Development Of Laser Beam Transmission Strategies For Future Ground-to-Space Optical Communications

Paper 6551-11
SPIE Defense & Security Symposium
Orlando, FL
April 11, 2007

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Outline

- Key elements of an uplink deep space optical communications ground station
- OCTL telescope
- Safety tiers
- Telescope performance
- Scintillation mitigation
  - Multi Beam
- Satellite tracking
  - Passive
  - Active
Historical JPL Laser Links

- 1992: Galileo Optical Experiment (GOPEX) => 532-nm
  - Nighttime beam propagation
    - Propagation to spacecraft at 6 million km
    - Demonstrated advantage of site diversity and need for scintillation mitigation
    - Propagation of 60-urad beams
- 1995 & 1996: GOLD Demonstration => 514.5 nm
  - Daytime and nighttime beam propagation
    - Propagation to ETS-Vi spacecraft at Geo ranges
    - 1 Mbps bidirectional link
    - Propagation of 30-urad beams
- 2005 to Present: Active satellite tracking => 532-nm & 1064-nm
  - Transmission to LEO satellites 30-urad beams
Key Elements of an Uplink Deep Space Optical Ground Station

- High power laser transmission
  - Beacons
    - 10’s Megawatts peak power
    - Hundreds of watts average power
- Safe laser beam transmission through navigable air space and near-Earth space
  - Aircraft and spacecraft avoidance
- Precision pointing and tracking
  - Initial acquisition
  - >8 hours/day tracking from ground station
- Daytime nighttime operations
  - Operation to 3 degrees sun angle
- Scintillation mitigation strategies for precision tracking and uplink communications
Optical Communications Telescope Laboratory

- **OCTL facility**
  - Is located in San Gabriel Mountains Wrightwood California
    - 34° 22.9’ North Latitude, 117° 40.9’ West Longitude
    - 2.2km (7400 ft) altitude MSL
  - Is fully instrumented for safe laser beam propagation
  - Houses 1-m El/Az telescope
    - Track rates 20 deg/sec azimuth 10 deg/sec elevation
    - Points and tracks to within 10 degrees of sun
      - Filter supports 3-degree sun angle operation
    - F/75.8 seven-mirror coude optical path
    - Four-port access with <17-urad pointing repeatability
  - Supports mono-static and bi-static links
2/8/07
692 A/C IN 24 HOUR PERIOD
ARRIVALS=GREEN
DEPT=RED
OVERFLIGHTS=BLUE & YELLOW
Safety Tiers

- Deep space network (DSN)-defined Safety Tiers for unattended remote operation
  - Tier-1
    - 0 (Sea Level) – 3.5-km (11,000 ft)
  - Tier 2
    - 0 (Sea Level) – 19-km (60,000 ft) (FAA airspace)
  - Tier-3
    - Above 19-km (USAF)
    - “Black” and high altitude projects
    - Spacecraft (USAF Space Command Predictive Avoidance)
- Tiers are designed to support future unattended remote operation
Tier 1 LWIR Cameras

- Bolometer LWIR sensors
  - 8-um to 14-um sensitivity
- WFOV camera
  - 18-mm focal length lens
  - FOV 34 degrees
- NFOV camera
  - 75-mm focal length lens
  - FOV 9 degrees
- Response time from detection of aircraft to shuttering laser
  - <0.5 seconds
Tier 2 Bore sighted Radar

- In situ bore-sighted radar system
  - Primus-40 X-band radar
    - Frequency 9345-MHz
    - 8-kW peak output power
      - 3.5-usec pulse width
      - PRF 121 Hz
      - 1.2-km blanking range
    - 80-km range
    - 7dB noise figure

QuickTime™ and a TIFF (LZW) decompressor are needed to see this picture.
Tier 3 Laser Clearinghouse

- LCH procedure
  - Transmitter location, laser parameters and operational scenarios are transmitted to LCH
  - LCH assesses need for predictive avoidance procedures
  - Transmit authorization for laser transmission to satellites to LCH
  - Submit transmission schedules to LCH (7-day notice of changes)
  - LCH transmits authorized propagation transmission windows to facility 24 hours before scheduled transmission.

### LCH Predictive avoidance

**SATELLITE TARGET NUMBER:** 14521 (COSMOS 1510)

**PERIOD OF INTEREST:** 07074000000.000Z - 07075000000.000Z

(U) **SAFE IRRADIATION TIMES FOR EMMITTER:**

<table>
<thead>
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<th>START TIME</th>
<th>DURATION TIME</th>
<th>STOP TIME</th>
<th>WAIT TIME</th>
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Telescope Blind Pointing and Tracking Performance

- Telescope performance measured Fall 2006 in 5-urad to 15-urad seeing conditions
  - Results show that blind pointing error
    - Is <17-urad
    - Is independent of date from last mount calibration
    - Depends on wind conditions
  - Tracking error bias drift <17-urad over 90 minutes
Scintillation Mitigation

- Atmospheric seeing degrades link quality
  - Causes signal fades and surges in uplink beam
- Mitigation strategies are to propagate either an atmosphere-corrected uplink beam or multiple beams
  - Large isoplanatic angles of deep space link preclude use of downlink signal as reference for exo-atmosphere guide star
  - Multi-beam propagation has demonstrated scintillation mitigation
Multi-Beam Optical Train Design
Active Satellite Tracking

- Active satellite tracking at OCTL
  - Approved for laser propagation to more than 20 U.S. and international satellites
  - Validates beam propagation models and develops ground-to-space operational strategies
- Approved operational period
  - Twenty hours/day
    - Four hour down time allocated for instrument servicing and repair
- Operations in the near-IR have replaced earlier operations at visible wavelengths
Theoretical Model

\[ S = E_p \left( \frac{\lambda}{hc} \right) \eta_{TX} G_T L_P L_s \sigma_{BS} \eta_{atm}^2 L_{atm\_Spread} L_{atm\_point} A \eta_{Rx\_Tel} \eta_{Strehl} \eta_{opt\_train} \eta_{POL} \]

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>Units</th>
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<tr>
<td>1</td>
<td>S</td>
<td>Signal photons incident on receiving detector</td>
</tr>
<tr>
<td>2</td>
<td>h</td>
<td>Planck's constant</td>
</tr>
<tr>
<td>3</td>
<td>( \lambda )</td>
<td>Laser wavelength</td>
</tr>
<tr>
<td>4</td>
<td>c</td>
<td>Velocity of light</td>
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<tr>
<td>5</td>
<td>E_p</td>
<td>Laser energy per pulse</td>
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<tr>
<td>6</td>
<td>( \eta_{TX} )</td>
<td>Transmission Efficiency</td>
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<td>7</td>
<td>G_T</td>
<td>Transmitter Gain</td>
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<td>8</td>
<td>L_P</td>
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<tr>
<td>9</td>
<td>L_S</td>
<td>Round-trip space Loss</td>
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<tr>
<td>10</td>
<td>( \sigma_{BS} )</td>
<td>Satellite Backscattering Cross-section</td>
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<tr>
<td>11</td>
<td>( \eta_{atm} )</td>
<td>Atmospheric transmittance</td>
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<tr>
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<td>Atmospheric Spreading Loss</td>
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<td>L_{atm_point}</td>
<td>Atmospheric Pointing Loss</td>
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<tr>
<td>14</td>
<td>A</td>
<td>Telescope collection area</td>
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<tr>
<td>15</td>
<td>( \eta_{Rx_Tel} )</td>
<td>Receive telescope efficiency</td>
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<tr>
<td>16</td>
<td>( \eta_{Strehl} )</td>
<td>Loss due to wave front error</td>
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<tr>
<td>17</td>
<td>( \eta_{opt_train} )</td>
<td>Receive Optical Train Loss</td>
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<tr>
<td>18</td>
<td>( \eta_{POL} )</td>
<td>Receive polarization incompatibility loss</td>
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Retro-reflector Satellite Signal Returns

Measured and predicted returns from Ajisai pass

Beacon C Bi-static 1064-nm Photon counting

Bi-static fiber-coupled 1064-nm receiver

Ajisai mono-static 532-nm
Active and Passive Satellite Tracking
## Conclusion

- JPL’s OCTL houses a 1-m fully instrumented telescope capable of tracking spacecraft from LEO to deep space and of safely propagating high power laser beams through navigable air space, near-Earth space and into deep space.
- The telescope is operated in the nighttime and daytime and can point and track objects as close as 10-degrees to the sun.
- A four-port, coude mounted telescope the facility can support a variety of beam propagation and reception experiments.
- OCTL has demonstrated both active and passive satellite tracking and the first reported coherent LADAR to a satellite and range-resolved Doppler imaging.
- The facility has special visiting experimenter quarters and lodging accommodations are available at the Table Mountain facility.
Backup
Safety Monitor Display

Operator Display

- **“Equipment Status” row displays operational status of each tier and the I/O board**
  - *Green* = Equipment functional
  - *Red* = Equipment not responding

- **“Treeline” warning**
  - *Green* = Pointing above site terrain
  - *Red* = Pointing below site terrain

- **5 minute time history plot of detection status for each tier**
  - Tier labels are highlighted according to corresponding detection status
  - *Green* = Safe for laser propagation
  - *Red* = Object Detection

- **5 minute time history plot of shutter response**
  - “Laser Beam” label is highlighted according to shutter response
  - *Green* = Verified that shutter commanded to open
  - *Red* = Verified shutter commanded to close

- **Running clock of current time**
  - Reference for time history plots
  - Evidence that software is executing
Data Acquisition System Block Diagram

- 532 nm OCTL Laser
- Photo Detector
- Main Telescope
- Mechanical Shutter
- Photo Multiplier Tube
- 10 nm Bandpass filter
- Delayed Trigger
- Range File
- 500 MHz 1 GSPS 8 bit digitizer
- A/D Set gain
- Data File
- Computer Clock
- Computer
- Target
- Range

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