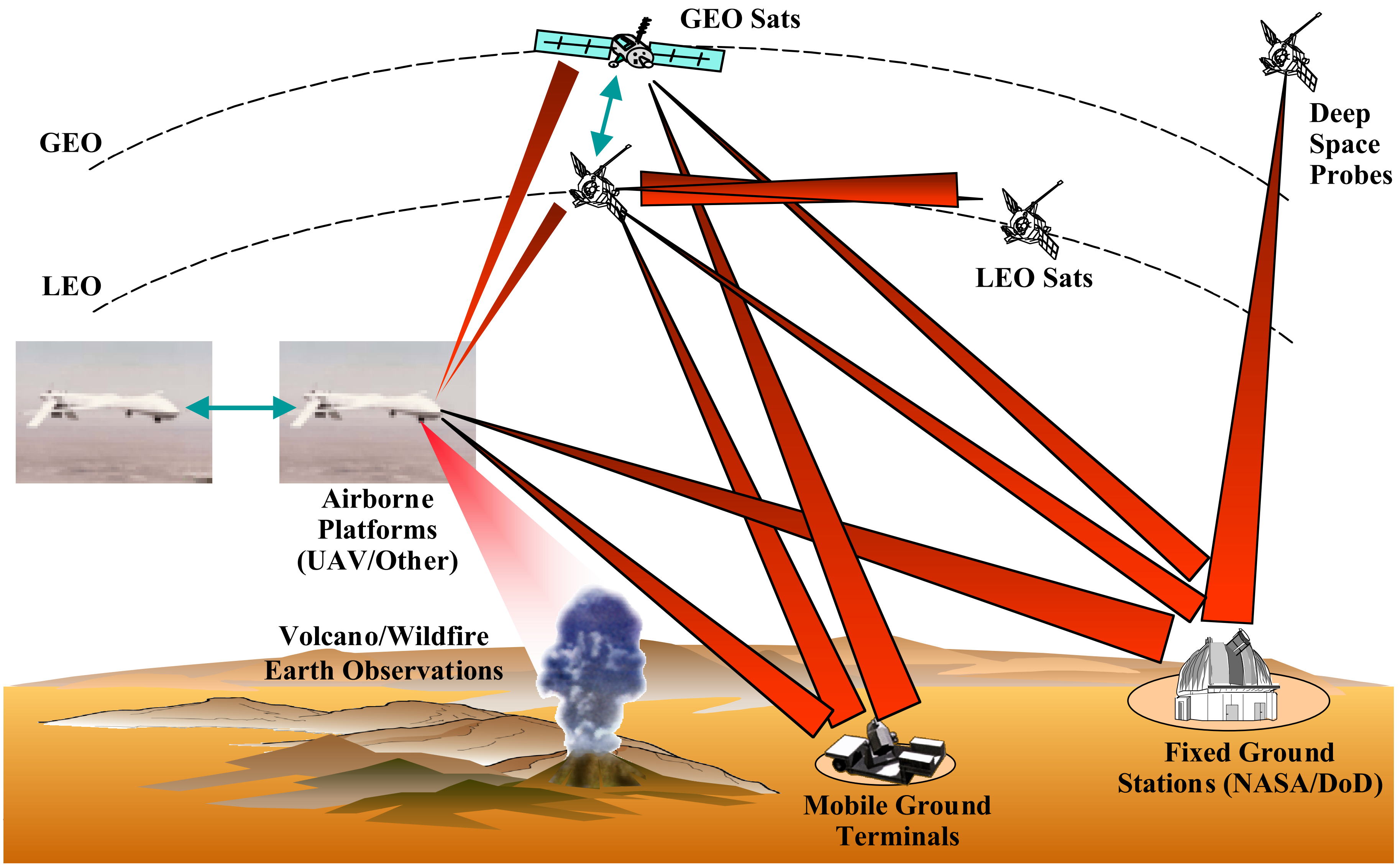


Free-Space Optical Communications at JPL/NASA

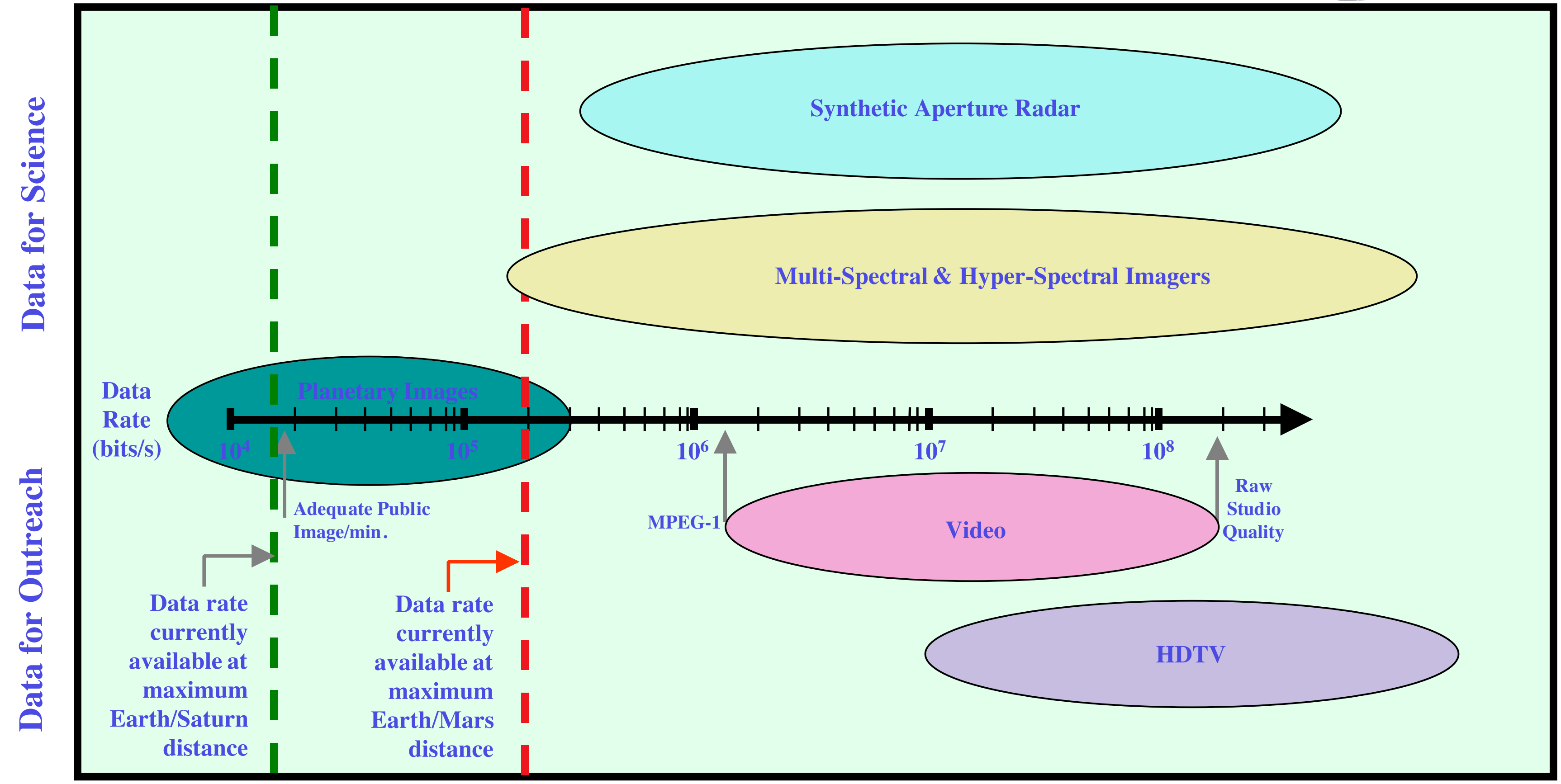
H. Hemmati

Optical Communications Group
Comm. Systems and Research Sec.
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA 91109
hamid.hemmati@jpl.nasa.gov

NASA Application Scenarios



Future Science and Outreach Needs



Data rate requirements for science and public outreach are factors of 10 to 100 higher than can be provided by current communications technology

Optical Communications
Vision and Mission

Vision:

To increase volume of space data transfer,

to enable affordable virtual presence throughout the solar system.

Mission:

10-100 times higher data-rate,

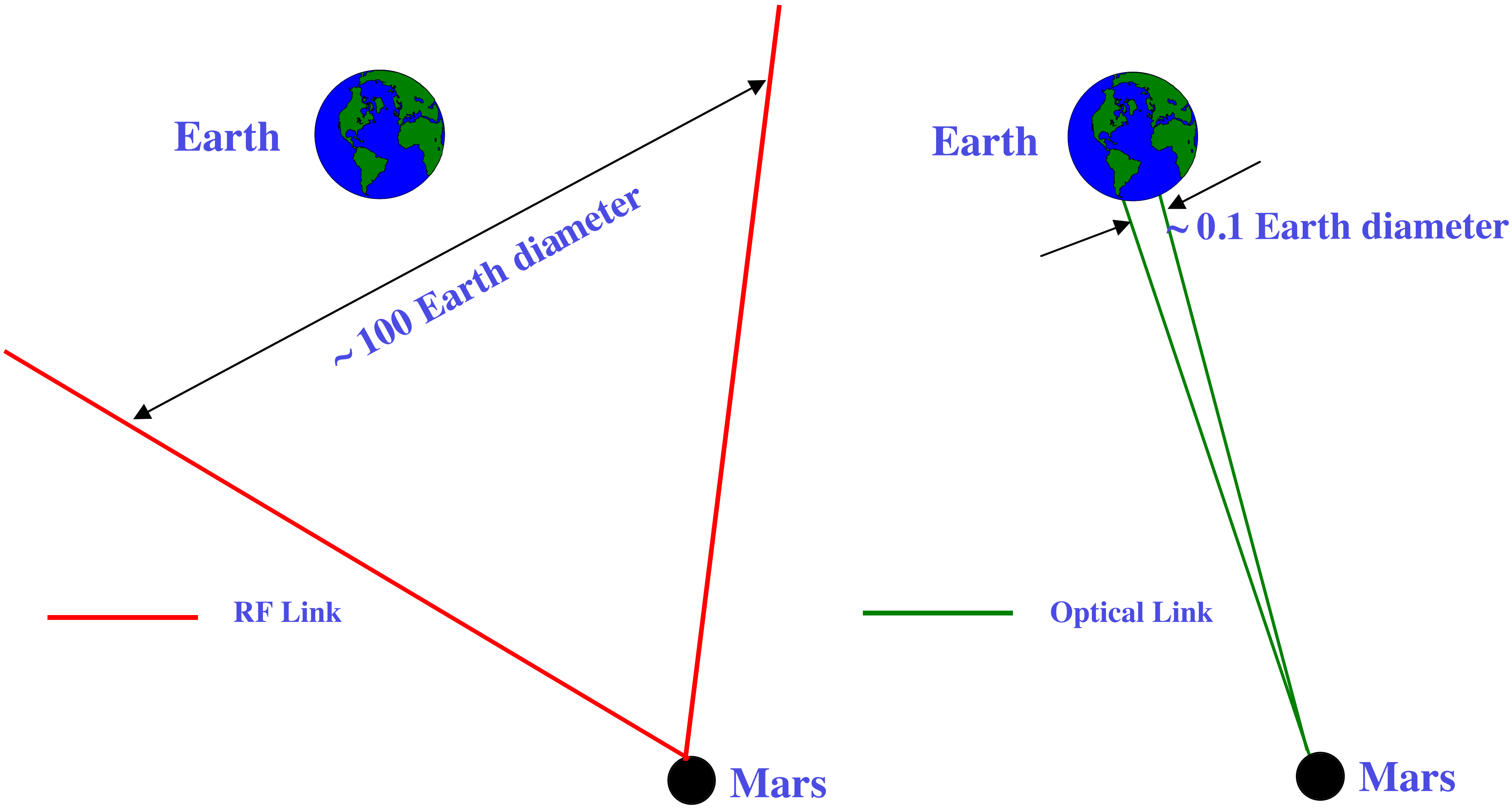
1/100 the aperture area,

less mass and less power consumption

…relative to current state-of-the-art.

Over the next 30 years to enhance the current communications capability (1Mbps for Mars 05) by 30 dB (3 orders of magnitude)

Beam Divergence (Frequency) Effect



Near Earth vs. Deep Space

Deep Space	Near Earth ($\leq$ moon range)
Need large ($\geq$10-m) diameter receiving aperture to collect sufficient photons - D/r_0 ratios higher causing focal spot blurring (D = telescope diameter, r_0 = atmospheric coherence length) - segmented primary for cost effectiveness introduces surface figure issues	**~ 1-m diameter aperture adequate** - near diffraction limited monolithic primary
Photon starved channel - photon counting detectors - photon efficient pulse position modulation (PPM) - low complexity high gain codes mandatory - channel efficiency traded for capacity	**Received signal moderately high** - high bandwidth moderate sensitivity detection - OOK or low order PPM modulation adequate - Can implement ARQ
High peak power (multi-kW) pulsed lasers - high electrical-to-optical conversion efficiency critical - usually solid state with ~ 1,000nm wavelengths - limits data rates to 10's of Mbps	**Telecordia quality transmitters** - typically 100's of mW to <10 W peak powers - EDFA @ 1550 nm - <1 to >10 Gbps data rates
Round trip light times mandate single-step acquisition tracking and pointing (ATP) strategies - beacon intensities weaker requiring longer integration times - large aperture diameters require tighter pointing	**Multiple light passes between transmitter and receiver possible** - intense beacons allow high frame rate tracking
Flight transceiver terminals - must be lightweight and thermally stable - narrow field-of-view (FOV) and stray light rejection strategies	**Mass restrictions less stringent** - may require larger (FOV) to accommodate higher slew-rates and larger attitude uncertainty

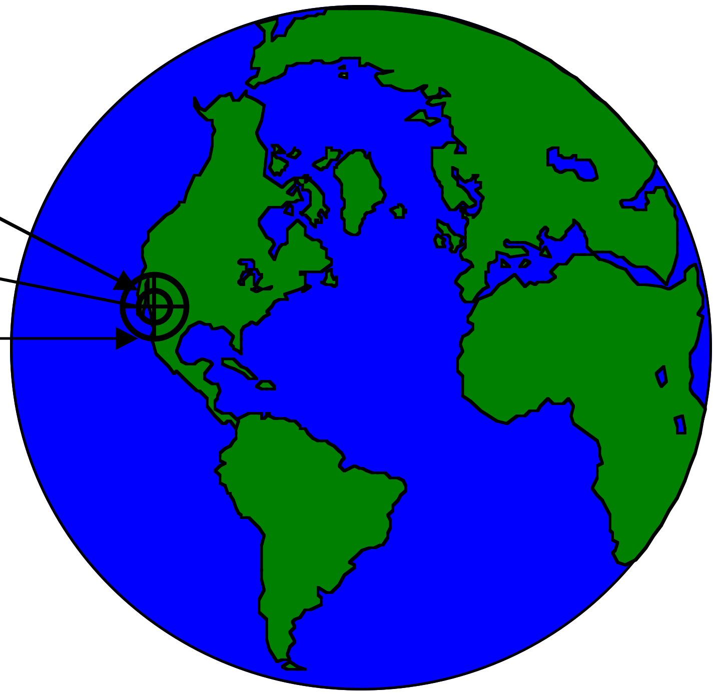
Deep space links involve ranges that are several orders of magnitude higher than that of Near-Earth missions

Illustration of Pointing Requirements (for Mars)

Static Error Allocation

Receiving Station

2dB Pointing Loss (worst case pointing circle)



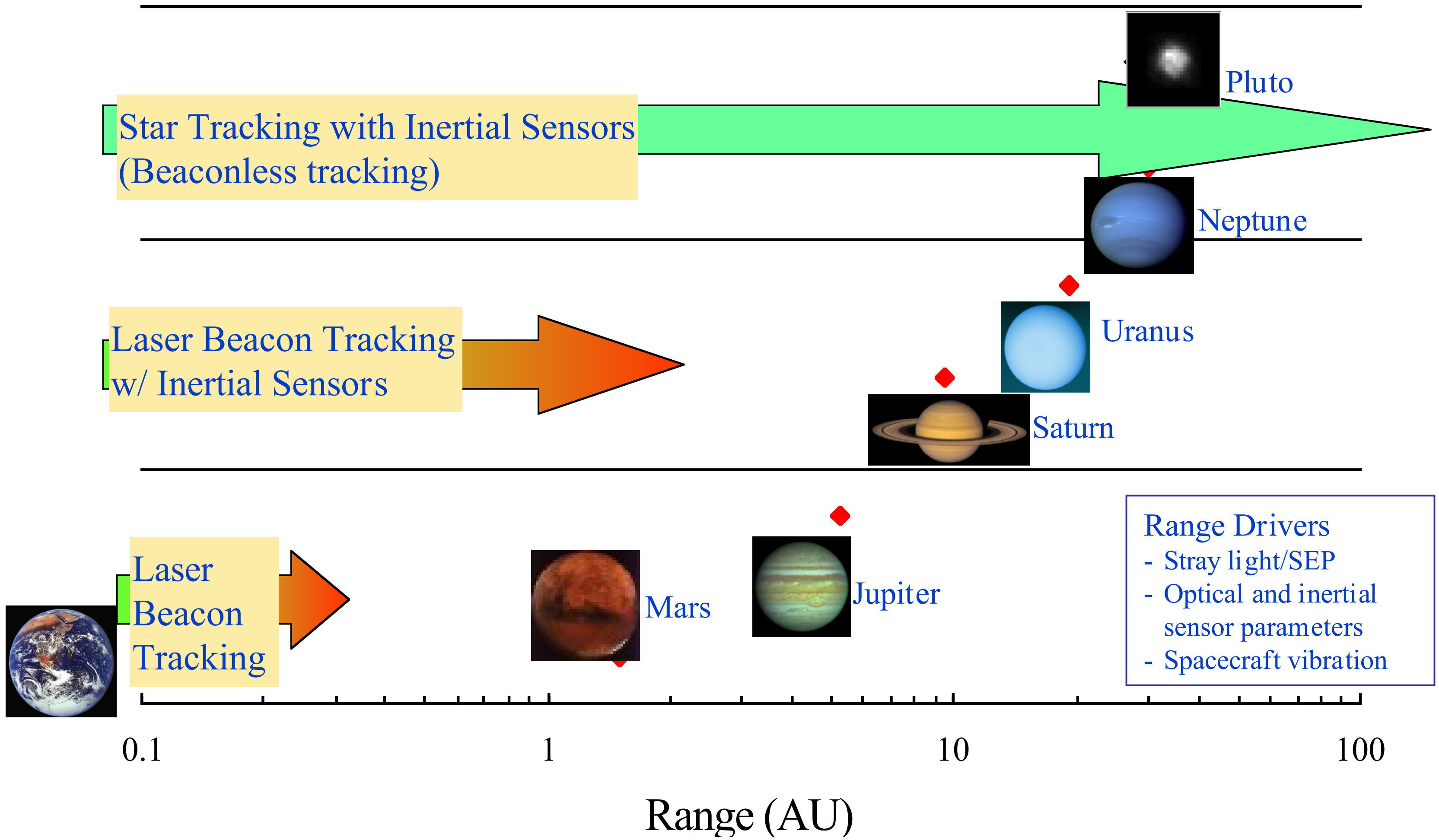
3-Sigma Pointing Accuracy
3*Jitter + Bias = 2.0 µrad

From Mars, Earth is about 35 urad FOV, then need to **point to ~ 1/18 of Earth diameter**

Pointing Jitter is ~1/10th Beamwidth
-30 cm telescope
-1064 nm

1 urad spacing

Implementation Concepts



ATP Technologies

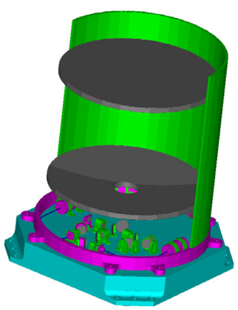
Beaconless Tracking:

- JPL-developed unified and simple ATP architecture for any communications range based on **precision star tracking**
- Independence from a cooperative target
- Achieves laser beam pointing accuracy to the sub-microradian level
- Minimal impact on S/C, low size, weight and power, improves random and system noise and dynamic range

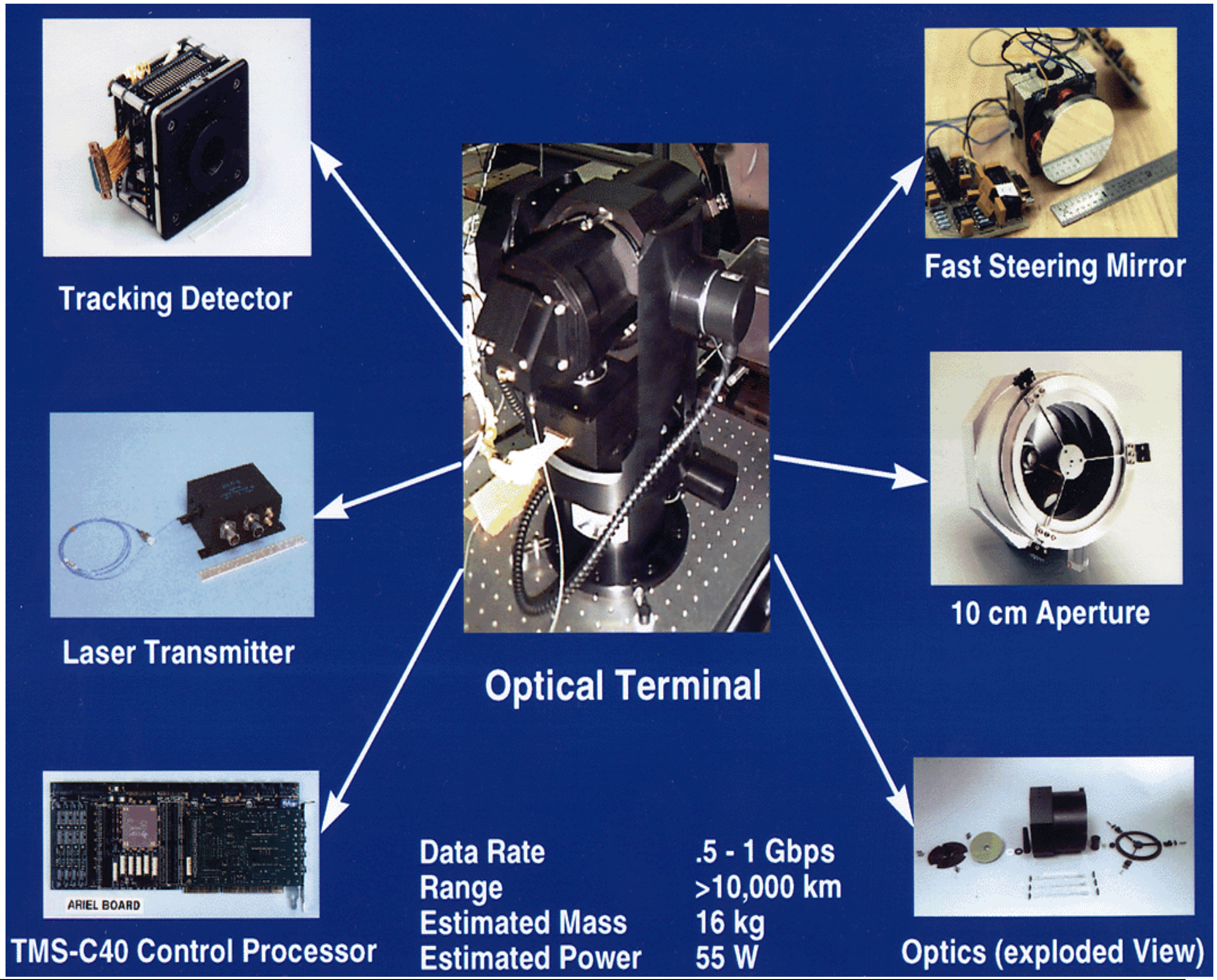
JPL's Low-Complexity Lasercomm Terminal
(Pre-EM model)

OCD (Optical Comm Demonstrator)

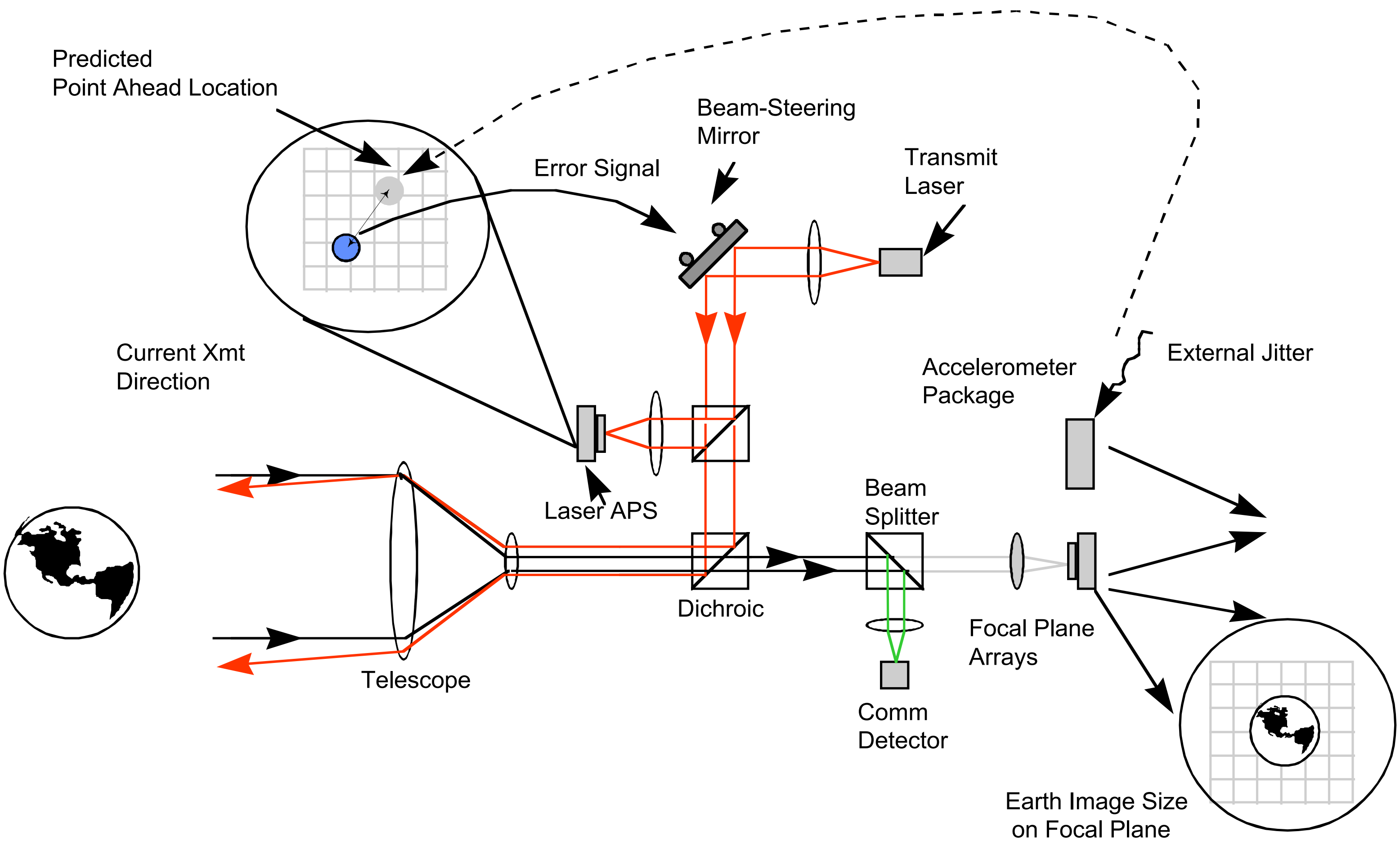
Tested over 50 km range



Next Generation



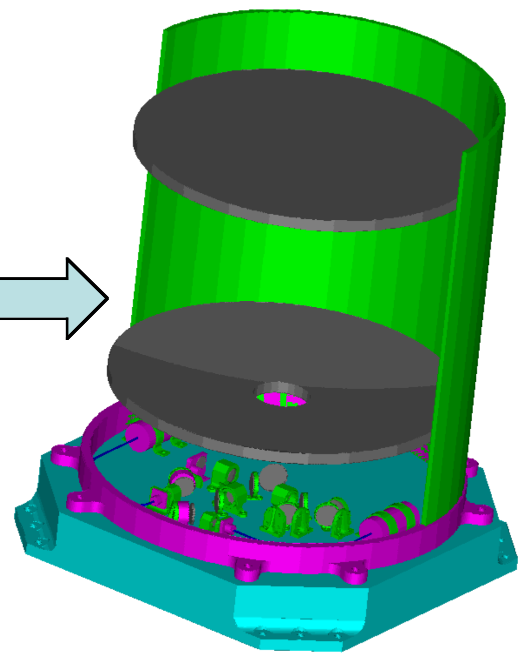
JPL's ATP Concept



Multi-Functionality

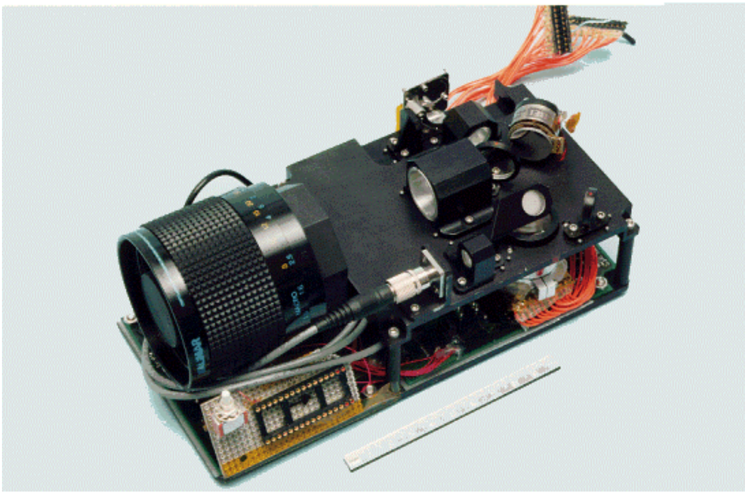
High-Resolution Science Imaging

Laser-Communications



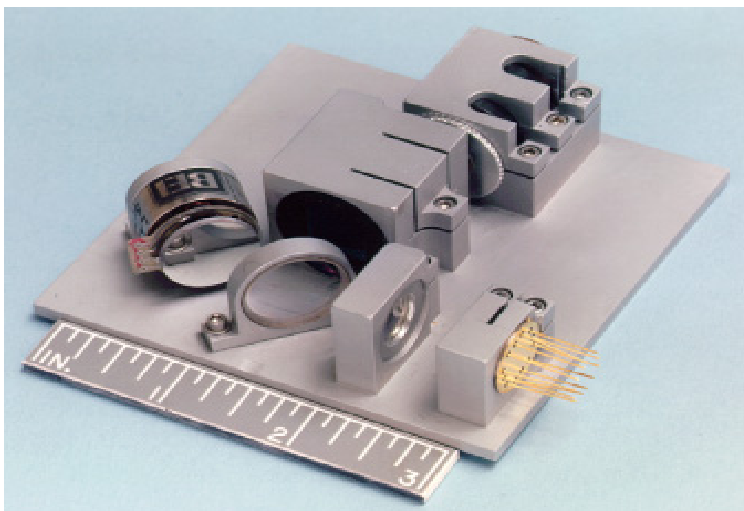
Hazard-Detection & Avoidance (for landing) &Laser-Altimetry

Low-Capability Lasercomm Terminals



ACLAIM

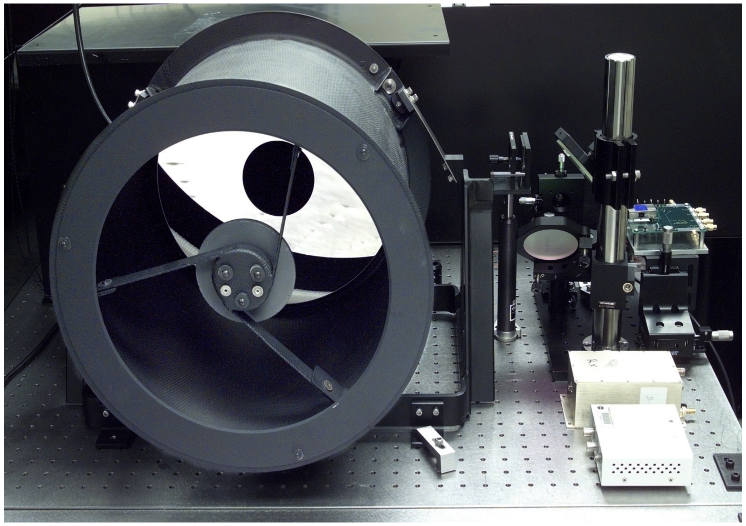
(A Combined Lasercomm and Imager for Micro-spacecraft)

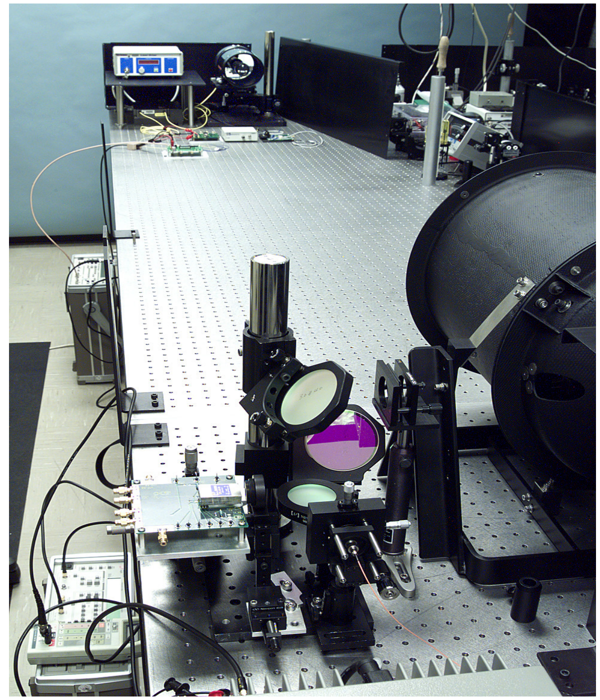


SCOPE

(Small Communications Optical Package Experiment)

1.5 to 7.5 Gbps Optical Comm Links Depicting Data transmission from LEO-to-GEO



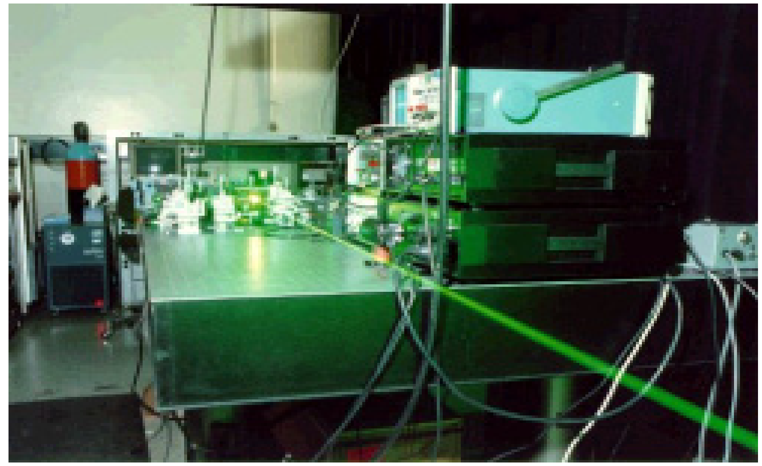


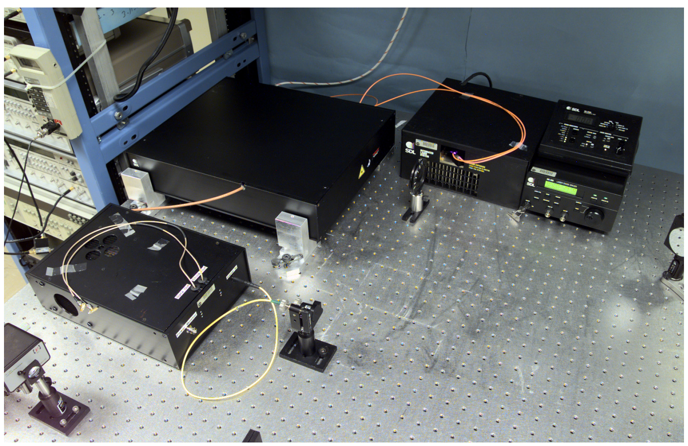
Objective:

Develop communications (in the range of 1 to 10 Gbps) and acquisition, tracking and pointing technologies for lasercomm to transmit science data from LEO-to-GEO or GEO-to-ground.

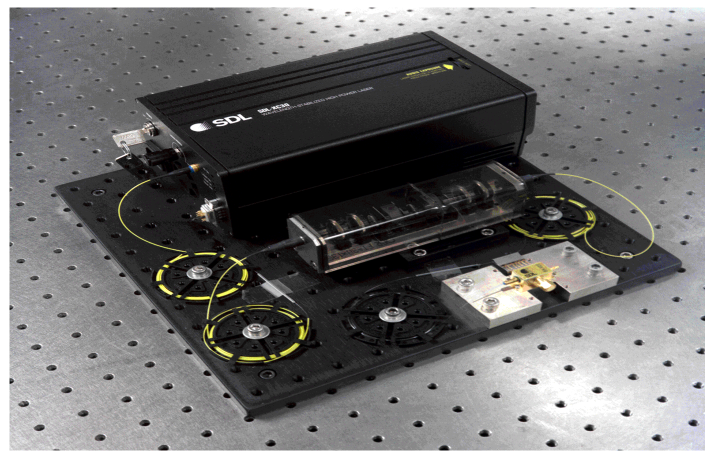
Laser Transmitter Developments at or for JPL

Pioneered the field of high efficiency diode-pumped solid-state lasers



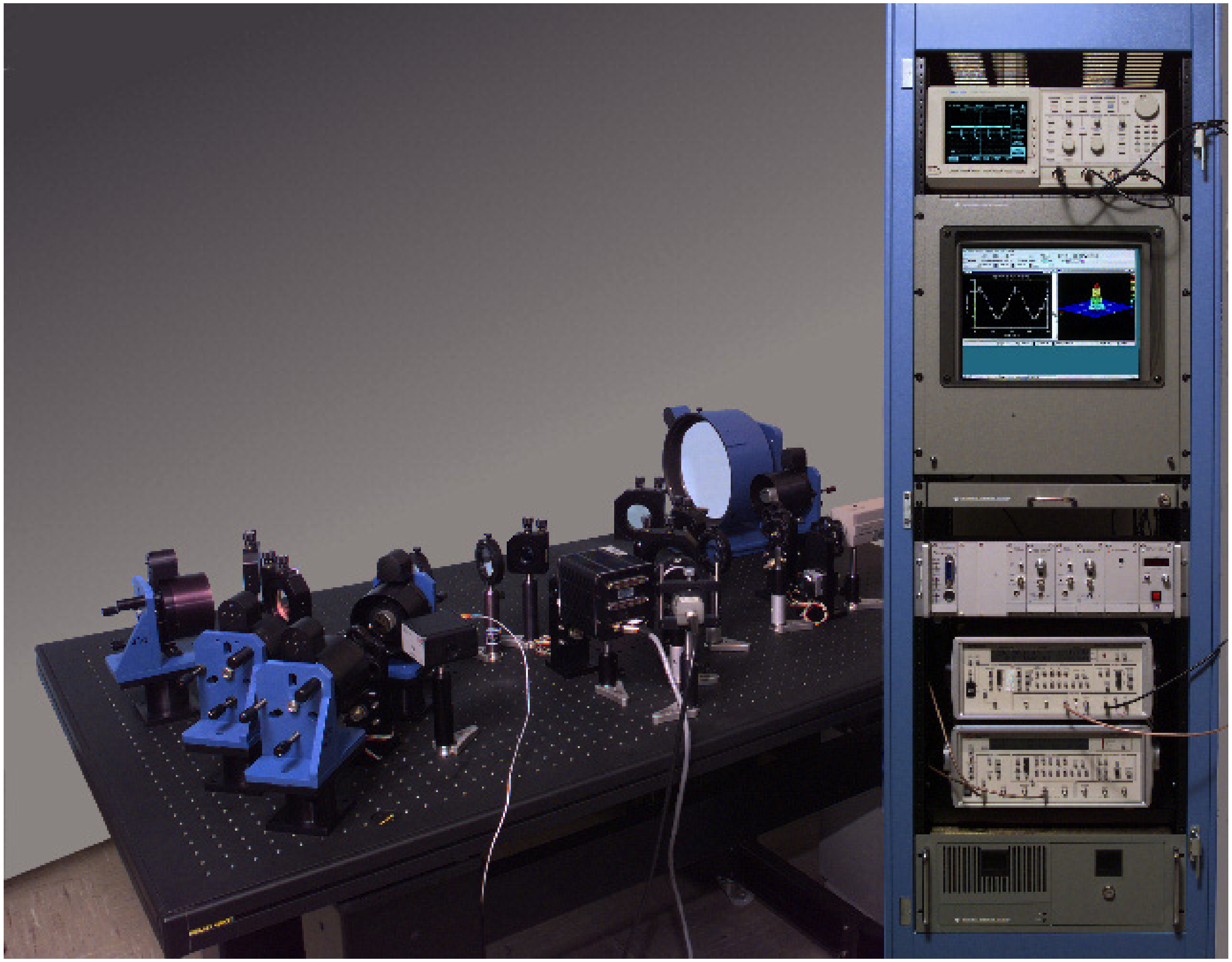


1995, 5-W, 5 Gbps 1072 nm Fiber Amplifier



1997, 1-W, 10 Gbps 970 nm Semiconductor Optical Amplifier

LTES
(Lasercomm Test & Evaluation Station)

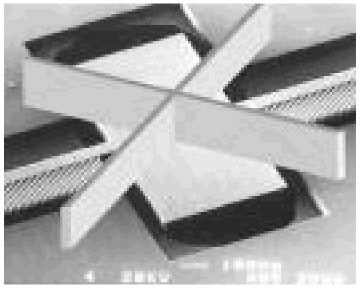


Mars Network with Retro-Modulator

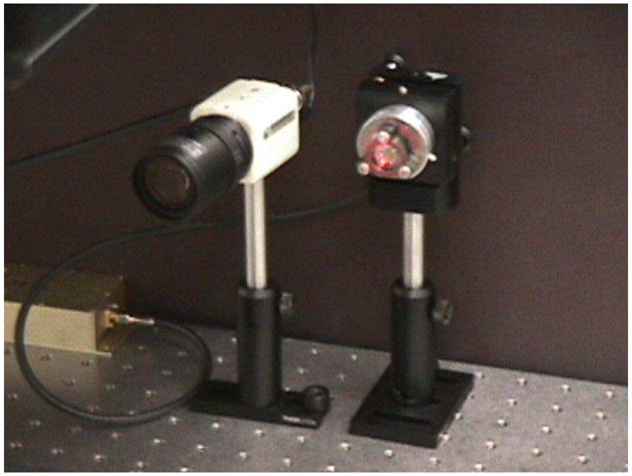
NRL

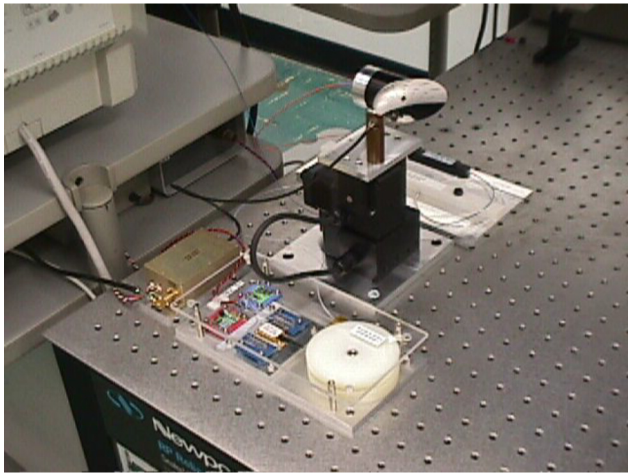
10 g, 30 mW

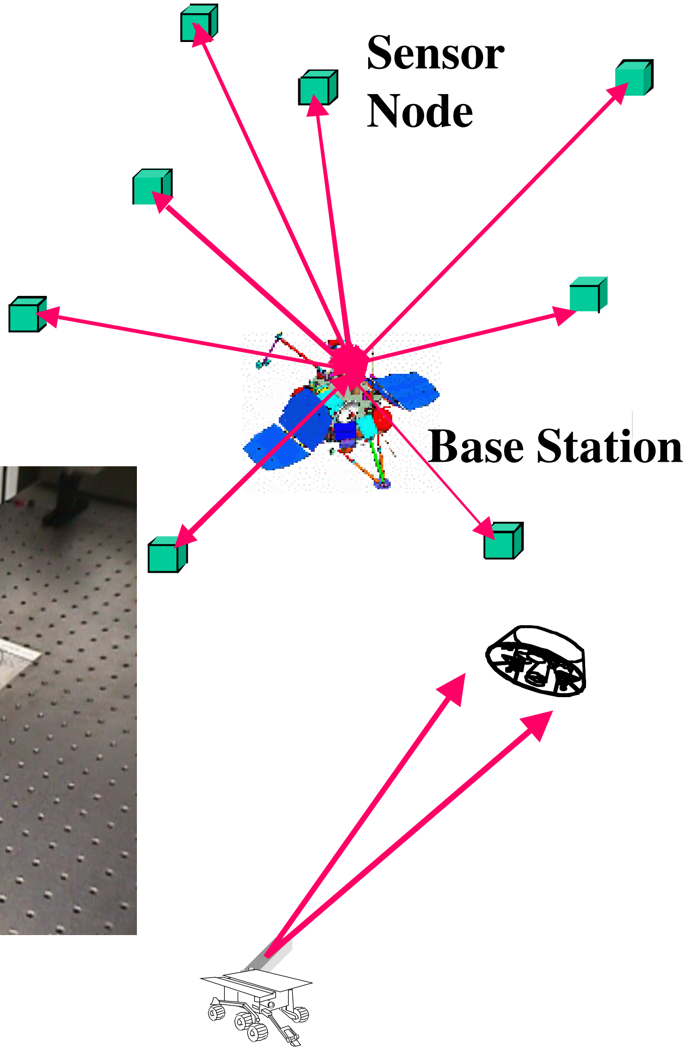
UC Berkeley



1 g, few mW



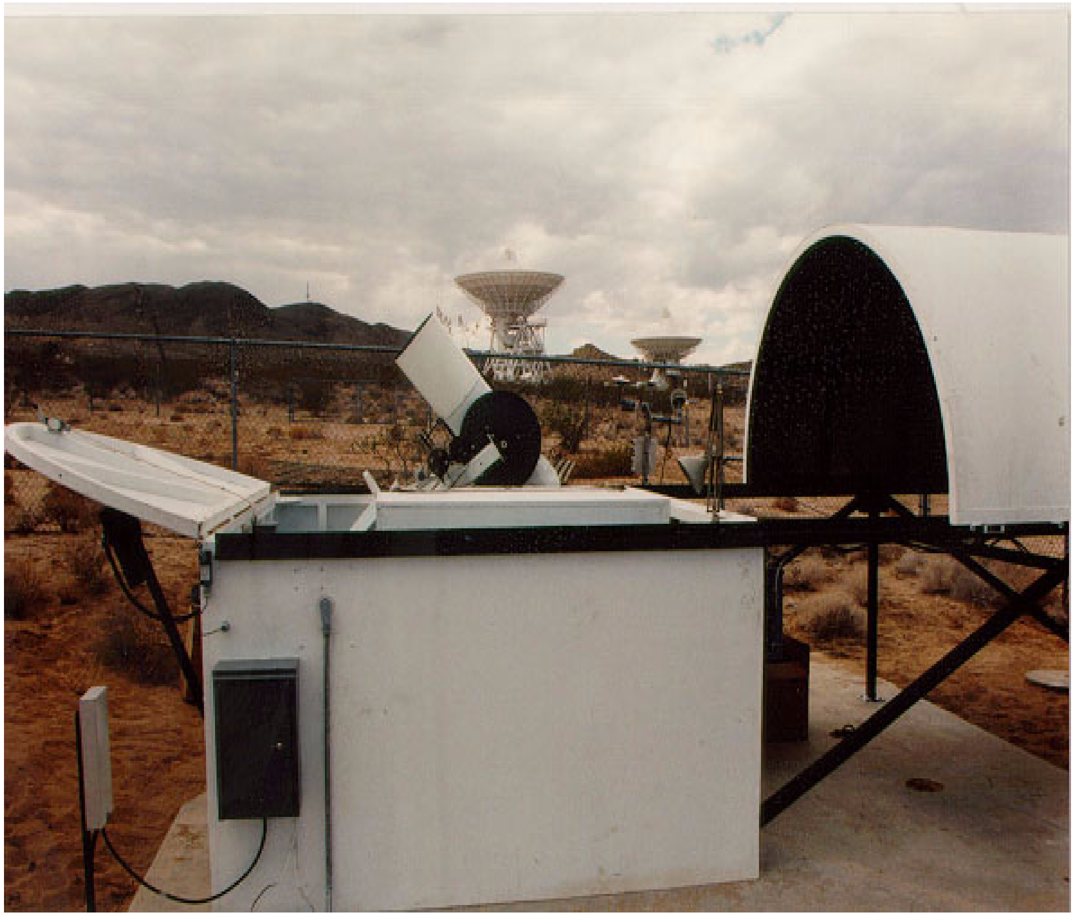


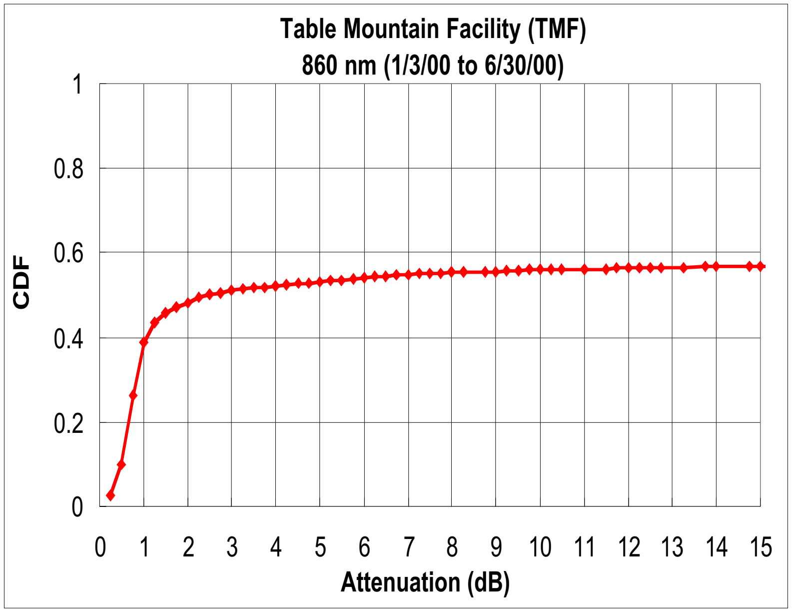


Demonstrated 4 Mbps real-time video

AVM
(Atmospheric Visibility Monitoring)

Set of three 25-cm diameter autonomous telescopes to measure atmospheric visibility

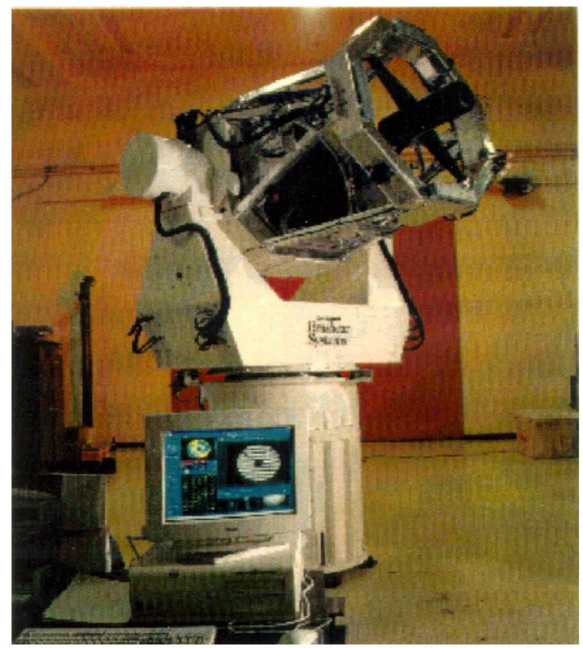




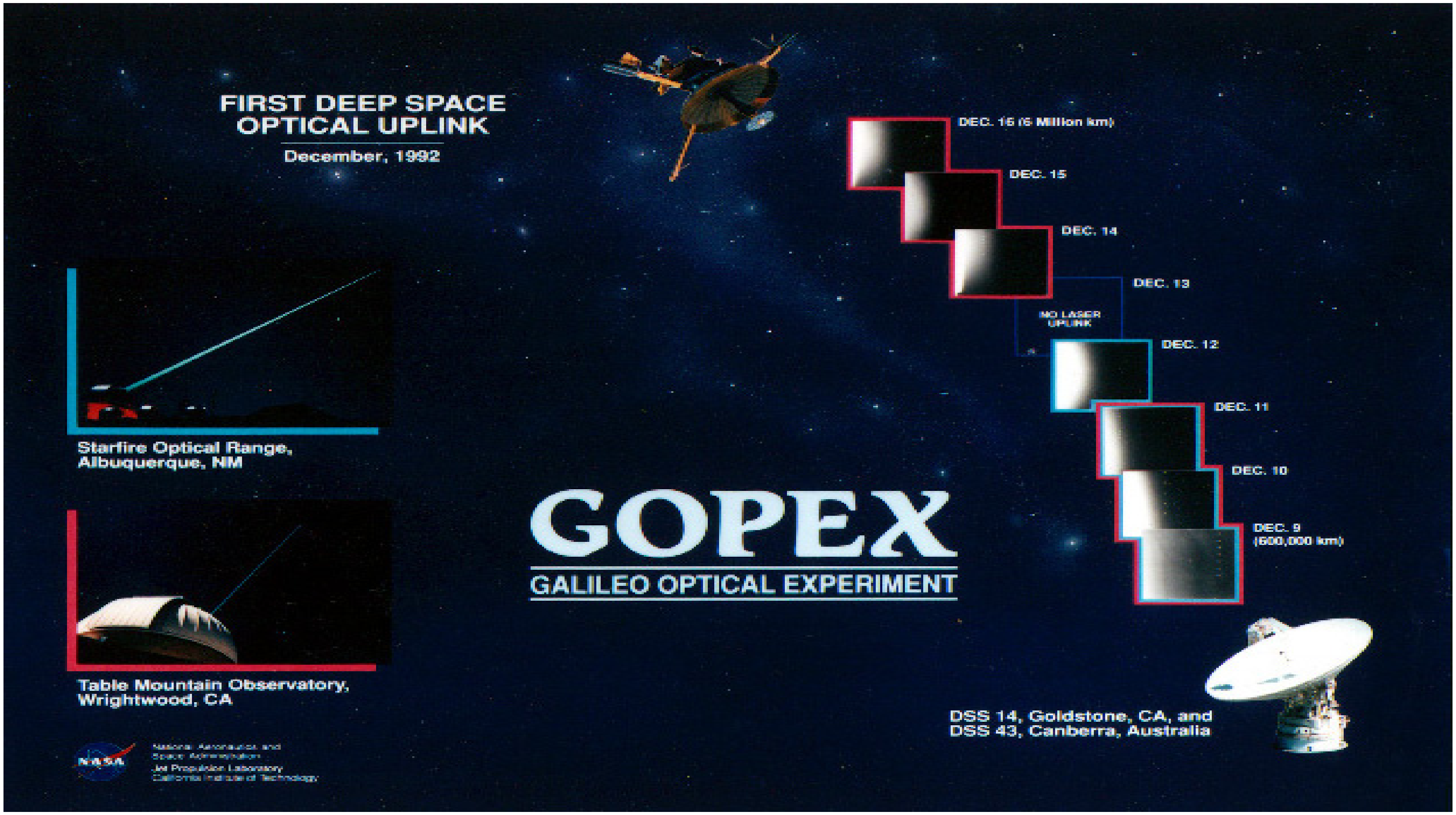
OCTL

(Optical Communications Telescope Laboratory)

- A 1-m telescope facility to track LEO Spacecraft, dedicated to lasercomm
- Awarded 1-m telescope contract to Contraves Brashear January of 2000
- Telescope to be delivered Summer of 2002



GOPEX (Galileo Optical Experiment)



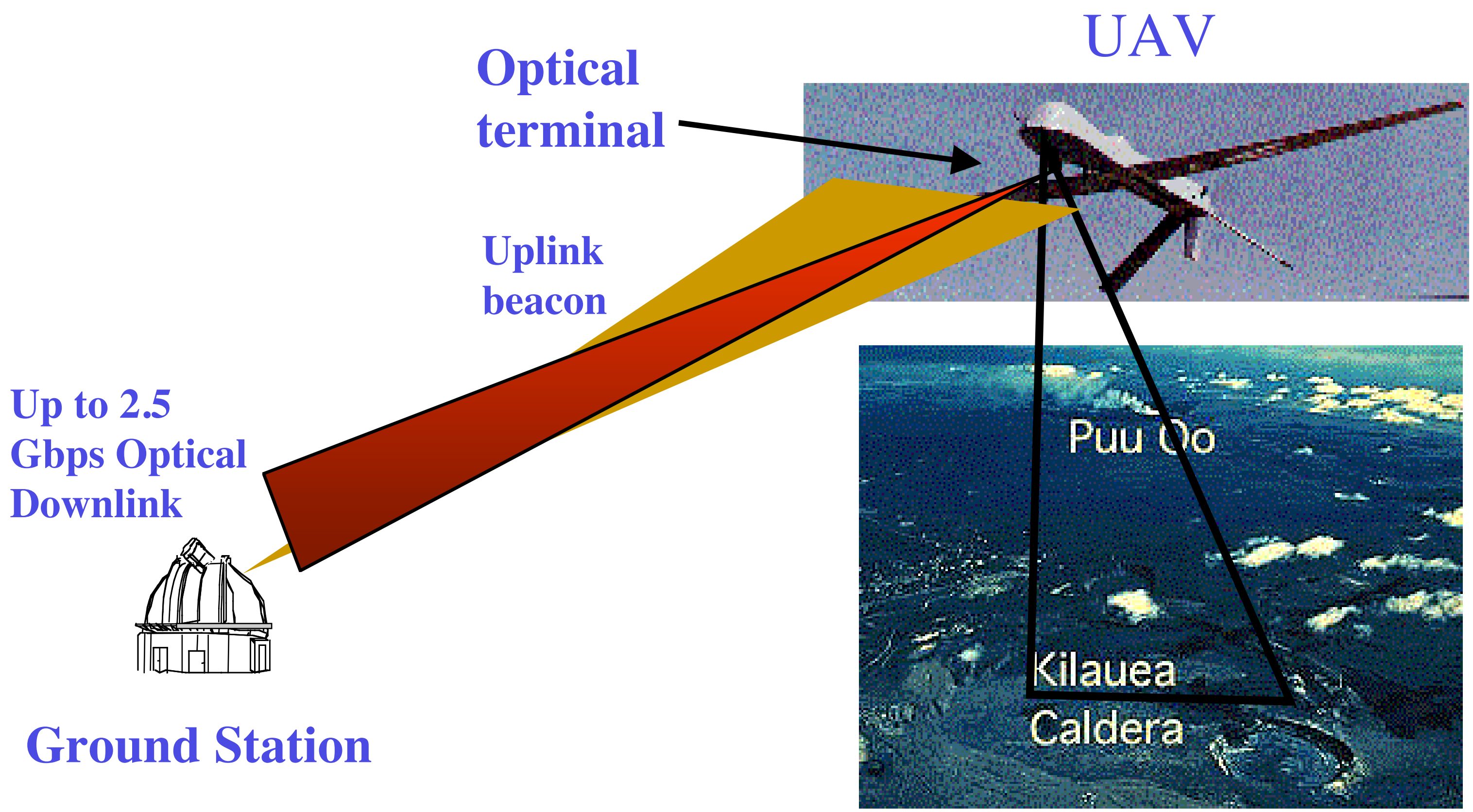
Uplink to Galileo spacecraft at 6E9 m range

GOLD (Ground-to-Orbit Lasercomm Demo)

Uplink and downlink with ETS S/C in GEO-type orbit

UAV Downlink Demonstration - Overview

Downlink of science data at the rate of 1 to 2.5 Gbps
from a plane (DC8) and a UAV to ground



Relevance of our Research to T.C.

A group of 15 people dedicated to Optical Communications in existence for about 25 years. Well-funded by NASA.

Demonstrated bi-directional optical link with spacecraft in GEO
Demonstrated uplink to spacecraft in deep-space
Developed low complexity lasercomm terminal and tested over 50 km range

Developed high update rate CCD focal-plane array for ATP
Developed high efficiency, high data-rate laser transmitters
Delivering flight-qualified lasers for flight
Developed laser communication characterization terminal
Own a 1-m LEO and GEO spacecraft tracking telescope dedicated to lasercomm

Developing a 2.5 Gbps lasercomm terminal for UAV-to-ground comm
Just completed 7.5 Gbps links simulating the LEO-GEO optical crosslink (both in comm and ATP).

The only NASA center working on lasercomm (both Deep Space & Near Earth)
Has been a pioneer and is a recognized leader in the field
Publishing 12 to 15 papers a year.

Utilized Air Force facilities at SOR (Albuquerque) and AEOS (Hawaii)
JPL's Team X and full space-qualification knowledge and infrastructure available to group

Challenges in the technology:

Further reduction of size, mass and power

Terminals developed so far are for point-to-point comm only

Need to flight validate our ATP scheme developed for the OCD terminal

Partners:

Have worked closely with Ball Aerospace in the recent past

Are working with Trex Enterprises now

Welcome partners for future anticipated work

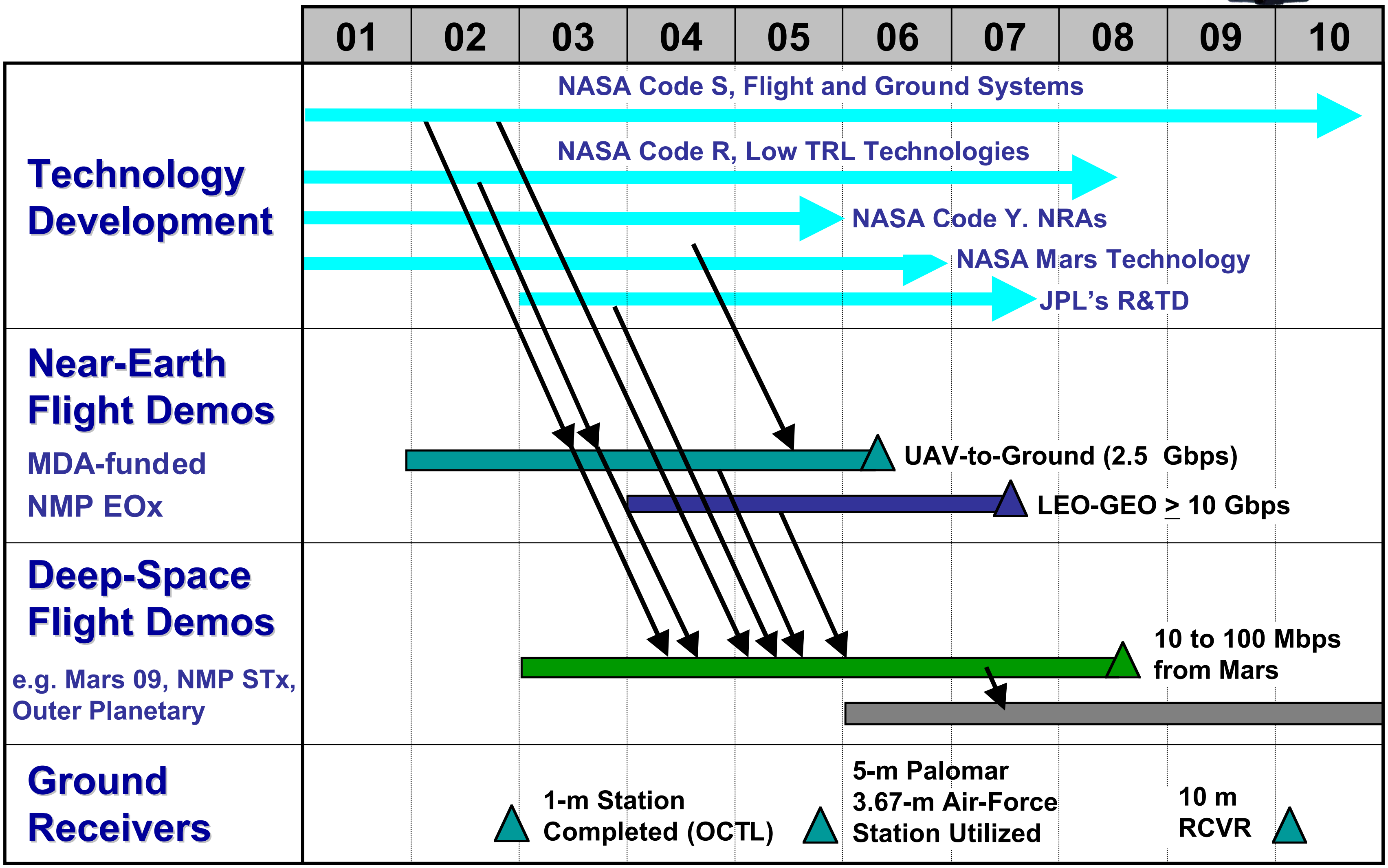
Estimated cost to TRL 6:

Several $M

Optical Communication Group's Technology Highlights

Year	Accomplishment
1982	**First** demonstration of 2.5 bits/photon detection
1886	**First** demonstration of moderate power diode-pumped Nd: YAG laser using diode arrays (for deep-space transmitter)
1987	**First** demonstration of a diode-pumped Tm,Ho: YLF laser operating at 25 °C, useful as deep space transmitter
1988	SCOPE (Small Communications Optical Experiment) lasercom terminal developed
1989	Detailed study of orbiting optical communication receivers completed; DSORA study
1990	**First** high power (12 W 1064 nm, 3.5 W 532 nm) efficient diode end-pumped solid-state laser demonstrated
1991	100 Mbps resonant phase modulator for coherent communication developed and demonstrated in a link
1992	**First** optical uplink to a spacecraft in deep-space; GOPEX (Galileo OPtical EXperiment)
1993	CEMERLL (Compensated Earth Moon Earth Reto-reflected Laser Link) using Air Force's SOR facility
1994	OCD (Optical Communications Demonstrator) terminal developed, useful to both near-earth and deep-space links
1995	**First** uplink and downlink experiment with a GEOS/C (Japan's LCE); GOLD (Ground Orbit Link demonstration
1996	First demonstration of scintillation mitigation on a ground-to-space optical link using multiple uplink beams
1997	Lasercomm Test and Evaluation Station (LTES) companion terminal completed
1998	ACLAIM (A Combined Lasercomm And IMager) instrument completed and integrated with a micro-spacecraft
1999	First set of instruments to quantitatively characterize the atmosphere; AVM (Atmospheric Visibility Monitoring) stations
2000	45 Km range horizontal link with OCD terminal successfully made
2001	HDTV (1.5 Gbps) and WDM (7.5 Gbps) links demonstrated to within 1 dB of link analysis predictions
2002	Demonstrated ATP (Acquisition, Tracking and Pointing) simulating LEO-GEO links in the lab

Optical-Communications Roadmap

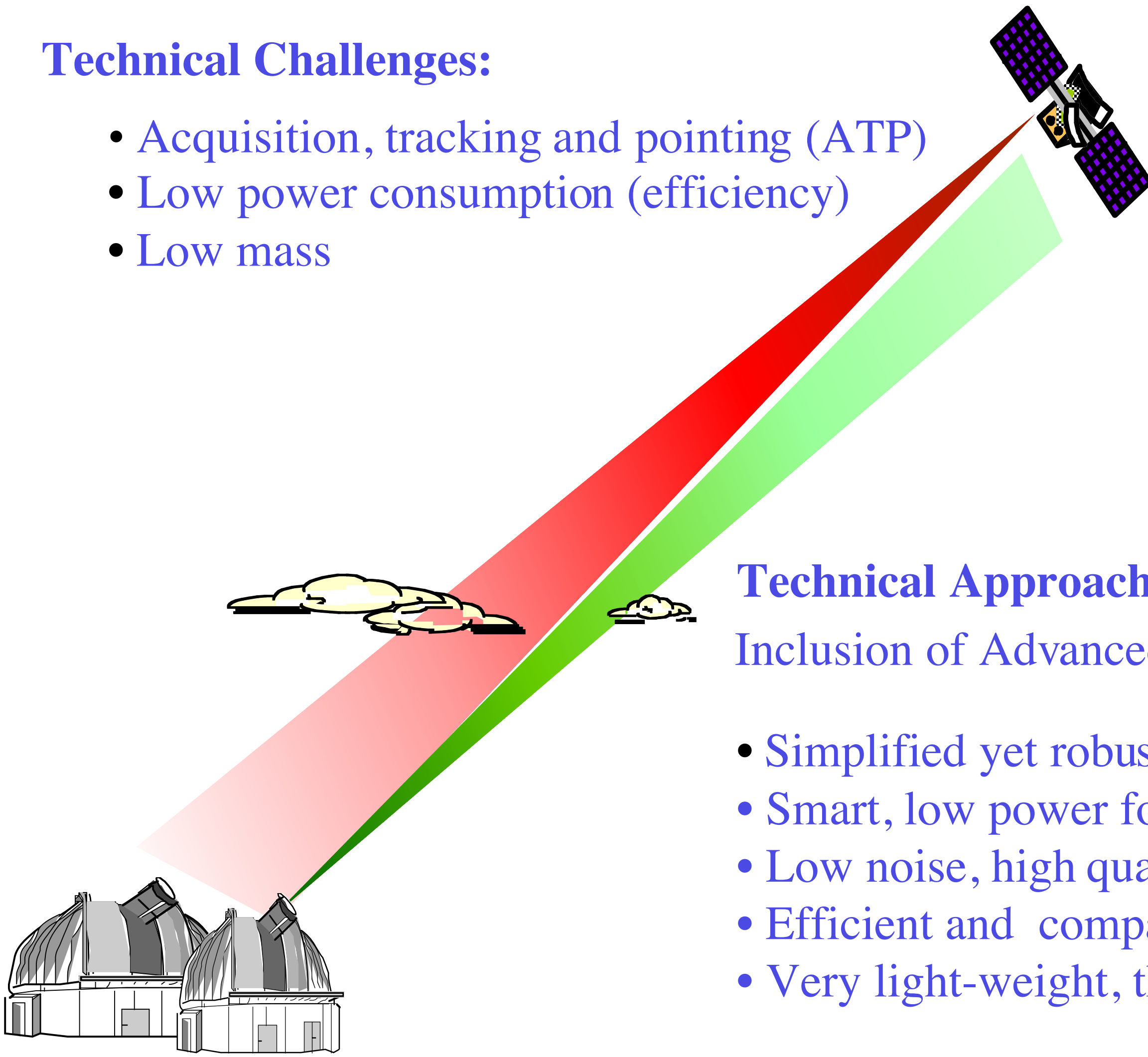


Back-up VGs

Optical Communications

Technical Challenges:

- Acquisition, tracking and pointing (ATP)
- Low power consumption (efficiency)
- Low mass



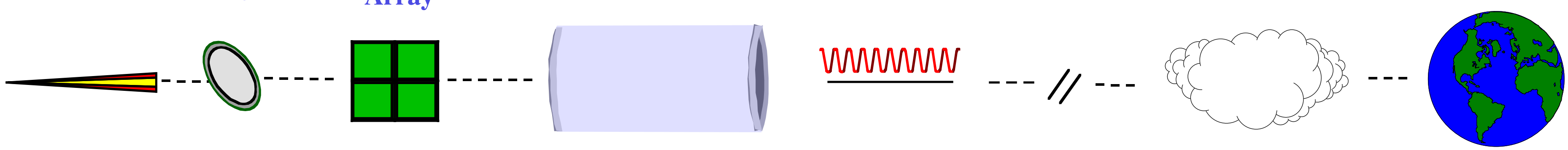
Technical Approach:

Inclusion of Advanced Technologies

- Simplified yet robust ATP architectures & algorithms
- Smart, low power focal-plane-arrays for ATP
- Low noise, high quantum efficiency data detectors
- Efficient and compact solid-state laser transmitters
- Very light-weight, thermally-stable optics & structures

Design Drivers / Technology Development

Laser | **Fine-Pointing Mirror** | **Focal Plane Array** | **Receiver (Optics)** | **Platform** | **Space** | **Atmosphere** | **Earth**



Laser
- Efficiency
- Power vs. data rate
- Extinction ratio
- Reliability

Fine-Pointing Mirror
- Bandwidth
- Reaction
- Performance
- Reliability

Focal Plane Array
- Type
- Array size
- Pixel size
- Noise
- Spectral band
- Field-of-view
- Dynamic range
- Sensitivity
- Readout rate
- Update rate
- Processing power
- Stray sun light
- Scattered transmit light
- Reliability
- SPE & SEP angles
- Acquisition time

Receiver (Optics)
- Aperture size
- Field-of- view
- Xmt-Rcv isolation
- Sensitivity
- Duplex operation
- Thermal effects
- Optics contamination

Platform
- Vibration environment (S/C jitter) - unknown
- Deadband cycle
- Earth exposure time

Space
- Radiation

Atmosphere
- Visibility
- Cloud cover
- Attenuation
- Elevation angle
- Sun angle
- Solar loading
- Turbulence
- Scattering

Earth
- Reflectance
- Albedo variations
- Crescent size
- Motion

Potential Applications

- NASA Earth-Science and Deep-Space Exploration Missions
- Battle Management Command, Control, and Communications
- Disaster and Natural Hazard Monitoring or Damage Assessment
- Commercial Data Transfer

Mission Challenges

Current (RF) communications systems require significant spacecraft resources:

- Approximately 40-70% of the spacecraft prime power is now allocated to the communications system during peak communications period
- The percentage of the communications system dry mass increases from 2% for Venus mission to >10% for Saturn and Neptune missions
- Antenna diameters vary from 1.5 to 3 meters

Communication Challenges

- Six (6) orders of magnitude range difference from LEO to end of solar system
- Very low signal strength
- Long round trip light time from 10's of minutes to several hours
- Asymmetric data path
- Stressing thermal, radiation and shock environments
- Stressing pointing accuracy requirement for Optical Communications
- Communication signal also used for navigation
- Link availability due to atmospheric and orbit conditions
- Extremely weight, size and power limited - Need to reduce fraction of spacecraft prime power and mass allocated to the communications system without sacrificing communications performance

Benefits of Optical Communications

- **Very-High-Rate Data Transfer (< 1Mbps to > 10 Gbps)**
  - Permits real-time ground receipt of Multispectral, Hyperspectral, Radar, and HDTV-quality imaging data without loss of information content due to the limitations imposed by onboard processing resources and techniques
  - Enhances the probability of data return from a potentially vulnerable observation site, where either natural or man-made environmental threats might threaten return of the data
  - Reduces the need for large data storage and processing power at the point of acquisition of the data where system resources such as power, pass, and volume may be highly limited, potentially permitting increased resource allocations for sensors, additional sensors, and/or reduced cost
- **Lower Demand for Mass, Power, and Volume Than Conventional RF Systems (× 1-4 Reduction) where Comparable RF Data Rates (up to ~1 Gbps) are Viable**
  - Frees up power, mass, and volume system resources to permit increased resource allocations for sensors, additional sensors, and/or reduced cost
- **Enhanced Data Transmission Security**
  - Offers data transfer largely secure from jamming and intercept

Performance Projections

- **X-band (8 GHz)** - Current baseline capability
- **Ka-band (32 GHz)** communications (ready for infusion)
  - 11.6 dB theoretical performance gain over X-band
  - 4-6 dB enhancement available immediately; more later with improvements
- **Optical Communications**
  - ~54 dB theoretical performance gain over X-band
  - ~10 dB enhancement relative to X-band (assuming 0.3-m space aperture at maximum Mars-Earth distance and 10-m ground telescope)
  - Additional 10 dB growth potential over time as technology matures (more efficient components and larger diameter ground telescope)
- **These performance gains can be used to:**
  - Increase science data return, ***or***
  - Reduce the impact (mass/power) on spacecraft (for a given data rate), ***or***
  - Reduce required contact time with (and costs of) ground reception station support

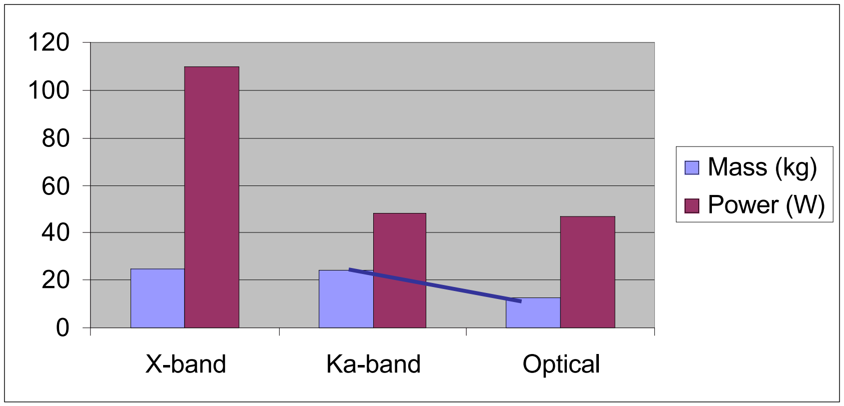
* Assumes power consumption dominated by XMTR Power Amp

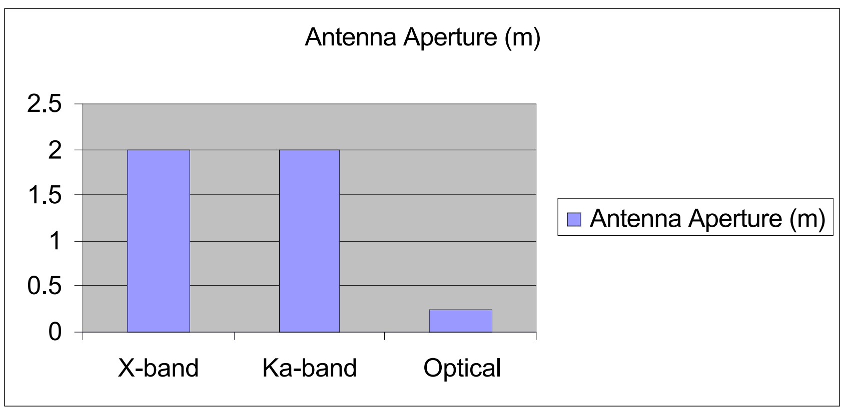
Benefit Example

A 3 dB gain can enable:
- 2x data return, ***or***
- 50% power reduction*, ***or***
- 50% reduction in GND tracking time

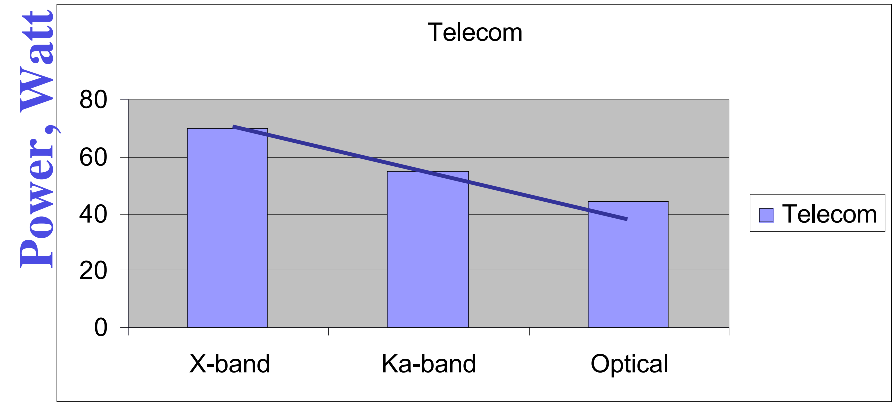
Performance Projections

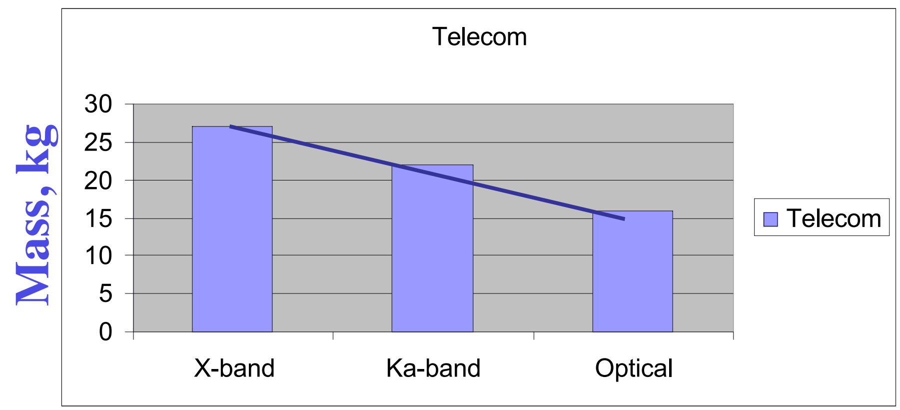
1997 Study for Mars Mission (10 Gbit volume per day)





Jupiter Deep Multi-probes Study ('09 launch)

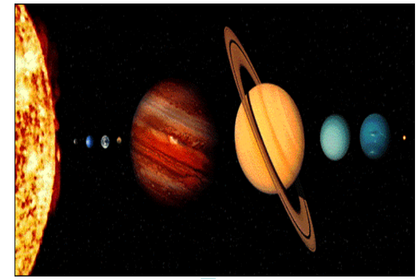




Optical communications: power and mass -- reduction of ~40% vs. X-band and aperture reduction of over 80% vs. X-band or Ka-band technology

Technology Roadmap

Mars
& Outer
Planetary



Neptune
Orbiter

Key Milestones to
be achieved

• Miniaturization
• Radiation Harden

• 10% Efficient Laser with < 1 Mbps modulation
• 30% Detector Quant. Effic.
• 1 urad pointing

• >20% efficient laser with >10 Mbps modulation
• 8 photons/bit detection
• 0.25 urad pointing
• 10-12 kg terminal

• 30% Efficient 10 W laser with > 100 Mbps modulation
• 4 photons/bit detection
• 50 nrad pointing
• <7 kg terminal

1-m R&D Optical Station

10-m Ground Receiver Infrastructure Ready

2000 2005 2010 2015