Recent research at the JPL Optical Communications Telescope Laboratory

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ABSTRACT

The Optical Communications Telescope Laboratory is a state-of-the-art facility located at 2.2-km altitude on Table Mountain Wrightwood, CA. Designed for nighttime and daytime operation, the 1-m OCTL telescope tracks targets as close as 10-degrees to the sun, and satellites as low as 250-km. Maximum slew rates are 10 deg/sec elevation and 20 deg/sec azimuth. Research projects at the OCTL include (i) passive and active satellite tracking of sun-illuminated and retro-reflecting satellites, (ii) technology development for safe laser beam transmission into deep space, (iii) line-of-sight cloud detection, and (iv) adaptive optics correction of atmosphere-induced optical wavefront aberrations. OCTL tracks LEO, MEO and HEO satellites and is authorized by various satellite owners to transmit 532-nm and 1064-nm laser beams to several of their retro-reflector bearing satellites. We have successfully demonstrated nighttime transmission to Stella and daytime and nighttime transmission to Ajisai. We have coordinated our strategies for safe laser transmission through navigable airspace with the FAA, and apply a JPL-developed three-tiered sensor system for safe laser beam propagation. The third tier is through coordination with the Laser Clearinghouse which provides daily predictive avoidance windows for transmission to target satellites. Backscatter from clouds along the uplink line-of-sight is measured by a 0.15 degree field-of-view 20-cm acquisition telescope bore sighted with the 1-m telescope transmitter. Designed for daytime wavefront correction, the ninety-seven actuator deformable mirror across the 1-m makes the OCTL adaptive optics system has one of the highest actuator densities in operation. This paper describes early results from these research areas.

1. INTRODUCTION

Located in the southern California San Gabriel mountain range-GPS location 34◦ 22.9' north latitude, 117◦ 40.9' west longitude, the JPL Optical Communications Telescope Laboratory (OCTL) shown in Fig. 1 houses a 1-m El/Az telescope. The telescope is a state-of-the-art optical communications terminal designed to track Earth orbiting satellites, deep space probes and stars. Since assuming ownership in July 2005, JPL has embarked on a series of technology developments designed to develop operational strategies for optical communications terminals for deep space and near-Earth support. Adaptive optics, safe laser beam propagation, line-of-sight cloud detection, and active satellite tracking are some of the key technologies, being explored at the OCTL. This paper describes the instruments, their integration at the OCTL and the progress made in supporting the development of these technologies.

Fig. 1: OCTL facility in Wrightwood California houses a 1-m Az/El four port coudé focus telescope capable of tracking satellites as low as 250-km altitude.

2. OCTL TELESCOPE

Designed for both nighttime and daytime operation the OCTL telescope primary is enclosed in louvers to allow operation as close as 10 degrees to the sun. To support links to low altitude spacecraft, the telescope slews at speeds up to 20 deg/sec azimuth and 10 deg/sec elevation. At these slew speeds, the telescope is capable of tracking Earth-orbiting satellites as low as 250-km, with a 6 degree keyhole at zenith.

Optically, the effective focal length of the telescope is 75.8-m and the measured residual RMS wave front error through the telescope's coudé path is λ/7 waves at 632-nm.telescope **[1]**. The seven coudé path mirrors are coated with protected Denton FSS-99 silver. Rapid support of a variety of experiments from the four-port coudé focus requires high accuracy M7 mirror pointing repeatability. We have measured pointing repeatability among the four ports of 2.7" +/-1.7". The measured telescope blind accuracy is 3" +/-1.5" (~15urad+/- 7.5urad). Fig. 2 shows the results of measurements taken over a one week period.

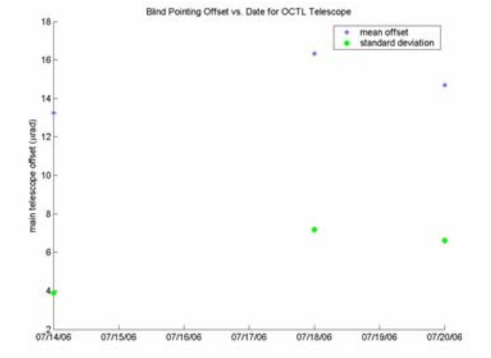


Fig. 2: Telescope blind pointing accuracy and standard deviation measured over a one week period based. Data were taken after single 20-point star calibration made at the beginning of the test period.

The telescope supports a variety of input pointing and tracking file formats. For satellite tracking, accepted input formats are two line element sets, state vector (time, Az, El), which is also the format for the new ILRS consolidated prediction format. Direct inputs from the Starry Night commercial astronomical s/w, star catalogs (Hipparcos, FK-5, etc) support astronomical observations. The "point telescope mount" command is limited to -5 degrees elevation and can support horizontal path experiments. These experiments are used to characterize the propagated laser beam or to assess the effect of atmospheric turbulence on the quality of the optical link; the OCTL has direct line-of-sight to accessible mountain peaks from 12-km (Mt. Lewis) in the San Gabriel mountain range to peaks in the adjacent San Bernardino Mountain range over 50-km away. Constant azimuth and/or elevation velocities are tracking options that could support links to aircraft or other assets.

3. SAFE LASER BEAM TRANSMISSION

A three-tier laser safety system is integrated with a redundant internal an external laser shutter to ensure safe high power beam propagation through FAA controlled navigable air space and beyond **[2]**. Tier 1 sensors are wide field (46° X 35°) and narrow field (9° X 12 °) LWIR cameras operating at 30 frames per second to alert operators to flying aircraft. Tier 2 consists of a bore sighted 9° X-band radar beam to monitor non-transponding aircraft up to a range of over 26 nautical miles. For the third tier, OCTL is registered with Strategic Commands Laser Clearinghouse and receives predictive avoidance de-conflicting notices from the Clearinghouse for laser beam transmission to designated satellites and stars. These systems are all operational.

4. OCTL LINE-OF-SIGHT ATTENUATION MONITOR SYSTEM

Sub-visible high cirrus clouds can attenuate the optical beams and degrade the quality of the optical link. These clouds can occur in patches such that the link margin varies as the telescope tracks the satellite across the sky. Monitoring cloud cover in real time provides the operator immediate feed back on this critical source of link degradation. The following system was integrated to the OCTL telescope for monitoring the presence of clouds. By timing the delay in the pulse returns it also provides a measure cloud height.

To avoid gating and channel crosstalk in the main telescope transmit/receive path, a receiver was installed on the 20 cm acquisition telescope. A beam splitter was installed in the acquisition camera's optical train to provide simultaneous access to both the camera with its wide field of view and high speed PMT detector. A relay lens and beam splitter aperture was designed to ensure the field of view between the transmitted and reflected two was nominally the same. Because of space constraints at eh acquisition telescope the light to the high speed detector port was refocused into a 600 μm core fiber and guided to the detector in the coudé room. Although multiple detectors could be readily substituted in the path, we selected a Hamamatsu model 5783P-60 PMT for these measurements. A digital storage oscilloscope supplemented with a 1 GS/s data acquisition board was used to capture the data. The uplink laser was a pulsed doubled YAG emitting 12 W average power at 532 nm with 7 nsec pulse widths at 50 Hz repetition rates. The uplink beam divergence was approximately 25 μrad.

System tests validated the concept for monitoring the line of sight attenuation during laser uplink operations. Satellites were tracked through clear sky and the on-set of high clouds as determined by noting independent cloud visibility data from real time weather maps and star attenuation. Background corrected signals can be seen for an example case shown in Fig. 3 where the cloud signals follow the strong Raleigh backscatter. Tracking several satellites over the course of a cloudy night verified the ability to monitor the presence of clouds up to range of 65 kft and at various azimuth and elevation angles.

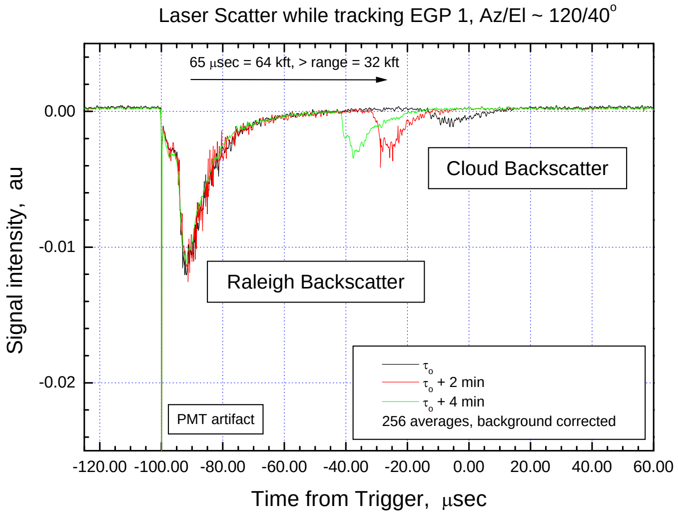


Fig. 3: Backscatter from a single satellite pass at various transit times. Secondary peaks reveal the presence of clouds at a range of 32 kft.

5. ADAPTIVE OPTICS

For ground-based optical receivers, the optical beam will experience significant wavefront distortion when propagating through the turbulent atmosphere. The optical signal field energy is dispersed into higher order modes, requiring larger receiver fields-of-view (fov) to capture the downlink signal. Enlarging the fov adds excess background noise to the receiver (either from the day sky or from the shine of the planet when the probe is in orbit) and degrades the link quality. Adaptive optics (AO) can correct the atmosphere-induced wavefront distortion, reduce the required receiver fov, and enable single mode near diffraction-limited operation of the receiver. This spatial filtering of the signal in the presence of atmospheric turbulence enables the suppression of the sky background noise even at small sun-Earth-probe angles enhancing the SNR of any communication channel.

An AO testbed was integrated to the OCTL and is shown in Fig. 4 [3]. The communications wavelength in the testbed is 1064-nm, the choice for the deep space link. The wavelength for the simulated guide star for wavefront correction in the wavefront sensor (WFS) is 635-nm. Both the communications and guide star laser beams at first follow a common path through the optical train and are made incident on the 97-actuator deformable mirror (DM) and tip/tilt mirror with a 2.4 kHz resonance frequency. The DM was designed for 10 cm on-sky actuator spacing. At this point, the paths of the two beams diverge with the communications beam directed to the communications detector and the scoring camera, and the guide star beam going to the Shack-Hartmann WFS. The WFS consists of a 10 x 10 lenslet array and an 80 x 80 CCD array of 24 micron pixels. We use the central 40 x 40 pixels with 2 x 2 on–chip binning to measure the tip/tilt and higher-order wavefront aberrations. The DM and tip/tilt mirror servo loops are closed to "null" out the wavefront errors (WFE) measured by the WFS. Loop delays, system noise and bandwidth constraints result in residual wavefront errors in the system.

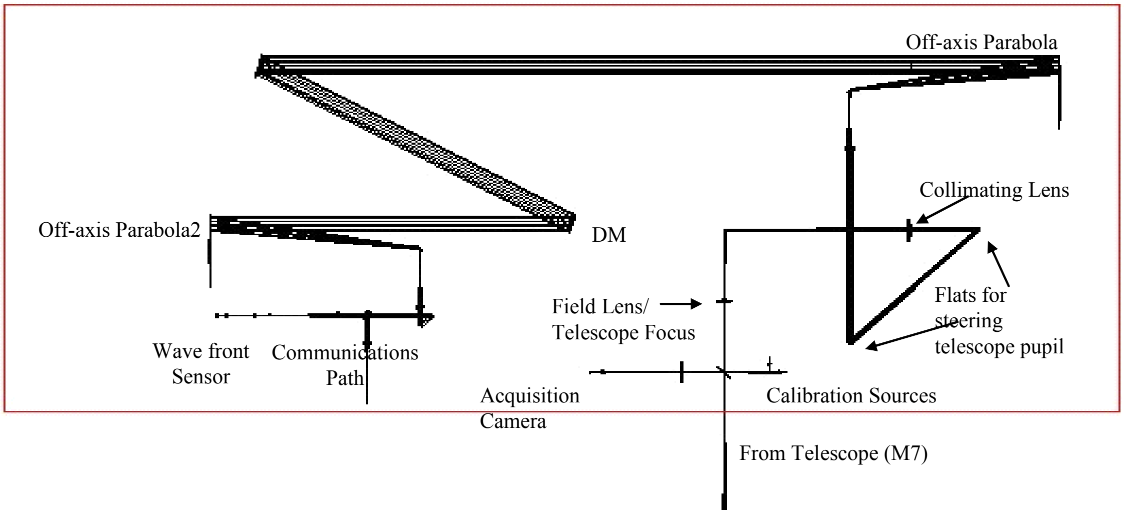
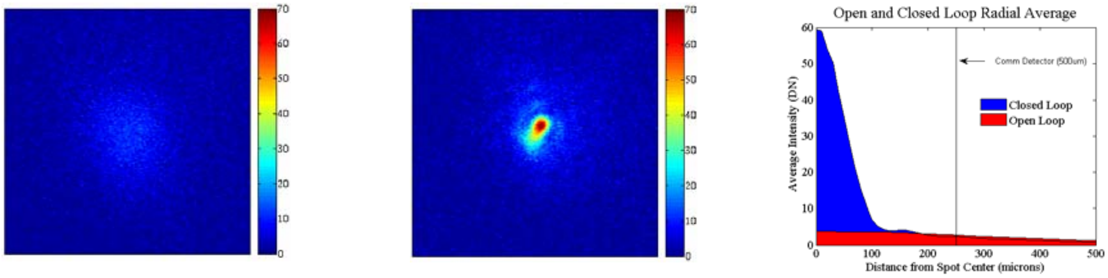


Fig. 4: Optical layout of the AO optical communications testbed at OCTL.

First light images of the 1.9 visual magnitude star, Polaris seen through the AO system are shown in Fig. 5; more recent experiments have demonstrated correction with visual magnitude 4 stars. The residual wavefront error for these initial measurements was 300-nm. The AO closed-loop bandwidth was measured to be up to 25 Hz from the power spectral densities for the deformable and tip/tilt mirrors. Reducing the non-common path errors and other optimizations should allow a Strehl of up to 70%, as was shown in another similar testbed.



(a) (b) (c)

Fig. 5: First light of Polaris star (a) uncorrected and (b) AO corrected image. The estimated residual post-AO wavefront error (WFE) is 300-nm. Note that the images in (a) and (b) are scaled by the automatic gain control of the camera and are not scaled relative to each other. (c) With AO correction implemented the intensity on detector increases enabling the receiver field of view to be reduced.

6. TRACKING EXPERIMENTS

We have tracked several LEO and MEO satellites during terminator passes with varying degrees of success as well as stellar sources for calibration purposes. Ephemeris files were obtained for a variety of public domain sources and at times target satellites came into view in the center of the field and at times not. We suspect that this was due to the age of the ephemeris file especially for LEO satellites. To evaluate the telescope performance we tracked the star Arcturus and measured the bias drift of the satellite over a period of fifty minutes, which corresponds to the duration of a LAGEOS I or II pass. The results given in Fig. 6 show that over the test period the telescope exhibits excellent tracking stability. The measurements show a small 5-urad bias drift over the test period. These data show that telescope bias drift is not a significant source of error when propagating laser beams, uncompensated for atmospheric turbulence, to actively track satellites.

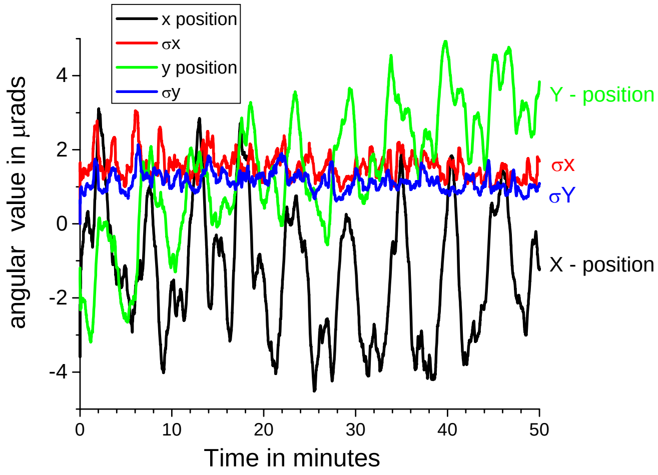


Fig. 6: Open loop tracking performance of the OCTL telescope over a fifty minute period.

OCTL has received permission from satellite owners to transmit to twelve retro-reflector bearing satellites from US and foreign sources. The active satellite tracking optical train supports transmit/receive isolation, narrow output beam divergence, high power laser beam propagation without mirror damage, multi-beam propagation, and verified telescope and laser beam boresight alignment. Currently a two-beam system is implemented with the capability of upgrading to four beams. Projected output beams are shown in Fig. 7 using a doubled Nd:YAG at 532 nm with up to 250 mJ/pulse and 7 ns pulse widths at 10 to 50 Hz repetition rates. The data acquisition system includes a tunable time delay for the PMT detected receive pulse.

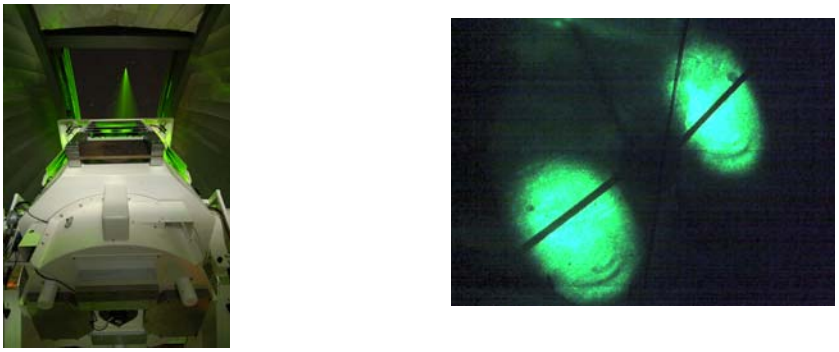


Fig. 7: Uplink laser propagation for active satellite tracking. Beam patterns are projected on the closed dome for reference.

Sample data for the September 13 Ajisai pass (13 hr 24 min 27 sec UT) are shown in Fig. 8. Ajisai is retro-reflecting orb that consists of 1436 retro-reflectors and 318 mirrors. It has a 116 minute orbit at an altitude of 1490-km and inclination of 50º. The satellite track as seen from the OCTL transited from 282º azimuth to 28º azimuth above 25º elevation; the maximum elevation was 42.7º. Preliminary analysis of the data shows a residual range error of approximately 2-km. We believe that the data gaps in the figure as the satellite sets are due to beam transmission interrupts caused by the detection of trees in the Tier 1 sensor exclusion zone; the OCTL has a 25º tree line mask to the NNE.

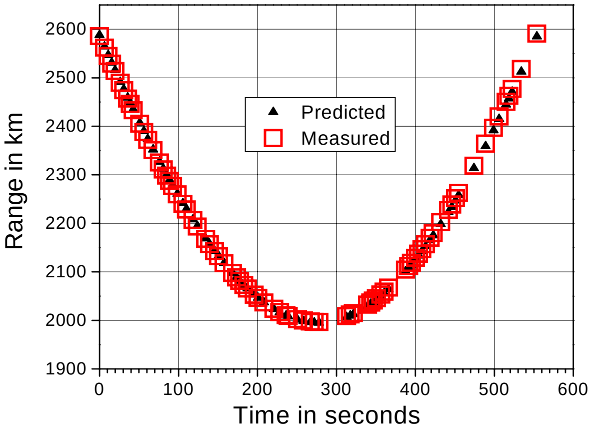


Fig. 8: Satellite returns for ranging experiment using Ajisai. Expected time of arrival is from ephemeris predictions.

Operationally, the Consolidated Predict Format pointing files from the ILRS ftp server were modified to accommodate for the uplink point-ahead and loaded in to the telescope pointing file. As the satellite rose above the horizon, the telescope tracked the target. Laser transmission was initiated when it was indicated clear to do so by the ILI cameras, the in situ radar, and predictive avoidance. No other action was taken during the track; no adjustment of the telescope pointing was needed for any of the tracks.

7. SUMMARY

The OCTL is a unique R&D facility located at 2.2-km elevation in the San Gabriel mountain range of southern California. Technology developments at the facility have focused on beam propagation issues relevant to deep space and near-Earth optical propagation. In particular, we have explored strategies for safe laser beam propagation, real time line-of-sight attenuation measurement, scintillation mitigation strategies using adaptive optics and multi-beam propagation approaches. We have begun the active satellite tracking phase of our experiments, successfully transmitting to Ajisai and Stella.

8. ACKNOWLEDGEMENTS

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9. REFERENCES

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