Free-Space Optical Communications at JPL/NASA

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NASA Application Scenarios

- LEO Sats
- GEO Sats
- Deep Space Probes
- Airborne Platforms (UAV/Other)
- Volcano/Wildfire Earth Observations
- Mobile Ground Terminals
- Fixed Ground Stations (NASA/DoD)
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

- RF Link: ~100 Earth diameter
- Optical Link: ~0.1 Earth diameter
## Near Earth vs. Deep Space

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

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

Star Tracking with Inertial Sensors (Beaconless tracking)

Laser Beacon Tracking w/ Inertial Sensors

Range Drivers
- Stray light/SEP
- Optical and inertial sensor parameters
- Spacecraft vibration

Range (AU)
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

Tracking Detector

Laser Transmitter

Optical Terminal

Data Rate
Range
Estimated Mass
Estimated Power

.5 - 1 Gbps
>10,000 km
16 kg
55 W

Fast Steering Mirror

10 cm Aperture

TMS-C40 Control Processor

Optics (exploded View)
JPL’s ATP Concept

Diagram showing components such as Telescope, Dichroic, Focal Plane Arrays, Comm Detector, Beam-Steering Mirror, Transmit Laser, Beam Splitter, Accelerometer Package, External Jitter, Earth Image Size on Focal Plane.
Multi-Functionality

- High-Resolution Science Imaging
- Laser-Communications
- Hazard-Detection & Avoidance (for landing) & Laser-Altimetry

Multi-Functionality
Low-Capability Lasercomm Terminals

ACCLAIM
(A Combined Lasercomm and Imager for Micro-spacecraft)

SCOPE
(Small Communications Optical Package Experiment)
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           UC Berkeley
10 g, 30 mW               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

<table>
<thead>
<tr>
<th>Year</th>
<th>Accomplishment</th>
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<tbody>
<tr>
<td>1982</td>
<td><strong>First</strong> demonstration of 2.5 bits/photon detection</td>
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<tr>
<td>1986</td>
<td><strong>First</strong> demonstration of moderate power diode-pumped Nd: YAG laser using diode arrays (for deep-space transmitter)</td>
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<tr>
<td>1987</td>
<td><strong>First</strong> demonstration of a diode-pumped Tm,Ho: YLF laser operating at 25 °C, useful as deep space transmitter</td>
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<tr>
<td>1988</td>
<td>SCOPE (Small Communications Optical Experiment) lasercom terminal developed</td>
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<tr>
<td>1989</td>
<td>Detailed study of orbiting optical communication receivers completed; DSORA study</td>
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<tr>
<td>1990</td>
<td><strong>First</strong> high power (12 W 1064 nm, 3.5 W 532 nm) efficient diode end-pumped solid-state laser demonstrated</td>
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<tr>
<td>1991</td>
<td>100 Mbps resonant phase modulator for coherent communication developed and demonstrated in a link</td>
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<tr>
<td>1992</td>
<td><strong>First</strong> optical uplink to a spacecraft in deep-space; GOPEX (Galileo OPtical EXperiment)</td>
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<tr>
<td>1993</td>
<td>CEMERLL (Compensated Earth Moon Earth Retro-reflected Laser Link) using Air Force’s SOR facility</td>
</tr>
<tr>
<td>1994</td>
<td>OCD (Optical Communications Demonstrator) terminal developed, useful to both near-earth and deep-space links</td>
</tr>
<tr>
<td>1995</td>
<td><strong>First</strong> uplink and downlink experiment with a GEOS/C (Japan’s LCE); GOLD (Ground Orbit Link demonstration)</td>
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<tr>
<td>1996</td>
<td>First demonstration of scintillation mitigation on a ground-to-space optical link using multiple uplink beams</td>
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<tr>
<td>1997</td>
<td>Lasercomm Test and Evaluation Station (LTES) companion terminal completed</td>
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<td>1998</td>
<td>ACLAIM (A Combined Lasercomm And IMager) instrument completed and integrated with a micro-spacecraft</td>
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<tr>
<td>1999</td>
<td>First set of instruments to quantitatively characterize the atmosphere; AVM (Atmospheric Visibility Monitoring) stations</td>
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<tr>
<td>2000</td>
<td>45 Km range horizontal link with OCD terminal successfully made</td>
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<tr>
<td>2001</td>
<td>HDTV (1.5 Gbps) and WDM (7.5 Gbps) links demonstrated to within 1 dB of link analysis predictions</td>
</tr>
<tr>
<td>2002</td>
<td>Demonstrated ATP (Acquisition, Tracking and Pointing) simulating LEO-GEO links in the lab</td>
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</table>
Optical-Communications Roadmap

**Technology Development**

- NASA Code S, Flight and Ground Systems
- NASA Code R, Low TRL Technologies
- NASA Code Y, NRAs
- NASA Mars Technology
- JPL’s R&TD

**Near-Earth Flight Demos**

- MDA-funded
- NMP EOx
- UAV-to-Ground (2.5 Gbps)
- LEO-GEO > 10 Gbps

**Deep-Space Flight Demos**

- e.g. Mars 09, NMP STx, Outer Planetary
- 10 to 100 Mbps from Mars

**Ground Receivers**

- 1-m Station Completed (OCTL)
- 5-m Palomar 3.67-m Air-Force Station Utilized
- 10 m RCVR
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

- 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

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

- Dewar
- Detector 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
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

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

* Assumes power consumption dominated by XMTR Power Amp
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

Key Milestones to be achieved

- 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

Mars & Outer Planetary

- Miniaturization
- Radiation Harden

Neptune Orbiter


1-m R&D Optical Station

10-m Ground Receiver Infrastructure Ready