Planned Operations for the JPL Optical Communications Telescope Laboratory (OCTL)

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Abstract

JPL is building a 1-m R&D optical communications telescope at NASA's Table Mountain facility to support high data rate communications from deep space. We shall perform a series of active satellite tracking experiments to develop atmospheric scintillation mitigation strategies.

1. Introduction

As JPL pursues the development of optical communications technology for deep-space applications, our research extends from the development of a deep space terminal[1], to investigating the effects of cloud cover on the availability of the optical channel[2]. Yet, a large focus of our research effort is on ground station development[3]. Our research has shown that acquisition, tracking and pointing of an optical terminal onboard a spacecraft at Mars can be accomplished using a combination of uplink laser beacon and inertial sensors[4]. Scintillation-induced fades on the laser beam uplinked from the ground station will degrade performance of a laser-beacon tracking system and introduce errors on commands transmitted to space via the optical beam. The focus of the early experiments at the Optical Communications Telescope Laboratory (OCTL) will be on the development of strategies to mitigate scintillation-induced fades.

Figure 1 shows the OCTL building and dome. The building will house a 1-m precision tracking El/Az mounted telescope, designed to track objects from 250-km range to deep space. The telescope has a coude optical path, and all seven telescope mirrors are coated with Denton FSS-99 protected silver for high optical transmission in the visible and near-IR. It is designed to operate in both in the daytime and the nighttime and will enable us to evaluate the performance of the optical link under various atmospheric conditions. This will allow us to develop the appropriate background rejection and scintillation mitigation strategies for ground to space links. The telescope is being built by Brashear-LP of Pittsburgh, PA and is shown partly in Figure 2. The scattered light requirement of less than 20 pW/Å from 5,000 Å to 20,000 Å - less than 10pW/Å at 10642 Å- in a 100-urad square field-of-view when pointed 30 degrees to the sun is a key specification for daytime operation. Brashear plans to meet this and other daytime operational requirements by using a system of fans and louvered baffles to control the heat flow. The baffles are painted white on the outside to reduce heat loading on the structure and black on the inside to reduce scattered light.

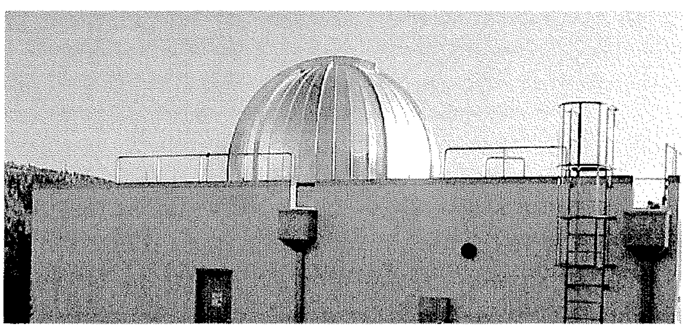

Figure 1: OCTL telescope building and dome at Table Mountain Facility, Wrightwood CA.

Upon completion of the on site checkout by the vendor Brashear-LP, we shall integrate a high power laser to the telescope and perform a series of active satellite illumination experiments. The objectives of these near-term experiments are to validate:

- Multi-beam atmospheric mitigation strategies
- Predictions of wavelength dependence of atmospheric scintillation

We shall also investigate the beam wander effects and wavelength dependence of beam wander under various atmospheric conditions.

Autonomous ground station operation will reduce the cost of future deep space mission support. Yet, in the US, laser beam propagation through the atmosphere is regulated by several government regulatory agencies and requires implementation of strategies to ensure that neither the flying public nor space assets are at risk. To support future deep-space optical communications, OCTL research will explore approaches to meet the stipulations imposed by these agencies and will work with them to:

- Develop strategies for predictive avoidance
- Validate aircraft avoidance strategies that would support future autonomous and remote operation.

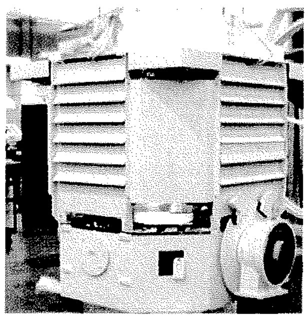

Figure 2: OCTL telescope frame showing louvered baffles, the elevation axis motor. The opening for the 20-cm finder telescope is shown between the baffles sections.

In this paper we describe the plans for tracking and for illuminating target satellites from OCTL. In section 2, we discuss the effects of atmospheric scintillation on our past laser communications experiments and our atmospheric mitigation strategies. In Section 3 we describe future work planned for the OCTL with the emphasis on the near-term tasks, and present a conceptual design for the multi-beam optical train that will support our near-term work.

2. The Effect of Atmospheric Scintillation in Past Laser Communications Experiments

In 1992, JPL validated the tracking capability of its 0.6-m astronomical telescope in a series of active tracking precursor experiments to its Galileo Optical Experiment (GOPEX) [5]. Retro-reflector bearing satellites were illuminated by the GOPEX frequency-doubled Nd: YAG laser, and the retro-reflected signals were detected by a photomultiplier tube located at the telescope focus. Transmit/receive isolation of the retro-reflected signals was accomplished using a holey mirror loaned to the project by the McDonald observatory satellite laser ranging team. During these experiments, it was observed that the retro-reflected returns were sporadic, with the signal strength dominated by scintillation on the uplink beam. The effects of scintillation were also seen in the signals detected by the Galileo spacecraft (Figure 3). The GOPEX results showed large variations in the detected signal strength over 800-millisecond exposures[6].

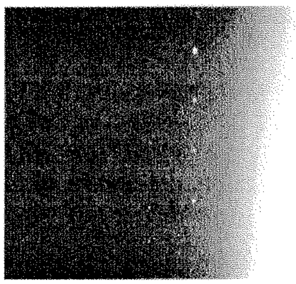

Figure 3: Laser uplink detected during GOPEX demonstration. The brighter dots are the uplink from the Starfire Optical Range, the fainter are from the Table Mountain telescope.

Scintillation in the laser beams transmitted from the ground to retro-reflector bearing satellites was characterized in the Ball Aerospace relay mirror experiment (RME) [7]. This was again observed by JPL in the 1995 – 1996 GOLD (Ground-to-Orbiter-Lasercom Demonstration) experiment with the Japanese ETS-VI spacecraft[8], when a single beam was uplinked to the satellite. However, significant scintillation mitigation was demonstrated as the number of beams was increased to two and subsequently to four. The results measured by the LCE's (laser communications equipment) [9] coarse tracking CCD are shown in Figure 4. The figure shows the measured reduction in uplink intensity variance as the number of uplink beams was increased from one to two to four in the GOLD demonstration. Although the data were taken at one-second intervals, one can clearly see the reduction in intensity variance with increased number of uplink beams. The data show that the most probable signal strength detected at the spacecraft increased from near zero to approximately 5-nW as the number of beams was increased from one to four.

3. Planned OCTL Experiments

Among the key OCTL experiments planned over the next five years are:

- Validation of multi-beam propagation strategies
- Development of strategies for autonomous telescope operation and safe laser beam propagation
- Development of adaptive optics capability to reduce sky background noise
- Demonstration of an air-to-ground optical link from a DC-8 and a UAV platform in 2004.
- Demonstration of optical communications with other targets of opportunity.

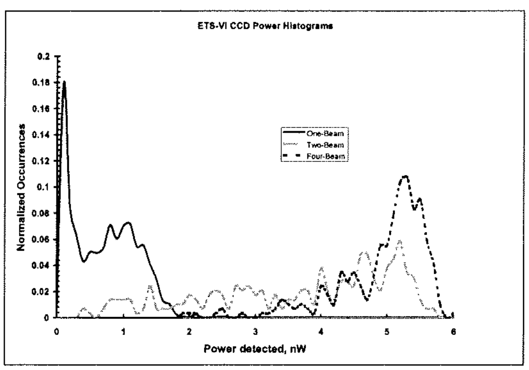

Figure 4: Histograms of the single-beam two-beam, and four-beam laser uplink detected by LCE's CCD camera on board ETS-VI satellite. Data were sampled at 1 Hz.

In the near-term, OCTL experiments shall focus on developing strategies to mitigate the effects of atmospheric scintillation on the uplink beam. Active tracking of a multitude of retro-reflector bearing satellites by laser beams transmitted through the OCTL telescope will provide a rich data base for us to evaluate scintillation effects and to develop mitigation strategies.

Current plans call for transmitting up to four uplink beams at the 532-nm wavelength to assess the scintillation mitigation afforded by the multi-beam uplink. Experiments will also be performed at and 1064-nm to validate predictions of the wavelength dependence of atmospheric scintillation. Targets satellites ranging in altitude from 700-km to 19,000-km altitude will be illuminated using the pulsed Nd:YAG OCTL laser. The laser characteristics are given in Table 1.

Table 1:OCTL laser characteristics at 50 Hz repetition rate.

Parameter		
Wavelength, nm	532	1064
Beam Diameter at exit		
Vertical (mm)	11.5	11.5
Horizontal (mm)	7.4	7.4
Beam pulse width (nsec)	6.6	7.8
Mean Pulse width (nsec)	6.6	8
Standard deviation (psec)	219.9	151.9
Pulse jitter (nsec)	2.7	2.1
Average power (W)	12.8	29.7
Power stability (%) 1s	5	6.5
Beam Divergence (mrad)	0.49	1.0
Polarization extinction ratio	5.80E-03	0.1
Standard deviation	1.30E-04	1.00E-03

Because our objective is to measure the strength of the return signal, we shall detect the return signal retro-reflected from the satellites using a combination of time division multiplexing (TDM) and polarization isolation to achieve transmit/receive isolation. Currently, the OCTL uplink laser operates at a fixed repetition rate of 50 Hz. To allow continuous TDM active illumination of Earth-orbiting satellites at the farthest ranges, we plan to modify the laser to operate at sub-multiples frequencies of 50 Hz. To ensure that the beam quality and divergence is unchanged at the various repetition rates, we shall maintain flash lamp operating at 50 Hz so that the thermal loading of the cavity is constant. We shall then activate the Q-switch at the required sub-multiple of the flash lamp repetition rates. This approach will only vary the average output power of the laser while maintaining the peak power per pulse constant.

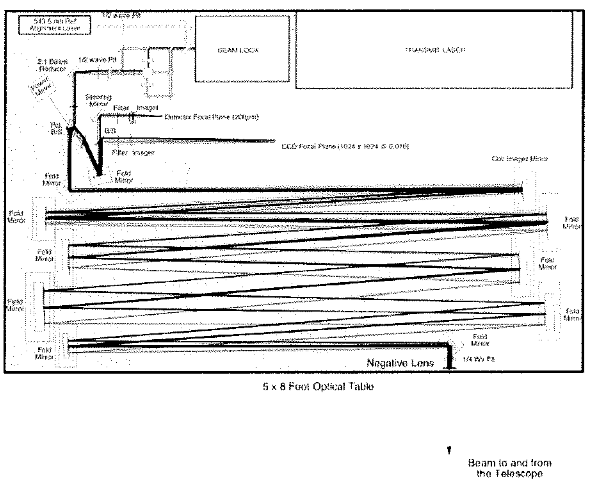

Figure 5: Schematic of multi-beam optical train for active satellite tracking.

The schematic in Figure 5 shows the optical train. The laser output is divided into four equal-intensity beams so that they are incident on the telescope primary with a separation greater than the atmospheric coherence cell size. To reduce the probability of damage to mirror surfaces, the optical train is designed so that the power density is maintained less than 10 MW/sqcm on all optical surfaces.

Figure 6 is a plot of the maximum number expected number of retro-reflected photons per corner cube reflector for a 700-km high satellite as a function of elevation angle. The plot was calculated using the expression in equation 1.

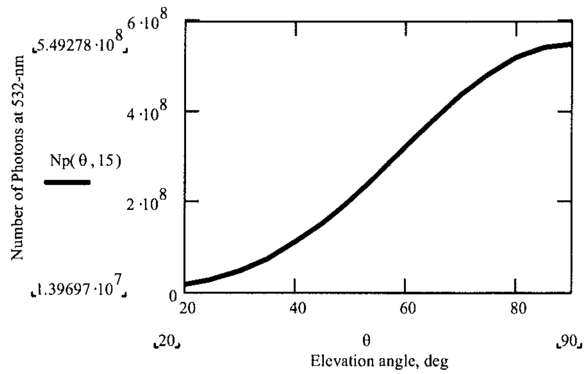

Figure 6: Maximum expected signal return strength from a single retro-reflector on a 700-km high satellite as a function of elevation angle.

In equation 1, ε is the effective reflectivity of the retro-reflector of diameter Dc, h is Planck's constant, and c is the speed of light. El is the laser energy per pulse at wavelength λ, η_o (0.58) is the optical train transmission, η_t(0.8) is the telescope transmission, and η(θ) is the atmospheric transmission as a function of elevation angle θ. Dp (1.0) and ds (0.14) are the diameters of the telescope primary mirror, and of the secondary or tertiary mirror whichever has the larger obscuration of the primary. The uplink beam divergence in equation 1 is given in microradians by ξ (15), and s(θ) is the slant range.

$$Np(\theta,\xi) = \varepsilon \cdot \frac{\lambda}{hc} \cdot El \cdot \left(\frac{Dc}{s(\theta)}\right)^4 \cdot \left[\frac{(\eta o \cdot \eta t \cdot \eta(\theta))}{2.44\lambda \cdot \left(\xi \cdot 10^{-6}\right)}\right]^2 \cdot \left(Dp^2 - ds^2\right) \qquad 1$$

In the presence of atmospheric scintillation the far-field intensity distribution will be a speckle pattern with a normalized intensity variance given by equation 2[10]; where k is the wave number for the 532-nm wavelength optical beam, θ is the angle of elevation, and C(h,V) is the atmospheric structure constant as a function of height h, relative to sea level and wind speed V.

$$\sigma(\theta, V) := 2.24 \cdot 100 \cdot k^{\frac{7}{6}} \cdot (\mathrm{cscd}(\theta))^{\frac{11}{6}} \cdot \int_2^{13} C(h,V) \cdot h^{\frac{5}{6}} \, dh \qquad 2$$

The probability of a fade is given by equation 3, where σ is the normalized log intensity variance and ς is the fade depth in dB. Equation 3 is plotted in Figure 7 for fade depths of 3, 6, and 10 dB.

$$F(\sigma, \zeta) := 100 \cdot 0.5 \cdot \left(1 + \mathrm{erf}\left(\frac{-0.23 \cdot \zeta + 0.5 \cdot \sigma}{\sqrt{2 \cdot \sigma}}\right)\right) \qquad 3$$

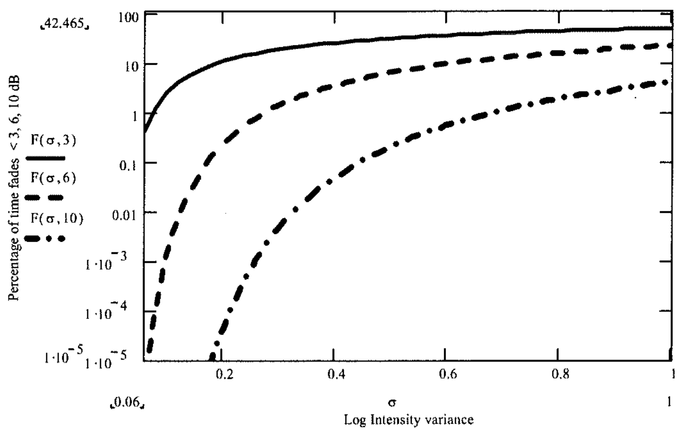

Figure 7: Probability of signal fades on the laser uplink as a function of scintillation-induced intensity variance.

When the uplink laser beam is split into N equal intensity beams and propagated through uncorrelated atmospheric cells, the scintillation-induced intensity variance is reduced. Reported results show reductions that range from √N to N [11, 12]. Figure 8 shows equation 2 plotted as a function of elevation angle for three cases of wind speed (27, 30, and 33 meters/s). Also plotted in the figure is the scintillation for four uplink beams where we have assumed a reduction in scintillation by N.

Because scintillation effects on the downlink are mitigated by aperture-averaging across the large 1-m receiver aperture[13, 14]. In the absence of beam wander and other uplink pointing errors detected signal fades are primarily due to uplink scintillation. Without uplink scintillation mitigation strategies, the number of photons returned from the retro-reflectors can vary by as much as 10-dB[10]. The multi-beam uplink strategy reduces both the depth and frequency of scintillation-induced fades and will result in a greater number of returned photons per transmitted pulse.

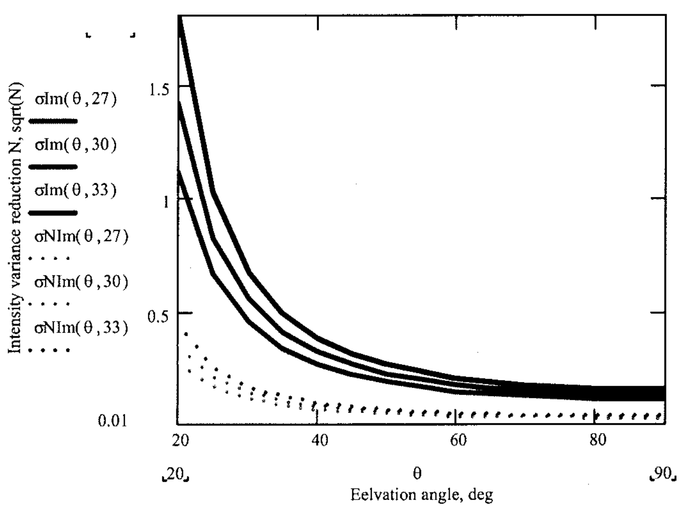

Figure 8: Normalized intensity variance for a single beam (solid lines) and dashed lines showing the reduction in normalized intensity variance for four independent beams propagated through the atmosphere.

4. Conclusion

JPL is building an R&D Optical Communications Telescope Laboratory at its Table Mountain Facility. The 1-m OCTL telescope is capable of precision tracking of satellites as low as 250-km, and will be installed on site around mid-year 2002. We have a suite of experiments planned for the telescope. However, our near-term focus is on developing strategies to mitigate the effects of atmospheric scintillation on the uplink. By measuring the return signal strength and frequency from actively tracked retro-reflecting satellites, we plan to validate models for the scintillation mitigation achieved by multi-beam uplink transmission under various atmospheric conditions. The models developed from these early experiments will be further exercised in planned air to ground optical links. In the far-term we plan to develop an adaptive optics capability at the OCTL to assess the enhancement in receiver performance during daytime operation when the telescope is pointing within 30 degrees of the sun.

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