Development of the Optical Communications Telescope Laboratory: A Laser Communications Relay Demonstration Ground Station

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Abstract—**The Laser Communications Relay Demonstration (LCRD) project will demonstrate high bandwidth space to ground bi-directional optical communications links between a geosynchronous satellite and two LCRD optical ground stations located in the southwestern United States. The project plans to operate for two years with a possible extension to five. Objectives of the demonstration include the development of operational strategies to prototype optical link and relay services for the next generation tracking and data relay satellites. Key technologies to be demonstrated include adaptive optics to correct for clear air turbulence-induced wave front aberrations on the downlink, and advanced networking concepts for assured and automated data delivery. Expanded link availability will be demonstrated by supporting operations at small sun-Earth-probe angles. Planned optical modulation formats support future concepts of near-Earth satellite user services to a maximum of 1.244 Gb/s differential phase shift keying modulation and pulse position modulations formats for deep space links at data rates up to 311 Mb/s. Atmospheric monitoring instruments that will characterize the optical channel during the link include a sun photometer to measure atmospheric transmittance, a solar scintillometer, and a cloud camera to measure the line of sight cloud cover. This paper describes the planned development of the JPL optical ground station.**

I. Introduction

Coherent differential phase shift keying (DPSK) affords robust operation under high sky background noise conditions of low sun-Earth-probe (SEP) angles. NASA plans to demonstrate a high bandwidth DPSK and pulse position modulation (PPM) link from Geostationary Earth Orbit (GEO) as a precursor to the development of a future Advanced Telecommunications and Data Relay Satellite Service (ATDRSS) [1]. DPSK link supports near-Earth links, while the energy-efficient PPM is accepted as the appropriate format for deep space optical communications [2].

The Laser Communications Relay Demonstration (LCRD) project is led by Goddard Space Flight Center (GSFC) with the participation of Massachusetts Institute of Technology–Lincoln Laboratories (MITLL), Jet Propulsion Laboratory (JPL), and Loral Space Systems. Current plans call for a December 2017 launch on a Loral Space Systems GEO satellite to be located between 62° W and 162° W longitude; on orbit locations that correspond to minimum elevation angles of 20° from the ground stations GS-1, the JPL Optical Communications Telescope Laboratory (OCTL) ground station at Table Mountain, California (Fig. 1), and GS-2, the modified Lunar Laser Communications Ground Terminal (LLGT) at White Sands, New Mexico.

The optical terminal in space has similarities to the Lunar Laser Communications Demonstration (LLCD) terminal that will be flown on the Lunar Atmosphere and Dust Environment Explorer (LADEE) satellite [3]. The LCRD space terminal will transmit 0.5-W average power at 1550 nm from a 10-cm aperture. The order of magnitude difference in range between the LLCD and LCRD links affords two orders of magnitude increase in the signal intensity at the ground terminal. At these higher intensities the PPM and DPSK signals are readily detected by avalanche photodiode detectors, instead of the single photon detector arrays that will be used to detect the weak downlink signals from the Moon.

An integrated optical system (IOS) at the back end of the OCTL telescope will use adaptive optics (AO) techniques to correct the wave front distortions on the link. On the downlink, AO will allow efficient coupling of the aperture-averaged signal into the single mode fiber modem. The uplink will consist of separate beacon and communications lasers. The PPM and coherent DPSK communications beams emanate from a integrated modem with a single fiber output. Beams of both modulation formats will be transmitted as single beams using error correction and interleaving to mitigate the effect of fades. Because the 18-µrad point-ahead angle to the geostationary satellite exceeds the isoplanatic angle, it precludes full pre-correction of the uplink beam from the aberration measured on the downlink beam. The measured

Figure 1. OCTL, Table Mountain, California.

aberration will be used to partially mitigate tip/tilt beam wander effects on the uplink.

Requirements from LCRD customers and stakeholders are reflected in the project's mission requirements document. These are flowed down to the ground and space segments requirements and inform the development of the ground stations' requirements. The ground stations systems engineer flows down these requirements to the ground stations; subsystem leads use the requirements from the systems engineer to develop requirements, implementation plans and schedules that meet the project's milestones.

Remote operations of ground and space assets, the use of Delay/Disruption-Tolerant Network (DTN) over high speed optical links and the simultaneous characterization of the optical channel during operations are key objectives of the LCRD project that differentiate it from previous laser communications demonstrations.

The GSFC Integrated Test and Operating System (ITOS) will be used to command and control the space and ground network nodes [4]. Remote operation of the ground stations through the ITOS connection to the LCRD Missions Operation Center (LMOC) will be explored with a view towards future ATDRSS operations.

Forward error correction and interleaving are key strategies to mitigate the effects of scintillation-induced fades in the bursty optical communications channel. Although demonstrated on low bandwidth links in space, demonstration on a high bandwidth optical link has only been performed in the laboratory environment [5]. Moreover, LCRD will demonstrate DTN custody transfer service that can ensure the integrity of file delivery over the optical carrier even in the presence of intermittent outages, such as caused by partial cloud cover.

Atmospheric instruments deployed at the ground station will characterize the optical channel performance during operations and will measure:

- Ground level scintillation
- Line of sight atmospheric coherence length, r_0
- Atmospheric transmittance
- Sky background
- Cloud cover
- Ground station relative humidity
- Wind direction and wind speed
- Local ambient temperature

In this paper, we describe the development of the GS-1 at the OCTL to support the two-year long LCRD demonstration. In section 2 we describe the key ground station requirements derived from the ground segment requirements. In section 3 we present the link budget analysis for the DPSK and PPM links for GS-1. We describe the atmospheric measurement instruments and their operation in section 4, the IOS in section 5, and the user gateway and DTN protocol in section 6. The technical discussion closes with a discussion of LASSO (Laser Safety System at OCTL) in section 7. Conclusions, Acknowledgements, and References are presented in sections 8, 9, and 10, respectively.

II. LCRD Ground Station Requirements

The two LCRD ground stations will simulate a subset of the operations of a future ATDRSS relay. The ground stations will have optical loop-back support capability with simultaneous uplink and downlink channels both in real-time and in store-and-forward data streams within each channel. Currently, there are no dedicated users (e.g., a science instrument in LEO or its Mission Operations Center on the ground) for LCRD. To simulate a service network, the project will develop and deploy user simulators that will inject data streams into the optical network, emulating a variety of users with data rates stressing system capacity.

The optical links will be capable of operating day or night for the duration of the mission interrupted only by inclement weather (rain, snow, high winds, high humidity), cloud cover, or aircraft and spacecraft at risk of intercepting the beam. One goal of the demonstration is to operate 24/7 to evaluate the constraints that would preclude continuous operation of a future operational ATDRSS network. Levied requirements are for operations from the OCTL ground station to support the links at sun-Earth-spacecraft angles down to 5°; a 0.5% impact on the link availability, at elevation angles as low as 20° that correspond to atmospheric coherence lengths r_0 ~3.3 cm (measured at zenith) and at a wavelength of 500 nm.

Requirements call for three key strategies to be implemented to mitigate the impact of turbulence-induced fades and outages on the optical links. These are (i) DVB-S2 (Digital Video Broadcasting-Satellite-Second Generation) coding, (ii) DTN, and (iii) interleaving. The optimum interleaver parameters for the data rates and expected fading channel performance are currently under study.

The GSFC LMOC provides the central planning and operations functions. The OCTL ground station will receive schedules and parameters of upcoming events and will configure the subsystems to perform one or several of the following functions:

- Satellite acquisition
- Uplink beacon transmission
- Downlink reception
- Closing adaptive optics loop around received data
- Uplink communications
- Execute real-time data transfer and/or store-and-forward
- Report status and/quick-look data to LMOC
- Archive data for return to LMOC

To identify possible impediments to ATDRSS operations, the reliability of the system's components will be analyzed to assess the impacts of planned and unplanned maintenance. To that end, the ground station will participate in around-the-clock tests lasting for several days to characterize the system under a variety of atmospheric conditions.

III. LINK ANALYSIS

The LCRD project has considered various types of communications links between the two planned ground optical stations and the two flight optical terminals located on a geostationary satellite. The error correction codes considered for the DPSK and PPM modulation formats are the Low Density Parity Check (LDPC) codes adopted by the commercial DVB-S2 digital television broadcast standard [6] and the Serially Concatenated PPM (SCPPM) codes invented at JPL [7].

Key factors that affect the uplink communications beam, and hence the uplink budget, are the beam-width of the uplink optical beam, the pointing error of the uplink telescope, air turbulence and refractive index variations along the path that cause beam scintillation and beam spreading, and atmospheric attenuation. At the space terminal, the key factors that affect the link margin are receiver pointing error, Earthshine, sky background and implementation losses.

Like the uplink, the downlink is affected by pointing errors at the space terminal, the atmosphere (attenuation and turbulence), and sky background. Yet, unlike on the uplink, adaptive optics systems can be implemented at the ground receiver to mitigate turbulence effects. Also, the receive aperture size can be appropriately scaled to mitigate losses and scintillation effects. We have analyzed the performance for the DPSK and PPM links. A model of the DPSK receiver is shown in Fig. 2.

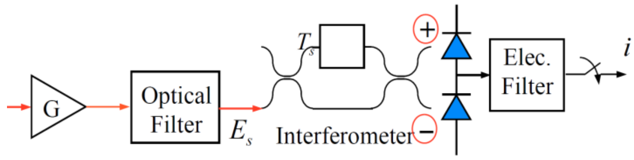

Figure 2. Model of a DPSK receiver.

To maximize operational opportunities under a variety of atmospheric conditions, we analyzed the link performance for several operational scenarios. Our baseline was a 7 W peak power uplink in a 20-μrad $1/e^2$ beam divergence at the output of the OCTL telescope. The most stressing link from this analysis proved to be the so-called edge-to-edge coded DPSK relay link at maximum rate (1.244 Gb/s) from the 1 m OCTL to a single 40 cm aperture of the LLGT station, where no decoding/re-encoding is done on the satellite: the symbols are hard-detected by the receiving flight terminal and re-modulated on the downlink beam. The symbols are soft-decoded at the ground receiver. The analysis of this link yielded simultaneous, independent margins of 6 dB on the uplink and 4 dB on the downlink. In the edge-to-edge coded 1.244 Gb/s loop back operations mode, the 1-m telescope afforded in excess of 6 dB of link margin in both directions. Link margins of the order of 10 dB resulted from the analysis of the PPM link.

IV. ATMOSPHERIC MEASUREMENTS

A LCRD requirement is to improve our understanding of the impact of atmospheric channel on the optical link. background conditions on the optical link. Atmospheric turbulence effects,, sky background, and attenuation all increase with zenith angle. If not adequately considered in the design of the interleavers and forward error correction codes, these effects will limit the data rate achievable [8]. The requirement to operate at maximum data rate at 20° elevation is therefore a major driver in the ground receiver and transmitter designs.

Atmospheric channel measurements from the sensors illustrated in Fig. 3 are collected in real time and time tagged. The monitor and control (M&C) system periodically collects these and other data from other ground subsystems and returns them to the LMOC where they are archived for later analysis.

Two radiometrically calibrated cloud cameras sensitive in the thermal infrared spectrum will measure and record cloud cover. A cloud camera with a wide field-of-view (FOV) of approximately 110° camera will monitor the cloud distribution around the ground station, while a narrow FOV camera of approximately 5° will be co-aligned with the telescope to measure the radiance and temperature of the sky along the beam path.

These cloud camera systems are based on bolometer sensor arrays that have been successfully deployed by NASA/JPL at Table Mountain and Goldstone [9]. The weatherproof cameras operate autonomously generating pixelated images of the sky at 5-minute intervals. Data from the local weather station will be used to convert the sky temperature information to cloud optical depth.

A sun photometer measures the sun irradiance and sky background over a broad spectrum. From measurements of the sun irradiance over different wavelengths from the UV to near IR spectral band can be identified the concentration of aerosol and the related atmospheric loss due molecular and aerosol absorption and/or scattering [10].

Results of sun-photometer measurements made at Table Mountain between 2006 and 2011 are given in Fig 4. The figure shows the variation in daytime atmospheric loss spectral on cloud free days. The points represent the 90%, 50%, and 10% statistics of the cumulative distribution function of the data at the measured wavelengths and show good agreement with that simulated using a radiative transfer program MODTRAN. These measurements indicate that OCTL ground station at Table Mountain should expect zenith atmospheric losses of 0.25 dB or less approximately 90% of the time over the planned the two years of operation.

The atmospheric coherence length, r_0, is a figure of merit that characterizes atmospheric turbulence. It is generally

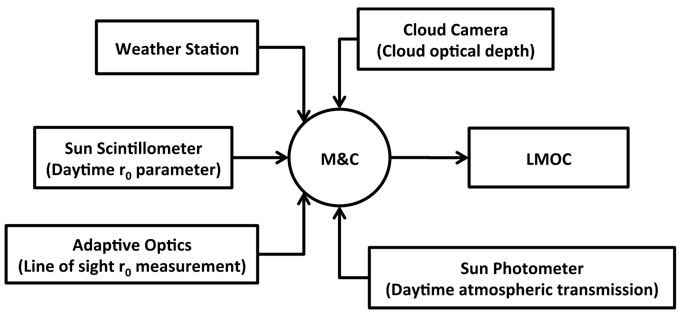

Figure 3. Block diagram of atmospheric data collection by the M&C system with return to LMOC.

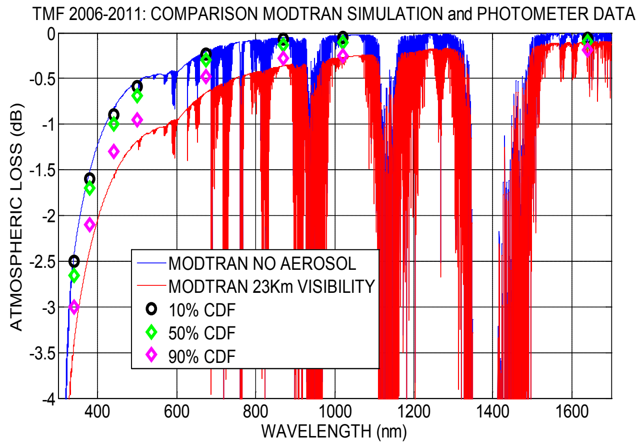

Figure 4. Statistical representation of the atmospheric loss at Table Mountain, California.

measured using differential image motion measuring of star images. Because LCRD also operates in the daytime, r_0 measurements will be made with the sun scintillometer [11]. The downlink signal, specifically information gleaned from the AO system, can provide a direct measurement of r_0 during both daytime and nighttime operations [12]. Daytime measurements will be calibrated against the sun scintillometer measurements.

The measure of turbulence along the optical path, r_0, is heavily weighted by the effect of the ground layer turbulence [13]. A ground scintillometer will be deployed at the ground station to characterize the boundary layer turbulence at the site over the duration of the project.

V. INTEGRATED OPTICAL SYSTEM

The IOS consists of (i) the AO system, which compensates for atmospheric turbulence, (ii) the transmitter optics, which relay the beam from the uplink lasers to the telescope and (iii) the receiver optics, which couple the downlink beam into the single mode fiber in the modem. The IOS AO system development will be based on Palomar Observatory's Palm 3000 AO system developed for the 5-m Hale telescope [14].

Required to function under high turbulence conditions (3.3-cm r_0 at 500 nm) the IOS AO system will use the woofer/tweeter approach with two deformable mirror (DM); one to correct the high amplitude, low spatial frequency aberrations, and another to correct the low amplitude, high spatial frequency aberrations. Reusing a modified version of the Palm 3000 software architecture will provide both a cost and risk reduction to the LCRD project [15].

The system will use a Xenics Cheetah InGaAs camera as the wavefront sensor and Boston Micromachine micro-electromechanical systems DMs [16]. These DMs have diameters of less than 1 cm, which reduces the size and cost of the rest of the optical train. The full opto-mechanical layout of IOS is shown in Fig. 5.

The IOS will be located on an optical bench in the telescope's coudé path. The system as architected produces a Strehl ratio of 73% under the required operating conditions. This corresponds to an expected 57% coupling efficiency into the receiver modem's single mode fiber (Table I).

Until the LCRD host spacecraft is selected, we will not know its elevation. The maximum possible elevation of the GEO is 54°, and that is if the spacecraft is at the same longitude as OCTL. Fig. 6 is a plot of the coupling efficiency as a function of r_0, for possible satellite elevation angles. As Fig. 6 shows, the larger the value of r_0 and the higher the elevation angle, the better the coupling efficiency.

TABLE I. THE KEY PARAMETERS OF THE ADAPTIVE OPTICS SYSTEM.

Parameter	Value
r_0	3.3cm
Wavefront sensor frame rate	17 kHz
Actuators across pupil	28
Expected coupling efficiency	57%

VI. USER SERVICES GATEWAY

The User Service Gateway (USG) provides a number of essential functions within the LCRD system. These will be described in terms of its several interfaces and perspectives: (i) as the access interface for LCRD users employing different services, (ii) to convert data for optical link transmission/ reception, (iii) interacting as a protocol peer entity with the flight segment, (iv) coordinating with the M&C system, and (v)

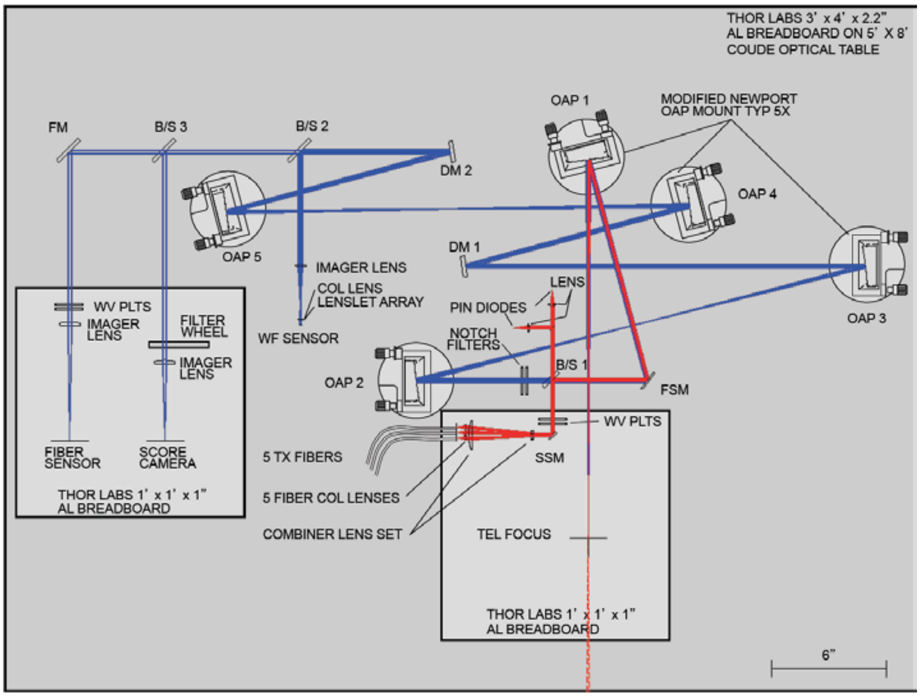

Figure 5. Opto-mechanical layout for the integrated optical system. The blue beam is the downlink beam and the red beam is the uplink beam. The various off-axis parabola (OAP) mirrors form pupils at the appropriate places, the deformable mirrors (DM) move at high speed to compensate for distortions in the wavefront. The fast steering mirror (FSM) compensates for jitter in the beam.

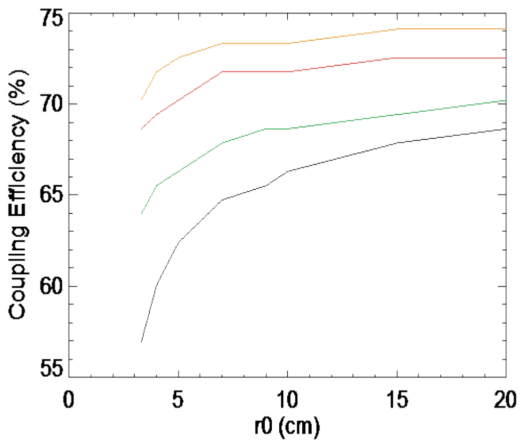

Figure 6. Predicted performance of the IOS AO system as a function of r_0. The black curve is for an elevation of 20°; the green curve is for an elevation of 30°, the red curve is for an elevation of 40°, and the orange curve is for an elevation of 50°.

as a node in the larger end-to-end LCRD network.

Users will access relay services through the USG. Several service types are planned: user-formatted data streams for direct transfer on the optical communications subsystem, CCSDS Encapsulation (ENCAP) [17] packet services, and DTN services. ENCAP packets are general variable-length data units that may contain Internet Protocol (IP) packets or other data constructs. DTN service is provided using the Bundle Protocol [18], including selection of optional custody transfer service for increased reliability. Unlike the other services, DTN enables automatic store-and-forwarding of data through a multi-hop relay even if the links are intermittent. The USG will impose ingress rate control for all services. In the case of DTN, the user and USG will interact as nodes in a DTN network, including custodial signaling and exchange of bundle status reports. The USG will also provide access/retrieval services to user data that is stored locally.

The USG will prepare user-provided data for optical transmission. DTN bundles will optionally be processed for automatic retransmission error control, and will be encapsulated into ENCAP packets. ENCAP traffic will be multiplexed. These variable-length data units will be segmented into fixed-length frames, and passed to the communications subsystem. Reverse processing will occur in the return (receive) direction.

In the case of DTN operation, the USG operates as a higher protocol layer entity. Thus the USG interacts directly with the flight payload, which also acts as a DTN node. Custody transfer signaling will occur between the USG and the flight terminal DTN node to enable optional custodial reliability in transfer, with retransmission of bundles as needed. “Custody” is a strong form of acknowledgement, in which custodians place the data in persistent memory. A more link-efficient form of Automatic Repeat Query without this “custody” stringency is the DTN Licklider Transmission Protocol (LTP) [19], which will also be selectable. In this case, the LTP control loop will be established and operated between the USG and the flight terminal.

The LCRD ground station M&C system will control the USG processes based on link schedules/rates and user traffic contracts. This will enable the USG to properly operate its interfaces with ground users and the communications subsystem. In addition, the USG will provide status messaging to the M&C system to enable monitoring and trending of its resources.

Finally, it is important to view the USG in the context of the larger end-to-end LCRD relay network. A common scenario will be: user LEO spacecraft to LCRD flight terminal to LCRD ground terminal to user MOC. With DTN operations, each of these four elements will be a DTN node in a multi-hop network, with the flight terminal providing space-based relay and the USG providing ground-based relay. LCRD will be critically enabling in proving fully automated end-to-end multi-hop relay networking, and the USG will be essential in this advancement.

VII. Safety System

The Federal Aviation Administration (FAA) and the U.S. Strategic Command’s Laser Clearing House (LCH) are agencies that regulate laser beam propagation through navigable air and near-Earth space, respectively. The FAA Advisory Circular AC 70.1 addresses beam propagation from sea level to 18.3 km (60,000 ft.), and describes the rationale and process for informing the agency of planned laser operations and the method for calculating the laser intensities in the various aircraft flight zones [20]. In response to submittals, the FAA provides the laser operator a Letter of Determination in which the agency specifies its objection or non-objection to the proposed laser beam propagation in the national airspace.

The LCH process for approving laser beam propagation is an active and iterative one. The proposed operator submits to the agency a form that specifies the location of details the laser, the planned operations, and beam propagation characteristics and control systems. If a determination is made that the laser beam transmission needs to be regulated, the LCH follows up with a site visit to confirm the site’s operational capabilities. To ensure safe beam propagation of laser beam transmissions that require regulation, the operator submits the dates, times, and targets for the transmission. The LCH responds with predictive avoidances (PA) that specify approved transmission intervals during the operations.

To support remote and unattended laser beam transmission to future near-Earth deep space satellites using optical communications, JPL has developed LASSO (Laser Safety System at OCTL), a three-tier safety system to ensure safe laser beam propagation through navigable air and near-Earth space [21] (Fig. 7). The first two tiers are designed to avoid illuminating aircraft. Long-wave infrared for detection up to 3.4-km and radar for detection out to 54-km sensors automatically trigger interrupt laser transmission should an aircraft approach the laser beam [22]. Tier-3 is the LCH-provided PA that ensures safe transmission through near-Earth space.

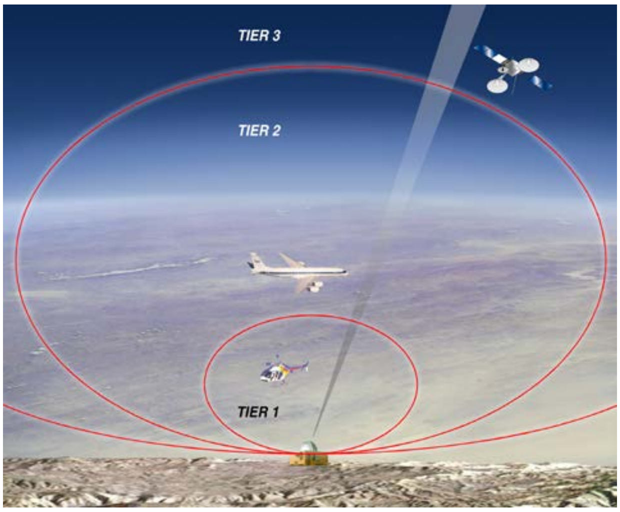

Figure 7. Three-tier laser safety system.

VIII. CONCLUSION

We have described key technology developments planned for the OCTL as a ground station to support a 2-year-long LCRD optical link. Atmospheric monitoring instruments, an IOS system that included an adaptive optics system to support near-IR operation, and an advanced M&C system are among the key technologies to be developed to characterize the performance of the optical channel and support its demonstration.

With an eye towards future ATDRSS operations, LCRD will explore network strategies that could support assured data delivery on high bandwidth space-to-ground optical return links, and strategies for remote and unattended operations. The project is currently in pre-Phase A and we are continuing to refine our requirements, subsystem designs and operations concepts in preparation for our mission concept and system requirement reviews.

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