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

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Keith E. Wilson, Joseph Kovalik,
Abhijit Biswas, William T. Roberts

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

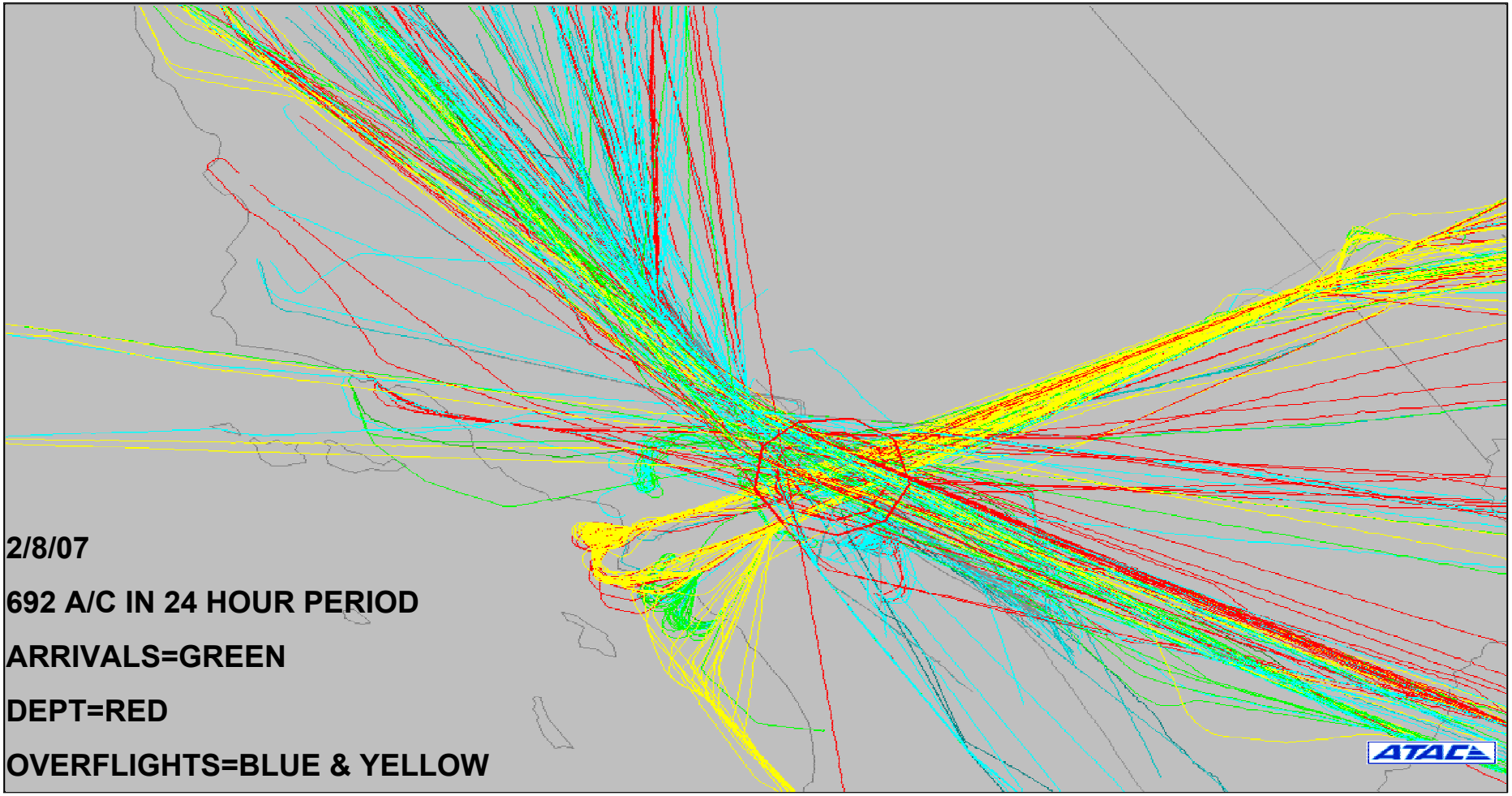
Key Elements of an Uplink Deep Space Optical Ground Station

- 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

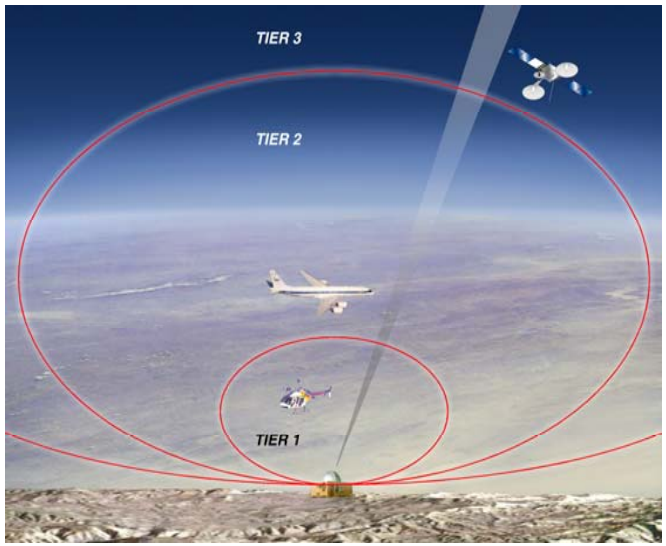
- **OCTL facility**
  - **Is located in San Gabriel Mountains Wrightwood California**
    - **34° 22.9' North Latitude, 117° 40.9' West Longitude**
    - **2.2km (7400 ft) altitude MSL**
  - **Is fully instrumented for safe laser beam propagation**
  - **Houses1-m El/Az telescope**
    - **Track rates 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**

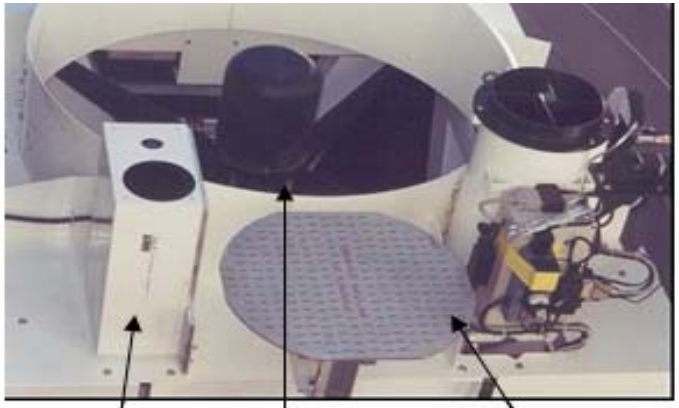
Air Traffic Over The OCTL



Safety Tiers

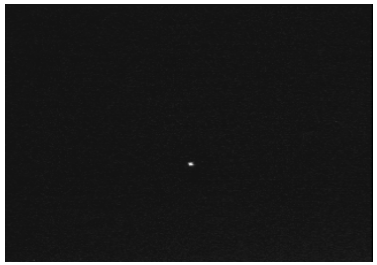
- **Deep space network (DSN)-defined Safety Tiers for unattended remote operation**
  - **Tier-1**
    - **0 (Sea Level) – 3.5-km (11,000 ft)**
  - **Tier 2**
    - **0 (Sea Level) – 19-km (60,000 ft) (FAA airspace)**
  - **Tier-3**
    - **Above 19-km (USAF)**
    - **“Black” and high altitude projects**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



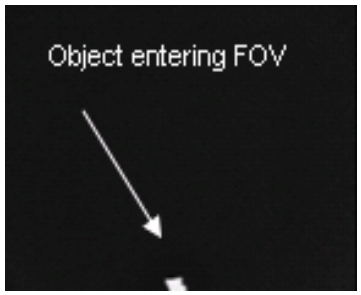


Tier 1 LWIR Cameras

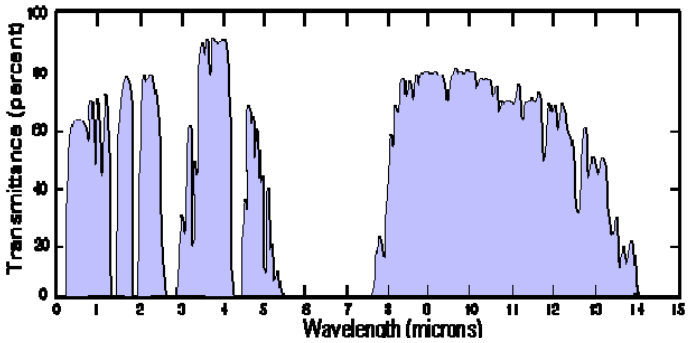
- Bolometer LWIR sensors
  - 8-um to14-um sensitivity
- WFOV camera
  - 18-mm focal length lens
  - FOV 34 degrees
- NFOV camera
  - 75-mm focal length lens
  - FOV 9 degrees
- Response time from detection of aircraft to shuttering laser
  - <0.5 seconds

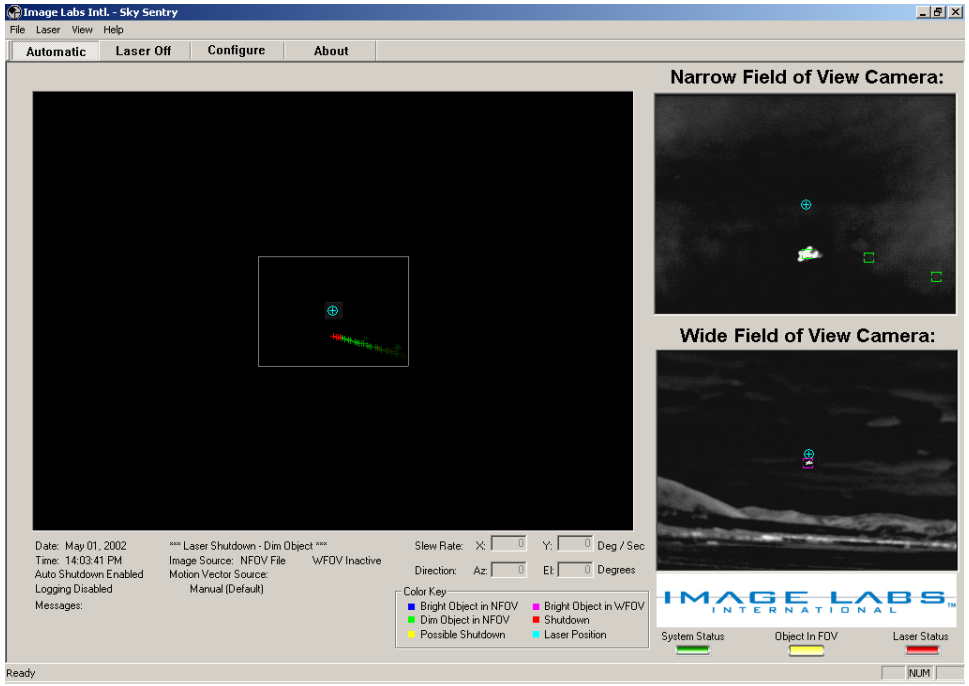


WFOV Camera



NFOV Camera





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

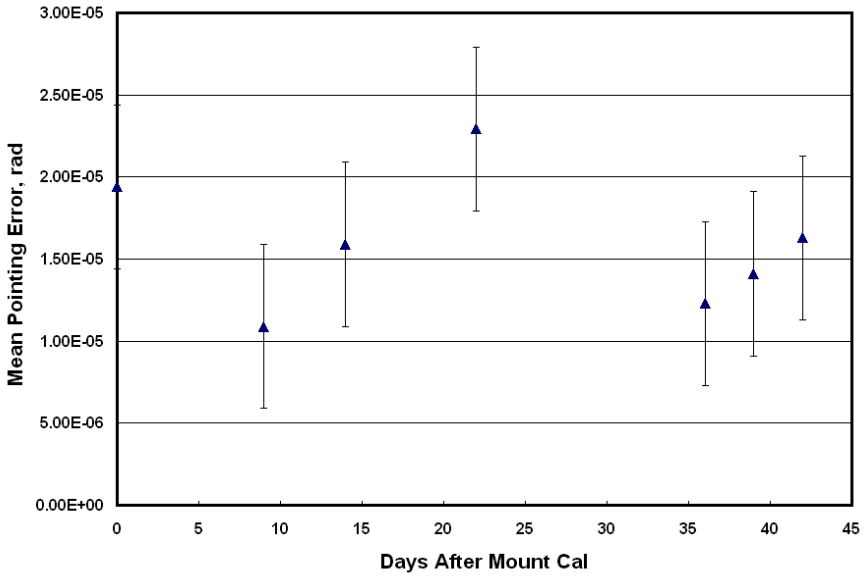
SATELLITE TARGET NUMBER: 14521 (COSMOS 1510)

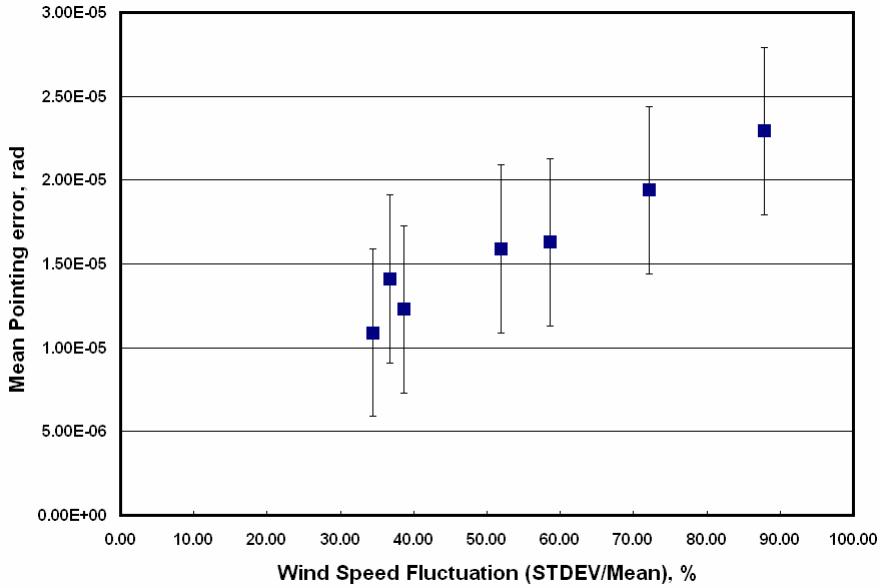
PERIOD OF INTEREST: 07074000000.000Z - 07075000000.000Z

(U) SAFE IRRADIATION TIMES FOR EMITTER:

START TIME	DURATION TIME	STOP TIME	WAIT TIME
074000000.000Z	000815.874	074000815.874Z	000032.428
074000848.301Z	000505.699	074001354.000Z	055812.000
074061206.000Z	000212.849	074061418.849Z	000021.321
074061440.170Z	000311.896	074061752.066Z	000132.637
074061924.704Z	000100.332	074062025.036Z	000115.592
074062140.628Z	000408.890	074062549.518Z	014416.482
074081006.000Z	000710.675	074081716.675Z	000216.025

Telescope Blind Pointing and Tracking Performance

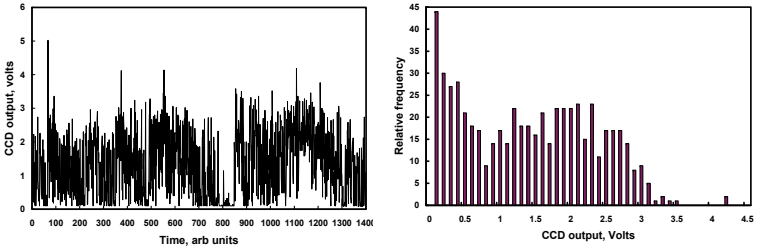




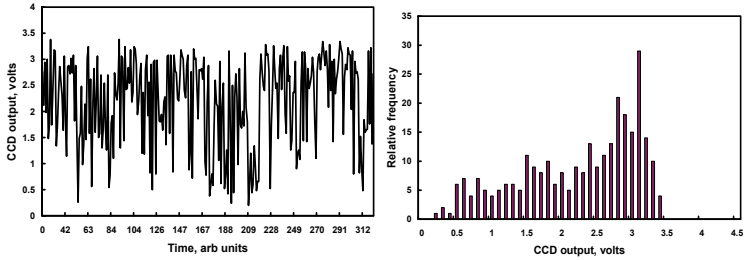
- Telescope performance measured Fall 2006 in 5-urad to 15-urad seeing conditions
  - Results show that blind pointing error
    - Is <17-urad
    - Is independent of date from last mount calibration
    - Depends on wind conditions
  - Tracking error bias drift <17-urad over 90 minutes

Scintillation Mitigation

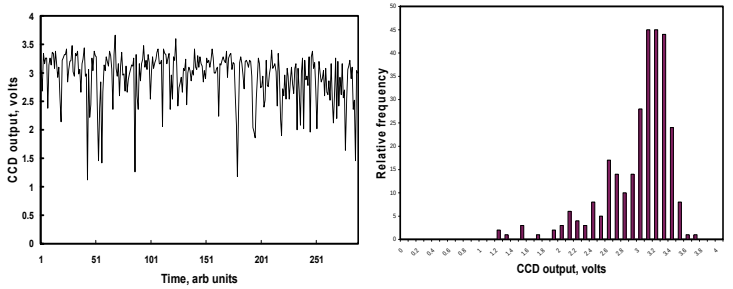
- Atmospheric seeing degrades link quality
  - Causes signal fades and surges in uplink beam
- Mitigation strategies are to propagate either an atmosphere-corrected uplink beam or multiple beams
  - Large isoplanatic angles of deep space link preclude use of downlink signal as reference for exo-atmosphere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



Single beam uplink: Surges of 5.7 dB and fades of –12.3 dB from the mean

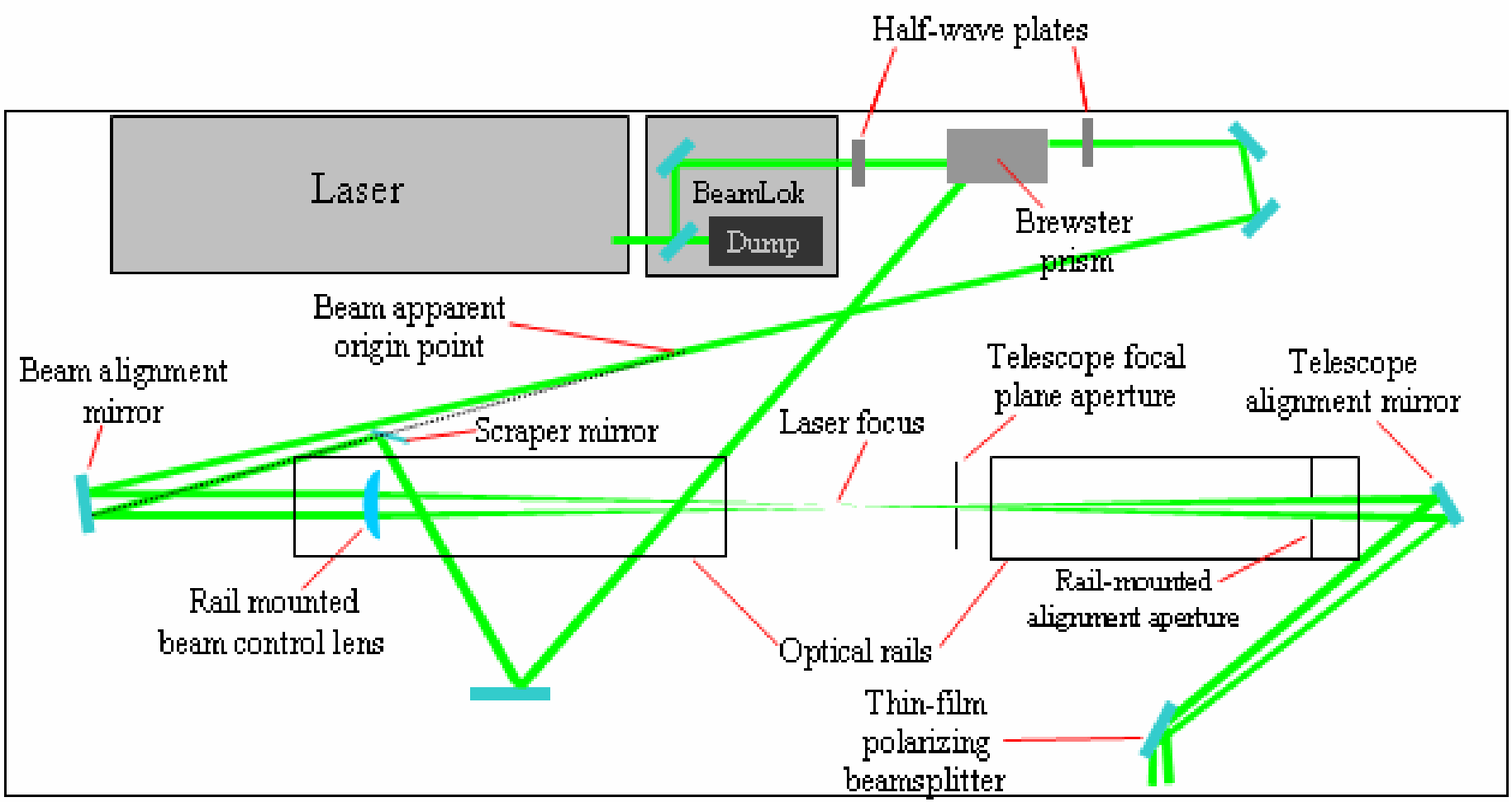


Two-beam uplink: Surges of 1.9 dB and fades –10.4 dB from the mean



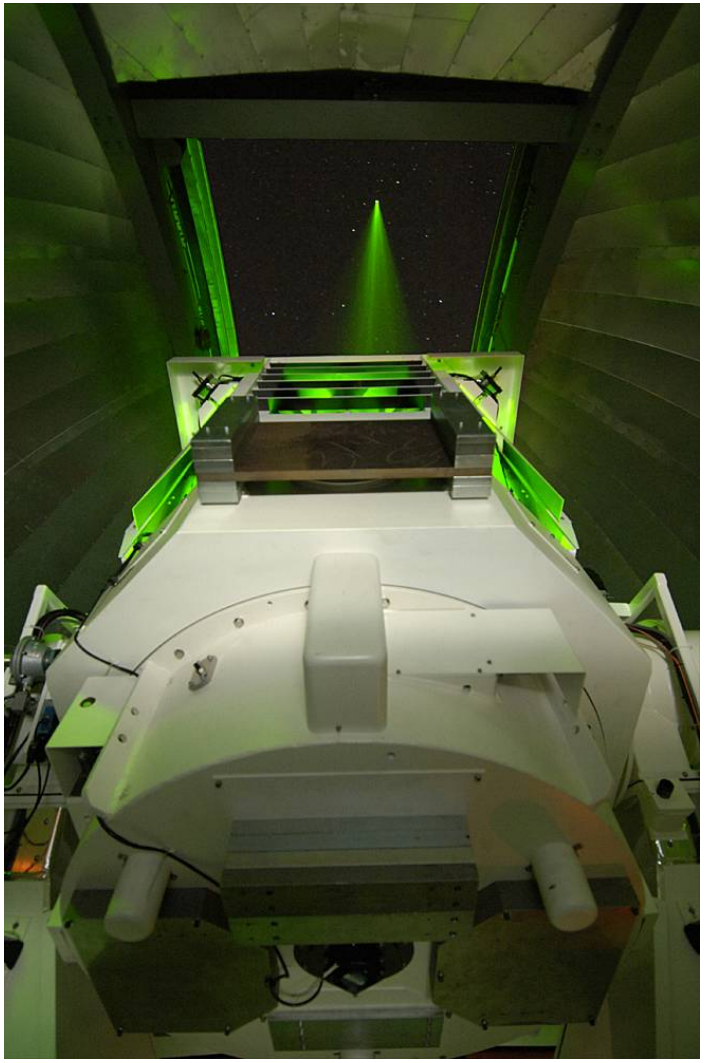
Four-beam uplink: Surges of 1 dB and fades of –4.2 dB from the mean

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

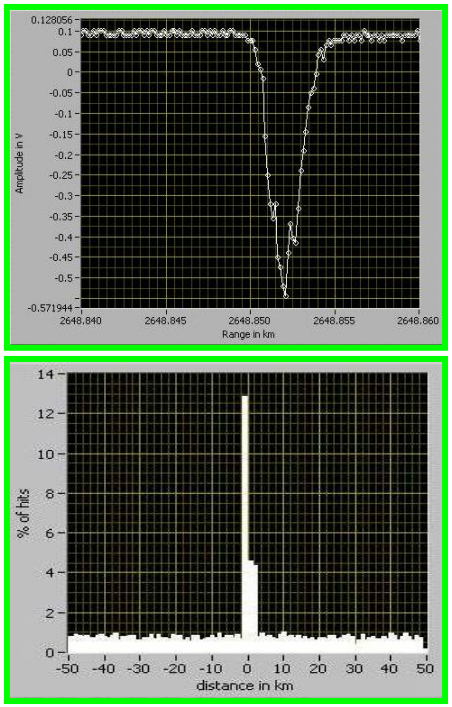


Theoretical Model

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

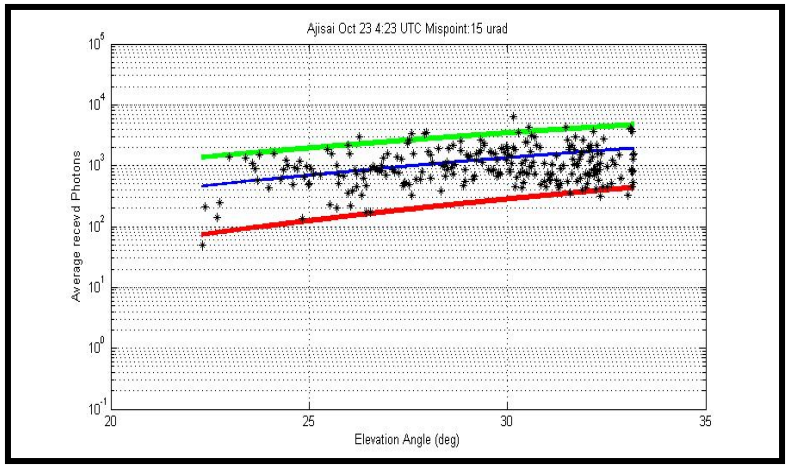
	Symbol	Parameter	Units
1	S	Signal photons incident on receiving detector	Photons per pulse
2	h	PlanckÕsconstant	Joule-second
3	λ	Laser wavelength	meters
4	c	Velocity of light	meters/second
5	E_p	Laser energy per pulse	Joules
6	η_{TX}	Transmission Efficiency	
7	G_T	Transmitter Gain	
8	L_P	Pointing Loss	
9	L_S	Round-trip space Loss	meters^{-4}
10	σ_{BS}	Satellite Backscattering Cross-section	meters^2
11	η_{atm}	Atmospheric transmittance	
12	L_{atm_Spread}	Atmospheric Spreading Loss	
13	L_{atm_point}	Atmospheric Pointing Loss	
14	A	Telescope collection area	meter^2
15	η_{Rx_Tel}	Receive telescope efficiency	
16	η_{Strehl}	Loss due to wave front error	
17	η_{opt_train}	Receive Optical Train Loss	
18	η_{POL}	Receive polarization incompatibility loss	

Retro-reflector Satellite Signal Returns



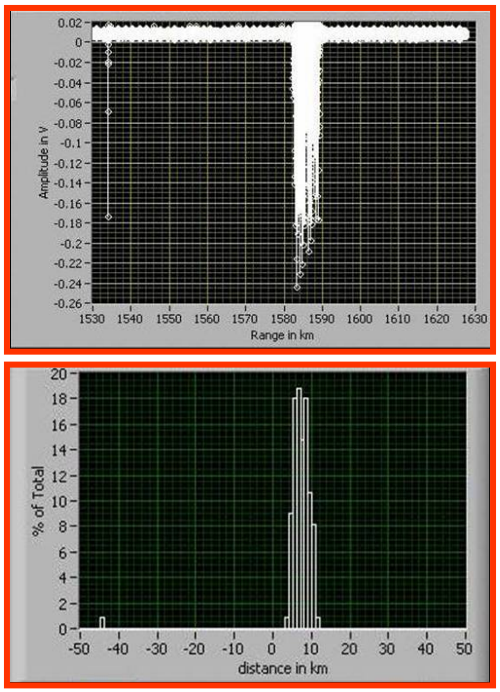
Ajisai mono-static 532-nm

Measured and predicted returns from Ajisai pass



Bi-static fiber-coupled 1064-nm receiver

Beacon C Bi-static 1064-nm Photon counting



Active and Passive Satellite Tracking

QuickTime™ and a
Sorenson Video 3 decompressor
are needed to see this picture.

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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

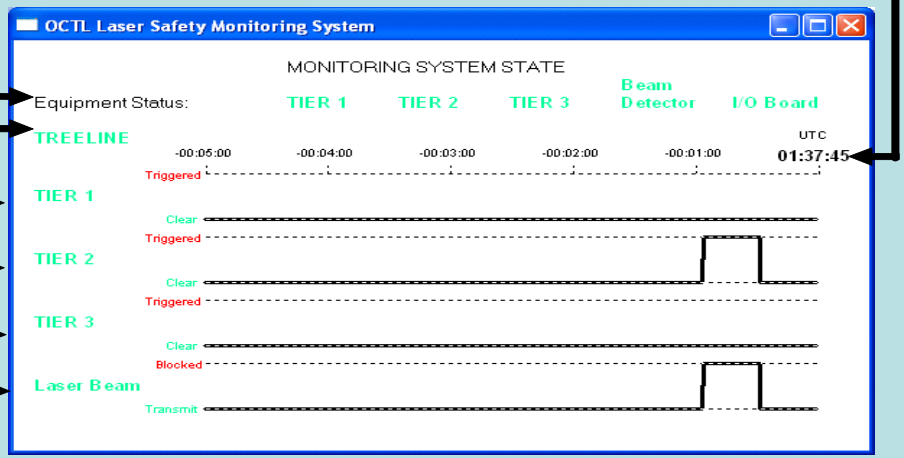
"Equipment Status" row displays operational status of each tier and the I/O board
- Green = Equipment functional
- Red = Equipment not responding

"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