Proc. International Conference on Space Optical Systems and Applications (ICSOS) 2012, 1-1, Ajaccio, Corsica, France, October 9-12 (2012)

The Laser Communications Relay Demonstration

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Abstract - This paper provides an overview of NASA's Laser Communications Relay Demonstration Project (LCRD). LCRD will fly two optical communications terminals on a Loral commercial communications satellite in GEO orbit to communicate with two ground stations. It is a joint project between NASA's Goddard Space Flight Center (GSFC), the Jet Propulsion Laboratory, California Institute of Technology (JPL), and the Massachusetts Institute of Technology Lincoln Laboratory (MIT LL). LCRD will operate for a minimum of two years in GEO, demonstrating how optical communications can meet NASA's growing need for higher data rates and be a path finder for providing optical services on NASA's Next Generation Tracking and Data Relay Satellite. In addition, the optical communications capability of LCRD will allow it to serve as a developmental testbed. This paper reviews the mission concept and preliminary designs for the flight and ground optical segments, and reports preliminary conclusions from several trade studies conducted.

I. Introduction

The communications link between a spacecraft and Earth is typically a critical mission systems driver. The information from a scientific or exploration discovery has to get back to Earth and typically, the more data that can be sent, the better. This is particularly true of science missions in that more data increases the probability that the mission will produce more valuable science. Several technologies such as higher data bandwidth RF communications and lossless data compression have improved the capability over time, but are failing to keep pace with the needs of advanced instrumentation that can be flown in space today.

Optical communications (or laser communication or "lasercom") is the next step in communications technology that will enable NASA to undertake more complex missions in the future that, when compared to typical RF systems, require much higher data rates or decreased mass, size, and power burden on the spacecraft:

- For approximately the same mass, power, and volume, an optical communications system will provide significantly higher data rates than a comparable radio frequency system.
- For the same data rate (e.g. 1 Gbps of output), an optical communications system will require less mass, power, and volume than a comparable radio frequency system.

The near-term demand for high-bandwidth communications services is driven by NASA's Science Mission Directorate, which wishes to deploy more capable instruments onboard spacecraft. Near Earth, including lunar, spacecraft will need bi-directional links supporting hundreds of Mbps to Gbps. Deep Space missions will need tens to hundreds of Mbits/second from distances such as Mars and Jupiter. An image from the Mars Reconnaissance Orbiter currently takes 1.5 hours to transmit back to Earth at the MRO maximum data rate of 6 Mbps. This bottleneck is the limitation on the science return. The Lunar Reconnaissance Orbiter has been able to transmit more data than all planetary missions combined with a downlink of 100 Mbps. Order of magnitude or more increases of data rate over these current mission capabilities is possible using optical communications.

Due to the vastly differing ranges and data rates for Near Earth versus Deep Space missions, some of the optical communications technologies applicable to each domain differ in profound ways; however, there are also many technologies which are similar to both! Coordination of system development for these two domains maximizes NASA's return on investment. The LCRD flight payload will demonstrate technologies relevant to both Near-Earth and deep space optical communications systems, including photon counting detectors, modulations, codes, pointing and tracking techniques, adaptive optics, etc. LCRD will also demonstrate network-based relay operations in Near Earth, but will simulate a Deep Space scenario as well.

Optical communications technology has recently demonstrated the ability to achieve bi-directional Near Earth data links at 10 Gbps and beyond utilizing Differential Phase Shift Keying Modulation (DPSK). Similarly, deep space links with downlinks up to 1 Gbps and uplinks up to 100 Mbps can be achieved using Photon Counting and Pulse Position Monitoring (PPM) modulation techniques. Photon counting PPM is highly photon efficient but the ultimate data rate is limited due to detector limitations and the requirement for faster electronics. The LCRD mission will provide a space based technology demonstration of optical communications, using both DPSK and PPM modulated signals.

II. Leveraging NASA's Lunar Laser Communication Demonstration

NASA is currently developing the Lunar Laser Communication Demonstration (LLCD) [1] which is scheduled to launch in August 2013 as a secondary payload on the Lunar Atmosphere and Dust Environment Explorer (LADEE). LLCD will demonstrate:

- Photon Counting Pulse Position Modulation
- Inertial stabilization
- Integrating an optical communications terminal to a spacecraft
- Link operations from lunar orbit
- Scalable array ground receiver

LLCD will prove the feasibility of optical communications, but due to the very limited operating time (potentially less than 16 hours over the life of the mission), it will not provide the necessary operational knowledge to allow optical communications to support mission critical communications on future missions. To make optical communications useful to future projects, long mission life space terminals must be developed and proven. Operational concepts for reliable, high-rate data delivery in the face of terrestrial weather variations and real NASA mission constraints needs to be developed and demonstrated. To increase the availability of an optical communications link and to handle cloud covering a ground terminal, there needs to be a demonstration of handovers among multiple ground sites. For Near Earth applications that forsee using a GEO relay satellite (like today's Tracking and Data Relay Satellite), a demonstration needs to show both real-time and store and forward relaying of an optical communications signal in space.

NASA's new LCRD optical communications project will answer the remaining questions for Near Earth applications. LCRD's flight payload will have two optical communications terminals in space and two optical communications ground stations on Earth to allow the mission to demonstrate:

- High rate bi-directional communications between Earth and Geostationary Earth Orbit (GEO)
- Real-time optical relay from Ground Station 1 on Earth through the GEO spacecraft to Ground Station 2 on Earth
- Pulse Position Modulations suitable for deep space communications or other power limited users, such as small Near Earth missions
- Differential Phase Shift Keying Modulations suitable for Near Earth high data rate communications
- Demonstration of various mission scenarios through spacecraft simulations at the Earth ground station
- Performance testing and demonstrations of coding, link layer, and network layer protocols over optical links over an orbiting testbed.

The LCRD Project Office and NASA HQ are also investigating the possibility of flying an optical communications terminal on a Low Earth Orbit (LEO) spacecraft, such as the International Space Station, or Highly Elliptical Orbit (HEO) spacecraft to demonstrate with LCRD. Thus the flight payload on the GEO spacecraft has a requirement to be able to support high rate bi-directional communications between LEO and GEO as well as between Earth and GEO.

III. The Flight Payload

The LCRD flight payload consists of two individual optical communications terminals and a High Speed Electronics unit to interface to the two terminals and to the spacecraft host. The flight payload will be flown on a GEO spacecraft and the major subsystems are:

- Two optical communications modules (heads)
- Two optical module controllers
- Two modems capable of supporting both Differential Phase Shift Keying (DPSK) and Pulse Position Modulation (PPM)
- High Speed Electronics to interconnect the two optical modules, perform network and data processing, and to interface to the host

spacecraft

Each individual optical communications terminal consists of an optical module, a modem, and an optical module controller.

IV. The Flight Optical Communications Module

Each of the two optical communications terminals to be flown on the GEO spacecraft will transmit and receive optical signals. When transmitting, the primary functions of the GEO optical communications terminal are to efficiently generate optical power that can have data modulated onto it; encode, format, and interleave incoming electronic data; modulate the optical beam with this data; amplify and transmit this optical power through efficient optics; and aim the very narrow beam at the ground station on earth, despite platform vibrations, motions, and distortions. When receiving, the GEO optical communications terminal must provide a collector large enough to capture adequate power to support the data rate; couple this light onto low noise, efficient detectors while minimizing the coupled background light; and perform synchronization, demodulation, deinterleaving, and decoding of the received waveform.

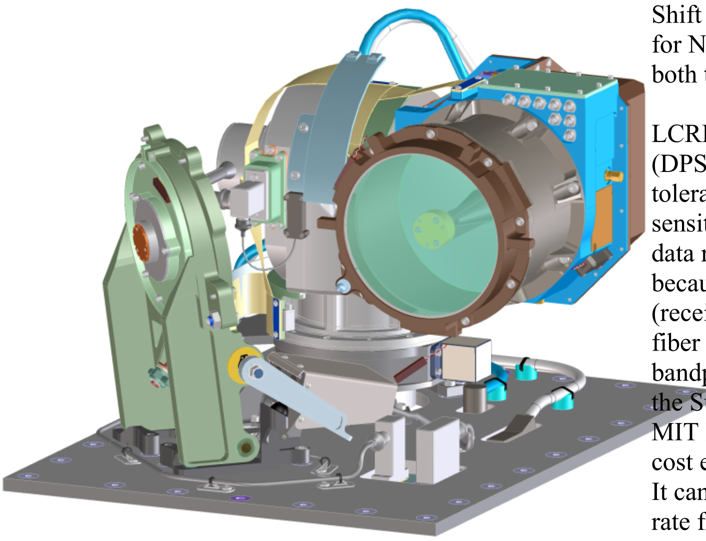

Figure 1- Inertially Stablized Optical Module

Each optical module, shown in Figure 1, is a 4-inch reflective telescope that produces a ~15 microradian downlink beam. It also houses a spatial acquisition detector which is a simple quadrant detector, with a field of view of approximately 2 milliradians. It is used both for detection of a scanned uplink signal, and as a tracking sensor for initial pull-in of the signal. The telescope is mounted to a two-axis gimbal and stabilized via a magnetohydrodynamic inertial reference unit (MIRU). Angle-rate sensors in the MIRU detect angular disturbances which are then rejected using voice-coil actuators for inertial stabilization of the telescope. Optical fibers couple the optical module to the modems where transmitted optical waveforms are processed. Control for each optical module and its corresponding modems is provided by a controller. Each optical module is held and protected during launch with a cover and one-time launch latch.

V. Flight Modem

As stated previously, there exist some differences between the technological approaches to optical communications specifically designed for Near-Earth missions versus deep space missions. This is mostly due to the vastly differing ranges and data rates for Near-Earth versus deep space missions. One area that has been looked at for some time within NASA is the appropriate modulation, coding, and detection scheme for the two different classes of missions. Photon counting and Pulse Position Modulation (PPM) has been identified as the technique of choice for deep space missions, while Differential Phase Shift Keying (DPSK) is the current preferred choice for Near-Earth mission. LCRD will demonstrate both techniques.

LCRD will support Differential Phase Shift Keying (DPSK) which has better sensitivity and fading tolerance than simply on-off-keying, although less sensitivity than PPM, can be used at extremely high data rates using commercial components, and because of the use of a single-mode receiver (received light is coupled into a single-mode optical fiber which serves as a spatial filter) and optical bandpass filtering, supports communications when the Sun is in the field of view. LCRD leverages a MIT LL previously designed DPSK modem [5] as a cost effective approach to providing a DPSK signal. It can both transmit and receive data at an (uncoded) rate from 72 Mbps to 2.88 Gbps. In future relay scenarios, it could be replaced by a higher rate DPSK modem that would support data rates beyond 10 Gbps.

The DPSK modem employs identical signaling for both the uplink and downlink directions. The DPSK transmitter generates a sequence of fixed duration pulses at a 2.88 GHz clock rate. A bit is encoded in the phase difference between consecutive pulses. As demodulation is accomplished with a single Mach-Zehnder optical interferometer regardless of data rate, the clock rate remains fixed. The DPSK transmitter utilizes a MOPA architecture similar to the PPM transmitter[5]. The EDFA amplifies the optical signal to a 0.5-W average power level. Data rates below the maximum are accomplished via "burst-mode" operation, where the transmitter sends pulses only a fraction of the time, sending no optical power the remainder of the time. Since the EDFA is average power limited, the peak power during the bursts is increased; thus the rate reduction is accomplished in a power efficient manner.

The DPSK receiver has an optical pre-amplifier stage and an optical filter, at which point the light is split between a clock recovery unit and the communications receiver. The receiver uses a delay-line interferometer followed by balanced photo-detectors to compare the phases of consecutive pulses, making a hard decision on each channel bit. While coding and interleaving will be applied in the ground terminal to mitigate noise and atmospheric fading, the DPSK flight receiver does not decode nor de-interleave. The modems instead support a relay architecture where up- and down-link errors are corrected together in a decoder located at the destination ground station [6].

LCRD will also support pulse position modulation (PPM) utilizing the same modem that supports DPSK. The transmitter utilizes the same 2.88 GHz clock rate, and modulates the signal with a sequence of 16-ary PPM symbols (signal is placed in exactly one of each 16 temporal slots). The maximum data rate achieved with a ½-rate error corrections code is 360 Gbps. Lower data rates are achieved by combining consecutive slots, effectively lowering the clock rate.

When operating in PPM mode, the receive modem utilizes the same optical pre-amplification and optical filter as is used in DPSK. The optical signal is converted to an electrical signal by means of a photo-detector. The electrical signal in each slot is compared to a threshold (which can be varied to account for atmospheric turbulence) in a simple, yet sensitive PPM receiver implementation. This method leverages previous work by MIT Lincoln Laboratory [12].

VI. High Speed Electronics

To be an optical relay demonstration, LCRD will create a relay connection between two ground stations. A significant objective of LCRD is to demonstrate advanced relay operations on the GEO spacecraft. LCRD will enable a wide variety of relay operations through the high speed electronics (HSE) that connect the two optical terminals. A known challenge with optical communication through the atmosphere is the susceptibility to cloud cover. The HSE will include a significant amount of data storage in order to demonstrate store and forward relay services for when the uplink is available but the downlink is unavailable. The HSE will support delay tolerant network (DTN) protocols [11]. To support DTN over the optical links, the HSE will implement any required decoding and de-interleaving so the payload can process and route the data (at a rate less than the maximum DPSK throughput). The link operations will be configurable to allow support for a variety of scenarios.

VII. The Ground Segment

The LCRD Ground Segment is comprised of the LCRD Mission Operations Center (LMOC) and two ground stations. The LMOC will perform all scheduling, command, and control of the LCRD payload and the ground stations.

Each Earth ground station must provide three functions when communicating with one of the two optical communications terminals on the GEO spacecraft: receive the communications signal from the GEO space terminal, transmit a signal to the GEO space terminal, and transmit an uplink beacon beam so that the GEO space terminal points to the correct location on the Earth.

The receiver on Earth must provide a collector large enough to capture adequate power to support the data rate; couple this light onto low noise, efficient detectors while trying to minimize the coupled background light; and perform synchronization, demodulation, deinterleaving, and decoding of the received waveform.

The uplink beacon, transmitted from each Earth ground station, must provide a pointing reference to establish the GEO space terminal beam pointing direction. Turbulence effects dominate the laser power required for a ground-based beacon. Turbulence spreads the beam, reducing mean irradiance at the terminal in space, and causes fluctuations in the instantaneous received power.

VIII. LCRD Ground Station 1

JPL will enhance its Optical Communications Telescope Laboratory (OCTL) so that it can be used as Ground Station1 of the demonstration. In this section we describe the major modifications that will be made to the OCTL to support LCRD. These are the dome, the adaptive optics optical train, and the atmospheric monitoring system the Monitor and Control (M&C) system and the LCRD User Service Gateway (LUSG). The OCTL is located in the San Gabriel mountains of southern California and houses a 1-m f#75.8 coudé focus telescope. [7] The large aperture readily supports the high data rate DPSK and PPM downlinks from the LCRD space terminal with adequate link margin. Required to operate 24/7, in the presence of winds, and as close as 5 degrees solar angles, the OCTL telescope shown in Figure 2 will be enclosed in a temperature controlled dome with a transparent window to allow laser beam and radar transmission. The Laser Safety System at the OCTL (LASSO) will ensure safe laser beam transmission through navigable air and near-Earth space. [8]

Figure 2 - OCTL telescope will be modified with an optical flat to support links in the presence of more windy conditions.

The seven coudé mirrors will be coated with high reflection low absorption coatings to reduce the amount of sunlight scattered into the receiver when pointed at the required 5 degrees solar angle and of backscatter from the uplink laser. The estimated reflection loss from all seven mirrors is 0.4-dB.

The integrated optical system at the telescope coudé focus is shown in Figure 3 below. A shutter controlled by a sun sensor protects the adaptive optics system should the telescope inadvertently point closer to the sun than specified. The downlink is collimated by an off axis parabolic mirror is incident on a fast tip/tilt mirror and dichroic beam splitter before reflecting off a deformable mirror (DM). A fraction of the beam is coupled to the wavefront sensor to measure the aberrations in the downlink beam. A scoring camera monitors the quality of the corrected beam that is focused into a fiber coupled to the DPSK/PPM receiver. A waveplate adjusts the polarization into the fiber to the DPSK Mach-Zehnder interferometer and a slow tip/tilt mirror ensures maximum signal input to the fiber. In the uplink system the beacon and communications beams are first reflected from slow tip/tilt mirror to track out satellite motions and is then coupled to the telescope through a dichroic mirror.

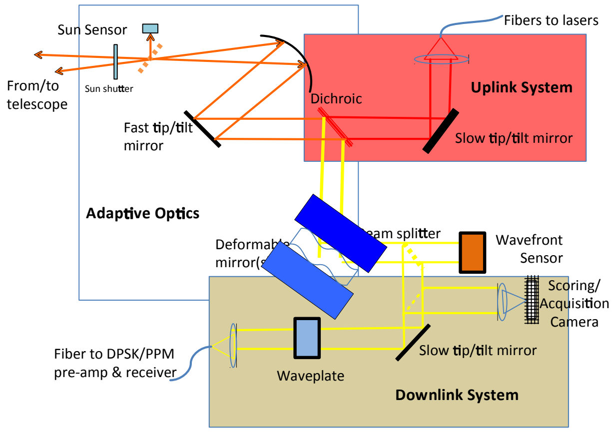

Figure 3 - Schematic of the integrated optical system to be located at coudé focus in OCTL

As a prelude to an operational system, understanding the optical channel and the performance of the link under a variety of atmospheric conditions informs the definition of requirements for future operational ground stations. Figure 4 - is a picture of some of the atmospheric monitoring instruments that will be implemented at the OCTL. The sun photometer measures atmospheric transmission and sky radiance, the ground scintillometer measures the boundary layer turbulence that is the major contributor to the scintillation in the downlink signal, and the cloud imager measures cloud coverage and cloud optical depth. In addition, a differential image motion monitor integrated into the monitor and control software will measure the Fried coherence length r_0 using the downlink signal. The weather station measures wind speed and direction along with relative humidity and temperature at the OCTL.

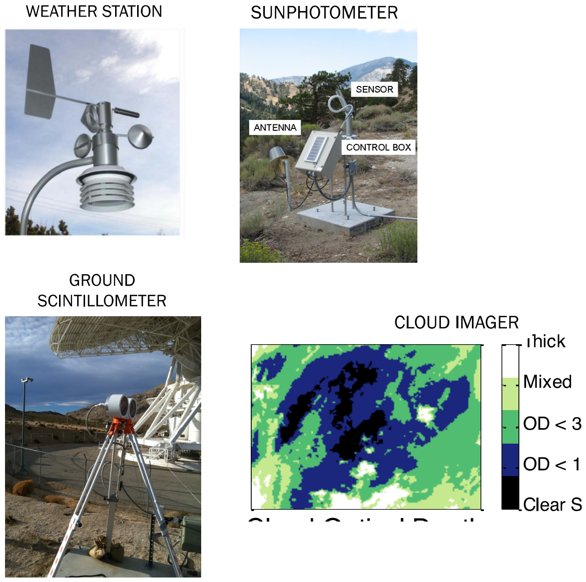

Figure 4 - Suite of atmospheric monitoring instruments to characterize the optical channel.

The ground modem supports both DPSK and PPM. For DPSK, the same signaling structure as before is used, namely phase modulated pulses at a 2.88 GHz slot rate and burst-modes to vary the channel data rate between 72 Mbps and 2.88 Gbps. In addition, the ground modem must implement forward error correction coding – anticipated to be a low density parity check (LDPC) code from the digital video broadcasting (DVB-S2) standard – and interleaving to mitigate atmospheric scintillation. The PPM receiver in ground station 1 will be an equivalent implementation to the flight terminal PPM receiver – an optically pre-amplified receiver with thresholded-PPM demodulation.

The LUSG will interface simulated (and potentially real) Users to the LCRD optical service network, providing real-time bit stream and store-and-forward Delay Tolerant Network (DTN) services. The LUSG provides network data performance measurements, and coordinates with the M&C subsystem.

The monitor and control subsystem will provide the intelligent control of the LCRD ground terminal. It will implement the software to provide the interface for remote control and status monitor of all of the OCTL subsystems. It will provide a gateway to the LMOC to support remote control, status reporting and data return. The M&C subsystem will also implement a high-speed data recording system and engineering interface. The data recorder will archive all of the OCTL system data for post analysis of the system performance. The Engineering Interface will be a temporary user interface for early evaluation of the integrated OCTL subsystem prior to delivery of User Simulator and LMOC connection.

IX. LCRD Ground Station 2

MIT Lincoln Laboratory designed and is building the Lunar Lasercom Ground Terminal (LLGT) [9] for NASA's Lunar Laser Communications Demonstration (LLCD). The LLGT, shown in Figure 5, will be refurbished and enhanced to serve as Ground Station 2 for LCRD. A summary of the LLGT, as designed for LLCD, follows below. The primary enhancements for LCRD will be an adaptive optics system to couple received light into single mode fiber (to support the DPSK signal), and further development of the single photon detectors (to support the PPM signal), including the development of more robust and scalable optical packaging, cabling, and readout electronics.

The LLGT is an array of four 40-cm receive reflective telescopes and four 15-cm transmit refractive telescopes. For the uplink, the optical signal (PPM for LLCD, to include DPSK for LCRD) is modulated onto four separate carrier wavelengths, each very slightly detuned. Each modulated signal is amplified to a 10-W average power, and coupled to a transmit aperture via single-mode fiber. For LCRD only a single uplink telescope will be necessary because of the tenfold reduction in range vs. the moon, and the corresponding hundredfold reduction in diffractive loss (not counting turbulence-induced beam broadening and wander). For the downlink, each of the four receive apertures couples into a few-mode multi-mode optical fiber connected to an array of super-conducting nanowire single photon detectors (SNSPDs) [10]. The SNSPDs must be cryogenically cooled to ~3K, and it is impractical to locate them in the focal planes of the receive apertures. The multi-mode fiber was designed to efficiently couple the received light from the aperture to the detector over a distance of 22 meters. By using multi-mode fiber, efficient coupling is achieved without an adaptive optics system.

Figure 5 - Lunar Lasercom Ground Terminal will be enhanced with Adaptive Optics and the ability to receive and demodulate a DPSK signal

For LCRD, the DPSK signal requires the received light to be coupled into single-mode fiber. For this reason, at least one of the receive apertures will utilize an adaptive optics system to support DPSK. To support PPM, ground station 2 will leverage the array of superconducting nanowire single photon detectors utilized in the Lunar Laser Communication Demonstration (LLCD). The photon counting array demonstration will provide an element of the LCRD ground terminal directly relevant to future deep space laser communications systems.

Ground Station 2 (GS2) will make use of the same ground modem design as used in Ground Station 1 (GS1). However, GS2 requires an additional interface module to transfer synchronization and thresholding information from the modem to the superconducting detector post-electronics, and to feed the detected signal into the modem. GS2 will also be capable of receiving PPM through the receive telescope equipped with the new adaptive optics system, into single mode fiber and the optical preamplifier, bypassing the SNSPDs, but thereby incurring a substantial loss in sensitivity.

To the extent possible, GS2 will leverage the M&C and LUSG designs from GS1. GS2 will support all of the same services supported by GS1. The M&C system will interface to the LLGT, leveraging as much of the LLCD software as possible.

Due to their high photon efficiency and fast reset times, the SNSPDs are a significant enabler for high speed laser communications from deep space terminals to Earth terminals. For this reason, LCRD will investigate updates to the detector technology. This will include efforts to make the detectors more robust; more scalable; and require reduced size, weight, and power (SWaP). The main LCRD efforts will be directed towards optical packaging and improved cabling and cryogenic readout circuitry.

X. Demonstration Operations

Control of all activities during LCRD will take place from the LCRD Mission Operations Center (LMOC) to be located at Goddard Space Flight Center. The LMOC is connected with all other segments, and communicates with the two ground stations using high capacity connections. Connection to the space segment will be provided either through one of the ground stations, or through a lower capacity connection to the host spacecraft's Mission Operations Center (HMOC) and then to the LCRD flight payload by RF link.

The LMOC will provide services such as:

- Planning and scheduling
- Control
- Status Monitoring
- Reporting and Accountability

The mission operations for the spacecraft and the optical communications demonstration are intimately intertwined. The unique nature of the demo is that there is a path to and from the spacecraft that is outside the usual RF connection. Commands for the GEO optical communications terminal can be sent via either the optical uplink or via the Host Spacecraft RF uplink. There are two paths for getting engineering data (health and status), again via optical or RF. The LMOC coordinates all optical communications activities and provides an interface to the spacecraft operations.

On the telemetry side there are again two paths, though for somewhat different reasons. Data (user information or engineering telemetry) can be sent to Earth via the GEO optical communications terminal. It is possible that the GEO terminal may add/multiplex additional engineering data into the data stream. The spacecraft monitors terminal parameters like power and includes those in engineering telemetry that is passed over the RF link. In addition to these, there are many ‘test points” within the GEO terminal that are sent via RF as part of the engineering telemetry.

Due to the vagaries of weather and atmospheric conditions, operations strategies for mitigation of these effects will be explored. One possibility would be to have multiple terminals within the same beam simultaneously receive the same data to guarantee getting through to at least one terminal at a reasonably high percentage of the time. On the other hand, buffering and retransmission strategies can be used to downlink the data to single geographically (and meteorologically) diverse stations in a form of temporal diversity.

The ground stations will have the capability to simulate both user spacecraft and user MOC data systems. This will allow the demonstration of high data rate scenarios without the requirement for high data rate connections external to the ground stations. The simulators will also allow multiple user and user-type scenarios. The LCRD payload itself will also include the ability to simulate user spacecraft data and multiple relay user spacecraft data systems.

The system will be continuously operating, as much as possible, over the two year mission. The system will either be configured to be demonstrating or testing a specific Direct-to-Earth (DTE) scenario, relay scenario, or be continually characterizing the optical channel and hardware. The DTE and relay scenarios will emulate different user and relay locations, orbits, and/or trajectories.

XI. Conclusion

Optical Communications is an important communications technology for future space missions. It has the potential to enable new science and exploration missions throughout the solar system. Optical communications can provide increasing higher data rates over comparable RF systems. While the capacity of current and near-term RF communications technology is still increasing, it is eventually limited by bandwidth allocation restrictions, power requirements, flight terminal antenna size, and weight limitations. The cost and complexity of expanding the existing Space Communications Networks to enable these higher data rates using RF solutions alone with large aperture antennas is a significant undertaking. A future Space Communications Network should offer both RF and optical communication services. RF can be reserved for those cases where high availability and thus low latency is absolutely required, since optical communications through the atmosphere for space to Earth links will always be impacted by clouds. For space to Earth links, optical communications can be reserved for scenarios in which a potential delay in reception is not a problem; in space to space links, optical communications can provide both high data rates and high availability. In both space to space and space to Earth links, optical communications can potentially provide high data rates with smaller systems on user spacecraft and on the ground.

LCRD will provide two years of continuous high data rate optical communications in an operational environment, demonstrating how optical communications can meet NASA's growing need for higher data rates or how it enables lower power, lower mass communications systems on user spacecraft. In addition, LCRD will serve as a developmental testbed in space. LCRD is a critical stepping stone to providing optical communication services on NASA's Next Generation Tracking and Data Relay Satellite to be flown sometime next decade. We strongly believe that the next generation satellite will supply both RF and optical services. Doing this demonstration will allow initial operational capability (IOC) of an optical service on the first next generation satellite.

Acknowledgments

The work described in this paper was carried out at NASA's Goddard Space Flight Center; at Lincoln Laboratory*, Massachusetts Institute of Technology; and at the Jet Propulsion Laboratory, California Institute of Technology, under contract with NASA. It is funded by NASA's Office of Chief Technologist and NASA's Space Communications and Navigation Program Office.

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* This work was sponsored by NASA Goddard Space Flight Center under Air Force Contract FA8721-05-C-0002. The opinions, interpretations, conclusions, and recommendations are those of the author and not necessarily endorsed by the United States Government.

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