The Lunar Laser OCTL Terminal (LLOT) Optical Systems

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ABSTRACT

The Lunar Laser OCTL Terminal is an auxiliary ground station terminal for the Lunar Laser Communication Demonstration (LLCD). The LLOT optical systems exercise modulation and beam divergence control over six 10-W fiber-based laser transmitters at 1568 nm, which act as beacons for pointing of the space-based terminal. The LLOT design transmits these beams from distinct sub-apertures of the F/76 OCTL telescope at divergences ranging from 110 µrad to 40 µrad . LLOT also uses the same telescope aperture to receive the downlink signal at 1550 nm from the spacecraft terminal. Characteristics and control of the beacon lasers, methods of establishing and maintaining beam alignment, beam zoom system design, co-registration of the transmitted beams and the receive field of view, transmit/receive isolation, and downlink signal manipulation and control are discussed.

Keywords: Laser communication, multi-beam beacon, deep-space communication

1. INTRODUCTION

The Lunar Laser Communication Demonstration (LLCD) project is a NASA optical communications experiment designed to demonstrate the viability of optical communications for space systems beyond earth orbit [1]. The project will launch a bi-directional optical communications flight terminal, the Lunar Lasercom Space Terminal (LLST), aboard the LADEE lunar satellite in August, 2013. NASA is developing an auxiliary receive-only ground terminal for the mission by using the Optical Communication Telescope Laboratory (OCTL) near Wrightwood, California, as a secondary receiver called the Lunar Laser OCTL Terminal (LLOT). As such, the system must be designed in a constrained environment, using an existing large focal-ratio telescope to establish and maintain a communication link with an already-designed flight terminal.

During passes in which it is designated to operate, the LLOT ground station will initiate the link with the space terminal by projecting a laser beacon to the expected location of the flight terminal. This beacon must be bright enough to be observed by the scanning flight terminal and wide enough to cover the uncertainty ellipse in the spacecraft location. We have chosen to balance these two competing requirements by implementing a step-stare system, in which the beacon is scheduled to scan the uncertainty ellipse, dwelling at each position long enough for the LLST scan to be certain of detecting the beacon. The acquisition sequence is described in more detail in Ref. [2]. Once the LLST detects the upwelling beacon, it points a widened downlink beam at the point-ahead location of the beacon source. When this return beam is detected at the LLOT ground terminal, a zoom system narrows the transmitted beacon beam from its nominal 110 µrad acquisition beacon to a high-intensity 40 µrad beam. This provides sufficient flux at the LLST that it can narrow its beam as well, allowing for high-rate communication downlink to proceed.

To achieve the high intensities, and continuity of flux required of the beacon at the LLST, six independently controlled lasers are projected together from the OCTL 1-meter primary mirror. The beams form a hexagonal pattern on the primary mirror, each beam separated from its nearest neighbors by approximately 310 mm (Figure 1).

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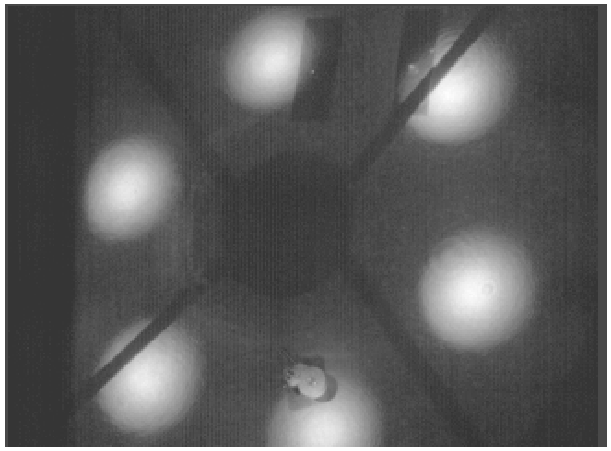

Figure 1 Six transmit beams projected from the telescope primary mirror onto an observation screen. The shadows of the telescope secondary mirror and support spider are also evident.

This paper provides details and specific characteristics of the lasers, the transmit optical system, and the receive optical system. The remainder of the LLOT system, including the telescope and operations concept and receiver system are described in companion papers [2,3].

2. BEACON LASER SYSTEM DESCRIPTION

The requirements for the LLOT laser transmitter are shown in Table 1. The driving requirements are the ability to deliver 60 W average power in a narrow line-width with good beam quality and the ability to support low rate modulation. The latter is needed for background subtraction during spatial acquisition by the flight terminal, since no communication signal will be sent on the uplink, and the former for compatibility with the flight receiver. Multiple laser sources are base-lined for atmospheric scintillation mitigation and to relieve the power requirements of a single transmitter. Given the required laser power of a single source and optical design of the initial combiner and spatial placement of the beams around the telescope primary mirror, a quantity of six lasers was chosen. The wavelength separation of the multiple sources is required to avoid any interference effects at the receiver. A custom fiber-based master oscillator-power amplifier design from Manlight (now 3S Photonics) was able to satisfy these requirements following a prototype development, as shown in Fig. 2. Single mode fiber in the final amplifier stage ensured good output beam quality, while direct modulation of the pump diodes in this last stage proved sufficient for the required extinction ratio (ER) of the low-rate-modulated output from a TTL input signal. A collimator with nominal 0.64 mrad divergence was integrated on the output fiber. A cw DFB laser was used as the seed laser source in the oscillator and could be temperature tuned +/- 0.1 C^o (0.01 nm) to optimize throughput of the receive filter and provide the wavelength separation of the sources nominally set at the specified center wavelength. A tap fiber from the oscillator section allowed monitoring of the seed wavelength for diagnostic testing.

Power measurements were performed with a thermal meter or sampled and detected on a PIN detector for the extinction ratio measurements on an oscilloscope. Coarse wavelength was measured on an optical spectrum analyzer with 0.01 nm resolution, and fine wavelength measurements were performed either using an Optical Channel Power Monitor (OCPM) that interpolated the peak wavelength fit to within 1 pm, or a fiber Fabry-Perot Interferometer with a 10 MHz bandwidth and FSR of 5 GHz.

Table 1. Laser Transmitter Requirements

Requirement	Value	Comment
Average Power, W	10	Link Budget requires 60 W
PRF, kHz	1	
Pulse-width, μs	500	50% duty cycle
Peak Power, W	20	
Center Wavelength, nm	1567.95	+/- 0.1 nm
Wavelength Separation, MHz	> 10	
Line-width, nm	< 0.05	
Polarization	Unpolarized	
Extinction Ratio, dB	13	
Beam Quality	SM	$M^2 < 1.3$

Figure 2. Single fiber-based MOPA laser transmitter with 20 W cw power at 1567.95 nm.

3. LLOT TRANSMIT OPTICS DESCRIPTION

The driving requirements for the LLOT optical system are shown in Table 2 below:

Table 2. Transmit Optics Requirements

Beacon Transmit Driving Requirements
Transmit six 10-W beams at 1567.95 nm
Limit beam losses to 3.5 dB (including 2.5 dB telescope losses)
Beams may not converge beyond the telescope pupil
Implement a zoom system to zoom beams from 40 μrad to 110 μrad
Maintain far-field beam alignment to within 5 μrad
Monitor beam alignment and divergence
Maintain high laser-safety standards
Receive System Driving Requirements
Image a 500 μrad FOV on an acquisition sensor at 2 μrad /pixel
Achieve at least 125 dB of isolation of the 1550 nm signal from the 1568 nm laser beacon
Split the receive signal between 100% to acquisition sensor to 90% to data channel
Acquire a randomly-polarized signal
Couple the downlink signal to a 62 um multimode fiber

The design of the beacon transmit system was undertaken with the objective of assuring that all of the beams overlap at the telescope focus, thus assuring that they overlap in the far field. Each collimated beam is fed into the optical system and aligned by controlling the tip and tilt of the beam collimator mount and a secondary tip-tilt mirror. This allows fine control over both the position from which each beam originates, as well as the angle into which it enters the system.

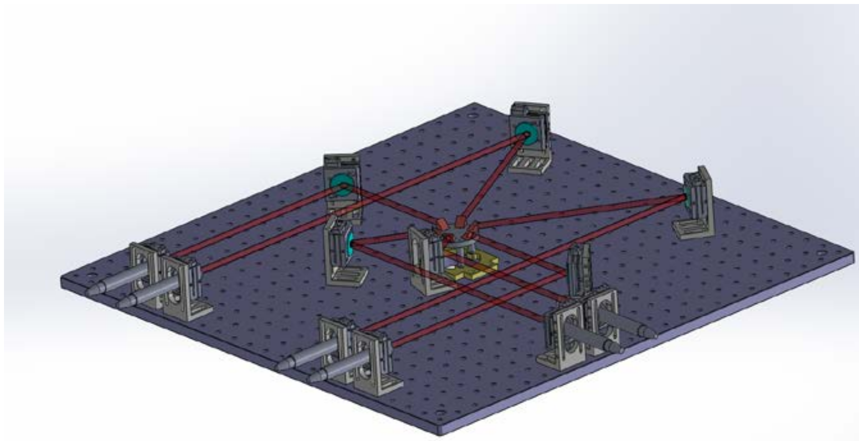

Figure 3 Layout of collimated laser inputs and reflecting mirrors on the 60 cm x 60 cm upper breadboard. The lasers are all directed downward by the set of right-angle prisms mounted in the center of the breadboard.

Initial beam alignment is performed on a small breadboard elevated above the main optical table (Figure 3). This places the individual mounts close to the stable breadboard surface, and allows all of the beams to be directed together down to the main table below. It also provides easier top-access to the mounts in the laser enclosure system, and limits interference with the crossing beams on the table below. The hexagonal pattern of the beams is achieved by sending the beams into an assembly holding six right-angle prisms, similar to an approach verified in previous experiments[4]. This assembly is necessary to place the beams close enough together that they can be propagated through the F/76 telescope system without vignetting or diffracting from mirror edges. To minimize losses in the telescope each beam must be angled at approximately ¼ degree from the telescope's optical axis to make it through the 76 meter telescope focal length. To generate this angle, the six parallel-propagating beams are brought to a common overlap at the telescope focal plane using a long focal length, positive combiner lens. The focal length of the combiner lens, f_c, is related to the telescope effective focal length, f_{tel}, and the spacing of the beams in the aperture d_{ap} and at the combiner lens d_c according to

$$f_c = f_{tel} \frac{d_c}{d_{ap}}.$$

In our case, a combiner lens focal length of slightly less than 5 meters was chosen as a compromise to allow convenient spacing of the co-aligned beams, while simultaneously keeping the required propagation distance from the combiner lens to the telescope focus to a reasonable length.

An additional requirement is that the beams diverge from the telescope exit pupil; converging beams are believed to be more prone to beam wander as they traverse the turbulent lower atmosphere near the telescope, and they present an unnecessary hazard to nearby aircraft. By designing the system such that the beams diverge from the aperture, both of these effects are minimized. This requirement ultimately results in an imposed requirement that a real beam waist must fall somewhere between the telescope focus and the telescope pupil.

Finally, there is a requirement to implement two different beam divergences, nominally at 110 μrad for acquisition, followed by a narrowing to 40 μrad to generate enough irradiance at the spacecraft to allow the LLST to center its narrow beam on the downlink receiver. This can be achieved either by routing the group of beams through two discrete optical systems with motorized fold mirrors that switch between systems, or through the implementation of a zoom system. The zoom system was chosen for its relatively low cost, and its flexibility; the system could be used at a different zoom position to affect a late-stage beam divergence change, and supports continuous operation through the divergence switching process [5].

The zoom system consists of arrays of individual lenses, one for each beam, in effect has its own individual zoom lens set to affect only the beam divergence, but not the beam angle. All beams continue to propagate parallel to one another through the zoom elements. By changing the divergence of each beam as it enters the long-focal-length combiner lens, the longitudinal location of the beam waist is affected, but the beams maintain their overlap at the focus of the combiner lens. As mentioned above, the beam waist must be located within the telescope (*i.e.* past the focus of the combiner lens), so each beam must be diverging as it enters the combiner lens. The location of the beam waist determines the diameter of the beam at the telescope focus, which in turn determines the size of the beam in the far field after projection through the telescope. By driving the beam waist farther up toward the primary mirror of the telescope, the beam diameter at the telescope focus is increased, generating a wide divergence on the sky. Alternatively, by drawing the beam waist down closer to the telescope focus, the beam diameter at the telescope focus is smaller, generating a smaller far-field divergence.

All of the beam control and beam shaping is completed in a light-tight enclosure on one side of the coudé optical table. This enclosure adds another layer of laser safety, maintains the transmit optics in a clean state, and limits the amount of scattered beam light and amplified spontaneous emission (ASE) from the lasers from entering the receive system. The beams exit the enclosure through a narrow-band filter which reduces the ASE in the beams by several orders of magnitude, maintaining the dark environment of the receive system. The converging set of beams finally reflect off of a dichroic filter which inject them into the telescope path, prior to the telescope focus. This dichroic filter is a critical feature of the system, allowing the faint received signal at 1550 nm to be seen in spite of the extremely bright beacon lasers co-propagating at 1568 nm.

4. LLOT RECEIVE OPTICS

The receive optical system uses the full aperture of the 1-meter F/76 OCTL main telescope to collect the data signal from the LLST. The LLST laser signal emerging from the telescope first encounters the dichroic filter described above to fold the beacon beam into the telescope. An identical dichroic filter is placed behind the first to enhance the system's transmit/receive isolation, and also to compensate for the small degree of walk-off generated in the received. The loss of these combined filters has been measured at 0.17 dB at the 1550 nm downlink wavelength. . The image generated at the telescope focal plane is next relayed to the receive channel enclosure by a doublet lens set up to convert the F/76 beam from the telescope to an F/20 image (Figure 4). Because the telescope is commanded to the spacecraft point-ahead location, the signal from the re-imaging lens is directed to a fine steering mirror, which allows for centering the downlink signal on the acquisition detector array.

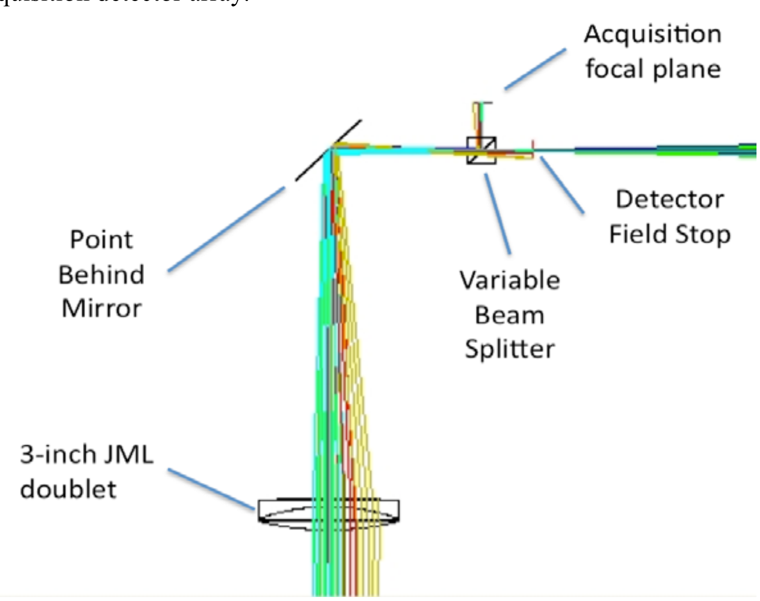

Figure 4 Receive channel layout. The real far-field image generated at the telescope pupil is relayed to the acquisition sensor by a doublet lens. The point-behind angle is introduced by a tip-tilt mirror, which reflects the beam into a variable beam splitter, and on to either the acquisition sensor or to the data receive channel.

Initially, all of the signal is to be directed to an InGaAs acquisition camera, which provides a seeing-limited field of view of 640 x 512 μrad . Once the signal from the LLST is acquired, the beam splitter is commanded to a mostly transparent state in which 10 % of the transmitted light is directed to the acquisition camera to maintain pointing, while 90% of the transmitted light is sent to the data receive channel. A field stop at the image location after the variable beam splitter limits the field of view to reduce background light. From this field stop, the F/20 beam is collimated by an achromatic doublet, and focused onto a fiber-coupled detector with a short focal length aspheric lens.

5. INTEGRATION AND TEST

The system described above has been implemented and tested at the subassembly level.

5.1 Laser System Tests:

Following initial testing of the prototype in the lab, the six devices were installed at the OCTL facility and tested prior to integration with the transmit optical system. The transmitters were characterized at full power including their spectral and temporal response with typical power vs. current and extinction ratio (ER) data shown in Fig. 5. When modulated at 1 kHz 50% duty cycle, average power exceeding 10 W was recorded for each of the six devices with temperature tuning of the seed to match the required center wavelength. The OSNR (optical signal to noise ratio) exceeded 50 dB with greater than 99 % of the energy within +/- 0.1 nm of the center wavelength. Beam scan measurements revealed an M^2 = 1.09 for a typical device, well within the requirement. Beam profile measurements revealed some variation of the output beam divergence of the collimator around the nominal design of 0.64 mrad as well as some power dependence which is thought to arise from collimator fabrication non-uniformities. The ER requirement required operation at near full power to be met, so if reduced power is required for certain link scenarios, the laser beams must be attenuated rather than operating the laser transmitters at lower power.

Preliminary testing of the wavelength drift showed 0.7 GHz over 15 min, the typical pass duration. However, this was without implementation of the fine temperature control in the latter devices so better stability is expected during operation.

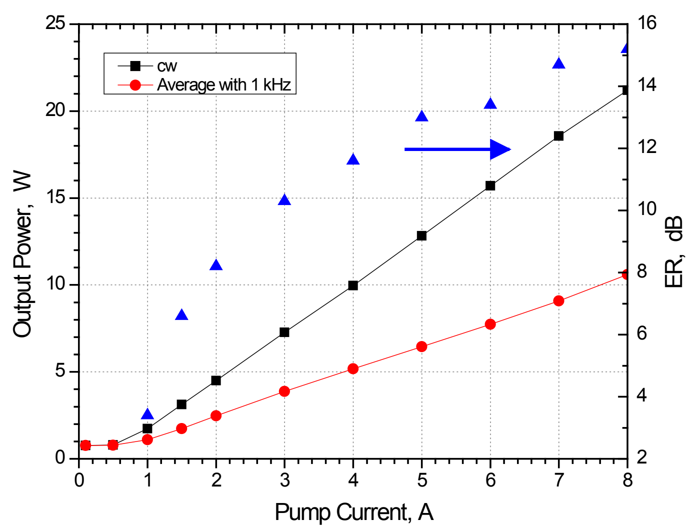

Figure 5 Typical laser performance. CW power and 1 kHz power (left scale) meet requirements. Measured extinction ratio (right scale) exceeds the 13 dB requirement.

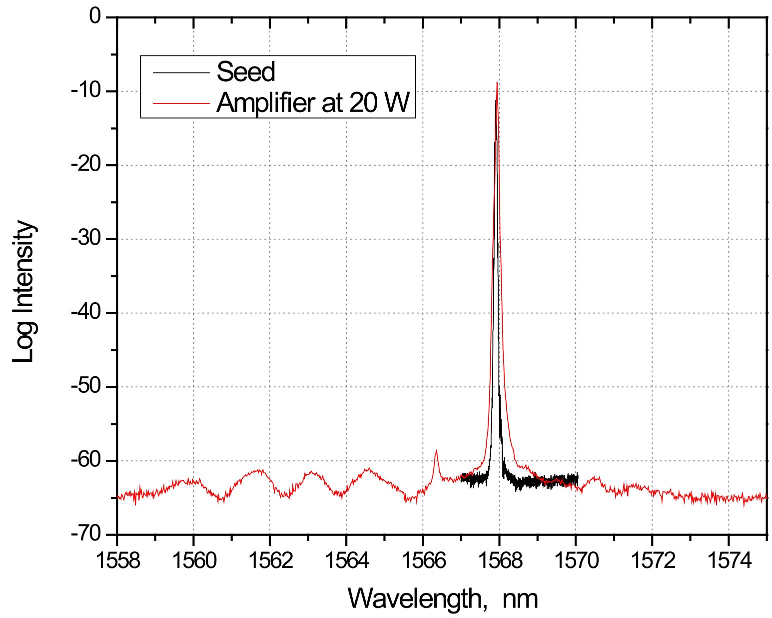

Figure 6. Power and wavelength of typical laser temperature tuned to match required wavelength. Spectrum resolution is instrumented limited to 0.01 nm.

5.2 Transmit Optical System Validation:

As of this writing, only four of the six lasers were available for integration and alignment, but there are no reasons to expect different results for the remaining two beams. The available transmitted beacon beams were aligned to the telescope's optical axis such that they overlap at the telescope focus, as described previously in the design section. Each of these beams was independently measured by scanning a 200 um pinhole across the center of the beam in the horizontal dimension with the beams at low power. The data, and Gaussian fits to the data, are shown in Figure 7 below.

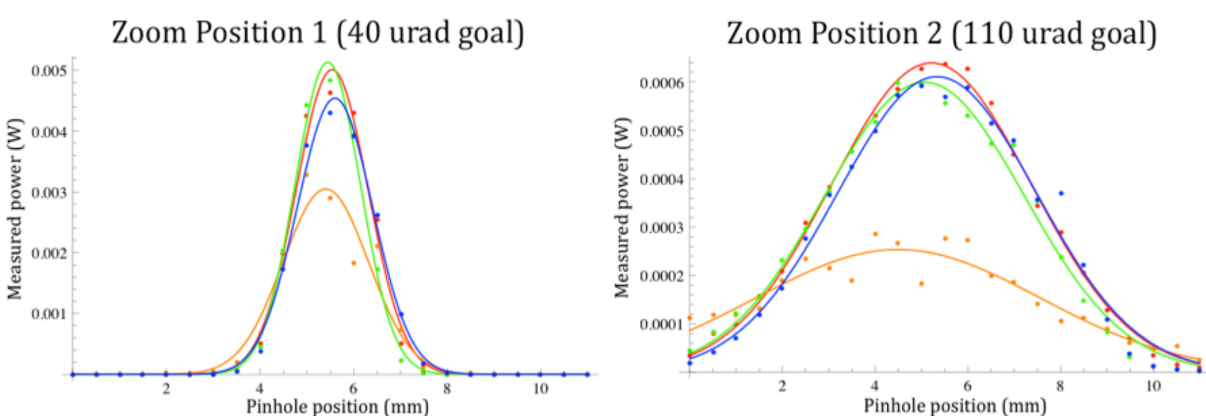

Figure 7 Scans of individual beams at the telescope focus. The data confirm that, except for beam 2, the system has very good alignment, good beam quality, and intended divergence.

Note that three of the four beams conform closely to one another, while beam number 2 departs significantly. The cause of this is still under investigation. Analysis of the Gaussian fits to each independent data set are shown in Table 3

Table 3. Preliminary beam performance for 4 of the 6 beacon beams.

Measurement	Mean (all beams)
Beam width (40 µrad goal)	42.1 µrad
Beam width (110 µrad goal)	125.7 µrad
Maximum misalignment at 40 µrad	1.3 µrad
Alignment wander through zoom	6.2 µrad

The requirements are very nearly met, in spite of the problems with beam 2. Excepting this beam results in all requirements being met. Once the departure in performance of beam 2 is understood, and the performance of the remaining two beams is established, the project will decide whether to accept the performance of the system as it stands, or whether additional effort to recover the performance of beam 2 is warranted.

The loss allocations in the transmit optical train were limited to a total of 0.8 dB (about 17%). Preliminary power measurements indicate the losses are currently about 0.9 dB (about 19%). It appears that the largest share of losses (about 0.5 dB) are occurring in the six dielectric beam-folding mirrors within the laser enclosure, required because of the large f.l. Again, the decision to accept the system as it currently stands or to try to improve performance will be made once all measurements are complete.

5.3 LLOT Receive Channel

Aligning the receive acquisition channel is performed by placing an iris aperture at the telescope focus as a target for the imaging system. The coudé laboratory is outfitted with LED lighting which allows alignment of the optical system and the InGaAs camera in illuminated conditions, since the visible LEDs do not emit in the sensitive band of the camera. The alignment aperture is illuminated directly with an incandescent lamp to achieve proper centration and focus in the final alignment.

Alignment of the data channel is performed by locating a 100 um pinhole at the telescope focus, back-illuminated by an incandescent lamp. The variable beam splitter is placed in transmission mode, and the focusing F/20 beam coming from the output of the data-channel side of the beam splitter is observed. A pinhole aperture is placed at the focus of this F/20 beam, and centered in all three linear dimensions with the aid of a detector placed behind the pinhole. It is anticipated that a variety of pinhole sizes may be used to optimize the signal-to-noise ratio. During daylight operations, smaller pinholes (e.g. 500 um for 25 µrad FOV) will be selected to limit the background, while during poor-seeing but low background conditions, larger pinholes will be used to assure capture of as much signal light as possible.

Light from this field stop is then collimated by an achromatic lens, and the collimated beam is then focused with an F/1 asphere into a 62.5 um low-dispersion multi-mode fiber. This fiber is imaged onto a WSi photon-counting detector in a cryogenic dewar.
To minimize stray light, whether from the laser beacon system or other sources, the receive optics are located in a light box similar to the laser beam-forming system. The reimaging lens is located at the optical entrance to this box, and is baffled to limit light from outside the system's field of view.
The optical throughput losses to the data collecting fiber are limited to 2.5 dB (about 44%). The final data channel's re-imaging system is limited by the Lagrange invariant, so the optics were chose to match the NA of the fiber for an on-axis point source, accepting the limited field of view and off-axis vignetting that imposes.

6. SUMMARY

The LLOT lasers have been manufactured and tested, and meet the requirements for the LLOT-LLCD experiment. The LLOT optical system incorporates many desirable features including a multi-beam system, a zoom system capable of 40-110 µrad divergences, high rejection efficiency of the emitted beacon, a variable split ratio between the acquisition camera and the data detector, and the ability to accommodate multiple detector systems. The most challenging aspects of the optical transmit assembly, maintenance of the beam alignment through zoom and beam uniformity through zoom, are in preliminary testing and appear to be largely met. Slight departures of the mean divergence and alignment are completely attributable to the poor performance of a single beam at present. Additional work is continuing to understand the performance of this errant beam, and determine the methods to be used to bring it into compliance if necessary. The receive channel design is diffraction-limited, and preliminary measurements confirm that it will meet the throughput and alignment requirements. At this point we anticipate that the laser and optical systems will be capable of supporting the LLOT-LLCD demonstration as designed.

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ACKNOWLEDGEMENTS

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