Laser Communication Requirements
Drive Cost-Effective Solutions

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Outline

- Crosslink applications and system requirements
- Benefits of laser communications
- Design trades
- LEO short-range links
- LEO medium-range links
- LEO and GEO long-range links
- Common and modular hardware solutions
- Development risk
- Summary
Crosslink Applications Support Commercial, Military and Scientific Users
Space-to-Space Applications Stress Different Aspects of the Design

- **LEO-to-LEO crosslinks**
  - Short range: Up to 1 Gbps over 5000 km
  - Medium range: Up to 7.5 Gbps over 10,000 km
  - Limited attitude knowledge increases acquisition search cone
  - Platform base motion drives residual pointing jitter

- **LEO-to-GEO uplinks**
  - Up to 10 Gbps over 44,000 km
  - Good attitude knowledge reduces GEO search cone
  - LEO platform base motion drives residual pointing jitter

- **GEO-to-GEO crosslinks**
  - Up to 10 Gbps over 84,000 km
  - Good attitude knowledge reduces acquisition search cone
  - Reduced platform base motion lowers residual pointing jitter
Benefits of Laser Communications

- Increased bandwidth (large carrier frequency)
- Small antenna and swept volume (large antenna gain)
- Secure communication (narrow beam with low probability of intercept and negligible interlink interference)
- Jam resistance (small receive FOV)
- Track and communicate through the sun (small receive FOV)
- Full-duplex communications
- Spectral separation from existing communication systems (non-regulated spectrum)
- Reduced weight and power
- Lower recurring cost
Laser Terminal Comprised of Several Key Subsystems

Spacecraft Computer

Operational Modes
- Quiescent Mode
- Warm-up/Stand-by
- Acquisition
- Fine Track/Communications
- Reacquisition
- Survival Mode

Control Processor

Software
- Flight operation and control
- Testing
- Software control
- Fault management

Electro-Optical Subsystem

Transmission Channel
- Free space
- Atmospheric Backgrounds
- Attenuation
- Scintillation

Optical Design
- Telescope designs
- FOR, FOV, IF0V
- Apertures and f/#
- Throughput
- Wavefront quality
- Spectral filtering
- Baffling/Stray light

Transmitter Subsystems
- Acquisition
- Fine Track
- Communications
- Laser types & powers
- Beam divergences
- Temporal characteristics

Receiver Subsystems
- Acquisition
- Fine Track
- Communications
- Detector types & array sizes
- Sensitivities
- Preamplifiers
- Background control
- Dynamic range

Thermal Control
- Thermal tolerancing
- Optical distortion
- Spacecraft interface

Optical Alignment
- Error budget
- Alignment techniques
- Acquisition-to-track
- Payload-to-spacecraft
- Software control

Support Electronics
- Power conditioning
- Health/status data
- Spacecraft data bus interface

Pointing, Acquisition, Tracking & Control
- Acquisition coverage & agility
- Fine track/Comm coverage & agility
- Pointing mechanisms
- Jitter rejection & pointing control bandwidth
- Spacecraft interface & inertial reference pointing
- Error budgets/Pointing accuracy & stability
- Calibration techniques

Processing Electronics
- Acquisition/Track handoff
- Track processing
- Data formatting
- Demodulation
- Background control
- On-board data reduction reqmts.

Optical Terminal Structure
- Vibration PSD
- Structural resonant frequency
- Spacecraft mounting

Contamination Control
- Aperture doors
- Aperture/Spacecraft thruster locations
Key Design Trades Define Cost-Effective Solutions

- Laser transmitter and receiver: 0.85-um AlGaAs Diode with Direct Detection; 1.06-um Nd:YAG with Coherent Detection; 1.55-um EDFA with Direct Detection Preamplifier
- Optical design: On-axis vs. off-axis telescope; Transmit/receive isolation; Solar background rejection; Wavelength multiplexing
- Coarse pointing: Gimbaled telescope vs. gimbaled mirror vs. gimbaled package
- Acquisition: Scanned beacon and quadrant or array position sensor
- Fine pointing: High bandwidth steering mirror; High-bandwidth control system; Sensitive position sensors (quadrant vs. nutation)
- Point-ahead: Accurate orbital data; High-precision point-ahead mirror
- Support electronics: Central processor; Servo control; Thermal control; Power conditioning
# Example Trade: Coarse Pointing Options

<table>
<thead>
<tr>
<th>Pointing Approach</th>
<th>Pro</th>
<th>Con</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gimbaled Terminal</td>
<td>Smaller laser terminal envelope</td>
<td>Larger gimbaled mass increases payload mass &amp; power (bearing size, motor size, etc.)</td>
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<tr>
<td></td>
<td>Fewest optical components that satisfy necessary slew &amp; agility</td>
<td>Data, electrical, power &amp; some thermal transfer across gimbal</td>
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<td></td>
<td>Straightforward telescope baffling</td>
<td>Higher pointing-induced momentum &amp; torque</td>
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<td>Stabilization between laser terminal and platform base motion</td>
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<td></td>
<td>Near-hemispherical angular coverage</td>
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<tr>
<td>Gimbaled Telescope w/</td>
<td>Lighter gimbaled mass</td>
<td>Coude' fold mirrors decrease throughput &amp; increase complexity</td>
</tr>
<tr>
<td>Coude' Optical Path</td>
<td>No thermal or data transfer across gimbal</td>
<td>Initial assembly and alignment more complicated</td>
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<tr>
<td></td>
<td>Limited electrical and power transfer across gimbal</td>
<td>Base motion directly imparted to focal plane</td>
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<tr>
<td></td>
<td>Straightforward telescope baffling</td>
<td>Moderate pointing-induced momentum &amp; torque</td>
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<tr>
<td></td>
<td>Near-hemispherical angular coverage</td>
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<td></td>
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</tr>
<tr>
<td>Gimbaled Flat Mirror</td>
<td>Lighter gimbaled mass</td>
<td>Additional large optic</td>
</tr>
<tr>
<td></td>
<td>No thermal or data transfer across gimbal</td>
<td>Requires larger envelope to separate pointing &amp; fold mirrors</td>
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<tr>
<td></td>
<td>Limited electrical and power transfer across gimbal</td>
<td>More-difficult telescope baffling</td>
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<tr>
<td></td>
<td></td>
<td>Stiff structure more difficult to achieve</td>
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<tr>
<td></td>
<td></td>
<td>Base motion directly imparted to focal plane</td>
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<tr>
<td></td>
<td></td>
<td>Less-than-hemispherical angular coverage</td>
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<tr>
<td></td>
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<td>Moderate pointing-induced momentum &amp; torque</td>
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LEO Short-Range or Low-Data-Rate Applications

- 10 Mbps at 5000 km range
- 1 @ 75-mW AlGaAs transmitter
- Si CCD acquisition receiver; Si quadrant APD track and communications receiver
- BPPM modulation
- 1.2 inch transmit telescope, 4 inch receive telescope
- Gimbaled payload
- 15 lbs, 15 W
LEO Medium-Range Applications

- 7.5 Gbps at 6000 km range
- 3 @ 0.3-W EDFA transmitters
- EDFA LNA with 3 @ InGaAs pin photodiode receivers
- OOK modulation
- 7 inch transmit/receive telescope
- Gimbaled flat mirror
- 25 kg (55 lbs), 100 W
LEO and GEO Long-Range Applications

- 10 Gbps at 84,000 km range
- 4 @ 3-W EDFA transmitters
- EDFA LNA with 4 @ InGaAs pin photodiode receivers
- DPSK modulation
- 12-inch transmit/receive telescope
- Gimbaled telescope
- 90 kg (200 lbs), 300 W
Several Hardware Elements Support a Variety of Applications

- Fine pointing mirror
- Point-ahead mirror
- Processing electronics
- Optical bench
- Thermal radiator
Development Risk Is Manageable

- Laser and receiver reliability and lifetime must be fully verified
- Coarse and fine pointing requirements are met with flight-proven concepts that are modified to meet specific needs
- Electro-optic instrument development is similar to other proven flight systems
  - Optical design for telescope and bench
  - Thermal control
  - Flight processor
  - Software control
  - Heat rejection
  - Radiation effects
  - Contamination control
  - Telemetry and commands
  - Power conditioning
- Cost-effective system integration must be demonstrated
Laboratory Demonstration System Reduces Performance Risk

- Demonstrated 2.5 Gbps simultaneous Transmit/Receive operability
- Characterized optical components
- Developed software terminal control and data collection capability
- Demonstrated optical system performance
- Demonstrated performance of fine steering mechanism
- Performed characterization of gimbal
- Demonstrated tracking capability to comply with single-mode fiber coupling requirements
- Demonstrated track loop’s ability to reduce pointing errors
- Validated acquisition scenario
Summary

- Laser communications hardware is ready for flight insertion
- Key engineering issues have been conquered on prior electro-optic payloads
  - Optical designs
  - Pointing systems
  - Support electronics
  - Software control
  - Thermal control
- Increased data rate requirements will establish a user pull
  - Communications networks
  - Hyperspectral imaging systems
- Cost control will result after the first system is demonstrated
## Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>AlGaAs</td>
<td>Aluminum gallium arsenide</td>
</tr>
<tr>
<td>APD</td>
<td>Avalanche photodiode</td>
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<tr>
<td>AZ</td>
<td>Azimuth</td>
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<tr>
<td>BPPM</td>
<td>Binary pulse position modulation</td>
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<tr>
<td>CCD</td>
<td>Charge coupled device</td>
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<tr>
<td>DPSK</td>
<td>Differential phase-shift keying</td>
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<tr>
<td>EDFA</td>
<td>Erbium-doped fiber amplifier</td>
</tr>
<tr>
<td>EL</td>
<td>Elevation</td>
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<tr>
<td>FOR</td>
<td>Field of regard</td>
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<tr>
<td>FOV</td>
<td>Field of view</td>
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<tr>
<td>FSM</td>
<td>Fast steering mirror</td>
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<tr>
<td>GEO</td>
<td>Geostationary Earth orbit</td>
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<tr>
<td>IFOV</td>
<td>Instantaneous field of view</td>
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<tr>
<td>InGaAs</td>
<td>Indium gallium arsenide</td>
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<tr>
<td>LEO</td>
<td>Low Earth orbit</td>
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<tr>
<td>LNA</td>
<td>Low-noise amplifier</td>
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<tr>
<td>Nd:YAG</td>
<td>Neodymium-doped yttrium aluminum garnet</td>
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<tr>
<td>OOK</td>
<td>On-off keying</td>
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<tr>
<td>PAM</td>
<td>Point ahead mirror</td>
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<tr>
<td>Tx/Rx</td>
<td>Transmit/Receive</td>
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