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Preparations for Planned OCTL to OICETS Optical Link Experiment (OTOOLE)

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The Optical Communications Telescope Laboratory (OCTL) to Optical Inter-orbit Engineering Test Satellite (OICETS) Optical Link Experiment (OTOOLE) is a joint Jet Propulsion Laboratory (JPL), National Institute of Information and Communications Technology (NICT), and Japanese Aerospace Exploration Agency (JAXA) bidirectional link (2.048 Mb/s uplink and 49.3724 Mb/s downlink) demonstration between the JPL OCTL ground station and the JAXA OICETS satellite. Located in the San Gabriel Mountains of Southern California, the OCTL houses a 1-m elevation/azimuth coudé-mount telescope co-aligned with a 20-cm acquisition telescope. The telescope tracks orbiting satellites as low as 250 km and slews at a maximum rate of 20 deg/s in azimuth and 10 deg/s in elevation, and can readily track the 601-km altitude OICETS satellite. This article describes the objectives, plans, and preparations for the OTOOLE demonstration. It describes the multibeam beacon and communications uplink design to mitigate the effects of atmospheric scintillation — four 801-nm beacon lasers arranged around the telescope primary at separations greater than the Fried coherence length. At 4 W average optical power, the beacons are transmitted in a 2-mrad divergent beam to compensate for satellite position uncertainty and telescope pointing errors. The communications uplink is a binary pulse position modulation format and consists of three laser beams also separated on the primary mirror by greater than the Fried coherence length. The total average power is 60 mW and the beam divergence is 1 mrad. OTOOLE experiments began on May 12, 2009, when the satellite's orbit put it in high-elevation terminator passes over the OCTL.

I. Introduction

The Optical Inter-orbit Communications Engineering Test Satellite (OICETS) is a low-Earth-orbiting (LEO) optical communications satellite launched by the Japan Aerospace Exploration Agency (JAXA) in August 2005 to perform high-bandwidth optical communications with the European Space Agency (ESA) ARTEMIS geostationary satellite [1]. Designed to also support space-to-ground links, OICETS demonstrated this capability with both the National Institute of Information and Communications Technology (NICT) ground station at Koganei, Japan, and the Optical Ground Station Oberpfaffenhofen (OGS-OP) at the German Aerospace Center (Deutsche Forschungsanstalt fur Luft- und Raumfahrt, DLR, in Wessling,

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Bayern), in 2006 [2,3]. Reactivated by JAXA to perform a second series of ground-to-satellite experiments in October 2008, the OICETS makes terminator passes above the Jet Propulsion Laboratory (JPL) 2.2-km-high Optical Communications Telescope Laboratory (OCTL) (Figure 1) beginning in April 2009 [4,5]. These passes are shown in Figure 2, and afford an opportunity to demonstrate a bidirectional optical link between the OCTL and the onboard Laser Utilization Communications Equipment (LUCE) terminal [6].

Figure 1. Optical Communications Telescope Laboratory with the 1-m elevation/azimuth telescope shown through open dome.

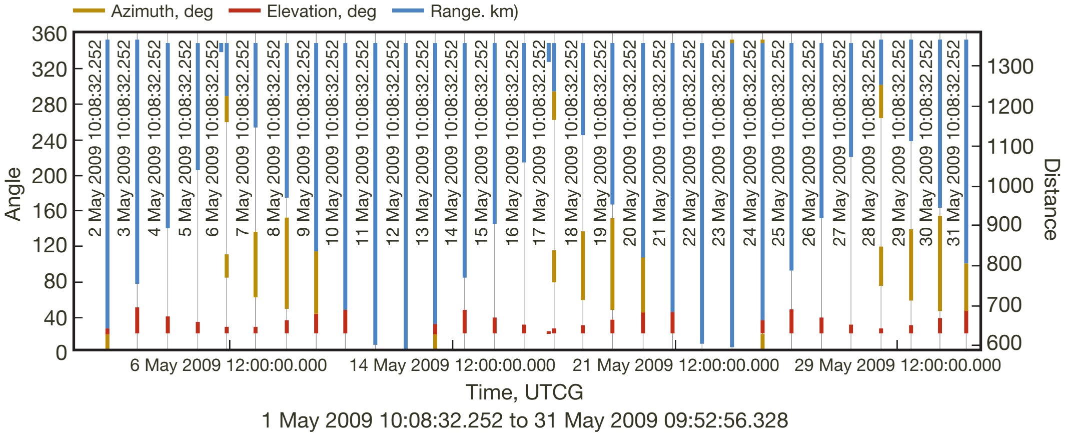

Figure 2. OICETS terminator passes over the OCTL for the month of May 2009 at elevation angles exceeding 20 deg; Analytic Graphics Inc. STK-8.

The objectives of the OTOOLE demonstration are as follows:

(1) Perform a bidirectional optical communications (2.048-Mb/s uplink and 49.3724-Mb/s downlink) link with the OICETS satellite and validate the JPL optical communications models.

(2) Characterize link performance under a variety of atmospheric and background conditions (e.g., partial cloud cover and moonlit sky).

(3) Explore operational issues involved with high-bandwidth LEO satellite optical communications support.

The OTOOLE demonstration will be performed in two phases. In Phase I, a series of precursor experiments designed to establish the accuracy of the OICETS consolidated predict files (CPF) ephemerides obtained from the International Laser Ranging System (ILRS) website will be performed [7]. The experiments follow the approach of previous OCTL active satellite tracking (AST) experiments that routinely track and illuminate the Beacon C, Stella, Starlette, and Ajisai retroreflector bearing satellites [8]. In these experiments, a 532-nm, 500-mJ/pulse, Q-switched laser is transmitted through the 1-m telescope in a dual-beam, subaperture configuration with divergence of approximately 32 μrad. Because of the high-uplink laser power, retroreflector precursor experiments with the OICETS will be coordinated with JAXA to ensure that the satellite is oriented with its retroreflectors facing the ground. The beam retroreflected from the OICETS corner cubes will be detected in the receive channel of the 1-m telescope.

Phase II is the bidirectional link with the OICETS satellite. Experiments will be conducted during nighttime passes above the OCTL, with JAXA reorienting the OICETS satellite from its outward-pointing LUCE orientation to a ground-pointed LUCE terminal. In the sequence of operations, the OCTL will acquire and track the OICETS satellite and initiate the link by transmitting the 801-nm beacon to the satellite as it rises above the OCTL tree line. Upon receipt of the uplink, the LUCE will transmit its 847-nm downlink to the OCTL. The OCTL will then uplink the 819-nm beam that serves both as the uplink communication signal and as a fine-tracking beacon for the LUCE downlink. Once the bidirectional link is established with the communications beam, the 801-nm coarse-track beacon is turned off and the link is continued with the LUCE tracking on the 819-nm beam to the end of the pass.

II. The OCTL Ground Station

Located at 34.382 deg N latitude and –117.683 deg longitude, the OCTL facility is at a 2.261-km altitude in the San Gabriel Mountains of Southern California. Designed to operate as close as 10 deg in sun angle, the OCTL telescope shown in Figure 1 slews at 20 deg/s in azimuth and 10 deg/s in elevation. The telescope tracks 250-km altitude satellites with only a 6-deg keyhole, and can readily track the 600-km, 98-deg-inclined OICETS satellite. Critical operating parameters for the OTOOLE experiment are the OCTL tree line (Figure 3), the telescope throughput through its seven-mirror coudé path, the telescope blind pointing and tracking error, and a precise knowledge of the ground station location.

The OTOOLE optical train is a bistatic design with the uplink beacon and communications beams propagated into subapertures from the 1-m telescope coudé focus. The downlink is received through a 20-cm telescope co-aligned with the main telescope. Using Vega (visual magnitude 0.03) as a source, transmission measurements of the 1-m telescope were made at the B, V, R, and I Bessel filter centered wavelengths over a period of two weeks at zenith angles ranging from 5 deg to 40 deg. The results are given in Table 1. At the 801-nm and 819-nm OTOOLE uplink wavelengths, the mean transmission is 54 percent, as shown from the I filter measurements.

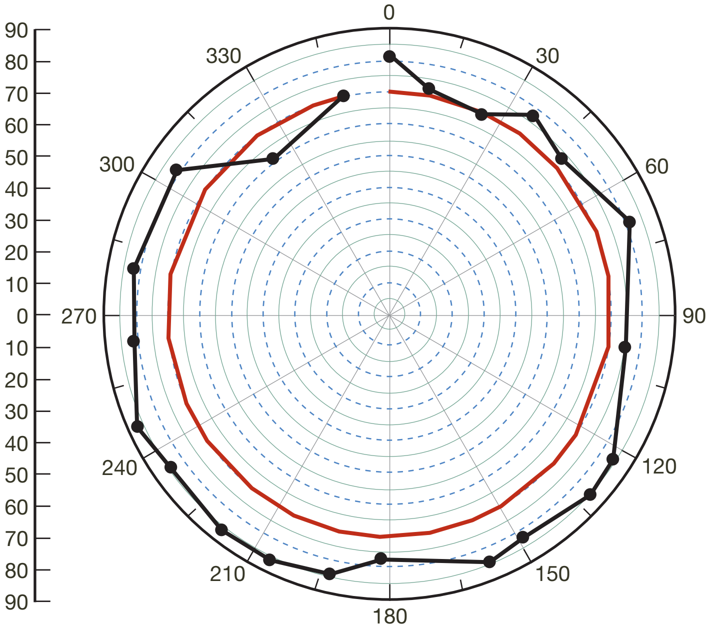

Figure 3. Tree locations around the OCTL facility are shown as points. The red curve is at 70 deg zenith angle and establishes the tree line at the facility.

Table 1. OCTL 1-m telescope transmission at Bessel B, V, R, and I filter wavelengths [9].

Filter	Center Wavelength, nm	Bandwidth, nm	Average Transmission, percent
B	440	100	47 ±4
V	550	90	63 ±3
R	630	120	56 ±3
I	900	300	54 ±2

The telescope blind pointing accuracy, its residual tracking error, and knowledge of the satellite position are important considerations in the design of the uplink laser beam divergence and receiver field of view. Measurements of the blind pointing and tracking performance of the OCTL telescope were made using stars at 30-deg and 60-deg elevations at 90-deg azimuth intervals in winds as high as 14 km/hr and under a variety of seeing conditions. The mean recorded pointing error over this period was 16 μrad ± 9 μrad [10]. The telescope tracking error was measured by tracking a target star for several hours and recording the deviation from telescope boresight at 15-min intervals. Atmospheric seeing at the facility typically ranged from 7.5 μrad (1.5 arcsec) to 15 μrad during the experiment, and established a lower bound for the tracking error. The measured tracking error was comparable to that of the blind pointing error. It must be noted, however, that this represents the optimum performance of the OCTL telescope. Video tracking will not be implemented since it is not an OCTL capability at this time. The expected OCTL telescope tracking error of the OICETS satellite from the CPF ephemerides is thus best represented by its blind pointing performance, subject to wind conditions.

The downlink beam from the LUCE is 6 µrad. At 1000-km range, the beam footprint just covers the 6-m OCTL dome. Global Positioning System (GPS) measurements position the center of the tertiary mirror M3 at 34.3818 deg N latitude, –117.6828 deg longitude, and 2.2613-km altitude mean sea level (MSL). The center of the M3 lies at the intersection of the telescope azimuth and elevation rotation axes, and remains fixed as the telescope rotates.

The OCTL has a three-tier outdoor laser safety system that was developed to ensure safe laser beam propagation through navigable air and near-Earth space [11]. The first two tiers are designed to protect aircraft from laser illumination. Two long-wave infrared Tier-1 cameras cover navigable airspace from the OCTL telescope out to 3.4 km. The Tier-2 sensor is a 9.345-GHz (X-band) radar system boresighted with the telescope and covers propagation in navigable airspace beyond the Tier-1 range [12].

Tier-3 is the coordination with the U. S. Space Command's Laser Clearinghouse (LCH). The OCTL receives daily predictive avoidance listings that stipulate intervals when laser beam propagation to designated targets must cease because a space asset is at risk of transiting the laser beam. The transmission outages are associated with the specific laser, and depend on the laser power and beam divergence. Transmission of the high-brightness laser used in the OTOOLE precursor experiments is subject to predictive avoidance outages. The OTOOLE beacon and communications lasers are low-power lasers with wide beam divergence — eye safe at ~200 m from the telescope aperture. The LCH has excluded these lasers from predictive avoidance control.

III. OTOOLE Precursor Experiments

Precursor beam propagation experiments in preparation for OTOOLE are designed to validate:

(1) The uplink laser far-field beam divergence. The reported knowledge of the satellite's position is < 850 µrad [13]. The divergence of the communications (~1 mrad) and beacon (~2 mrad) beams is designed to cover this uncertainty. The beam divergences will be measured in the far field at a distance of 1.6 km from the telescope.

(2) The accuracy of the telescope tracking based on the ILRS-provided CPF ephemerides.

Figure 4 is a schematic of the optical train of the 532-nm OCTL high-power laser integrated to the OCTL telescope. The Quanta-Ray LAB190 is a Nd:YAG laser that can operate at either the fundamental 1064 nm or at the Type II frequency-doubled 532-nm wavelength in the KTP crystal. The laser has been recently modified to operate at 10 Hz with outputs of 600 mJ/pulse at 532 nm, and 1 J/pulse at 1064 nm. When operating at 532 nm, the unconverted 1064-nm beam is transmitted through a dichroic beam splitter and dumped. The beam exiting the laser is split into two equal power beams at a polarizing beam splitter. The dual-beam configuration mitigates uplink beam scintillation and reduces the power density on the telescope mirrors to a level below their damage threshold.

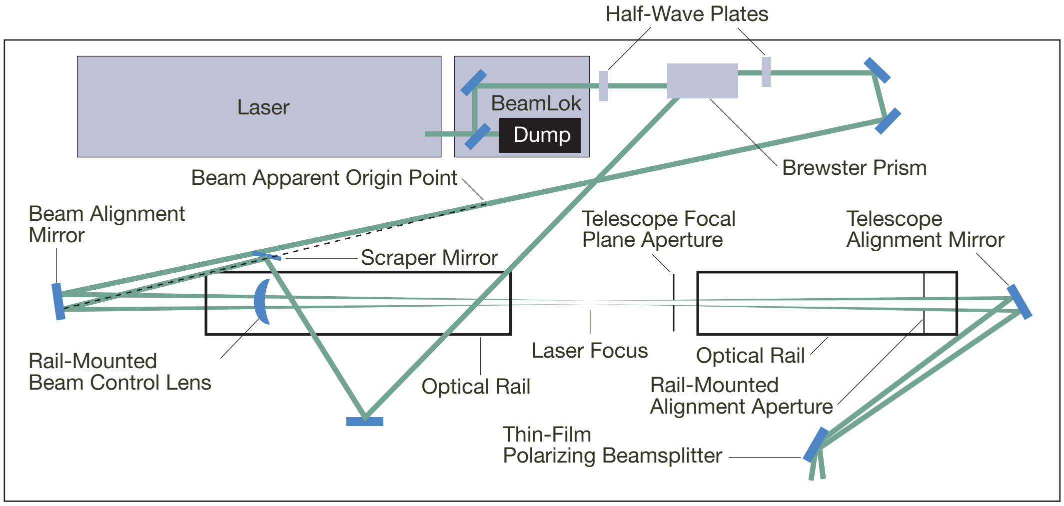

Figure 4. Schematic of OCTL high-power laser active satellite tracking optical train.

The two beams exiting the polarizer are angularly separated by approximately 140 deg. To juxtapose these beams prior to co-alignment in the optical train, the reflected beam is first reflected by a harmonic high-reflecting mirror and then by a specially fabricated square scraper mirror with the reflection coating extending to the mirror's edge. The transmitted beam is reflected from two high-reflecting harmonic mirrors and grazes past the side of the square scraper mirror, as shown. The beams are then incident on the beam-alignment mirror and onto the beam-control lens. The ensuing elements in the optical train are aligned to the 2.5-cm holes on the Newport optical table. This approach allows the beam divergence to be readily changed by translating the 1500-mm plano-convex beam-control lens relative to the beam-alignment mirror.

The lens brings the two beams to a focus, from which they expand and overlap at the iris aperture that defines the location of the telescope focus. Moving the lens toward and away from the focus aperture, the beam foci are moved toward or away from the aperture, and the relative size of the beams in the aperture is reduced or expanded, respectively. This beam projection approach is routinely used to range to target LEO satellites [8]. Figure 5 shows the laser propagating through the telescope. Propagation of this narrow uplink beam, which is less than 1/10th the width of the OICETS communications and beacon uplink beams, will validate the accuracy of the OICETS CPF files.

IV. OTOOLE Link Analysis

The required minimum and maximum irradiances at the satellite to establish the link and the OICETS and the expected downlink are published in the JAXA Optical Interface document and are given in Table 2 [14]. A preliminary link analysis of the margin for the coarse- and fine-tracking uplink beams is shown in Figure 6. The analysis shows a coarse tracking link margin of 15 dB at 20-deg elevation. The figure also shows that the fine tracking margin becomes positive at 28-deg elevation increasing to 10 dB at 84-deg elevation. This analysis forms the basis of our operational sequence of events and is consistent with the

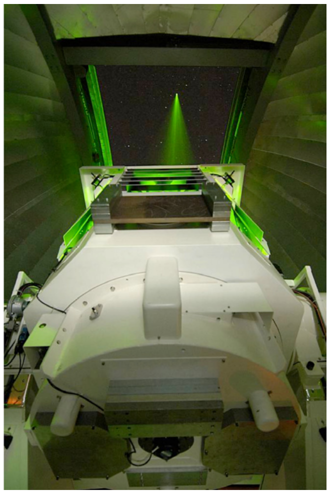

Figure 5. OCTL 532-nm high-power laser projected through 1-m telescope.

Table 2. Required irradiance at the OICETS for fine and coarse tracking of the ground station.

	Wavelength	Acceptable Irradiance	Uplink/Downlink
Coarse Pointing Uplink	797–808 nm	Minimum	2.25 nW/m2
		Maximum	7.4 nW/m2
Fine Pointing Uplink	815–825 nm	Minimum	11 nW/m2
		Maximum	110 nW/m2
Downlink	847 nm	Minimum	85E6 W/sr
		Maximum	780E6 W/sr

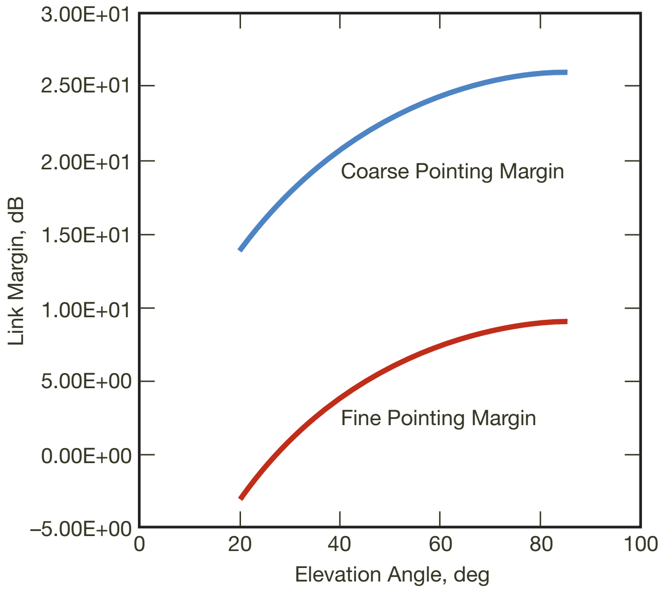

Figure 6. Coarse and fine tracking link margin as a function of elevation angle assuming 90 percent zenith angle transmission. The OCTL tree line is at a telescope elevation of approximately 20 deg.

scenario in which fine tracking signal is transmitted to the satellite after coarse tracking is established and validated by the return link to the ground station.

A preliminary analysis of the margin on the downlink for a 7-cm, 14-cm, and 20-cm diameter receiving aperture is given in Figure 7 for worst, nominal, and best case atmospheric conditions. These receiver apertures will be used to provide aperture averaging data on the downlink. The analysis assumes 2 dB transmitter loss, 2 dB pointing loss, and 0.14 dB obscuration loss at the 20-cm receiver telescope. The atmospheric conditions are defined by the Fried coherence cell size r_o and the atmospheric attenuation; with worst $r_o = 3.5$ cm, nominal $r_o = 6$ cm, and best $r_o = 10$ cm. Corresponding atmospheric transmission losses are 8.3 dB, 2.3 dB, and 1.3 dB at 70-deg zenith angle. The analysis shows that even under the worst atmospheric conditions, the link margin is positive for both the 14-cm and 20-cm apertures from the inception of the pass. For the 7-cm aperture, the link margin is positive for nominal and best case atmospheric conditions for the entire pass. Under the worst atmospheric conditions, the link margin for the 7-cm aperture is negative at greater than 60-deg zenith angle (30-deg elevation angle), becoming positive as the satellite ascends to higher elevations.

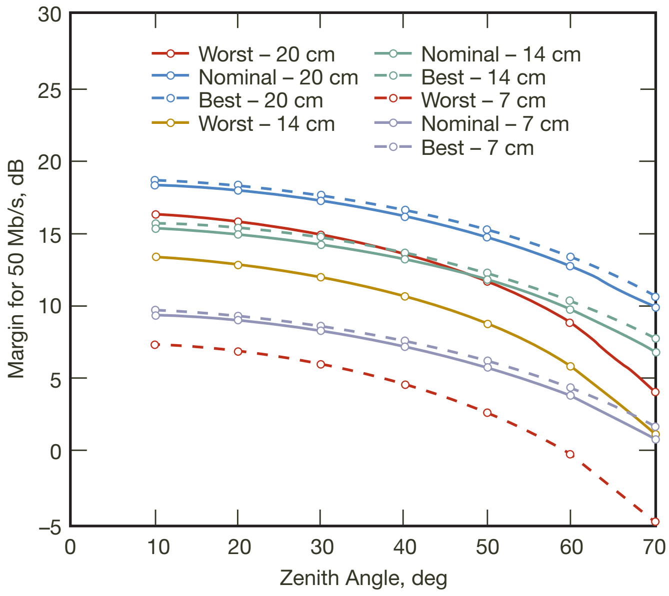

Figure 7. Downlink margin for 7-cm, 14-cm, and 20-cm diameter receiving apertures at the OCTL.

V. OTOOLE Transmitter Design

Figure 8 is the preliminary uplink optical design. The lasers are arranged in a multibeam pattern to mitigate scintillation effects on the uplink. Four 1-W CW 801-nm lasers are reflected from a Raman filter to a 45-cm focus off-axis parabola and coupled to the 1-m telescope through the coudé path. The LUCE on board OICETS acquires the beacon laser uplink and coarse tracks the OCTL ground station. Three 819-nm communications lasers, 60-mW average optical power, are transmitted through the Raman filter and also serve as a beacon for the LUCE fine-tracking system. High-power, single-mode lasers operating at 819 nm were not readily available, and the OTOOLE baseline design uses two 25-mW Lumics lasers temperature controlled at 55.5 deg C to operate at 819 nm and one Qphotonics 10-mW laser. Both communications and beacon lasers are coupled to the 1-m OCTL telescope through an off-axis parabola at the focus of the telescope. The beacon beam divergence on the sky is 2.6 mrad. The communications beam is a 1.0-mrad divergence 2.048-Mb/s binary pulse position modulated (BPPM) pseudorandom bit stream (PRBS).

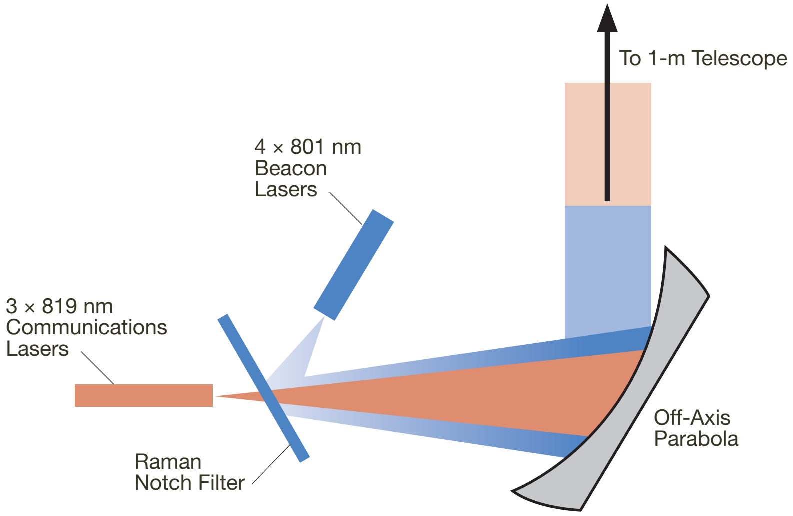

Figure 8. Schematic of OTOOLE transmitter optical train showing the beacon and communications lasers coupled to the off-axis parabola.

VI. OTOOLE Receiver Design

The 847-nm OICETS downlink is detected through the 20-cm telescope affixed to and co-aligned with the 1-m transmitter. Figure 9 is a schematic of the receiver platform at the 20-cm telescope. An acquisition camera; a 600-um core fiber; and a C5331 Hamamatsu avalanche photodiode detector (APD) module, 1.5-mm diameter, 100-MHz bandwidth are mounted on the receiver platform. The first beam splitter at the charge-coupled device (CCD) acquisition camera visually confirms the uplink beam propagation transmitting the Rayleigh backscatter from the 801-nm and 819-nm uplink beams and 20 percent of the 847-nm downlink signal. The bandpass filter has a 10-nm bandwidth centered at 850 nm that passes the downlink and rejects the Rayleigh backscattered uplink. The 49.3724-Mb/s on–off keyed (OOK) downlink signal passes through the filter and is split equally between the APD and the multimode fiber. The downlink bit error rate (BER) is measured at the output of the APD. The output of the multimode fiber is coupled to a 5-kHz bandwidth photodiode located in the coudé room and measures the effects of the atmosphere on the downlink signal and its variations with satellite elevation.

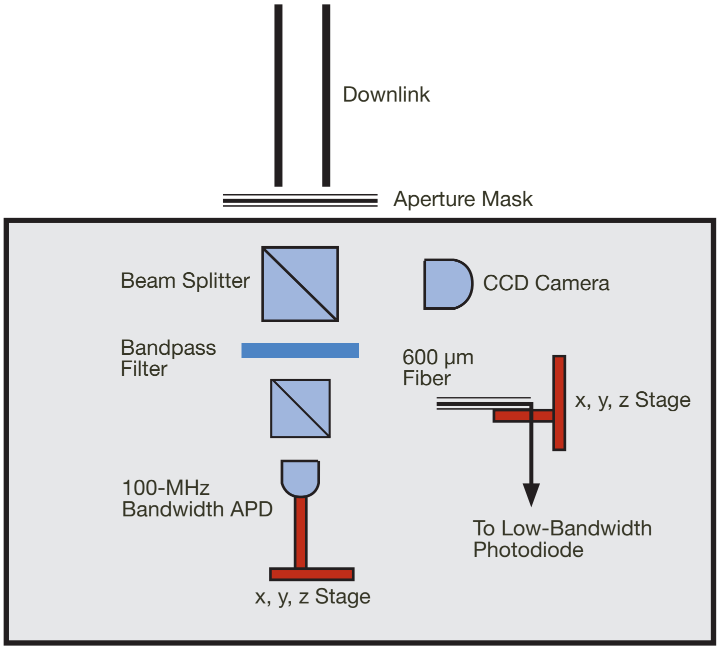

Figure 9. The schematic of the OTOOLE receiver shows the high-bandwidth detector that recovers the 50-Mb/s downlink signal for BER analysis and 600-µm core fiber that is coupled to the 5-kHz bandwidth detector to measure downlink signal fades. The CCD camera captures both the Rayleigh backscatter of the uplink and the downlink signal from the satellite.

VII. OTOOLE Data Products

The following are data products that will be collected during the pass for post-processing and analysis:

- Video of downlink and Rayleigh backscatter
- Measured downlink signal strength as a function of telescope elevation low-pass filtered at 5 kHz
- Display of 49.3724 Mb/s downlink modulation pattern
- Measured downlink BER as a function of satellite elevation angle
- Fade depth, fade frequency, and BER as a function of aperture size
- Uplink beacon strength and communications laser modulation pattern
- Local atmospheric conditions, including wind strength and wind direction
- Uplink BER and the power received at the satellite during the pass (recorded by OICETS)

VIII. Summary

The plans for the 2009 OTOOLE demonstration include horizontal path precursor experiments to validate the projected beam divergence, and ranging experiments to the OICETS retroreflectors satellites to validate the accuracy of the CPF ephemerides. A multibeam beacon and communications uplink design is used to mitigate atmospheric scintillation.

The 49.3724 Mb/s downlink is detected through the 20-cm acquisition telescope using a high-bandwidth silicon APD detector. Preliminary analysis shows robust uplink and downlink margins at elevations above the OCTL telescope tree line. Data products include BER measurements, tests of aperture averaging, and atmospheric effects. Preliminary link analysis shows that there is significant link margin for the designed beacon and communications laser beam divergences even at the low transmitted powers that are eye safe at 200 m from the telescope aperture.

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