5-4 The OCTL-to-OICETS Optical Link Experiment (OTOOLE)

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The OTOOLE demonstration was conducted in May and June 2009 and demonstrated a robust optical link between the low Earth orbiting (LEO) OICETS satellite and the JPL Optical Communications Telescope Laboratory. A series of precursor experiments with 20-μrad uplink beams were conducted with LEO retro-reflecting satellites to validate the telescope's ability to point to and track these targets from the proposed ephemeris file format. The OTOOLE experiments were successfully conducted on all four attempts under a variety of atmospheric conditions, and validated link models and proved out new strategies to acquire and track space-to-ground optical communications links.

Keywords
Free-space optical communication, Atmospheric propagation, Laser beam transmission, Scintillation index

1 Introduction

The success of the 2009 OTOOLE (OCTL {Optical Communications Telescope Laboratory}-to-OICETS Optical Link Experiment) is the latest in the series of laser communications related demonstrations conducted by National Aeronautics and Space Administration (NASA) Jet Propulsion Laboratory (JPL) over the past two decades. In the decade of the '90s JPL experiments such as GOPEX (Galileo Optical Experiment), CEMERLL (Compensated Earth-Moon-Earth Retro-reflecting Laser Link) and GOLD (Ground-to-Orbiter Laser Demonstration) identified and developed strategies to mitigate some of the key challenges to the optical space-to-ground link[1]-[3]. These seminal demonstrations discussed in more detail below have contributed to the accelerating pace of development of space-to-space, space-to-aircraft and space-to-ground optical links in the first decade of 2000, (GEOLITE, SPOT-4, ARTEMIS, OICETS, NFIRE) over the last decade[4]-[7].

Over a period of seven days in 1992, JPL conducted an optical link demonstration between the Galileo spacecraft and ground stations at the JPL Table Mountain Observatory (TMO), Wrightwood California and at the Starfire Optical Range (SOR) Albuquerque New Mexico. Although GOPEX was an uplink beacon only experiment, it demonstrated the first pointing of narrow microradian level (60 μrad, 110 μrad) laser beams to a deep space probe. The deep fades in the uplink signal strength seen in the recovered data identified the need for scintillation mitigation strategies. In addition, the impact of weather fronts that precluded uplinks, at first from TMO and then from the SOR over the last three days of the experiment, highlighted the need for ground station site diversity to ensure high link availability.

The 1994 JPL CEMERLL experiment conducted jointly with the SOR attempted to address the uplink scintillation challenge by using adaptive optics to pre-compensate for atmospheric turbulence. A Rayleigh guide star generated by a 200 W class copper vapor laser focused at 15-km high in the atmosphere above the SOR provided higher-order wavefront correction for the 1064-nm Q-switched uplink beam to the Apollo 15 lunar retroreflectors. Analysis predicted and the experiment confirmed that in the absence of tip/tilt compensation the retro-reflected returns would be large but sporadic. Tip/tilt correction required the presence of a reference beacon within the isoplanatic angle, and the technology of the time called for a bright natural guide star to serve as such a beacon. However, the 3-mrad separation between the location of the retro-reflectors at Hadley Rille and the edge of the moon was clearly much greater than the 12-μrad isoplanatic angle of the 1064-nm beam. The CEMERLL results highlighted the need for a different approach to mitigate scintillation effects, if a downlink beacon within the isoplanatic angle were unavailable; such as would be the case for a laser communications link with a spacecraft at Mars.

The general problem of beacon uplink scintillation remained unresolved until 1996 when JPL first demonstrated a multi-beam mitigation technique. The geo-transfer orbit of the ETS-Ⅵ satellite that was launched in August 1994 provided a unique opportunity to test a novel multi-beam approach. The ETS-Ⅵ satellite had a three-day orbit when the satellite was visible from TMO. The GOLD experiment demonstrated a 1.024 Mb/s Manchester-coded uplink and downlink. The downlink data stream was generated by either a 1.024 Mb/s PN sequence or by 8 X repetition of 128 kb/s onboard telemetry of the lasercom system status. GOLD also demonstrated regeneration of the detected uplink data stream with real-time downlink to the ground station.

In addition to the demonstration of a high bandwidth bi-directional optical link to a satellite at geostationary ranges, GOLD also afforded and opportunity to explore uplink scintillation mitigation strategies. The source of uplink beam scintillation is the interference of the beam with itself as it propagates through the atmosphere. The GOLD scintillation mitigation strategy was to: (i) make the uplink beam spatially incoherent by separating it into beamlets that were propagated from sections on the uplink aperture separated by greater than the Fried coherence length and (ii) make the beams spectrally incoherent by introducing a path length delay between the beamlets that was greater than the laser's coherence length [8][9]. This multi-beam approach was first demonstrated during the second phase of the GOLD campaign in GOLD in 1996[10]. It showed the progressive reduction in number and strength of surges and fades detected at the space terminal as the number of beams was increased from one to four. The multi-beam approach is now an accepted technique to mitigate scintillation on optical beacons uplinked to space probes when the point-ahead angles far exceed the isoplanatic angle.

2 OTOOLE preparation

OTOOLE was conducted from the OCTL located at 34.382 degrees N latitude, –117.683 degrees longitude, and 2.26 km altitude[11]. The OCTL facility is one of several telescope facilities at the Table Mountain Facility (TMF) in the San Gabriel Mountains of Southern California (Fig. 1). OCTL houses a 1-m primary Ritchey-Chrétien f#/75.8 coudé focus main telescope and a 20-cm f#/15 acquisition telescope bore sighted with the main telescope. Designed to track LEO objects as low as 250 km, the telescope has a 6-degree keyhole at zenith when tracking at maximum speed, 10 deg/sec in elevation and 20 deg/sec in azimuth. At the time of OTOOLE, trees around the OCTL facility established a 20-degree elevation tree line as shown in Fig. 2. This constraint limited the number of passes that it was considered to be meaningful to support.

2.1 Laser safety system at the OCTL (LASSO)

Propagating laser beams from the OCTL requires coordination with the US Federal Aviation Administration (FAA) and US Space Command's Laser Clearing House (LCH). LASSO is a three-tier laser safety system developed by JPL that detects objects at risk of

Fig.1 OCTL telescope facility located in the Southern California San Gabriel mountains

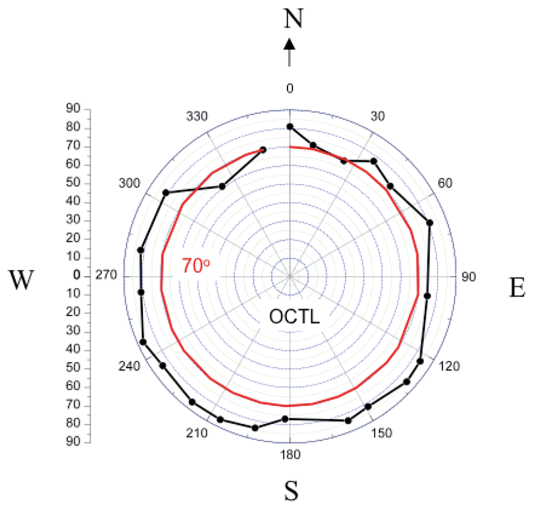
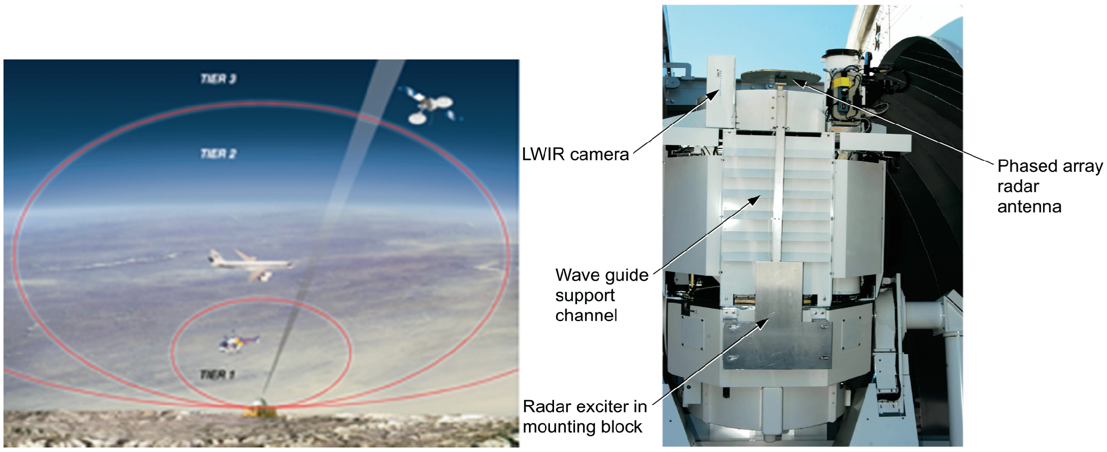


Fig.2 Trees around the OCTL limit uplink propagation to 20-degrees elevation

intercepting the laser beam and blocks the laser output to ensure safe laser beam propagation through navigable air and near-Earth space[12]. Tier-1 and Tier-2 systems ensure safe laser beam transmission through the airspace. The Tier-1, long wave (8 µm to 14 µm) infrared (LWIR) cameras detect objects at risk of intercepting the laser beam out to 3.4 km. The Tier-2 X-band radar detects aircraft out to 54 km (Fig. 3). In addition, the FAA required OCTL to post ground observers to ensure safe laser beam propagation through the airspace. Tier-3 safety measures were deemed to be unnecessary for OTOOLE and were waived by the LCH.

2.2 Precursor experiments

A series of precursor experiments were performed to validate the OCTL telescope pointing accuracy to the 600-km OICETS satellite (Fig. 4). International Laser Ranging Service (ILRS) consolidated predict format files were used to generate telescope-pointing files to LEO (Stella, Ajisai, and Starlette) and Medium Earth Orbit Lageos retro-reflecting satellites[13]. Although the divergence of the OTOOLE uplink beam designs were on the order of milliradians, transmissions of the narrow 20-µrad laser beam to these LEO satellites gave us confidence in our ability to point to



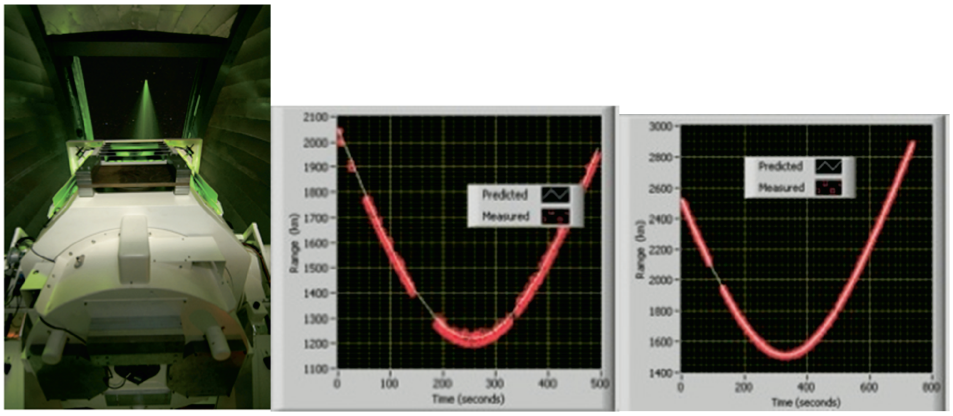
(a) (b)

Fig.3 (a) Depicts three-tier system for safe laser beam propagation through navigable air and near-Earth space. (b) LWIR cameras and X-band radar detectors integrated to OCTL telescope and track OICETS.

2.3 Uplink beacon and communications

The uplink beacon and communications beams adopted the multi-beam scintillation mitigation strategy that had been first demonstrated in the 1996 GOLD experiments. A schematic of the four multi-mode fiber-coupled 801-nm 1-W beacon laser diodes and three high-power single-mode 819-nm lasers communications lasers for the 2 Mb/s uplink is shown in Fig. 5. The availability of high-power single mode 819-nm lasers was limited, and two fiber-Bragg grating lasers 25-mW each temperature controlled at 55.5˚C for wavelength stability and one 10-mW laser, were used for the communications uplink.

Figure 6 is a picture of the transmitter arrangement on the optical bench at coudé focus. The beacon and communications beams were reflected and transmitted respectively through a Raman notch to a 46-cm focal length off-axis parabolic mirror and coupled to the M7 coudé mirror of the 1-m telescope aperture. The



(a) (b) (c)

Fig.4 *(a) Q-switched 532-nm laser beam propagated to retro reflecting satellites to validate ability to point narrow laser beams. (b) Retro-reflected laser signals from Starlette satellite March 29, 2009 and (c) from Ajisai March 30, 2009. Gaps in the return signals correspond to predictive avoidance safety system denial of transmissions from US Space command.*

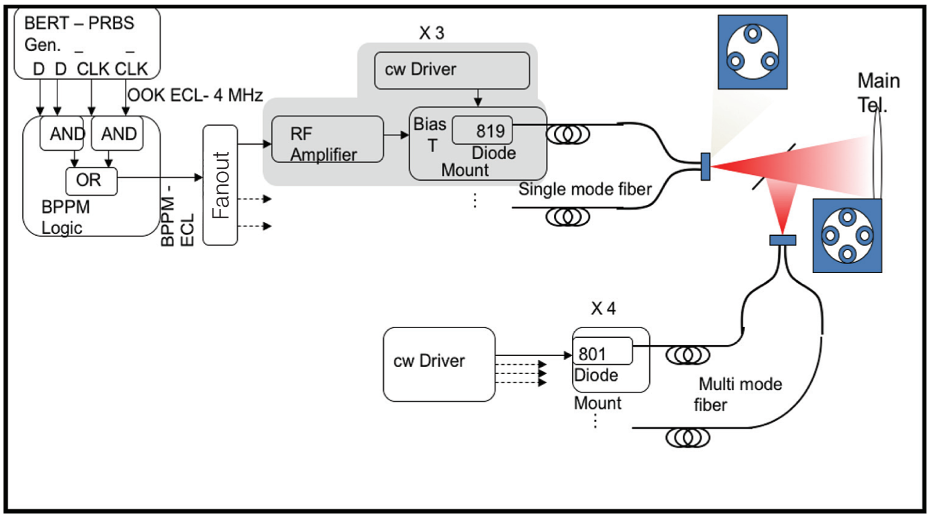


Fig.5 *Schematic of uplink communications and beacon lasers*

uplink beacon and communications beams exiting the telescope were 2-mrad and 1-mrad, respectively.

2.4 Downlink

Figure 7 (a) is a schematic of the receiver platform. A picture of the components is shown in Fig. 7 (b). The platform was mounted to the 20-cm acquisition telescope that is co-aligned with the 1-m uplink telescope. A portion, 20%, of the 847-nm received downlink signal was first beam split to the acquisition camera to visually confirm the downlink. The remaining 80% of the signal was transmitted through a 10-nm band pass filter centered at 850-nm to suppress the Rayleigh backscatter from the 801-nm and 819-nm uplink beams. The portion of the signal transmitted through the filter was equally split between a 600-µm multimode fiber and a 1.5-mm diameter, 100-MHz Si APD detector. The other end of the fiber was coupled to the 25-kHz bandwidth silicon photodiode detector to measure the power fluctuations in the downlink. The

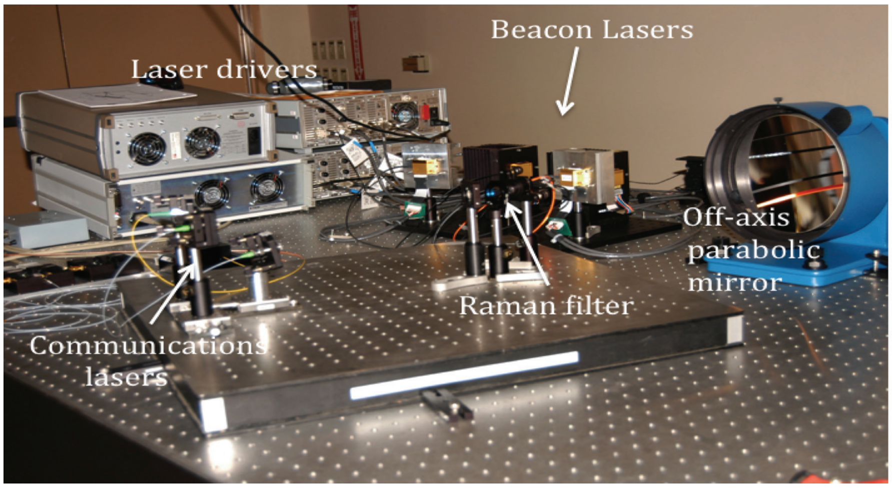


Fig.6 Uplink beacon and communications lasers coupled through the Raman filter to the off-axis parabola. Beams reflected from the off-axis parabola are coupled to the telescope M7 coudé mirror.

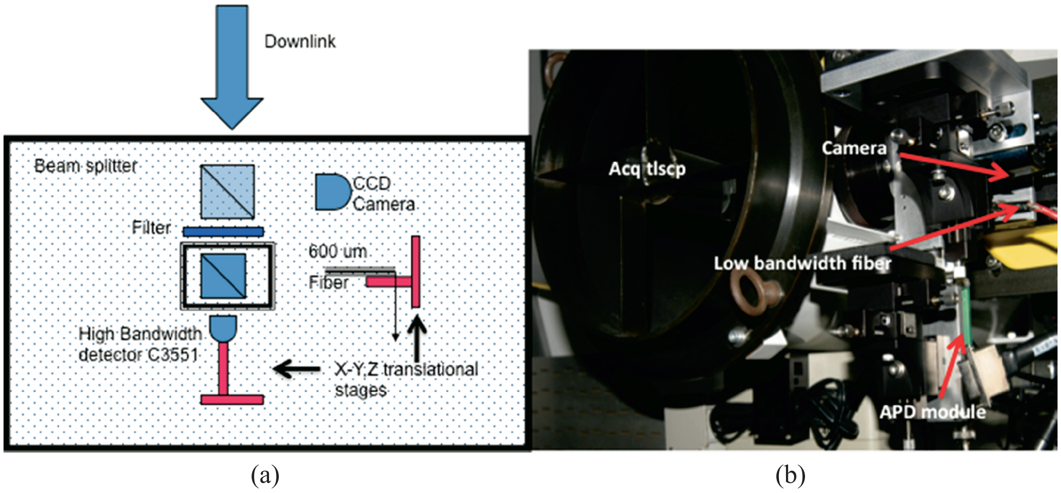


Fig.7 Schematic (a) and picture (b) of OTOOLE 20-cm receiver telescope with CCD camera, optical fiber to measure low-bandwidth downlink power fluctuations, and 100 MHz bandwidth APD module for BER measurement

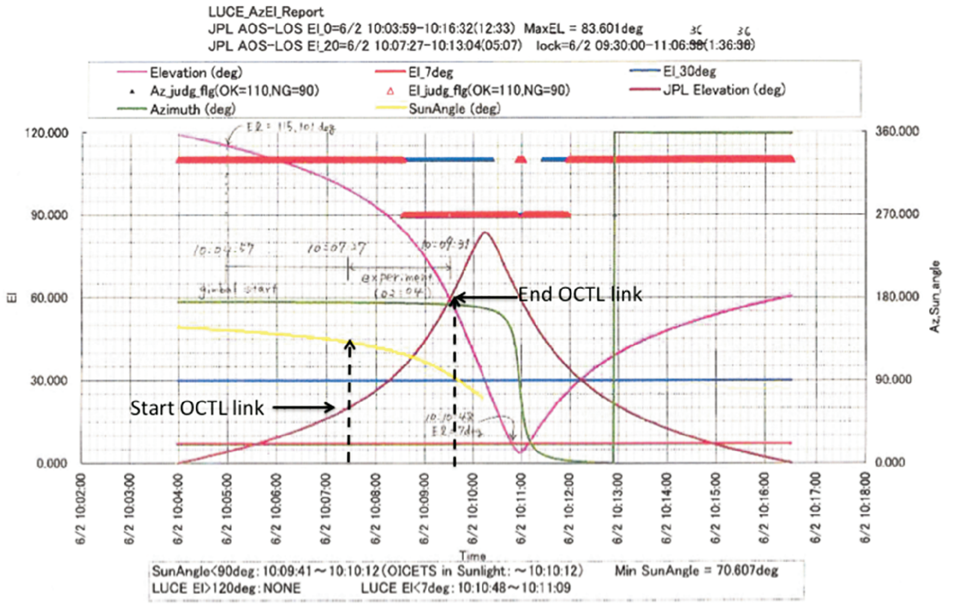


Fig.8 *Graphic of June 2, 2009 OCTL link to OICETS showing the elevation and azimuth of the spacecraft and the sun angle as it passes over the OCTL ground station*

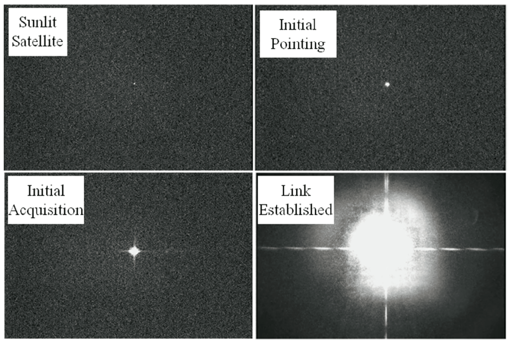


Fig.9 *Pictorial sequence shows the establishment of the link*

avalanche photodiode detector (APD) measured the 49.3724-Mb/s On-Off-Key (OOK) downlink data stream for bit error rate (BER) analysis.

3 OTOOLE Operations and Results

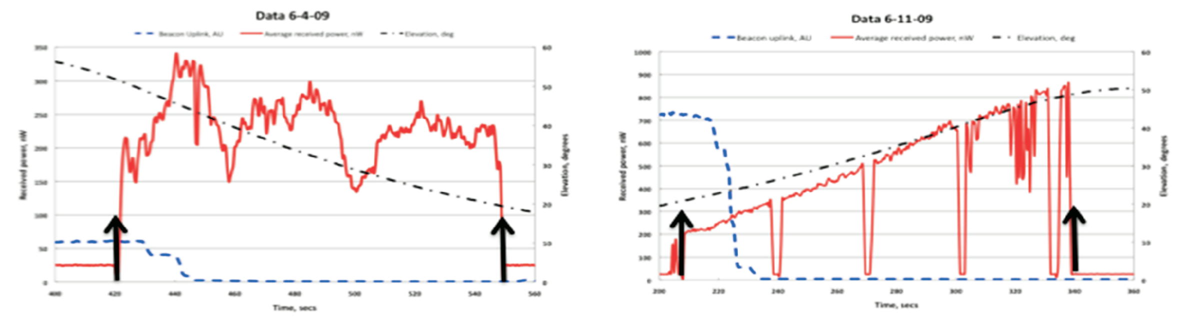
JAXA proposed ten opportunities to JPL between May 12 and June 18, 2009 for the link to the satellite. JPL received authorization to proceed on May 20, 2009 in time to support seven passes. Given the OCTL tree line, an a priori decision was made to support passes that culminated at greater than 50 degrees elevation. There were four OICETS passes culminated above 50 degrees, between May 21 and June 18, 2009. The duration of the optical links was determined by the elevation angle of the spacecraft from the ground and by the sun-probe-Earth angle. The graphic of the June 2, 2009 pass depicted in Fig. 8 shows the link beginning as OICETS rises above 20 degrees elevation from the OCTL and terminating at 60 degrees elevation as the sun angle as seen by the satellite drops below 90 degrees.

A pictorial sequence of the downlink is shown in Fig. 9. It starts with the sunlit satellite through the initial downlink pointing and acquisition to the established link. Table 1 gives the details of the four passes their duration and the atmospheric conditions at the site during the experiment.

The sequence of events was for the OCTL telescope to begin tracking the OICETS as the satellite passed zero degrees elevation. Both the beacon and communications lasers were operated at full power in the initial stage with the communications lasers temperatures stabi-

Table 1 Details of OTOOLE transmissions

Experiment date	5/21/09	6/2/09	6/4/09	6/11/09
Latest CPF files received, day, PST	5/20/2009 04:53	6/1/2009 04:52	6/3/2009 04:52	6/10/09 04:52
Start pass (0 deg elev.)	2:53:00	3:04:00	03:22:30	3:46:50
End Pass (0 deg elev.)	3:05:00	3:16:30	3:43:10	3:59:20
Max elevation, deg	61	81	58	51
LUCE start (el, PST)	19.8 deg, 2:56:25	20 deg, 03:07:27	53 deg, 03:28:25	20 deg, 02:52:04
LUCE end (el, PST)	54.2 deg, 3:01:49	60 deg, 03:09:31	20 deg, 03:30:43	48.7 deg, 02:54:19
Pass duration above OCTL tree line, sec	324	350	330	320
LUCE track duration, sec	324	124	138	135
OCTL link duration, sec	140	100	138	130
Link percentage of track	43.21%	80.65%	100.00%	96.30%
Weather	Clear	Clear	Overcast	Clear
Wind speed, km/hr	10.85 gusts to 29	10 gusts to 18	23 gusts to 40	6 gusts to 10
Data products				
Uplink beacon power, W	1.8	1.8	1.8	1.8
Average uplink comm power, mW	7	10	22	22
Downlink power received, nW	213-1075	170-300	150-300	100-750
Downlink comm BER	10E-1 to <10E-6	10e-2 to 10E-5	10e-4 to <10E-6	10e-1 to 10E-5

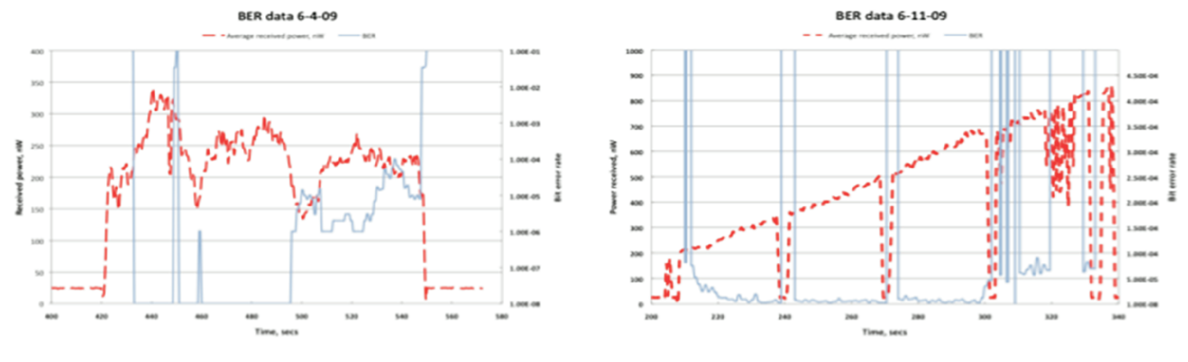


(a) (b)

Fig.10 *Plots of (a) the uplink beacon and downlink power from the OICETS satellite for the duration of the pass. The satellite's elevation angle is also shown. (b) The dropouts in downlink power are due to tracking issues on the spacecraft.*

lized at 55.5˚C. As the satellite acquired the uplink beacon and returned its downlink to the ground station the beacon beam power was reduced and the power in the communications beam that also served for the satellite's fine tracking was maintained.

Figure 10 (a) and (b) show the uplink beacon and downlink powers with elevation angle during the passes on June 4 and 11. Periodic dropouts seen in Fig. 10 (b) were characteristic of the link to OICETS. Although not observed during the June 4 downlink, Fig. 10 (a) does show two distinct fades during the pass. The dropouts were due to challenges that OICETS had in tracking the ground stations. Corresponding plots of the bit error rate (BER)



(a) (b)

Fig.11 *BER measurements are shown for passes on June 4, (a) and June 11 (b)*

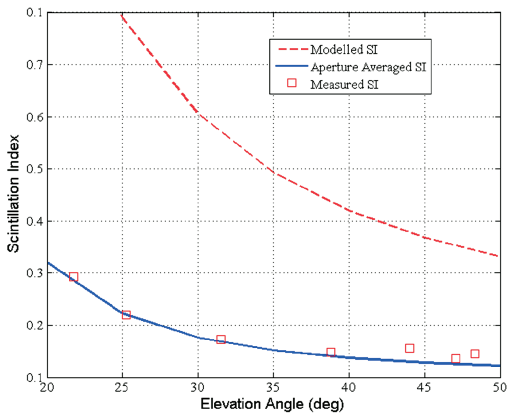


Fig.12 *The aperture-averaged mitigation of the scintillation for the 20-cm downlink receiver*

Table 2 *Uplink signal levels measured at the satellite by its coarse (801 nm) and fine (819 nm) track sensors*

	Coarse sensor		**Fine Sensor**		
Date	**Level, dB**	**SNR, dB**	**Level, dB**	**SNR, dB**	**BER**
May 21, 2009	–82.5	12.7	–58.34	20.7	7.4E-4
June 2, 2009	–88.6	6.6	–72.8	6.3	N/A
June 4, 2009	–84.7	10.5	–63.6	15.5	1.4E-4
June 11, 2009	–86.2	9	–68.3	10.8	7.7E-4

for these two passes is shown in Fig. 11 (a) and 11 (b). For the major part of the link, in the absence of dropouts, the BER on the downlink was ~10E-6. Averaging the downlink signal across an aperture that contains several speckles mitigates scintillation, enhances the SNR and improves the BER [14]. The OTOOLE downlink was aperture averaged across the 20-cm receiver telescope to mitigate scintillation effects. The measured results given in Fig. 12 as a function of satellite elevation show good agreement with the modeled aperture-averaged results.

Table 2 is the mean signal level as seen by the coarse and fine tracking sensors on the days of the experiment. It also gives the uplink BER as measured by the satellite.

4 Conclusion

While the tree line around the OCTL resulted in the selection of four of seven opportunities between May 21 and June 18, the OTOOLE team successfully demonstrated the bi-directional link with the OICETS satellite on all of its four attempts and under a variety of atmospheric conditions. The sun-angle of the satellite constrained the duration of the links during the experiments as the satellite rose to elevations above 20 degrees from the OCTL. Precursor experiments confirmed the telescope's ability to track the OICETS satellite using the ILRS consolidated predict format ephemeris files and the measured downlink signal strength validated our link models.

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