Early Results from NASA's Laser Communications Relay Demonstration (LCRD) Experiment Program

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ABSTRACT

The National Aeronautics and Space Administration's (NASA) Laser Communications Relay Demonstration (LCRD) mission began its two-year Experiment Program in June 2022. This experimental phase includes long-term measurement of the effects of the atmosphere (turbulence, weather) on the performance and availability of lasercom. Furthermore, various future operational scenarios including robotic and exploration missions and various network service configurations are being emulated. In addition to experiments and demonstrations proposed by the LCRD Investigator Team, NASA enables individuals and groups from government agencies, academia, and industry to propose experiments under the LCRD Guest Experimenters Program. This conference paper provides highlights of the early LCRD experiments and a preview of the future experiments, including relaying data to and from the Integrated LCRD Low-Earth Orbit (LEO) User Modem and Amplifier Terminal (ILLUMA-T) on the International Space Station.

The LCRD geosynchronous payload includes two laser communications terminals interconnected via an onboard electronic switch, and can relay information between two optical ground stations located in California and Hawaii. LCRD is a joint project involving NASA Goddard Space Flight Center (GSFC), the NASA Jet Propulsion Laboratory (JPL), and Massachusetts Institute of Technology Lincoln Laboratory (MIT LL).

Keywords: lasercom, communications relay, DTN, adaptive optics, optimetrics, optical communications

1. LCRD BACKGROUND AND DESCRIPTION

LCRD provides a space-based technology demonstration platform for bidirectional optical communications, leveraging work done in the past for NASA and the U.S. Department of Defense. LCRD is funded by the NASA Space Technology Mission Directorate (STMD) and the NASA Space Communications and Navigation (SCaN) Program and is led by a Principal Investigator (PI). The project is a collaborative effort between NASA GSFC, NASA JPL, and MIT LL. LCRD operations and experiments are managed by GSFC.

LCRD utilizes existing systems and designs with minimal modifications to gain operational experience while minimizing costs. LCRD will execute experiments for a minimum of two years, providing high data rate optical communications in an operational environment. LCRD experiments will demonstrate that optical communications can both meet NASA's and other agencies' growing need for higher data rates and enable lower-power, lower-mass communications systems on spacecraft.

In addition, LCRD's architecture will enable it to serve as a developmental testbed for advanced communication techniques including adaptive optics, symbol coding, link layer protocols, and network layer protocols. LCRD's dual optical link system will allow it to serve as the first step in demonstrating optical communications for use in a next-generation space-based relay system and potentially provide early operational support for low Earth orbit (LEO) terminals. LCRD will also enable experimenters to characterize atmospheric effects on optical communications and validate atmospheric models. LCRD will advance optical communications technology toward infusion into both deep space and near-Earth operational systems, while growing the capabilities of industry sources to produce affordable optical communications systems and components for use on the ground and in space.

The LCRD mission architecture, depicted in Figure 1, is composed of flight and ground segments. The flight segment is onboard the Space Test Program Satellite-6 (STPSat-6) spacecraft in geosynchronous Earth orbit (GEO), and includes the LCRD flight payload and the spacecraft-provided High-bandwidth Radio Frequency (HBRF) terminal. The flight payload includes two optical space terminals, OST1 and OST2, capable of simultaneous operation. The ground segment includes two optical ground stations (Optical Ground Station 1, or OGS-1, and Optical Ground Station 2, or OGS-2); a radio frequency ground station (RF GS); and an LCRD Mission Operations Center (LMOC), which includes an LMOC Extension (LMOC-E) for observation and monitoring of LCRD operations and experiments[1].

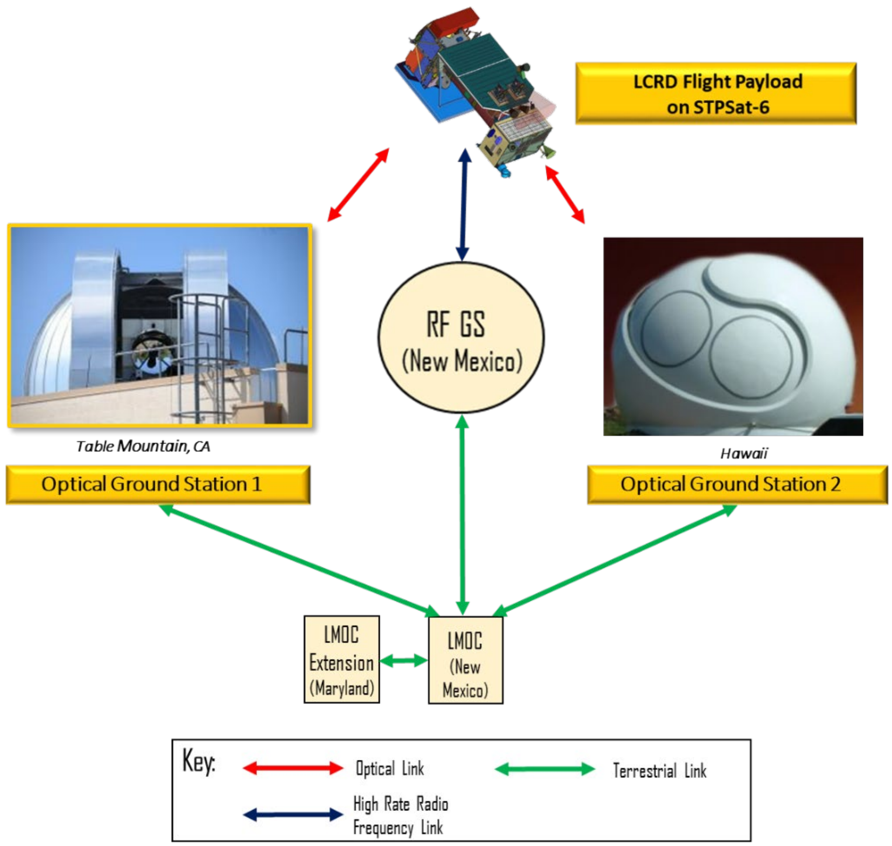

Figure 1. The LCRD mission architecture consists of a flight segment and a ground segment that will demonstrate two simultaneous bidirectional optical links.

The LCRD mission objectives include the following:

1. Demonstrate bidirectional optical communications between GEO spacecraft and Earth
2. Measure and characterize the system performance over a variety of conditions
3. Develop operational procedures and assess applicability for future missions
4. Transfer laser communication technology to industry for future missions
5. Provide an on-orbit capability for test and demonstration of standards for optical relay communications

During the two-year LCRD Experiment Program, NASA will execute a predetermined set of NASA experiments designed to achieve the mission objectives. The Agency may also supplement this predetermined set with experiments selected via the LCRD experiment proposal process. Proposers of such supplemental experiments may be internal or external to the LCRD Project, and may include individuals or groups from NASA, other government agencies, academia, or industry. More information on the LCRD experiment proposal process can be found at https://esc.gsfc.nasa.gov/projects/LCRD?tab=opportunities%20for%20experimenters.

LCRD integration and test (I&T) and pre-launch activities provided much useful information prior to launch[2]. NASA performed extensive unit-level and subsystem level testing in-house, including testing with a custom-built optical test set and thermal vacuum chamber testing. Testing was also performed using Pre-FlatSat and FlatSat emulators, which provided high-fidelity functional emulations of the space vehicle bus. Space vehicle integration followed Northrop Grumman's "open panel" testing approach prior to final integration, enabling modifications to be made relatively easily during space vehicle testing. Northrop Grumman designed and manufactured the STPSat-6 spacecraft and performed the integration of the nine STPSat-6 payloads.

Virtualization, extensive automation, and the use of multiple test rails in addition to the LCRD operational rail, enabled efficient parallel software development, reducing resource contention. Distributed version control systems (DCVSs), although requiring deeper training/fluency of personnel, were invaluable for overcoming the security and network barriers associated with software development at multiple, geographically diverse sites including GSFC, the LCRD Mission Operations Center (LMOC), and the ground stations.

LCRD's extensive on-Earth testing ironed out most of the challenges, but on-orbit activation testing identified a few more, and enabled refinement of procedures. One challenge was accurate and timely distribution of orbital elements to the ground stations. Another was timely access to the mission data and telemetry database. Acceptance testing also enabled refinement of procedures, such as optimizing delays for sequenced events, and effectively scheduling contingency events when a particular scenario cannot be completed, e.g., due to weather.

LCRD was launched on December 7, 2021, and the payload was powered on January 12, 2022. The first optical link was completed between the LCRD payload and OGS-2 on January 12, 2022. First light was achieved on January 27, 2022, when communications links were established between LCRD and both OGS-1 and OGS-2. Activation activities were completed in April 2022. After ground software updates and final testing, the two-year experiment program began on June 10, 2022.

The LCRD Experiment Program is currently developing and/or running 45 experiments in the areas of operational readiness and networking, and optical and relay link characterization. In addition to experiments proposed by NASA personnel and Co-Investigators (Co-I), several LCRD experiments are being developed in partnership with commercial, university, and other government agency (OGA) partners. See Figure 2 for a summary of the types of experiments being developed and executed. The LCRD team will continue to add to the experiment portfolio as additional experiments are proposed.

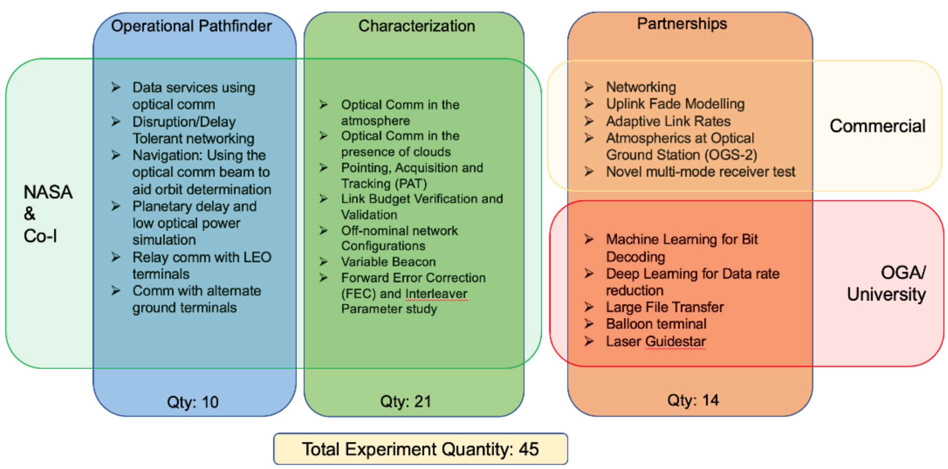

Figure 2. LCRD experiments currently being developed and/or executed.

2. LCRD EXPERIMENT AND AVAILABILITY STATISTICS

LCRD experiments run for 40 hours per week and five days per week. Hours of operation are shifted to capture diurnal and seasonal variations in the atmospheric optical channel.

Telemetry from the LCRD payload, OGS-1, and OGS-2 elements is collected and archived for post-pass analysis. Telemetry types captured include element health and safety, element performance, communications performance, frame statistics, and atmospheric conditions at each ground station.

The LCRD team tracks system utilization in two ways: Experiment Operations Statistics and System Availability. Experiment Operations Statistics capture the number of experiment test cases that are planned, executed, and cancelled. System Availability captures uptime of the major system elements. See below for the latest statistics and details on these tracking categories.

2.1 Current Experiment Operations Statistics

Table 1 below shows the number of experiments planned (Scheduled), as well as the number of experiments completed (Executed). The LCRD team also tracks how many experiments are cancelled prior to being run (Cancelled), attempted but not run for either weather (Attempt Not Successful [ANS] Weather) or technical (ANS Technical) reasons, as well as the number of contingency experiments that were scheduled, but not used (Contingency).

Table 1. LCRD Experiment Operations Statistics.

LCRD Experiment Operations Statistics Master Report Table											
	Data					LCRD Experiments					
Time Frame	First Date	Last Date	First DOY	Last DOY	Calendar Days Included	Cancelled	ANS Weather	ANS Technical	Contingency	Executed	Scheduled
Total	6/10/22	01/01/23	161	366	206	103	48	26	32	352	561

2.2 Current Availability Statistics

The LCRD team tracks availability of the various system elements (see Table 2). The Online Availability refers to the times planned for LCRD operations. The Offline Availability is the percentage of unstaffed time when LCRD could have been operated if staffed (i.e., the system was not down for maintenance or orbital maneuvers). The 24 hour Availability includes both online and offline availabilities. The Total Payload Availability indicates the availability of the entire payload, while the Total GS Availability captures availability of all three ground stations (GS): RF GS, OGS-1 and OGS-2. Total OGS Availability represents the availability of OGS-1 and OGS-2.

Table 2. LCRD Availability Statistics

	Online Availability Percentage (Overall)	Online Availability Percentage (Planned)	Offline Availability Percentage (Overall)	Offline Availability Percentage (Planned)	24 Hr Availability Percentage (Overall)	24 Hr Availability Percentage (Planned)
Total Payload Availability	98.21	99.71	99.62	100.00	99.19	99.91
Total GS availability	77.70	92.22	90.04	94.42	86.05	94.05
Total OGS Availability	67.29	88.59	86.00	92.48	79.93	91.72

3. LCRD DAY-IN-THE-LIFE PERFORMANCE

Figure 3 depicts a relay experiment that was run on day of year (DOY) 318 in 2022. The optical link starts in the OGS-2 User Platform Simulator (UPS) and terminates in the OGS-1 UPS after passing through the LCRD payload. The plots in Figure 4 depict various measurements collected during this experiment. The top plot (a) shows the received powers at the OST2 Flight Modem #2 (FM2), the OGS-1 telescope, and the OGS-1 modem. The middle plot (b) shows the uplink bit error ratio (BER) at OST2-FM2 and the downlink BER at OGS-1. Finally, the bottom plot (c) shows the number of data bits transmitted across the relay.

These plots show the communications performance of LCRD on a typical day when the weather is favorable. The received power at the uplink and the downlink resulted in channel BER that enabled the transmission of 40 Gigabits of data in approximately two minutes.

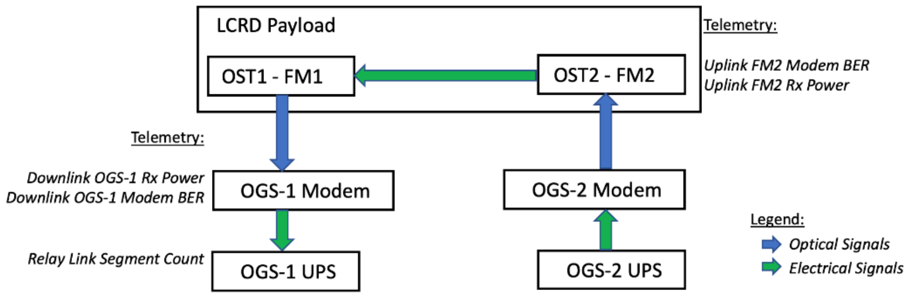

Figure 3. Signal flow in the LCRD relay experiment run on day of year (DOY) 318 in 2022.

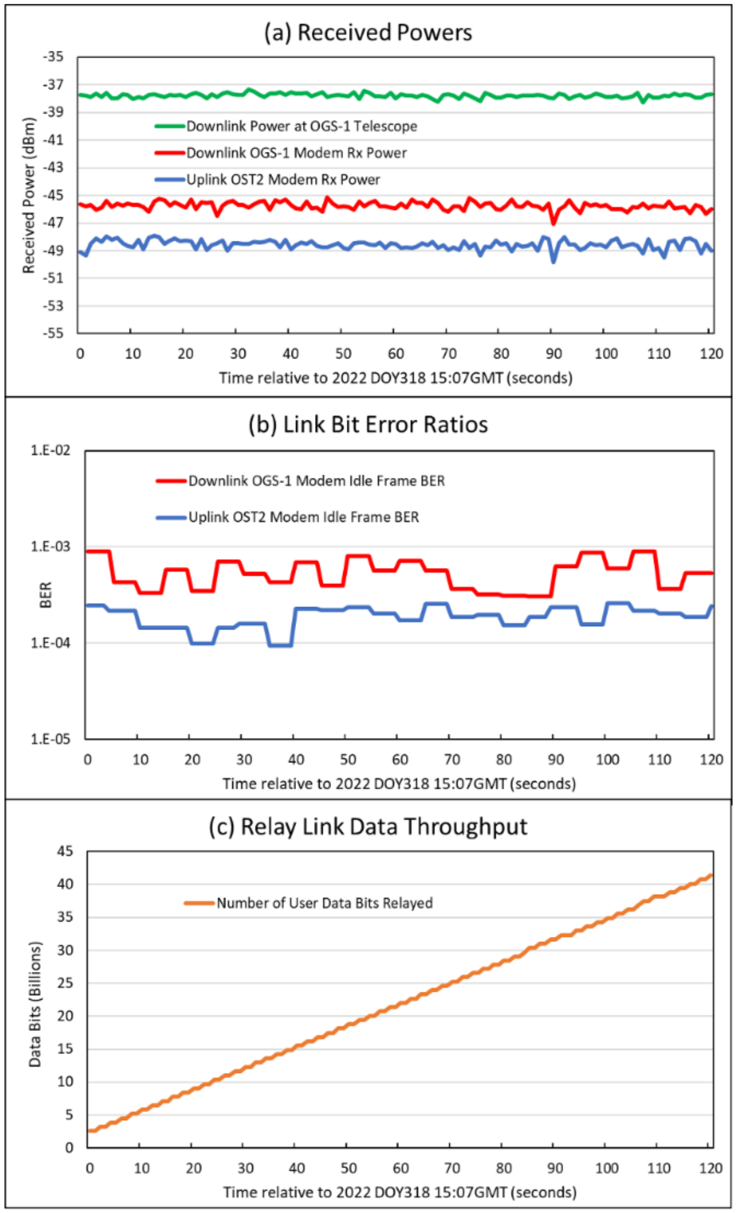

Figure 4. Measurements collected during the LCRD relay experiment run on DOY 318 in 2022, including: (a) the received powers at the OST2 Flight Modem #2 (FM2), the OGS-1 telescope, and the OGS-1 modem; (b) the uplink bit error ratio (BER) at OST2-FM2 and the downlink BER at OGS-1; and (c) the number of data bits transmitted across the relay.

4. EXPERIMENTS TO DATE

The subsections below provide an overview of some of the experiments that were performed during the first six months of the two-year LCRD Experiment Program.

4.1 Optical Communications and Atmospheric Optical Turbulence

An optical beam propagating in the atmosphere is affected by optical turbulence, in addition to other factors pertinent to the atmospheric optical channel[3]. In fact, due to optical turbulence, uplink and downlink optical signals experience a degree of aberrations and distortion due to the randomness of the atmospheric refractive index[4]. In particular, the uplink beam will experience a larger spreading of the beam with a consequential large loss (atmospheric Strehl loss) at the flight terminal, associated with a strong dynamic fading (scintillation) of the signal itself. Conversely, on the downlink beam, the optical turbulence will cause additional aberrations of the propagating optical wave with the fading of signal and the degradation of the quality of the point spread function (PSF) at the receiver (or at the modem's Single-Mode Fiber [SMF]) unless corrections from an adaptive optics (AO) system are used.

The purpose of one of the initial sets of LCRD experiments is to comprehensively characterize the effects of optical turbulence on LCRD optical communication links. The versatile LCRD architecture provides a number of different configurations to study the effects of optical turbulence on an optical communication beam in both uplink and downlink. For instance, during the loopback configuration, when the uplink and downlink are restricted to the same ground station, the uplink and downlink signal path experience the same atmospheric profile, and it is possible to verify how the same turbulence profile can affect the uplink and downlink beams differently. In addition, during a relay link, one can monitor how two likely different atmospheric profiles (one in Haleakala, Hawaii and the other in Table Mountain, California) can produce different effects on the uplink and downlink. The communication performance of LCRD loopback and relay links is affected by the overall path (uplink and downlink) in a cumulative fashion[5]; however, one way to isolate the effects of optical turbulence on a single path is to use LCRD's direct to Earth (DTE) configuration, where the communication signal is generated on the space payload and transmitted directly to the ground. To characterize the effects of the optical turbulence on the optical communication links, DTE links are alternated with relay links and loopback links to help quantify the effects of the optical turbulence on the uplink and the consequent degradation of the quality of the link.

Because of the diurnal and seasonal variation of the optical turbulence, these experiments are performed at different times of the day, with emphasis around noon (optical ground station local time) when the optical turbulence is expected to be the strongest.

The LCRD optical signal is modulated using differential phase shift keying (DPSK) (at OGS-1 and OGS-2)[5] and pulse position modulation (PPM) (OGS-1 only)[6]. Both modulations are tested during the experiment, while the data rate is varied from the highest (lowest peak power) to sequentially lower rates (higher optical pulse peak power) to understand/verify how higher pulse energy can offset the channel capacity loss due to turbulence-induced signal fading.

A number of instruments are deployed at the LCRD's optical ground stations to monitor the optical turbulence in situ. In particular, the OGS-1 1-meter telescope aperture is coaligned with an auxiliary 20-cm telescope that is dedicated, among other things, to monitor in real time the downlink irradiance originating from the space terminal at a 1-kHz sampling rate. This sampling rate is quite adequate to characterize the dynamics of the downlink signal fading that can occur on an optical path, even if the 20-cm aperture of the auxiliary telescope can provide a degree of signal averaging (see Figure 5).

Another figure of merit of the optical turbulence is the atmospheric coherence length or Fried parameter[3]. At OGS-1 the atmospheric coherence length is also monitored in real time by the ground acquisition camera system, which measures the magnitude of the Fried parameter at the rate of 1 Hz directly from the information of the point spread function (PSF) of the downlink signal[7] (see Figure 6). Furthermore, at OGS-1, the strength of the optical turbulence at the boundary layer is constantly measured by a boundary layer scintillometer (BLS) that provides updates in real time of the coefficient of structure index of the atmosphere refractive index (C_n^2).

To analyze the effect of the optical turbulence on LCRD communication links, measurements of the optical channel are compared to the main figures of merit of the optical link, including the radiometry of the uplink and downlink signal power, the uplink and downlink BER, the link code word error ratio (CWER), and channel state of information (CSI). The values of these measurements are recorded in real time and time-stamped during the experiment at a rate (generally) of 1 Hz and made available to the experimenter(s).

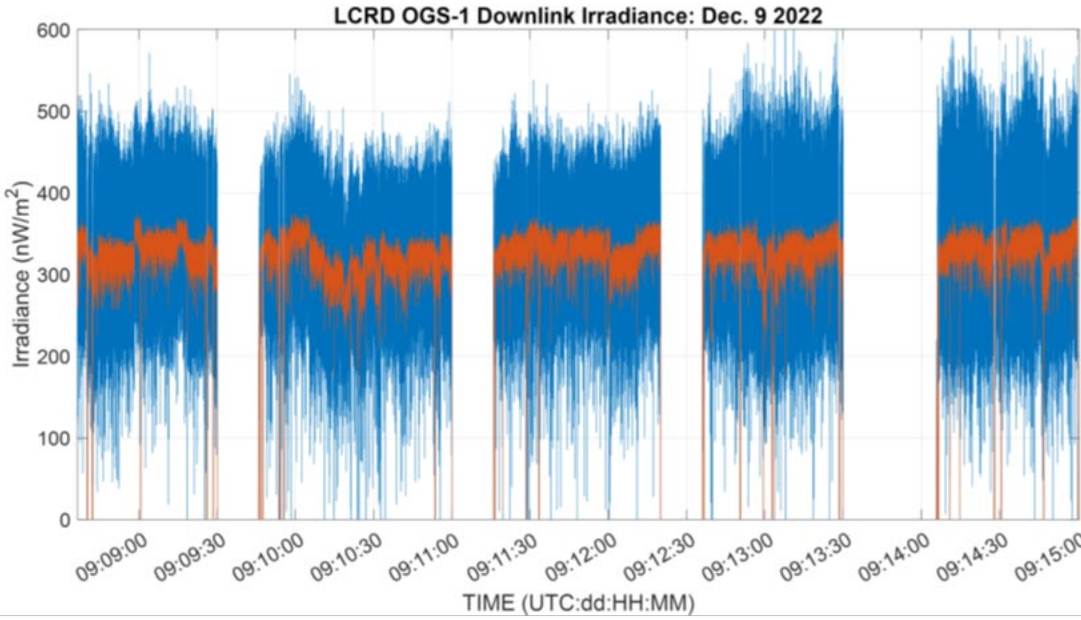

Figure 5. LCRD OGS-1 Downlink Irradiance on Dec. 9, 2022. Data are recorded at 1 kHz sampling rate: red curves indicate 1 s. signal average. The downlink was transmitting a number of distinct segments of a duration of approximately 90 minutes each.

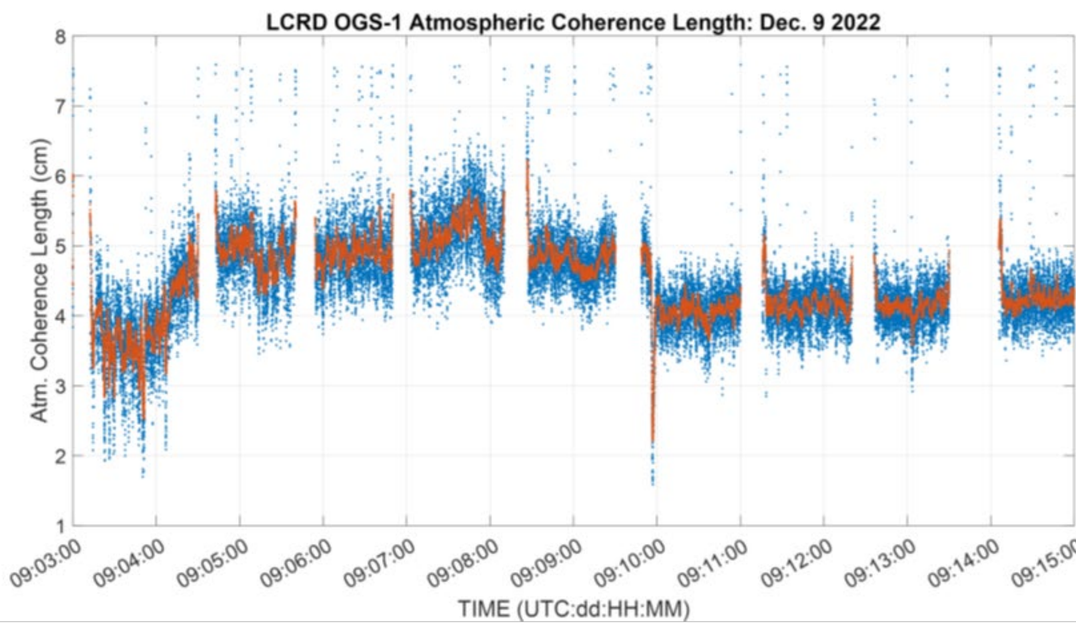

Figure 6. LCRD OGS-1 atmospheric coherence length during operations on Dec. 9, 2022. Data are recorded at 1 Hz sampling: red curves indicate 60 s. signal average. The reference signal is the LCRD downlink that was transmitting a number of distinct segments of a duration of approximately 90 minutes each. The atmospheric coherence length is scaled in wavelength and reported at 500 nm at zenith.

The interaction between optical turbulence and the propagating uplink and downlink beams will continue to be studied and monitored for the remainder of the LCRD Experiment Program. Data will be collected and experimental activity will continue to fully characterize the optical turbulence at the LCRD optical ground stations. The opportunity to collect measurements of the atmospheric optical channel and to characterize the evolution of the optical turbulence over different (seasonal) conditions will validate and extend the knowledge of optical beam propagation in the presence of turbulent media.

4.2 Adaptive Optics Optimization

Optical turbulence affects the quality of the downlink beam propagating from the LCRD payload. In fact, due to optical turbulence, the aberrations of the propagating wavefront cause the spreading of the signal point spread function (PSF) at the receiver, impairing an efficient coupling of the optical signal into the SMF at the input of the ground modem.

To improve the signal coupling into the receiver SMF, both optical ground stations use an adaptive optics (AO) system to dynamically compensate for the wavefront aberrations and to reduce the effective size of the PSF close to the diffraction limit. Figure 7 describes the layout of the integrated optical system (IOS) of the OGS-1 at Table Mountain, California. Among the different subsystems, OGS-1 IOS includes an uplink subsystem that delivers the uplink signal to the telescope and a downlink subsystem that includes the OGS-1 AO[8].

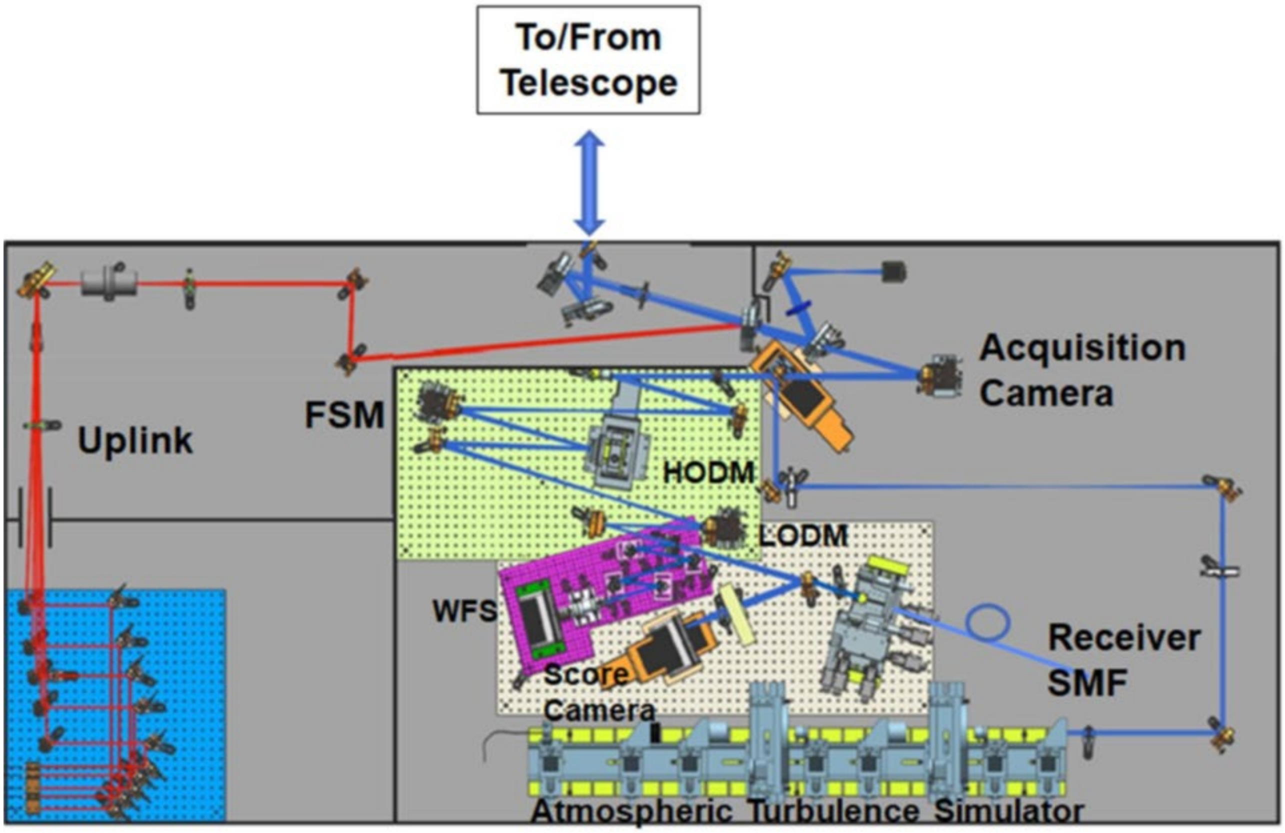

Figure 7. OGS-1 Integrated Optical System (IOS) layout that includes the uplink subsystem and the AO system. The atmospheric turbulence simulator is used to create an aberrated signal to test the performance of the AO at different optical turbulence strengths.

The OGS-1 AO (see Figure 7) is composed of a fast steering mirror (FSM) to compensate for the angle of arrival of the downlink signal and a beam splitter of fixed split ratio to redirect part of the downlink signal to a wavefront sensor (WFS) camera that samples the aberrations of the wavefront. Based on the measurements of the WFS, the wavefront aberrations are corrected by the FSM and two deformable mirrors (DM). In particular, OGS-1 AO use a low-order DM (LODM) to correct low spatial frequencies and large amplitude aberrations and a high-order DM (HODM) to correct high spatial frequencies and small amplitude aberrations. During testing, the atmospheric turbulence simulator is used to generate a dynamically aberrated signal to simulate the effect of optical turbulence and to validate AO performances in absence of a downlink signal.

Adaptive optics systems have been successfully used in astronomy to improve imaging from aberration due to astronomical seeing. However, the use of AO in ground-to-space free space optical communication is relatively more recent[9]. In the case of LCRD, there are several circumstances that differ from more typical astronomical-based applications. LCRD is operating for long periods, sometimes multiple days, experiencing the continuous diurnal variation of the optical turbulence that is stronger around noon and more favorable around sunset and dawn. LCRD is planned to operate during the daytime, at variable conditions of the daytime sky radiance, and the optical ground stations are required to operate at a relatively close angular distance from the Sun when experiencing large sky radiance. Moreover, when clouds are present during the daytime, the sky radiance can unpredictably increase, worsening the WFS signal-to-noise ratio and WFS functionality. Another factor that can affect AO performance is the wind speed profile, which can vary greatly during the day and the seasons.

One experiment performed during this first part of the LCRD activity has the scope to characterize and optimize the AO systems at OGS-1 under the different conditions of the atmospheric optical channel. The WFS frame rate and the gains of the FSM, HODM, and LODM are the main AO parameters that can be varied/tuned to optimize the AO performances and the overall coupling efficiency of the downlink signal into the receiver input SMF. The WFS frame rate is varied over a set of discrete rates ranging from 1 kHz to a maximum of 20 kHz, while the FSM, HODM, and LODM gains are concurrently varied to optimize the SMF coupling efficiency. At OGS-1, the coupling efficiency is derived from the measured irradiance at the telescope (see Figure 5), the telescope losses, and the measured optical power coupled into the receiver SMF. Figure 8 depicts the coupling efficiency at OGS-1 during the experiment for approximately three hours on January 7, 2023.

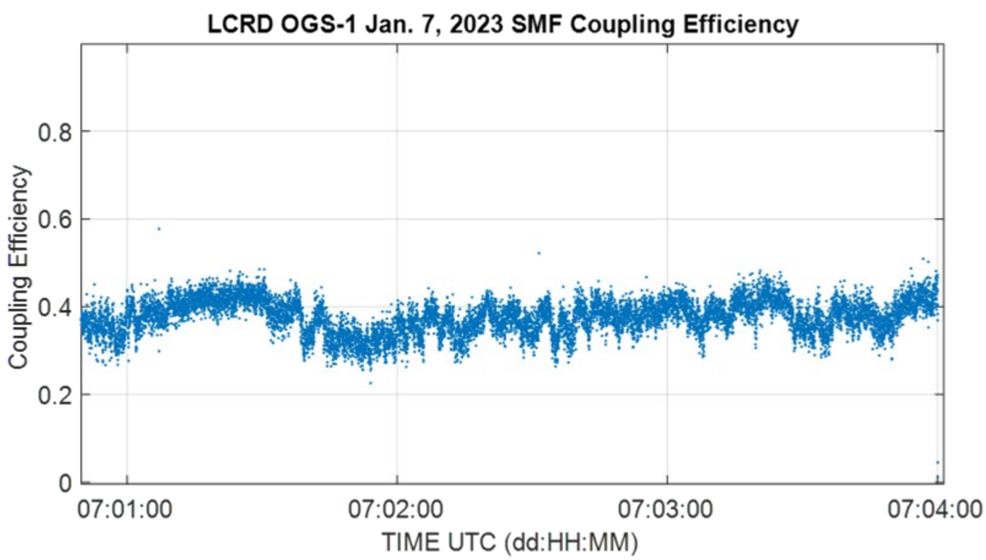

Figure 8. Coupling efficiency measured at OGS-1 during the experiment activities on January 7, 2023. The coupling efficiency data are provided at a rate of 1 Hz.

Besides the SMF coupling efficiency, other metrics are considered to understand the quality of the corrections performed by the AO system itself. These metrics include the normalized variance of the signal coupled into the SMF, communication link performances including BER and code word error ratio (CWER), and the quality of PSF in the form of the Strehl ratio that is measured in real time by the score camera (see Figure 7). All these metrics are recorded in real time, and they can be visualized in real time and/or archived and made available to the LCRD experimental group. All the LCRD link configurations are used during this experiment, including relay link (i.e., OGS-2 to OGS-1, RF to OGS-1), loopback, and DTE.

The AO optimization experiment is planned to run over the course of the two-year LCRD Experiment Program to validate the results in the different atmospheric optical channel conditions that occur during that time.

4.3 Data Services Using Optical Links

Beyond tests and demonstrations of the optical link technology and channel performance, LCRD will also provide experience and data to inform future operational concepts and mission designs. The first of these types of experiments will utilize the LCRD flight payload and ground systems to emulate operational relay scenarios. As seen in Figure 9, one optical ground station (OGS) performs the role of one or more LCRD users, receiving and transmitting an optical forward and return link respectively from the LCRD flight payload. The trunkline (i.e., the communications link designed to carry multiple data flows from one or more users) to the relay is either over RF to the RF Ground Station, as shown in the figure, or over an optical trunkline to the other OGS.

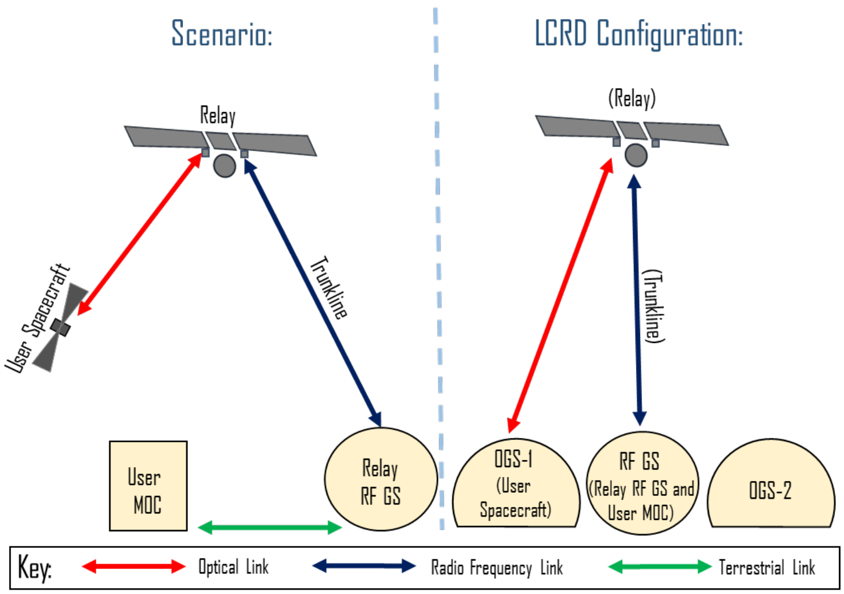

Figure 9. The LCRD configuration (right) used to emulate the operational relay scenario (left). One OGS is configured for the role of the user(s). The relay trunkline is provided either by via RF (as shown) or an optical link to the other OGS.

These tests provide the first demonstrations of an optical relay to support user data flows and provide the basic starting point for demonstrations of operational scenarios of increasing complexity. Each ground location includes a User Platform Simulator (UPS) and a User Mission Operations Center (MOC) Simulator (UMS), each capable of providing the functionality of the data endpoints they represent without requiring experiment data flows to extend past the LCRD ground locations. A UPS at one OGS is configured to provide simulated user data. The data rate and data service vary, with the simplest configurations used initially. Metrics collected include data completeness and proficiency (service received/service scheduled). Any loss of data and/or service time are tracked, to attempt to determine the source of losses.

Following the initial demonstrations, these experiments will be scheduled and executed in a manner more closely aligned to true operational supports. The simulated user will include orbit details, such that events will be scheduled based on when the simulated user would be in view of LCRD. This will allow measurements of data and service loss to be made relative to a schedule based on a user's requirements. Specific data rates and service types will also be determined based on the user being simulated. For example, the simulated user could be the International Space Station (ISS) (see upcoming experiment below). These scenarios would also include scheduling and/or required handovers between optical and RF trunklines.

The LCRD systems allow for the simulation of multiple simultaneous users, each receiving different types of data services and following their own mission schedules. By building up to more complex combinations of missions and data types, the LCRD systems and operations team will experience multiple "Days in the Life" of an operational optical relay provider. These experiences will lead to better understanding of the expectations and optimizations of optical relay service for users through weather and other events.

To date, LCRD has run 229 successful data service test cases focusing on RF-to-optical relay, OGS loopback, and Direct-to-Earth configurations. Optical-to-optical relay data service test cases are planned for the near future.

5. UPCOMING EXPERIMENTS

The subsections below describe some of the experiments planned to be conducted during the remainder of the two-year LCRD Experiment Program.

5.1 Integrated LCRD LEO User Modem and Amplifier Terminal (ILLUMA-T)

The first orbiting user of LCRD will be a user terminal on the ISS, the ILLUMA-T[10]. ILLUMA-T is scheduled to launch in 2023 and will demonstrate optical relay communications between the ISS and LCRD payload, with return rates up to 1.244 Gbps and forward rates of at least 51 Mbps (see Figure 10). ILLUMA-T experiments are planned for a six-month period. LCRD support of ILLUMA-T will demonstrate the capabilities of an optical terminal for communications and navigation for a user in low earth orbit.

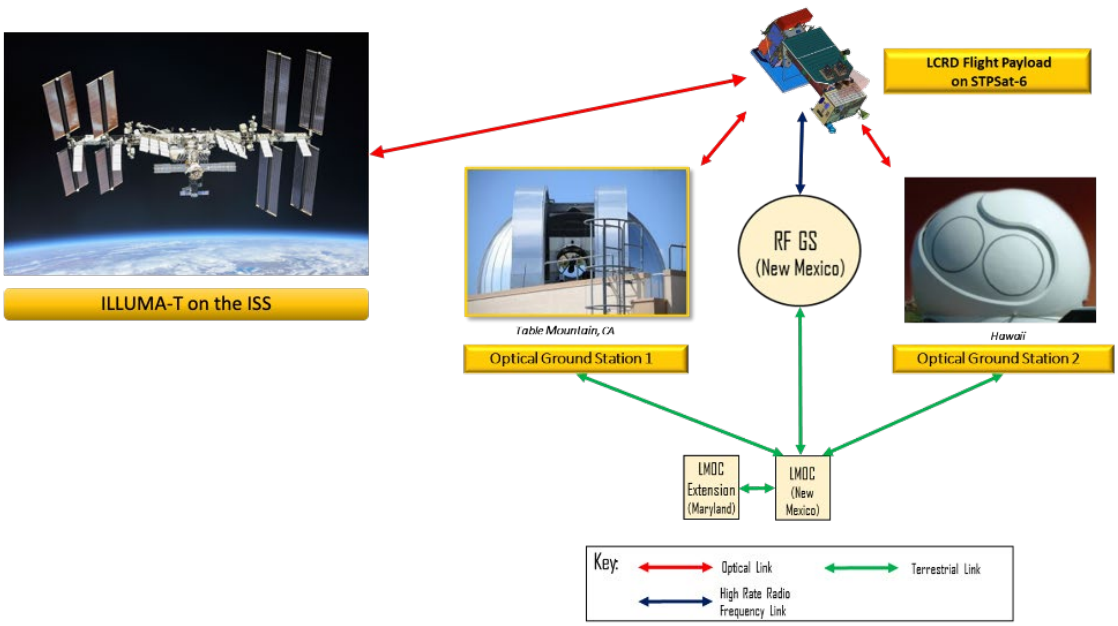

Figure 10. ILLUMA-T adds an orbiting user to the LCRD architecture.

ILLUMA-T experiments are grouped into several categories (see Figure 11). Experiments in the "Link Performance" and "End-to-End Performance" categories focus on the challenges of pointing, acquisition, and tracking between an orbiting user and a GEO relay, as well as the performance of the links. Experiments in the "Operations Concepts" category are an extension of the data services experiments described in section 4.3 above. ILLUMA-T will allow these experiments to include an actual orbiting user. The experiments in the "ISS Pre-operational Checkout" category will be executed if the ILLUMA-T terminal continues to operate after the planned six-month ILLUMA-T experiment period. In that case, a series of tests and training activities will occur to enable ILLUMA-T optical communications for operational use.

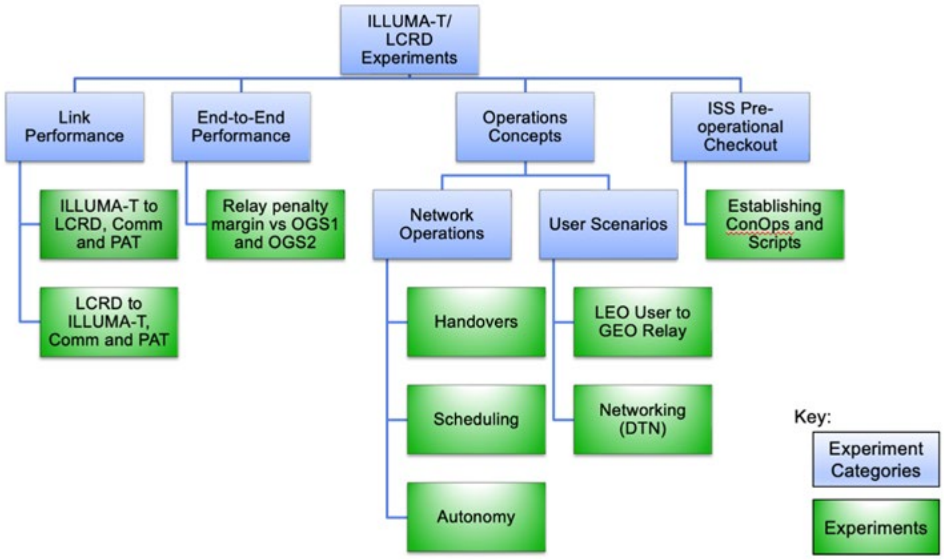

Figure 11. ILLUMA-T LCRD experiments.

5.2 Optimetrics

Optical links may be capable of providing tracking data (range and range rate) that is orders of magnitude more accurate than tracking data provided by RF links[11]. To validate this concept, the LCRD optimetrics experiments will be performed in two phases (see Figure 12). In the first phase, the LCRD flight modem will perform a coherent clock loopback (i.e., the receive and transmit clocks will be referenced to each other) on a bidirectional link with OGS-1. In the second phase, following the launch of ILLUMA-T, the ILLUMA-T modem will also provide a coherent clock loopback, enabling the first optimetric measurements through an optical relay to an orbiting user.

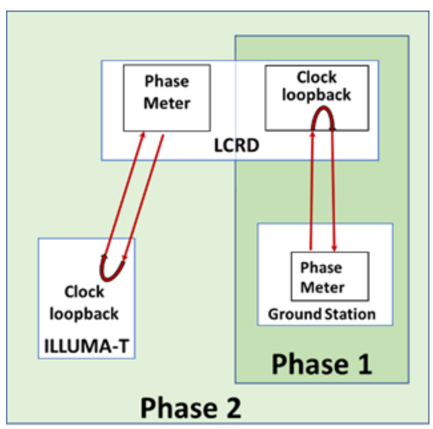

Figure 12. The two phases of LCRD optimetrics experiments.

5.3 Delay/Disruption Tolerant Networking

Delay/Disruption Tolerant Networking (DTN)[12] is a network architecture approach for networks with links subject to long and variable propagation delays and networks lacking continuous connectivity of nodes. Link connectivity can be lost for several reasons including excess range, occultations, or weather. These factors are all relevant to lasercom networks in space, and LCRD provides an opportunity to explore approaches and infrastructure for enabling DTN in future operational lasercom networks.

At a high level, the DTN-enabling goals for LCRD include measuring speed/reliability, implementing DTN Network Management (NM) capabilities, and preparing for operational DTN services. This LCRD experiment is divided into several phases, each one representing a step towards reaching the full operational capability.

The goal of the initial phase is to demonstrate transfer of bundles between two DTN nodes over the LCRD links, and capture information about the quality of the data transfer. These tests are expected to duplicate the performance of DTN as seen in the Lunar Laser Communications Demonstration (LLCD) in 2013[13]. Bundle Protocol version 6 (BPv6)[14] will be used with custody transfer enabled, and User Datagram Protocol (UDP)[15] will be used as the convergence layer.

During the next phases, multiple implementations of Bundle Protocol, including Bundle Protocol version 7 (BPv7)[16], will be tested at various data rates. Experiments will connect the LCRD links to NASA-controlled cloud-based DTN nodes. Subsequent experiments will pursue connection to broader DTN test networks, including existing nodes at other NASA centers and nodes external to NASA. Once ILLUMA-T is on-orbit, the DTN experiments will include nodes onboard the ISS.

6. SUMMARY

The two-year LCRD Experiment Program began in early June 2022. Since LCRD is NASA's first mission to specify, build, launch, and operate an optical communications relay, the full experiment really started with the initial proposal. There were many lessons learned and experiences before launch[2]. As described in this paper, the on-orbit experiments are yielding both experiment data and operational experience. As the data continues to be collected, and as planned experiments occur, individual papers dedicated to specific experiments and results shall be published. This collection of results concerning all aspects of optical relay performance and operations will be of great value as NASA and others plan to incorporate optical communications links into their future systems.

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