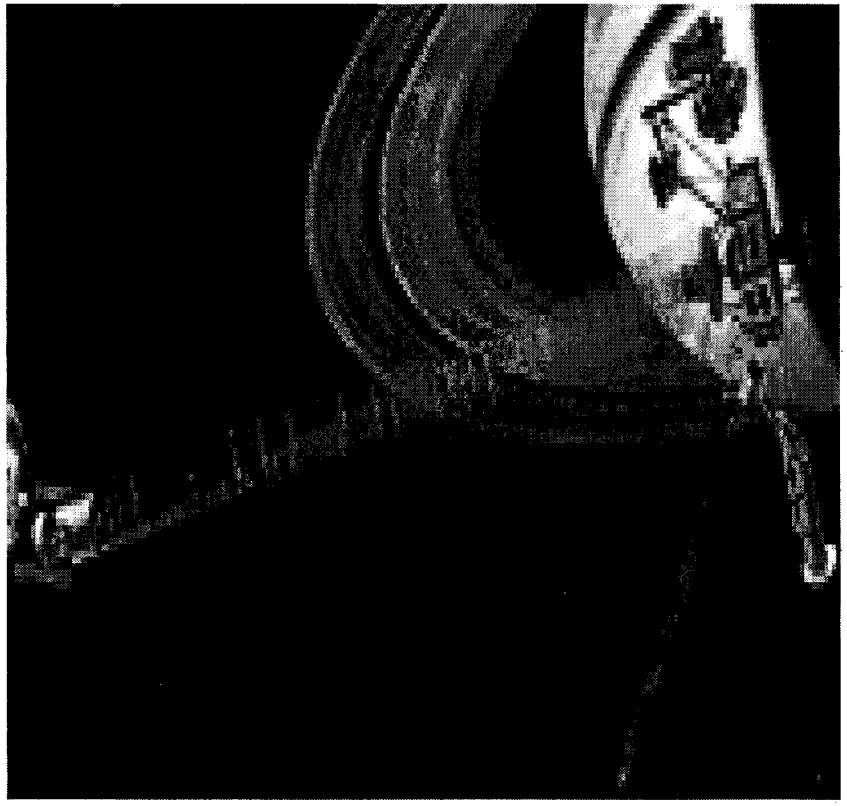
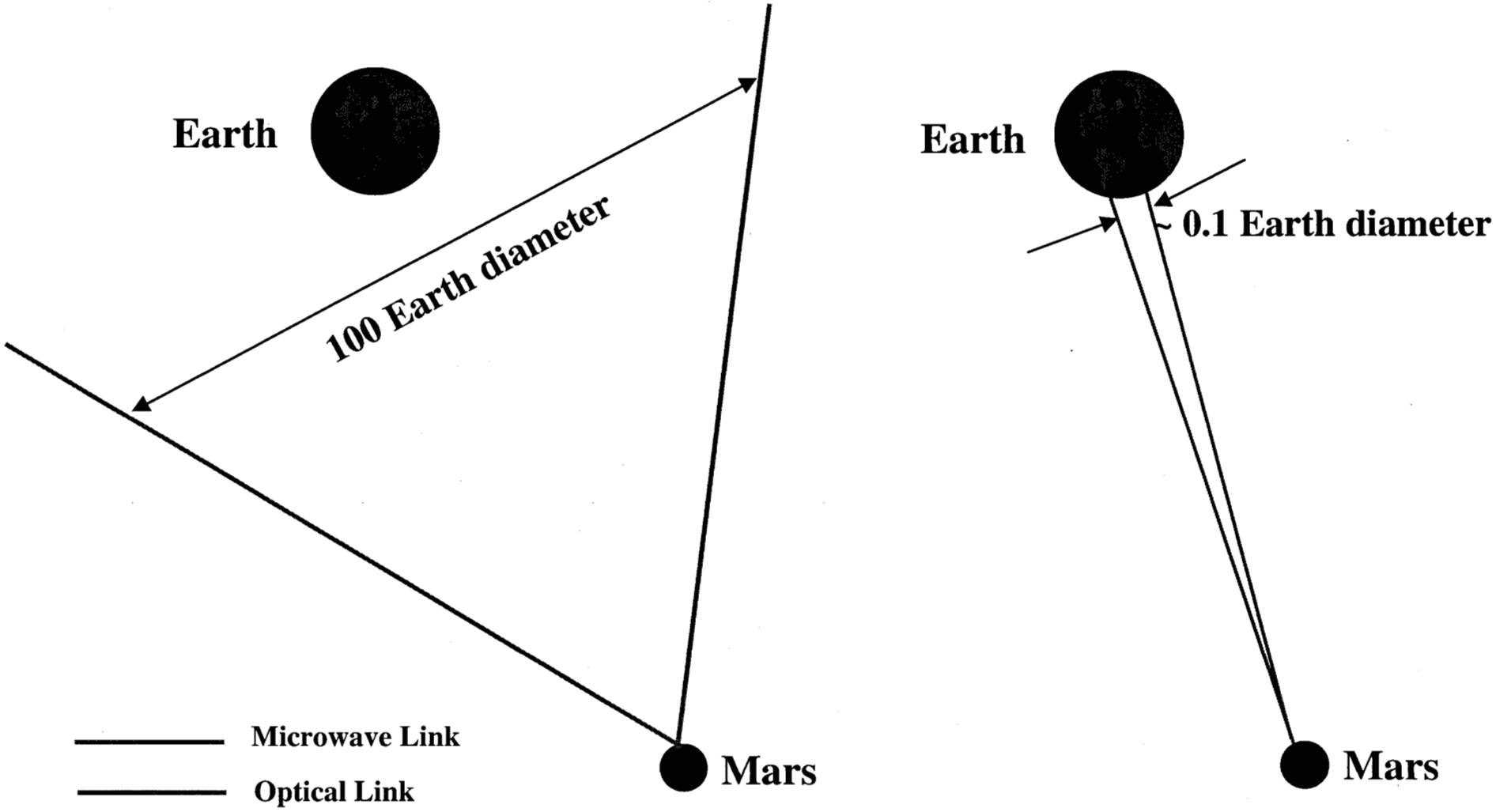


Free-Space Optical Communications at NASA

H. Hemmati

Optical Communications Group
Communications Systems and Research Sec.
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA 91109

Beam Divergence (Frequency) Effect



Potential of Laser-Communication Technology

	Gain, Losses & Efficiency (dB)		Optical Advantage (dB)		
			Year 2000	Year 2010	Notes
	X	Optical			
Transmitter aperture gain (dB)	39.86	116.03	76.17	76.17	1.5 m X-band (incl. struc. losses) and 0.3 m Optical
Receiver aperture gain (dB)	74.17	149.30	75.13	75.13	70 m X-band (incl. all losses) and 10 m Optical
Space loss (dB)	-282.44	-372.90	-90.46	-90.46	Nominal range = 2.5 AU
Transmitter antenna losses (%)	-1.00	-1.25	-0.25	0.00	Surface reflectance and struts, hot body noise
Transmitter beam-path losses (%)	-1.00	-1.25	-0.25	0.00	Includes: filter, splitter, circulator, cables, ...
Pointing losses (dB)	-0.20	-2.00	-1.80	-1.40	
Transmission path losses (%),	-0.80	-1.74	-0.94	-0.94	
Receiver antenna losses (%)	-1.30	-3.67	-2.37	-1.40	X-band losses are already accounted for
Transmitter power (W)	10.97	4.77	-6.20	-3.60	Laser transmitter efficiency improvement
Data rate delivery (bps)	6.40E+04	1.50E+06			Optical provides > 20 times data-rate advantage
Required power/data rate (W.sec/bit)	-214.44	-177.74	-36.70	-34.60	Receiver detector efficiency improvement
			12.33	**18.90**	Net advantage (assuming night-time reception)
			8.80	**15.50**	Net advantage (assuming day-time reception)

Assumptions:

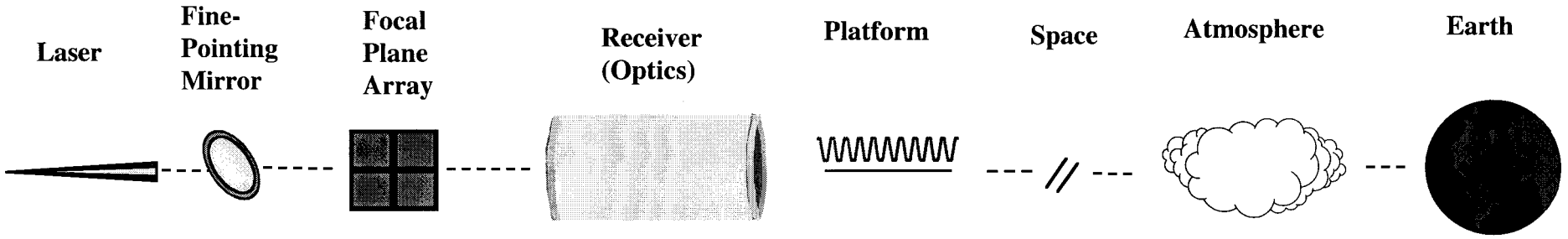
Link margin = 3 dB, Elevation angle = 15°, BER= 10^{-5}

DC input power for both systems = 35 W

Optical: 25 W to transmitter and 10 W to acquisition and tracking subsystem

X-band: 12.5 W to transponder and 22.5 W to amplifier (55% efficiency, year 2000)

Free-Space Optical Communications
Design Drivers / Technology Development



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

- Bandwidth
- Reaction
- Performance
- Reliability

- 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

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

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

- Radiation

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

- Reflectance
- Albedo variations
- Crescent size
- Motion

Technology Developments at JPL

- Space-Based Transceiver Component and System Technology Development
- Ground-Based Receiver and Uplink Command/Beacon Technology Development
- Flight Terminal Development for Space-Station-to-Ground Communications
- Engineering Model Development for Deep-Space-to-Ground Communications

Current Technology Development Tasks

1. Research

Flight Transceiver Components & Algorithms

- Acquisition, Tracking and Pointing
  - both point- & extended-source
- Efficient solid-state Lasers
- Efficient modulation
- Fine-pointing mirrors
- High update-rate focal-plane-arrays
- Background sun-light avoidance

Ground Receiver/transmitter

- Atmospheric visibility monitoring
- Channel capacity, efficient modulation and coding
- Terrestrial test of lasercomm terminals
- Definition of large-aperture receivers
- Efficient detectors/amplifiers, receivers

Current Technology Development Tasks, continued ...

2. Flight Programs:

ISSERT/OCD (near-earth)

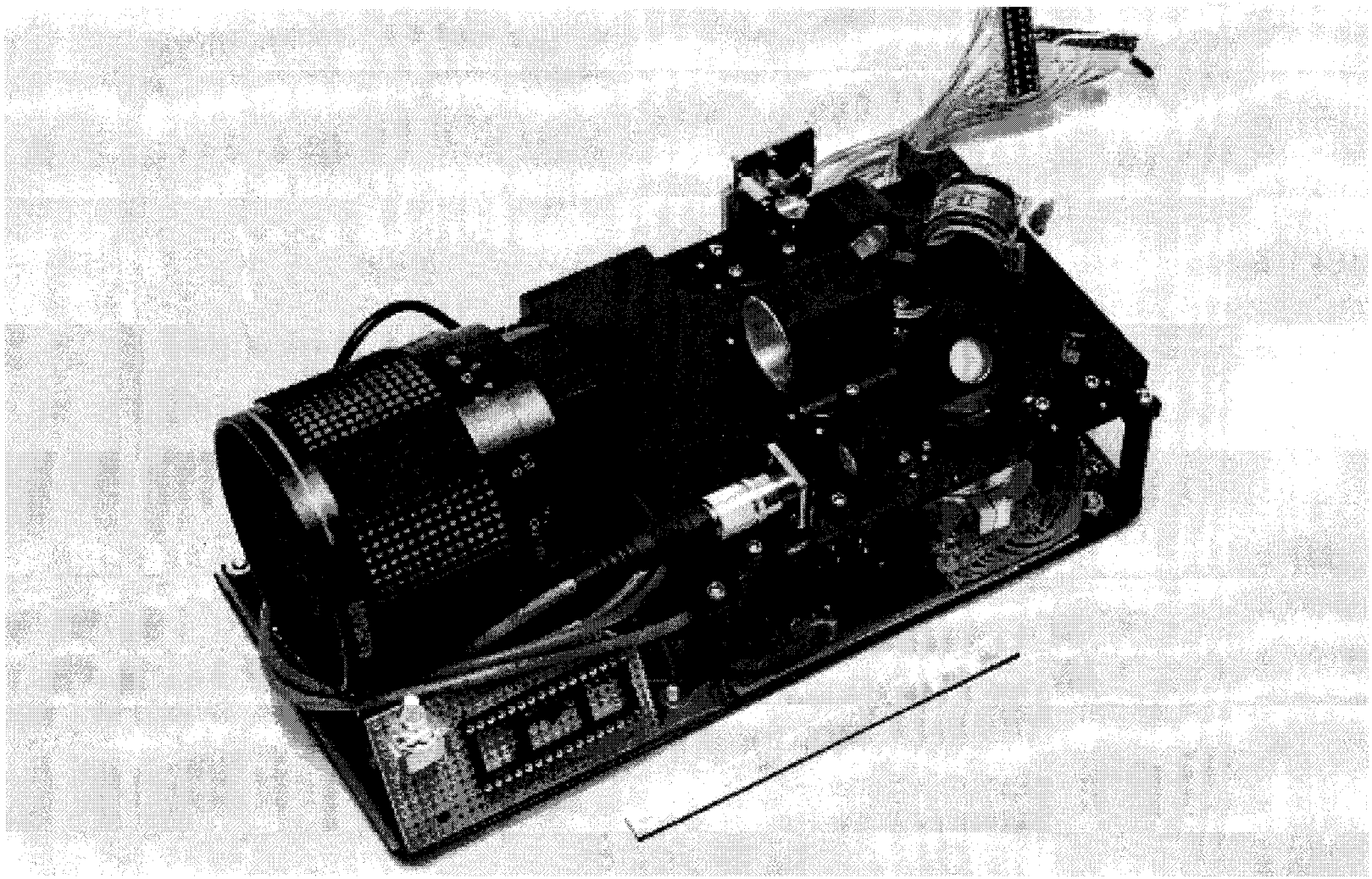
- Up to 2.5 Gbps data-rate communications from LEO (International Space-Station) to Ground demonstration/facility

ATTI (Advanced Technology Transfer & Infusion) (deep-space)

- Multi-function instrument:
  - 100 kbps from 2 AU from a 10-cm aperture on a micro-spacecraft
  - high-resolution science imaging
  - laser altimetry

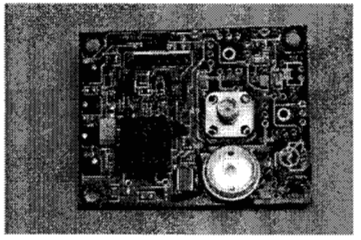
ACLAIM

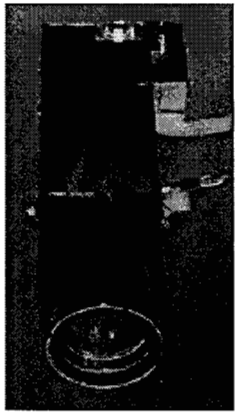
(A Combined Lasercomm and Imager for Micro-spacecraft)

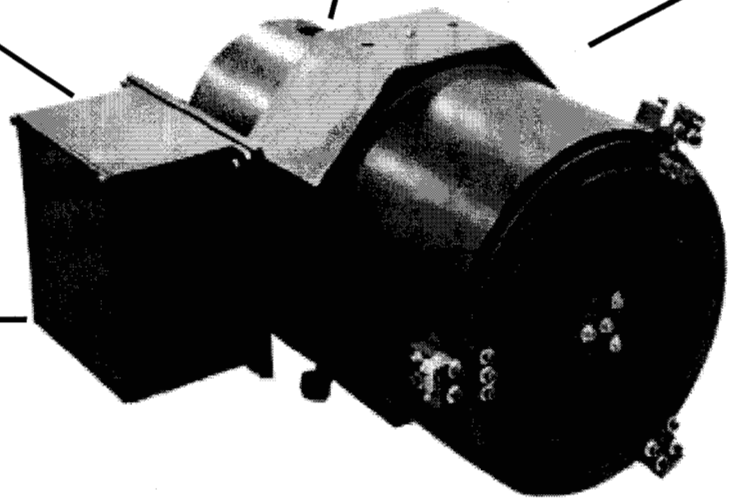


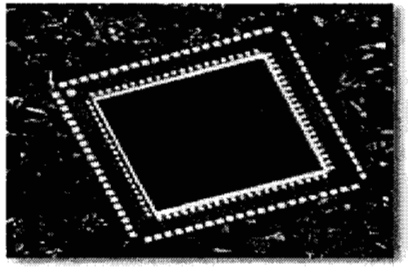
Optical Communication Demonstrator (OCD)
(Laboratory Model)

Fine-Pointing Mirror


Data Receiver

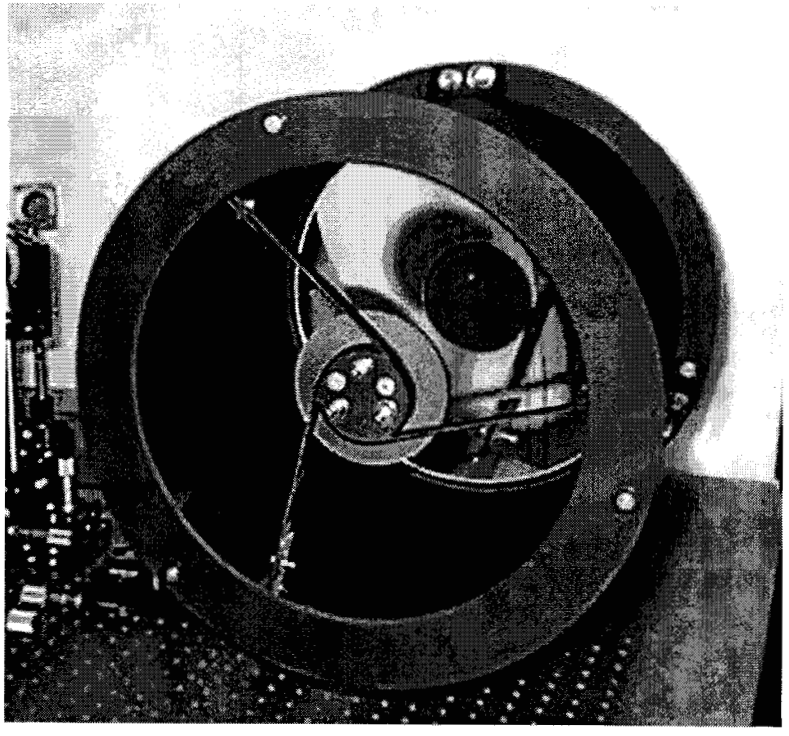

Laser Transmitter




Focal Plane Array

Lightweight Low Thermal Expansion Telescopes

- All SiC telescope
- 30-cm primary mirror
- Weight: ~ 6 kg

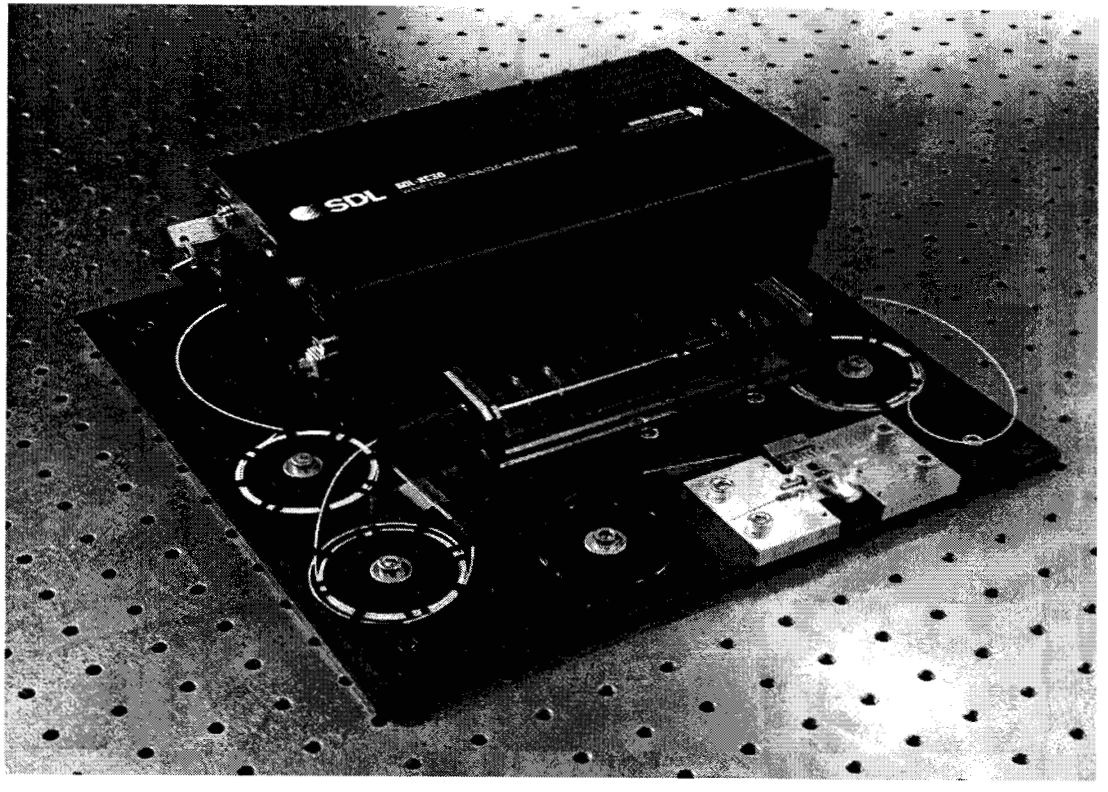


Developed by SSG Inc. under SBIR Phase II

Now developing a 3.5 Kg version

Semiconductor MOPA Development

Wavelength: 940 nm
Power: 1 Watt
Data-Rate: 2.5 Gbps (scalable to 10 Gbps)

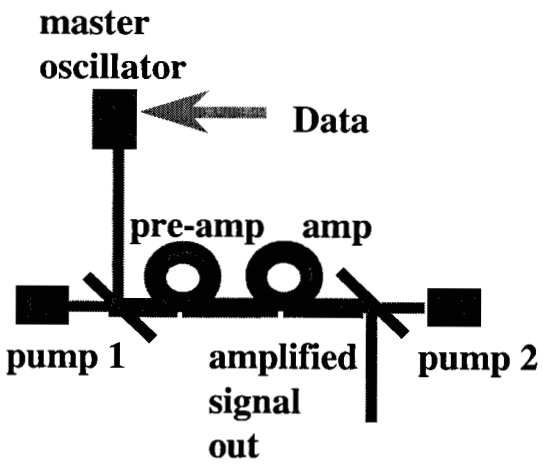


Developed by SDL
Under Phase II SBIR

Fiber MOPA Development

Yb-Doped Fiber Amplifier Transmitter and Nd-doped Receiver Amplifier Assembly Prototype by SDL Inc.

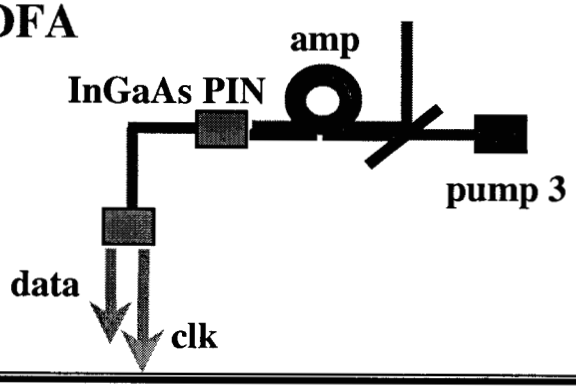
Tx YDFA

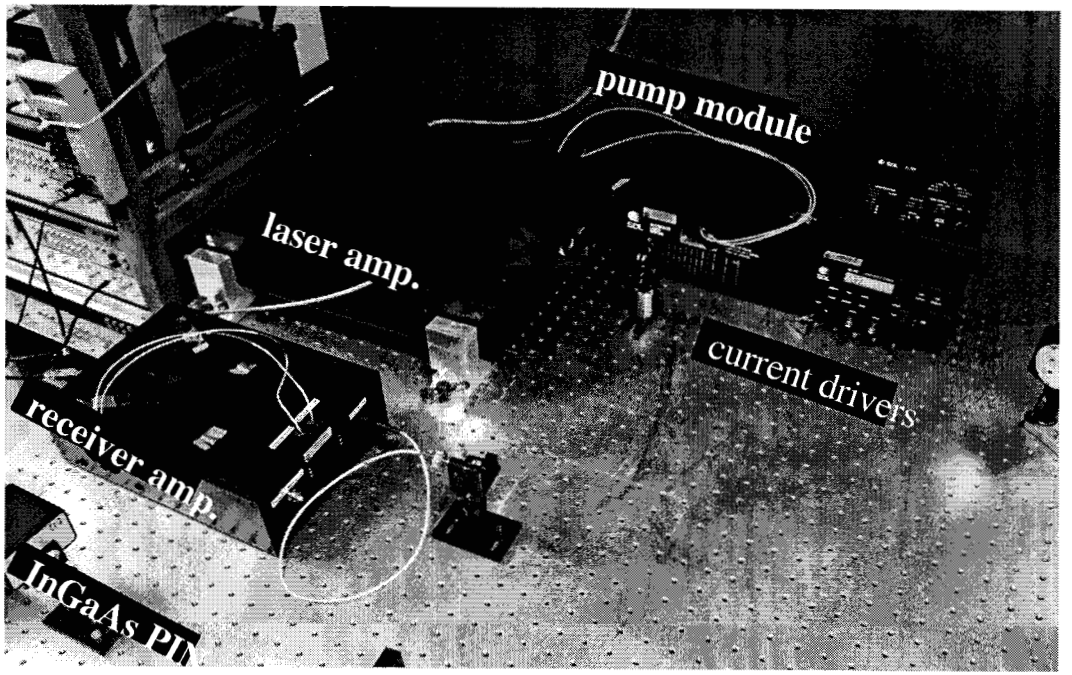


- λ = 1072 nm
- Data Rate = 2.5 Gbps
- Output Power = 6 W

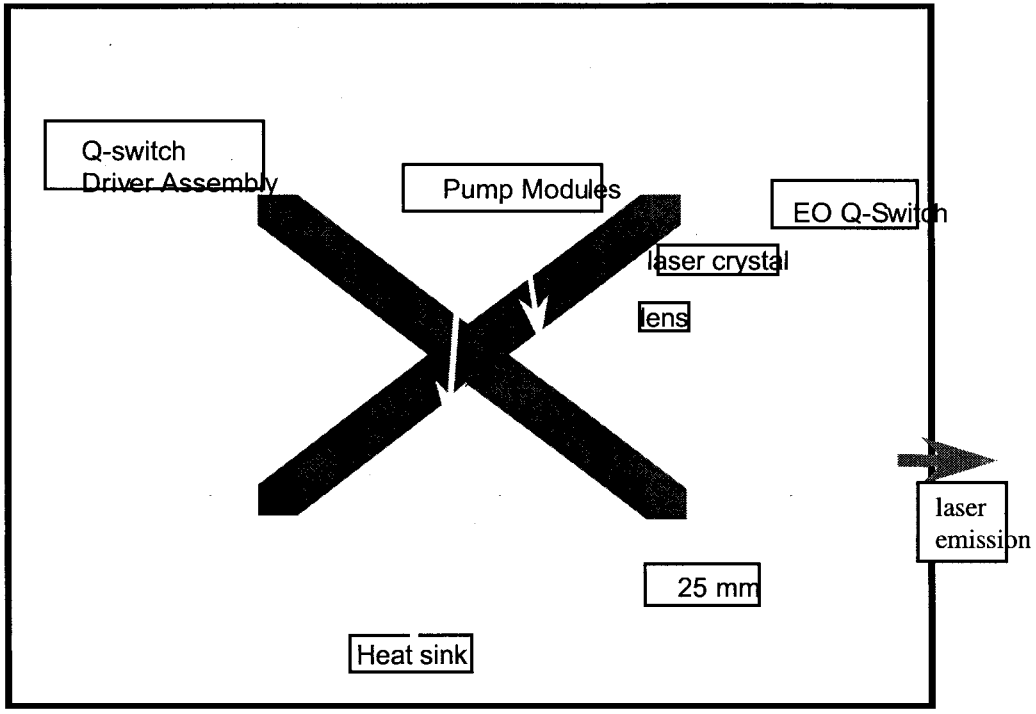
Pump 1 = 917 **nm**
Pump 3 = 808 **nm**

Rx NDFA





Efficient Diode-Pumped Laser Transmitters

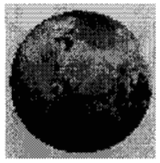


Wallplug Efficiency:

State-of-the art:	< ~ 7%
In FY99 developed	~ 10%
Now working on:	15%

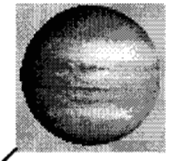
ATP Technologies for Deep Space Missions

< 1 AU



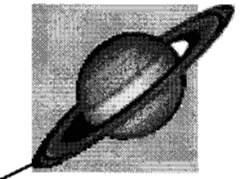
Laser Beacon tracking,
Earth Image Tracking

~1 to ~ 6 AU



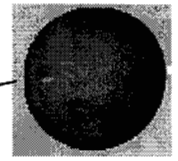
Earth-Moon Image Tracking
Star-Tracking with Inertial
Sensor Compensation

~6 to ~12 AU



Earth-Moon Image Tracking
Star-Tracking with Inertial
Sensor Sompensation

> ~12 AU



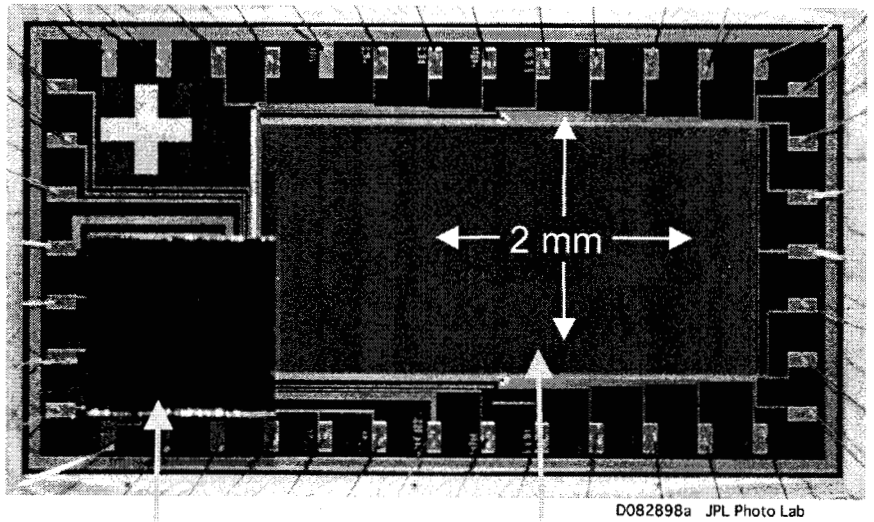
Star-Tracking with Inertial
Sensor Compensation

Advanced Focal Plane Arrays for ACQ/TRK

Hybrid Imaging Technology (HIT)

256 x 512 Pixel Imaging Array

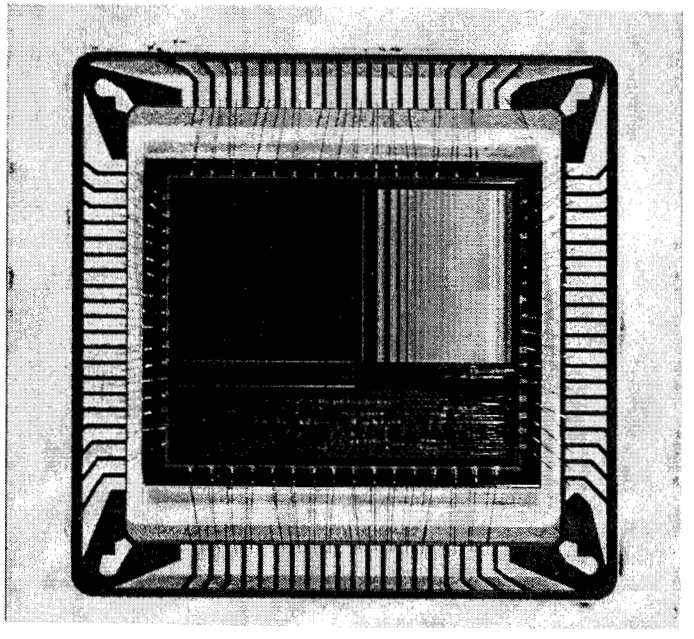
112 Micron Pixel Pitch With 100% Fill Factor



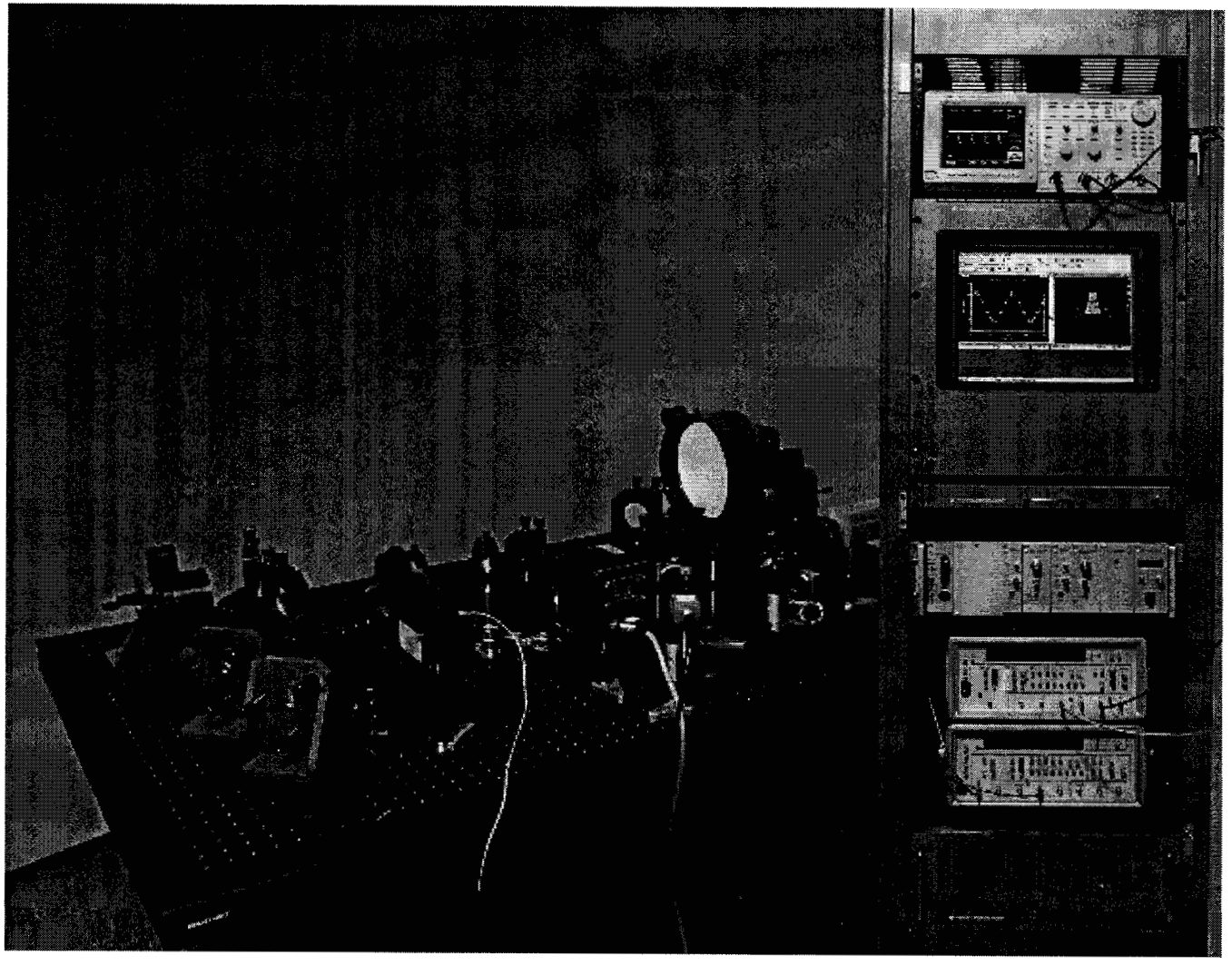
CMOS Amplifier

CCD Imaging Array

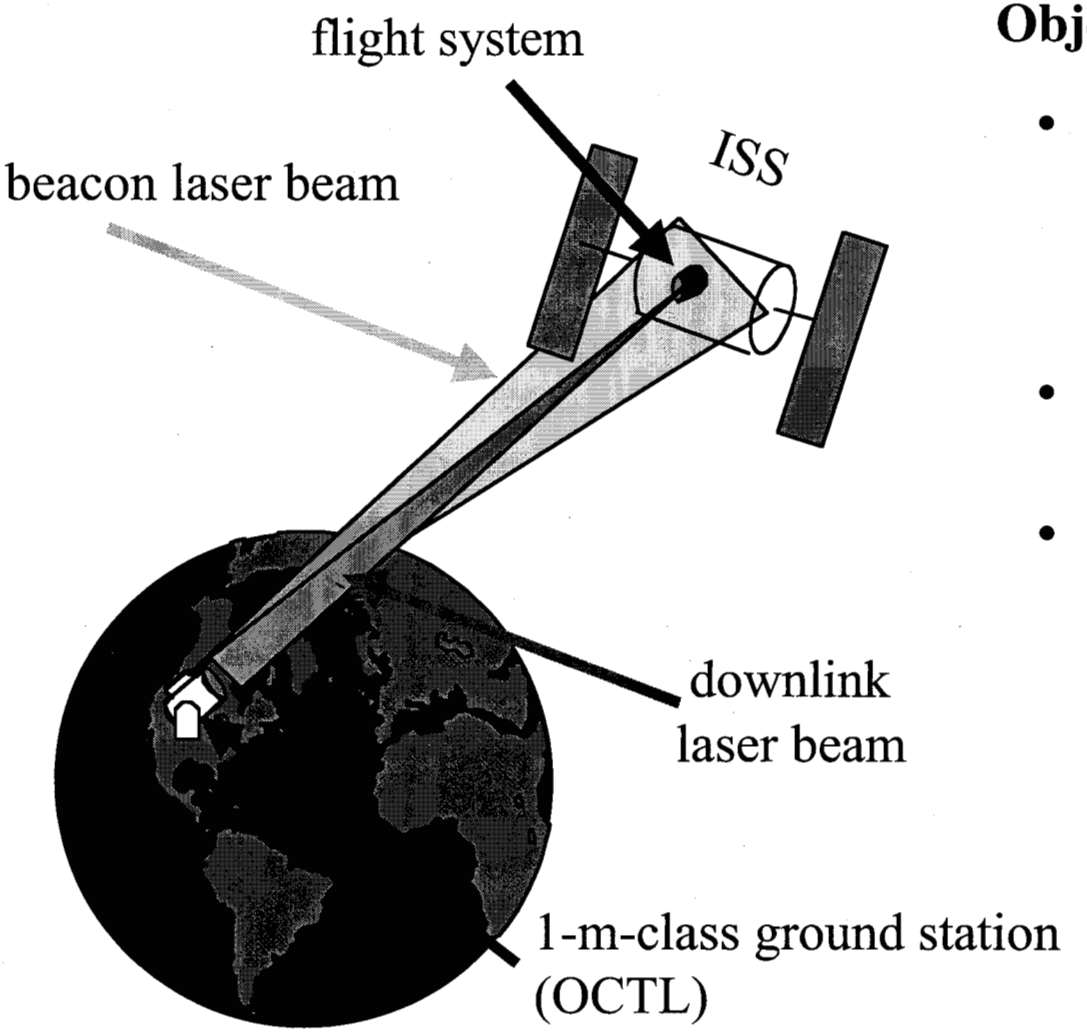
512 x 512 Active Pixel Sensors (APS)



LTES (Lasercomm Test & Evaluation Station)



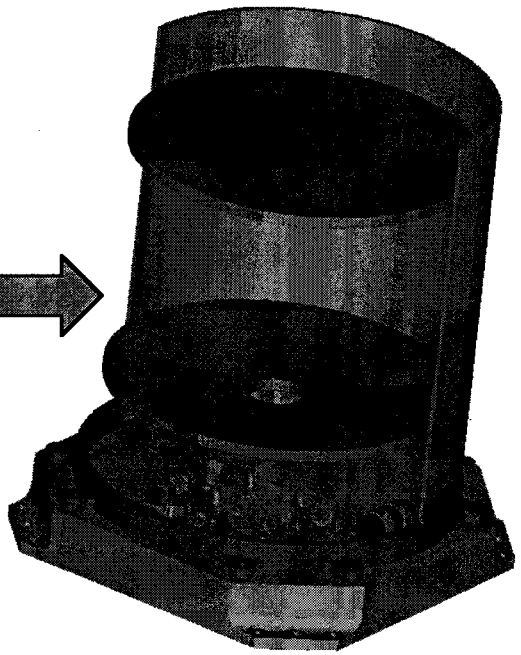
Flight Terminal for Space Station Demonstration/Facility



Objective

- Demonstrate high-rate (up to 2.5 Gbps) optical communication from the the International Space Station (ISS) to ground
- Provide a high-rate link facility capability
- Measure effect of atmosphere on beams

X2000 2nd Delivery Program
System Functions



High-Resolution Science Imaging

Laser-Communications

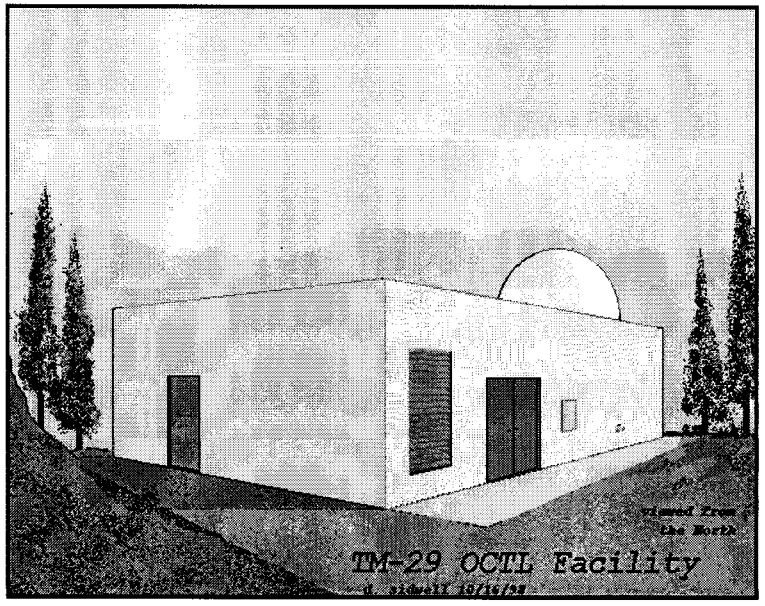
Hazard-Detection & Avoidance (for landing) &Laser-Altimetry

AVM
(Atmospheric Visibility Monitoring)

Set of three 10" autonomous telescopes to measure atmospheric visibility

OCTL
(Optical Communications Telescope Laboratory)

- A 1-m telescope facility to track LEO Spacecraft, dedicated to laser-communications
- Awarded 1 m telescope contract to Contraves Brashear Aug. 31, 1999
- Telescope will be delivered December 2000
- Initiated telescope building construction at JPL's Table Mountain Facility on May 1999



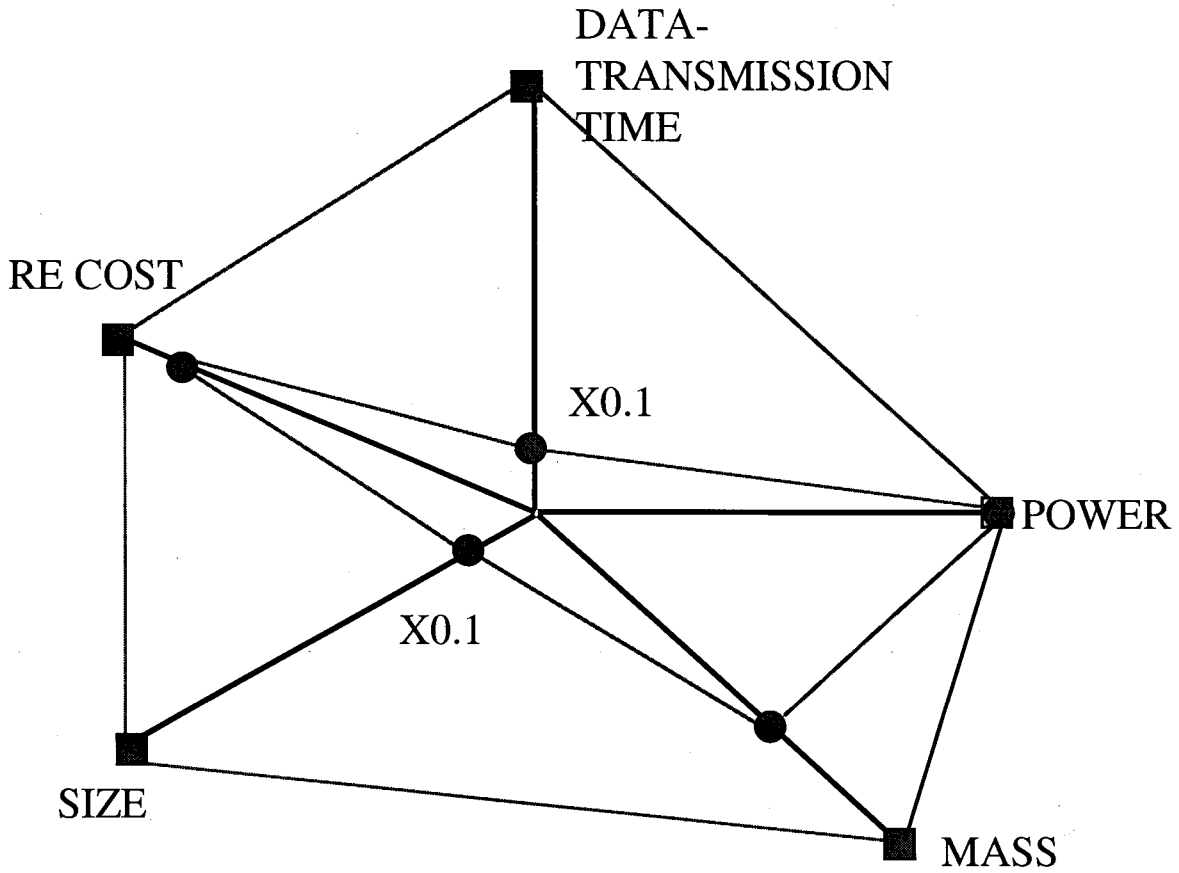
Artist's concept

View of building from southeast direction

Major Remaining Technology Challenges For Deep-Space Laser-Communications

- A complete set of algorithms for Acquisition, Tracking &Pointing (ATP) for ranges of 0.01 AU to > 30 AU (using Laser beacon, Sun-illuminated-Earth beacon, and Sun as beacon)
- Sun-light avoidance and mitigation of background sun-light and scattered light effects
- Development of inexpensive large aperture (> 10 m) ground receiver telescopes with sufficient surface quality for day-time reception
- Near-Earth acquisition and communication (first few days after launch) using optical communications
- More efficient solid-state lasers and detectors will substantially improve status of optical communication technology relative to X-band and Ka-band

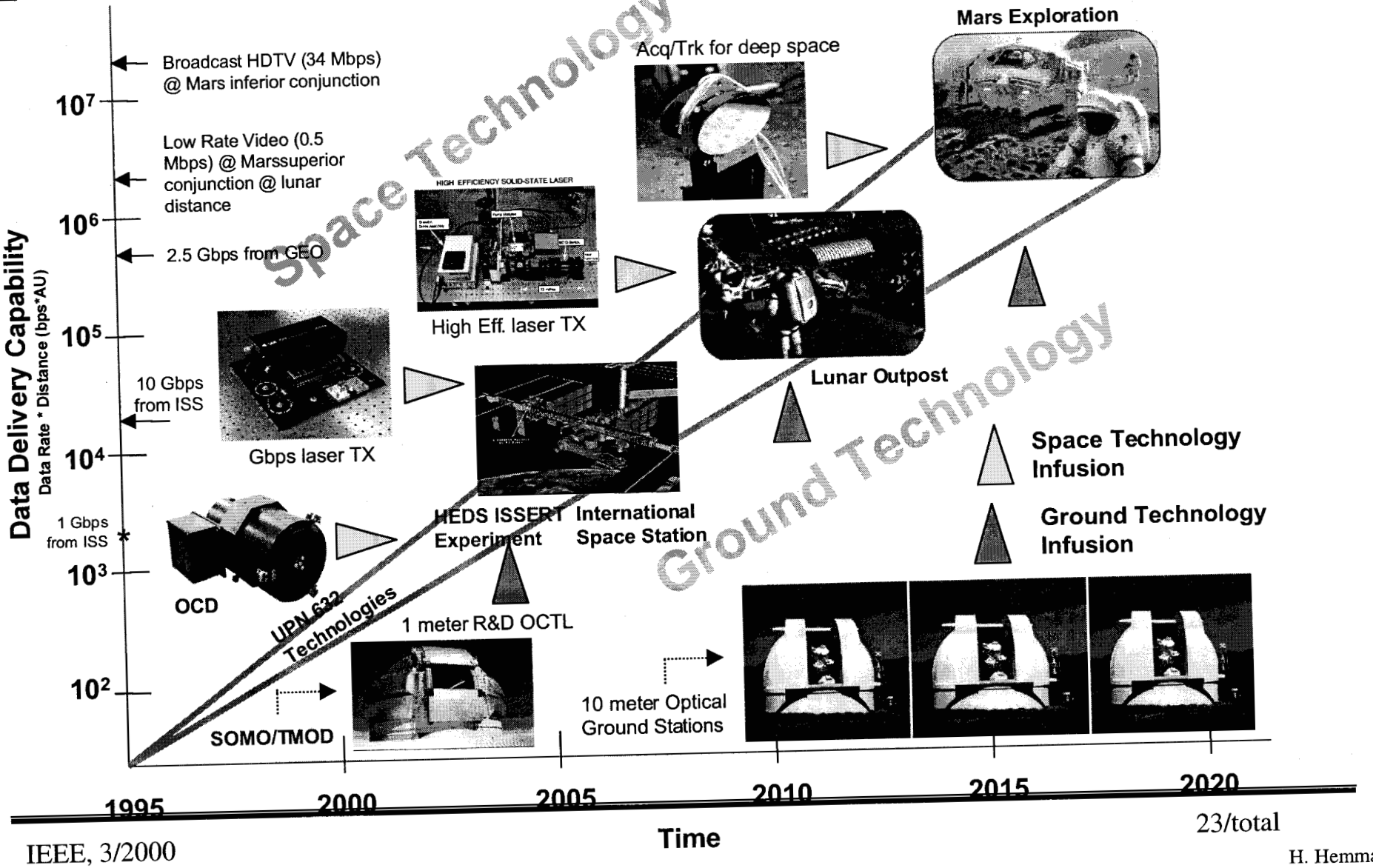
Promise of Technology Improvement Over RF Systems



Reference: ACBS Study, Published by SPIE 1996 & 1997
Performance is very much mission dependent

■ RF ● Optical

Deep Space Optical Communications Roadmap

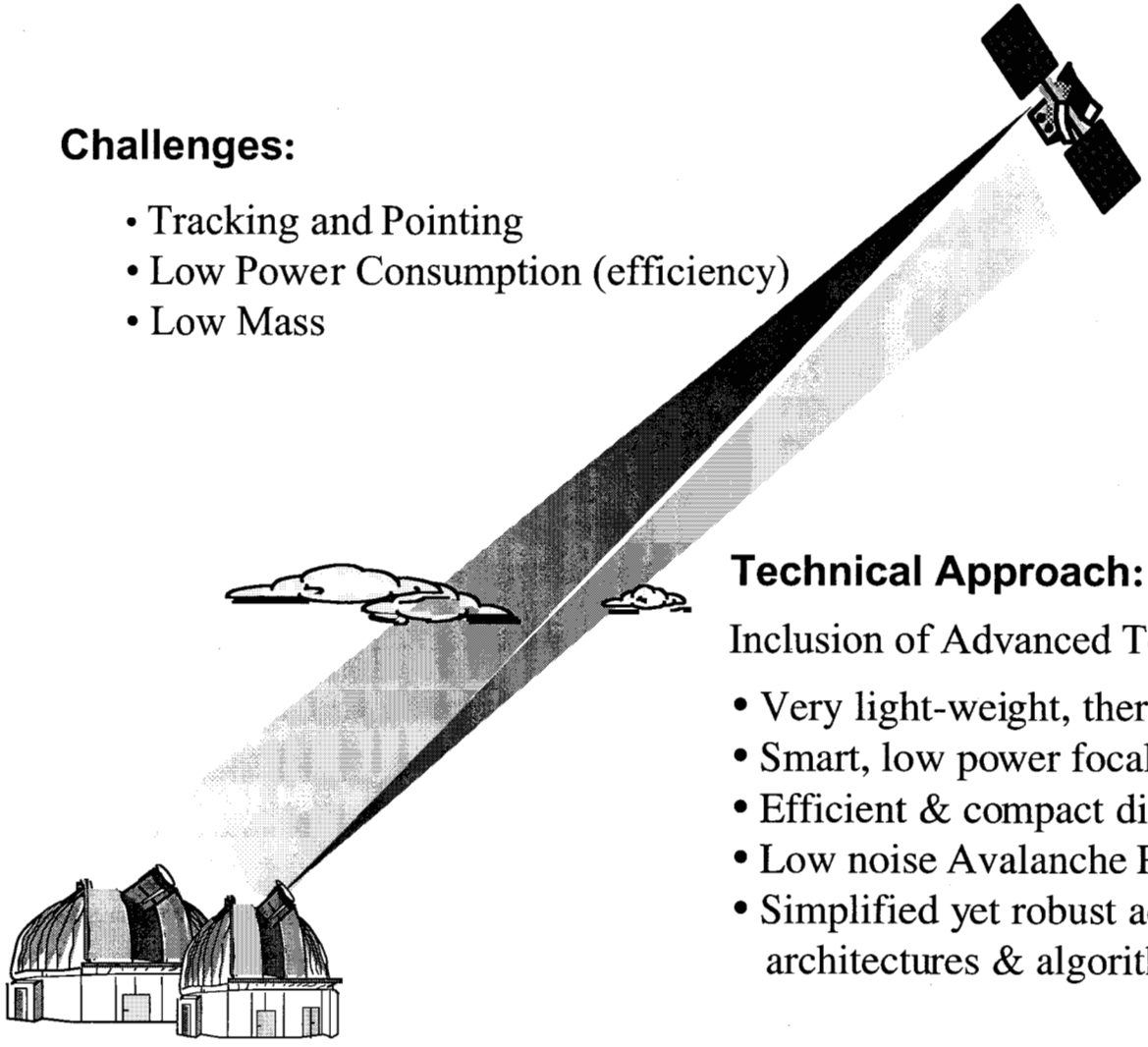


Conclusion

- Component efficiency improvements are now underway
- Solutions to remaining technology challenges are being identified/ developed
- Several space-to-ground demonstrations are being worked on for near-Earth and deep-space
- Development of a network of large aperture ground receivers are planned

lead to establishment of a credible technology making reliable operational deep-space laser-communication a viable option

Optical Communications



Challenges:

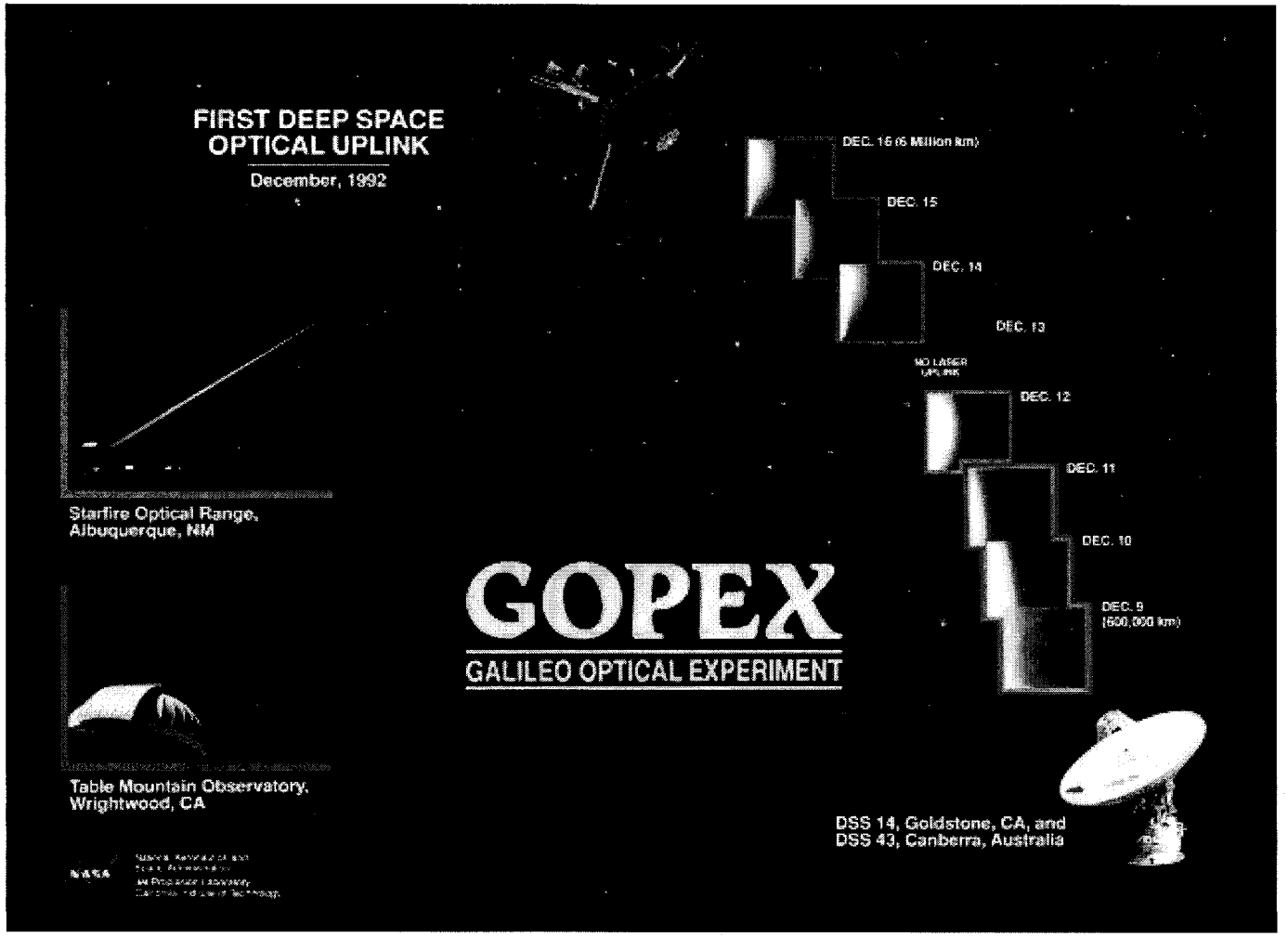
- Tracking and Pointing
- Low Power Consumption (efficiency)
- Low Mass

Technical Approach:

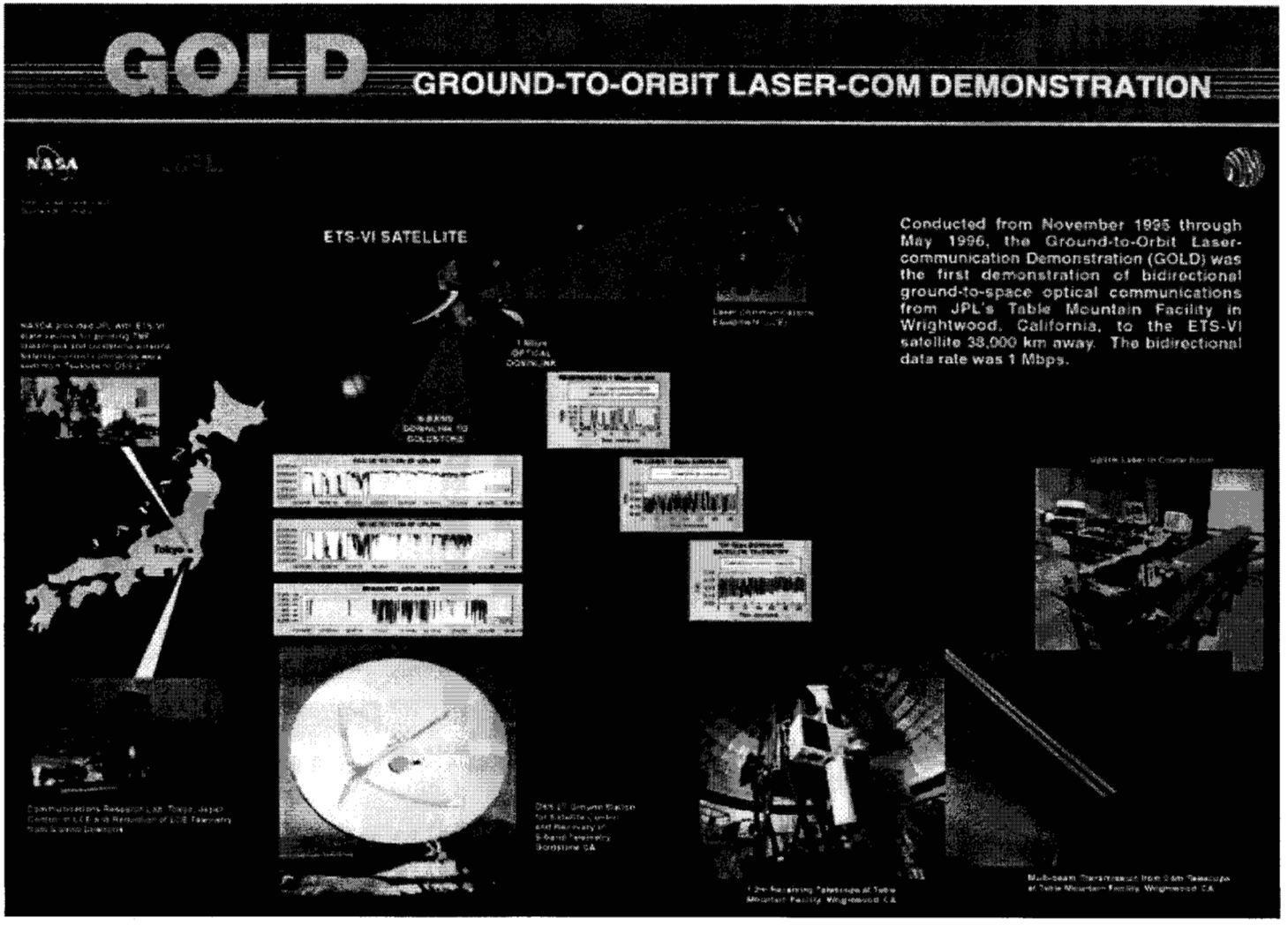
Inclusion of Advanced Technologies

- Very light-weight, thermally-stable optics & structures
- Smart, low power focal-plane-arrays for acquisition & tracking
- Efficient & compact diode-pumped solid-state laser transmitter
- Low noise Avalanche Photo-Diode (APD) data detector
- Simplified yet robust acquisition, tracking and pointing (ATP) architectures & algorithms

GOPEX (Galileo Optical Experiment)



GOLD
(Ground-to-Orbit Lasercom Demonstration)



H. Hemmati