NASA'S LASER COMMUNICATIONS RELAY DEMONSTRATION (LCRD) EXPERIMENT PROGRAM: CHARACTERIZATION AND INITIAL OPERATIONS

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ABSTRACT

The National Aeronautics and Space Administration's (NASA) Laser Communications Relay Demonstration (LCRD) completed the first 18 months of its Experiment Program in December 2023. Geosynchronous-ground experiments to date have included demonstrations of optimetrics and of Delay/Disruption Tolerant Networking (DTN), and measurements of the effects of the atmosphere on lasercom performance and availability. Future operational scenarios have been emulated. This paper provides an overview and highlights of the first 18 months of LCRD experiments, and a preview of the upcoming experiments, including relaying data to and from the International Space Station.

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

1. INTRODUCTION

The National Aeronautics and Space Administration's (NASA) Laser Communications Relay Demonstration (LCRD) completed the first 18 months of its Experiment Program in December 2023. During this time, LCRD performed experiments focusing on characterization of optical links and the system, as well as initial operations demonstrations. The LCRD mission architecture, which is designed to support a wide variety of experiments [1], is composed of flight and ground segments (see Figure 1). 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 (OST), OST1 and OST2, capable of simultaneous operation, as well as a data switch to interconnect the links for data relay. The ground segment includes two optical ground stations (Optical Ground Station 1, or OGS-1, in Table Mountain, California, and Optical Ground Station 2, or OGS-2, in Haleakalā, Hawaii) and a radio frequency ground station (RF GS) in New Mexico.

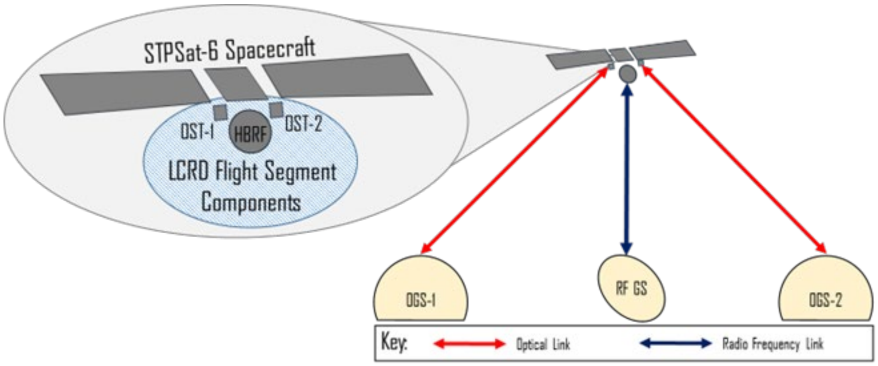


Figure 1. The LCRD mission architecture consists of a flight segment and a ground segment that will demonstrate two simultaneous bidirectional optical links.

Experiments to date have included measurements of the effects of the atmosphere (turbulence, weather) on the performance and availability of laser communications (pointing, tracking, data transfer, and adaptive optics), Doppler and ranging measurements (optimetrics), and Delay/Disruption Tolerant Networking (DTN) demonstrations. Furthermore, future operational scenarios including robotic and exploration missions with various network service configurations have been emulated.

This paper provides an overview and highlights of the first 18 months of the LCRD experiment program, availability statistics, lessons learned from daily operations, and a preview of upcoming experiments, including relaying data to and from the Integrated LCRD Low-Earth Orbit (LEO) User Modem and Amplifier Terminal (ILLUMA-T), an LCRD-compatible laser communications terminal on the International Space Station [2].

LCRD is a joint project involving NASA Goddard Space Flight Center (GSFC), the California Institute of Technology Jet Propulsion Laboratory (JPL), and Massachusetts Institute of Technology Lincoln Laboratory (MIT LL).

2. EXPERIMENT AND AVAILABILITY STATISTICS

LCRD schedules experiment sessions two weeks in advance, capturing all configuration parameters and timing of the experiments. LCRD operations are scheduled for forty hours a week, nominally for eight hours a day, five days a week. Completion of an experiment typically requires more than one experiment session. Each experiment requires at least one experiment session in which the LCRD system is configured to a particular combination of link settings and data is collected. In the context of LCRD experiment sessions, the term “link” refers to any activity involving pointing an LCRD OST for any combination of transmit or receive functions that can range from detection of light to full bidirectional communications.

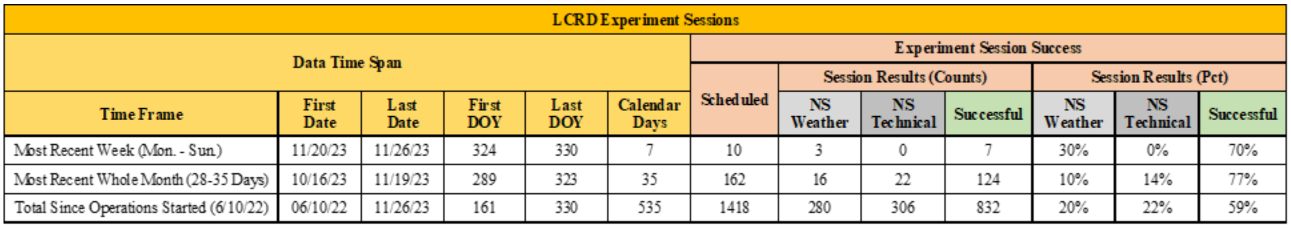
During execution, LCRD records the actual timing of the links and whether a session was successful. If a session is not successful, the reason why is also recorded.

2.1 Experiment Statistics

The LCRD experiment program includes 33 experiments. Twelve experiments are currently underway, two experiments have been completed and 19 experiments are currently in development.

As of November 26, 2023, the team has scheduled 1418 experiment sessions and successfully completed 832. Table 1 below shows the number of experiment sessions scheduled, as well as the number of experiment sessions executed. The LCRD team also tracks the number of experiment sessions that are attempted but not run for either weather (Not Successful [NS] Weather) or technical (NS Technical) reasons. Experiment session success indicates that the experiment session was configured and data was collected.

Table 1. Recent Experiment Session Statistics (June 10, 2022 – November 26, 2023)



LCRD Experiment Sessions												
Data Time Span						Experiment Session Success						
						Scheduled	Session Results (Counts)			Session Results (Pct)		
Time Frame	First Date	Last Date	First DOY	Last DOY	Calendar Days		NS Weather	NS Technical	Successful	NS Weather	NS Technical	Successful
Most Recent Week (Mon. - Sun.)	11/20/23	11/26/23	324	330	7	10	3	0	7	30%	0%	70%
Most Recent Whole Month (28-35 Days)	10/16/23	11/19/23	289	323	35	162	16	22	124	10%	14%	77%
Total Since Operations Started (6/10/22)	06/10/22	11/26/23	161	330	535	1418	280	306	832	20%	22%	59%

Gathering statistics for weather outages is a primary goal of LCRD. Thus, even if an experiment session is not achieved due to weather, it still successfully contributes towards this goal. As the statistics indicate, session success rate has been 59% for the full experiment period or 79% when counting sessions with weather outages as successful. Further discussion of the availability statistics and causes of unavailability follow in the next section.

2.2 Availability Statistics

The expected availability of future operational laser communications systems has been modeled and predicted for many years [3]. Unlike radio frequency (RF) communications, which can mitigate most weather-related outages with link margin, laser communications between ground stations and spacecraft can be interrupted by clouds. Mitigation approaches to reduce losses in ground network availability focus on having a network of multiple ground stations that are geographically diverse. LCRD provides the opportunity to collect empirical data for a two-ground-station network to inform future system requirements, designs, and expectations.

The LCRD team tracks availability of the various elements of the LCRD architecture: the flight payload, the optical ground stations, and the RF ground station. To be available to support a single lasercom user, at least one flight payload OST and the flight data switch need to be available, along with either an available optical trunkline or RF trunkline. An available optical trunkline requires an available flight payload OST and a single available optical ground station. An available RF trunkline requires an available flight RF terminal and an available RF ground station.

Availability of the various components of the flight relay payload includes the availability of the spacecraft itself and not just the availability of the component. For example, payload availability is reduced when payload operations are not possible due to spacecraft maneuvers, other operations, or unexpected spacecraft issues.

Likewise, the availability of the ground stations is reduced when systems are down for required maintenance and calibration activities or affected by hardware/software issues. Ground station availability is also affected by weather, which can significantly impact optical ground stations.

Since the various factors impacting availability calculations are not monitored at the same level during the unstaffed periods as they are during the 40 hours/week experiment operation periods, statistics are only calculated for the staffed time periods allocated for LCRD operations. The daily shifts are shifted in time over a thirteen-week cycle, so availability factors influenced by the time of day or the time of year will be better characterized as the LCRD experiment continues.

For the experiment period through December 6, 2023, the availability of the payload and ground stations independent of weather has been found to be approximately the following:

- Payload: 99.3%
- Optical Ground Station 1: 57.8%
- Optical Ground Station 2: 40.5%
- RF Ground Station: 99.2%

Factoring in the weather availability of 80%, the availability calculation aligns with the 59% experiment session success rate. These preliminary values are stated as approximate, because at the time of this writing, the data and calculations are under review. It is important to note that the flight hardware has not significantly impacted the overall availability.

The availability of the optical ground stations has been lower than expected. Besides weather outages, OGS-1 experienced some downtime to perform required improvements on its adaptive optics system. OGS-2 was unavailable for seven months due to maintenance issues. Both of these issues have been resolved, so the availability has been trending upwards. Excellent weather at the ground stations over the last few months and system upgrades have increased the fidelity of the data that has been captured in the second year of experiment operations. Weather outages are typically due to cloud cover or fog. Cloud blockage may be short-lived or intermittent, as with light cumulus clouds, or may persist for a full day or longer. Morning fog is a common occurrence at both OGSs, generally leading to relatively short-lived outages. When a heavy weather front moves in, a station can be out of service for days under persistent clouds. If a large snowstorm comes through, a ground station can be unavailable not only during precipitation and cloudy periods, but also during the time it takes to dig out the station (this scenario occurred at OGS-1 during the winter of 2022-2023). OGS-1 has also experienced an unusually wet winter; moreover, facility and road closures occurred due to wildfires and mudslides. Any natural disasters or other natural phenomena that lead to ground station outages are classified as "weather" outages.

3. SESSION OPERATIONS AND DATA EXAMPLES

Each eight-hour daily operating period for LCRD includes sessions of various types. In particular, LCRD experiments can involve three types of experiment sessions: one hour duration sessions, sessions of 3+ hour duration, or session schedules tied to real or simulated user visibility times. In a single day, multiple optical link configurations can be run in varying atmospheric conditions. Therefore, the one-hour sessions are repeated many times throughout the year to collect long-term trends. The 3+ hour duration sessions usually are for specific experiments or calibrations, and they may require more complex commanding.

At the beginning of each daily operating period, the lasercom ground and flight subsystems need time to warm up, and required trending measurements and/or complete calibration activities must be performed. Part of the experiment activity is to learn how to refine the timing and sequencing of these start-up activities.

LCRD experiments can also support sessions with user terminals (real or simulated). These sessions include setting up an optical trunk line to the ground to support multiplexed user service data flows, and then ensuring this link is stable prior to establishing the link with the user. This procedure is followed by configuring for a proximity link between LCRD and each user platform.

The LCRD flight and ground segment teams perform a series of operational processes to coordinate experiment execution. Each week the teams hold a scheduling meeting to review near-term schedules (for the upcoming week) and future activities (for the next week). This process allows the different LCRD teams to perform resource deconfliction, schedule maintenance activities, and account for planned outages. Additionally, the teams meet each morning to review the planned experiments for the day, reschedule activities when necessary (e.g., due to forecasted weather conditions), and plan for near-term changes to the schedule that have arisen since the weekly meeting.

The process of establishing an optical link includes some manual preparatory steps, followed by the automated steps of acquisition, tracking, and clock and frame synchronization. The OSTs are pointed at their estimated target locations, and the modems are taken through warm-up procedures. These preparations maximize available link time with user terminals. Once the spatial acquisition between the two telescopes occurs, the automated acquisition sequence begins, and the telescopes cooperatively interact as they search for each other's optical signals. On a good day with no pointing or interference issues, the acquisition and entry into fine tracking occurs within seconds. Depending on the quality of the link, it generally takes 30 – 45 seconds for the two modems to negotiate and achieve clock and frame synchronization. Once the modems are synchronized, data services can flow – i.e., the two terminals can exchange user data frames.

3.1 LCRD Operation Scenario

This section briefly describes an operation scenario, and for convenience, depicts the operations at OGS-1 at Table Mountain, California. The data shown below refer to the LCRD operations on September 5, 2023.

At the beginning of each session, a link is established between the ground station and the LCRD payload. To do so, the ground station uplink beacon is pointed toward the STPSat-6 spacecraft, whose ephemeris is derived by a two-line element (TLE) file provided at the beginning of operations. In the case of OGS-1, the uplink beacon signal is composed of four beams, each with beam divergence in excess of 200 microrad. The four beacon beams are mutually incoherent and spatially separated over the telescope's one-meter primary mirror to compensate for and reduce signal fading generated by optical turbulence (see Figure 2). The LCRD payload terminal acquisition system is composed of a quad detector able to detect and discriminate the direction of the uplink beacon signal. This initial acquisition phase is named "coarse track," and allows the downlink signal to point towards the optical ground station. In the case of the OGS-1 facility, the downlink signal is first acquired by a tracking camera with a large field of view and then the downlink signal is relayed to the integrated optical system (IOS) that directs the downlink optical signal to the ground modem.

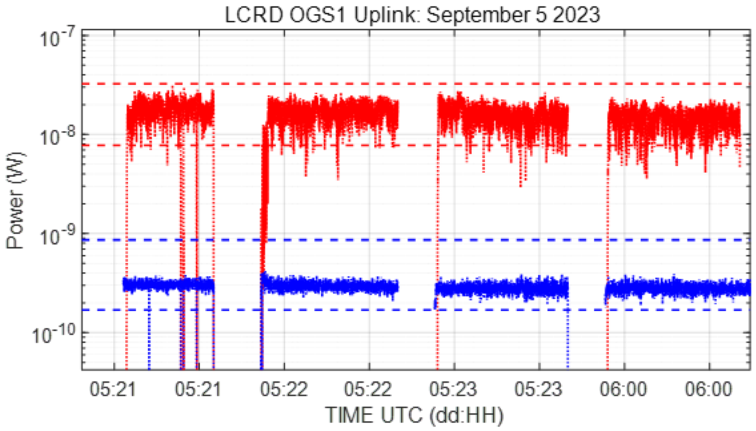


Figure 2. LCRD uplink beacon power (blue) and uplink communications power (in red) from LCRD OGS-1 at Table Mountain on September 5, 2023. The uplink beacon signal is composed of four beams in spatial diversity to reduce the

overall fading at the spacecraft. The uplink communication signal consists of a single beam. The plot depicts four sessions of approximately one hour each.

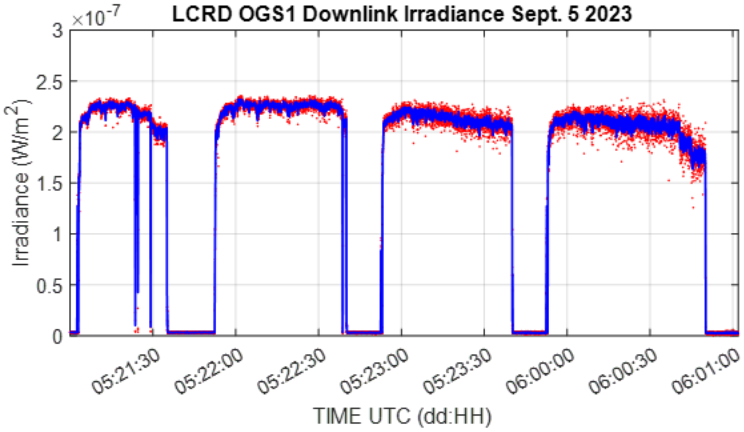


Figure 3. LCRD downlink irradiance at LCRD OGS-1 at Table Mountain on September 5, 2023. Four sessions of approximately one hour each are represented. The downlink irradiance is measured by a calibrated camera used as a wavefront sensor of the OGS-1 adaptive optics (AO) system.

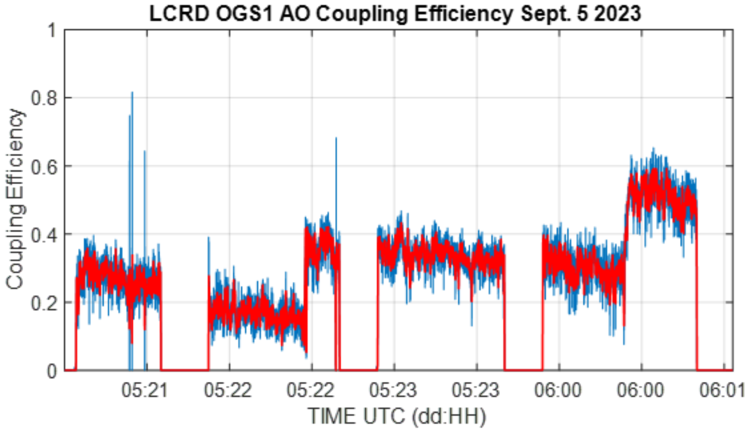


Figure 4. LCRD OGS-1 Adaptive optics coupling efficiency measured on September 5, 2023.

OGS-1 monitors the downlink irradiance using both a calibrated sensor located at the focus of a coaligned 20-cm telescope and a fast camera used as a wavefront sensor (WFS) of the ground station adaptive optics system (AO) (see Figure 3). As the ground station is tracking the downlink signal, the uplink communication beam is enabled and then tracked by the LCRD terminal that passes into the 'fine track' stage. The uplink communication signal (see Figure 2) consists of a single beam of relatively narrow divergence of approximately 20 µrad that is using a tip/tilt correction [4] to offset the beam wandering and part of the uplink signal fading caused by the optical turbulence along the uplink path.

The OGS-1 IOS adaptive optics system is needed to correct the signal optical aberration caused by the atmosphere's optical turbulence and to inject the downlink signal into the single mode fiber (SMF) at the input of the ground modem/receiver [5]. The ratio between the optical signal power injected into the modem SMF and the optical power available before the signal coupling is the AO coupling efficiency. The AO coupling efficiency depends, among other things, on the strength of optical turbulence, and it may change during the day and during each session during the day of operation (see Figure 4).

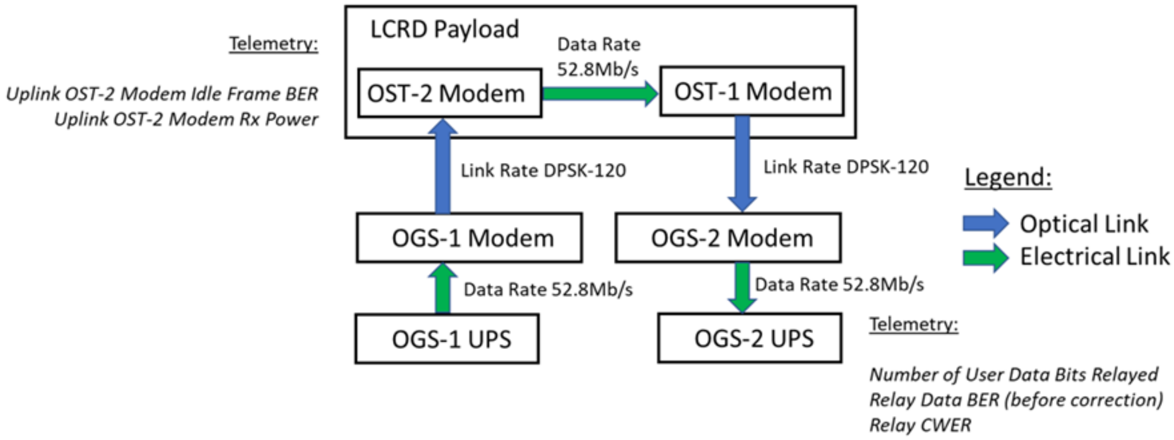
3.2 LCRD Performance: November 17, 2023

During year two of experiment operations, data relay linkups between OGS-1 and OGS-2 have become routine. As an example, this section describes the relay link operations on November 17, 2023, a nighttime link that presented favorable atmospheric conditions; the atmospheric coherence length averaged 4 cm, and the coupling efficiency in the AO subsystem was 35% at OGS-1.

A 35-minute bidirectional relay was established with data flows as illustrated in Figure 5. Figure 5a shows a schematic representation of the relay link from OGS-1 to OGS-2 via the LCRD payload. Figure 5b shows a schematic representation of the simultaneous reverse link. Differential Phase Shift Keying (DPSK) modulation with an uncoded data rate of 360 Mbps and a user rate of 158.5Mbps was used for the OGS-2 to OGS-1 link, which relayed more than 300 Gbits of error-free data. A DPSK modulation with uncoded data rate of 120 Mbps and a corresponding user rate of 52.8 Mbps was used for the OGS-1 to OGS-22 link delivered over 100 Gbits at a satisfactory error rate.

Link performance metrics captured at various points along the signal paths confirmed nominal operations for November 17, 2023. Averages are summarized in Table 2. The 160-second snapshots in Figure 6 illustrate typical variability.

a) Relay #1: Data flowing from OGS-1 to OGS-2



b) Relay #2: Data flowing from OGS-2 to OGS-1

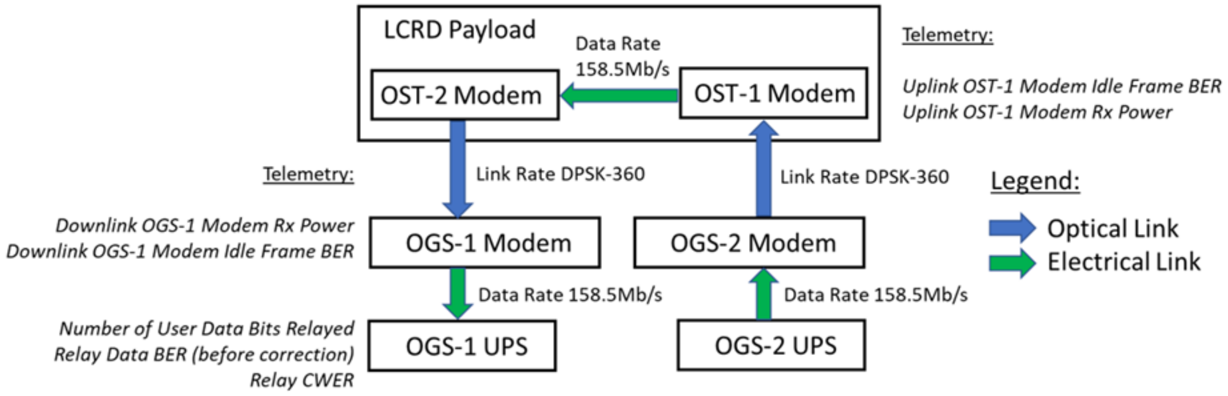


Figure 5. Relay Data Flow Diagrams. a) Relay #1: Data flowing from OGS-1 to OGS-2, b) Relay #1: Data flowing from OGS-1 to OGS-2.

Table 2. Summary of Results from Relay Experiment on November 17, 2023.

Performance Parameter	**Units**	**OGS-1 to OGS-2 Relay**	**OGS-2 to OGS-1 Relay**
Link Rate	Mbps	120	360
User Data Rate	Mbps	52.845	158.535
Average Uplink Modem Rx Power	dBm	-47.1	-54.3
Average Uplink Modem Idle Frame Bit Error Rate (BER)		9.0E-04	2.7E-03
Average Downlink Modem Rx Power	dBm	Not Available	-45.9
Average Downlink Modem Idle Frame BER		Not Available	1.0E-06
Average Relay Data BER (before correction)		8.9E-04	2.5E-03
Relay Code Word Error Rate (CWER) (Required < 1E-4)		6.9E-05	0
Time duration of link	Minutes	35	35
Volume of User Data Bytes Relayed	GByte	13.8	21.6

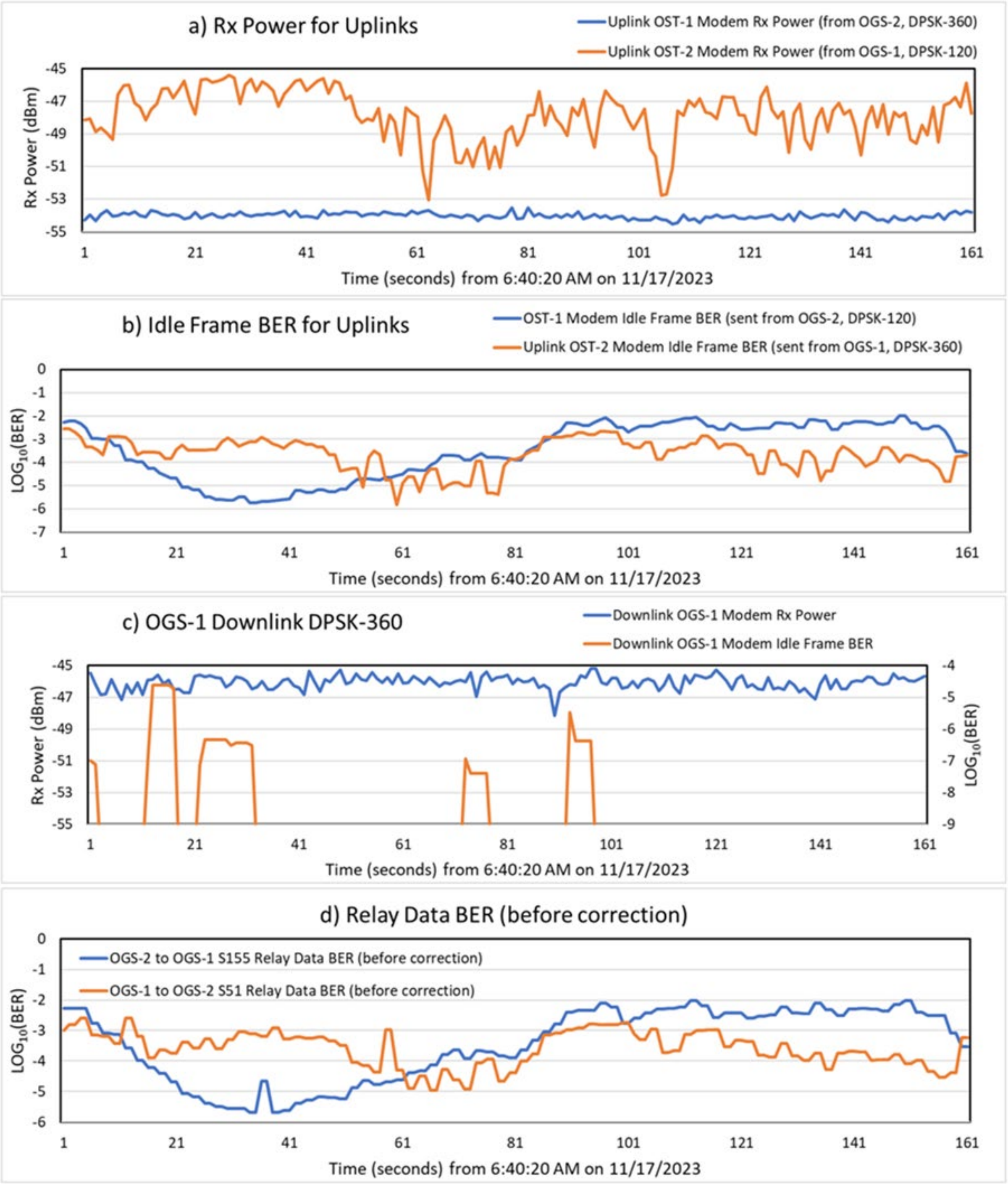


Figure 6. Telemetry from a typical 160-second period. a) Power Received at the flight modems for the uplinks, b) Idle Frame Bit Error Rates (BER) detected by the flight modems for the uplinks, c) Rx Power and BER for the downlink at OGS-1 (There is no data for OGS-2), d) Relay Data BER (uncorrected) for the two relay links, as measured by the CODECs.

4. LESSONS LEARNED

One of the goals of the LCRD mission is to gain experience operating an optical relay for extended periods. The following section describes a few of the lessons learned from operating the relay.

4.1 Wavelength and Pointing Calibration

One key lesson learned is the importance of periodic wavelength calibrations, because lasercom system performance degrades sharply with detuning. The LCRD team learned that it is beneficial to anticipate drift and correct based on trend lines (updating as necessary) instead of waiting for performance to degrade. The tuning process is not instantaneous, and the system can become out of tune while waiting for updates.

Temperature swings can cause performance issues maintaining the transmit and receive laser wavelengths. During activation, numerous heater on/off setpoints had to be adjusted to a narrower margin than originally anticipated to account for the temperature swings.

In addition, temperature swings of more than a few degrees in the payload optics cause noticeable alignment effects, which in turn degrade pointing and system performance. However, LCRD maintains a tightly controlled temperature range, and pointing calibrations were not needed during the entire first year of operation, following the initial post-launch calibrations. Pointing was recalibrated prior to the ILLUMA-T mission experiments.

4.2 Ephemerides and Two-Line Elements with Geosynchronous Satellites

Space-based laser communications require precise pointing and targeting knowledge. Both endpoints of the link have very narrow fields of view, and if either side is pointing incorrectly, the terminals may not be able to establish a link. Orbital ephemerides come in differing formats and precisions. A format that works well describing one type of orbit may not work well with another. For instance, for Radio Frequency (RF) communications systems, standard Simplified Perturbation Generation model 4 (SPG4) propagators work well for Low Earth Orbits (LEO) and are adequate for geosynchronous Earth orbits (GEO). The pointing margins for RF systems are large enough to overcome the errors in satellite location knowledge. But the accuracy for GEO Two Line Elements (TLE) using the SPG4 propagator is not within LCRD's baseline pointing/targeting margin, which is low since LCRD employs narrow beams. The TLE-derived propagated error has at times been more than three times the LCRD margin, which has resulted in significant time spent searching and applying corrections to establish links. There are improved TLE algorithms, but all propagators in the system must use the same algorithm.

Additionally, post-orbital-maneuver orbital determination requires enough data (and time) to converge on a solution, and the change in orbit (and location) that occurs between the maneuver time and the time when an Orbital Determination (OD) solution is determined can make it difficult to locate the target. The greater the time difference between the two, the more difficult target location is until the OD is completed and provided to the ground stations.

Much greater success (and much smaller error) has been achieved when using orbital ephemeris messages (OEMs) [6]. The difference between a predicted and definitive (actual) ephemeris has been well within the LCRD pointing budget. An additional benefit is that OEMs can include modeled maneuvers, whereas the TLEs only define a moment in time.

4.3 Star Tracker Placement

For accurate pointing, the Optical Space Terminals (OSTs) rely on ephemerides of the host vehicle, Global Positioning System (GPS) coordinates of ground stations, and very accurate vehicle attitude information from the orbiting host vehicle. An OST does not have a large margin for pointing errors, due to the very narrow field of view of the acquisition sensors on the telescope. A star tracker may be used on a host vehicle to determine vehicle attitude. For lasercom, it is important that the star tracker be located as close as possible to the optical modules in the OSTs. Any significant flexure of the vehicle, perhaps due to thermal gradients, could prevent the lasercom acquisition sensors in the OSTs from seeing incoming laser signals. The flexing of the satellite body is not constant; it varies with the environmental conditions and is not easily compensated for on-orbit. The LCRD team has observed that the difference between the readings from the two star trackers mounted at different locations on the STPSat-6 host vehicle can be greater than three times the acquisition field of view, which exceeds the pointing budget margin. There are methods to overcome some of this pointing error by performing scanning patterns, but this additional scanning increases acquisition time.

4.4 Links During Space Vehicle Maneuvers

Satellite thruster use can result in LCRD payload down time (i.e., the OSTs are not available to provide optical communication links). The STPSat-6 host vehicle performs two types of routine operations that use thrusters: station-keeping maneuvers and momentum unloads (using thrusters to dump excess momentum stored in the reaction wheels). During station-keeping maneuvers the LCRD payload loses its command and telemetry link (which is via RF), and the duration of the outage depends on the magnitude of the maneuver. Since LCRD operators do not have visibility into the health of the relay during these outages, the OSTs are not operated during station-keeping maneuvers.

In contrast to station-keeping maneuvers, momentum unloads cause minimal disruption to LCRD. There is often a brief loss of tracking capability, but the lasercom system reacquires automatically. In fact, there have been a number of instances in which LCRD has not lost signal at all during a momentum unload.

5. EXPERIMENTS AND DATA ANALYSIS HIGHLIGHTS TO DATE

5.1 Optical Communication and Atmospheric Optical Turbulence (LCRDEX-2)

During LCRD operations the optical turbulence at OGS-1 is continuously monitored via Fourier analysis of the modulation transfer function (MTF) of the downlink signal point spread function (PSF) at the focal plane of the optical ground system downlink signal acquisition camera [7]. During operations, OGS-1 performs measurements of the atmospheric coherence length (also known as the Fried parameter, or r0) at 1 Hz and archives the data in the mission operation database. Because LCRD operations were performed over the last eighteen months at different times of the day, it was possible to extensively characterize the daily and seasonal variation of the Fried parameter at OGS-1 at the Table Mountain Facility (see Figure 7). The strength of the optical turbulence manifests itself in a different fashion on the uplink and downlink paths of the optical link. Strong optical turbulence, corresponding to small values of the Fried parameter, affects the capability of the ground station adaptive optics system to couple the downlink optical signal into the ground modem input SMF. Strong optical turbulence also affects the capacity to deliver a reliable uplink communication beam to the LCRD payload, because it can cause large signal fading and beam wander.

The LCRD downlink signal can also be considered as a fixed source or signal beacon of near-infrared light in the 1550 nm wavelength range that originates outside Earth's atmosphere, and thus it can be used to characterize optical turbulence via other existing measurement techniques that employ star irradiance. For example, a dedicated Ring-Image Next Generation Scintillation Sensor (RINGSS) [8] was developed and deployed at OGS-1 to measure the profile of the optical turbulence. Details about RINGSS at OGS-1 are presented in another paper at this conference [9].

During experiments, LCRD uplink and downlink performance are quantified and tested against the atmospheric coherence length to correlate the interaction between the strength of the optical turbulence and the optical communications beams.

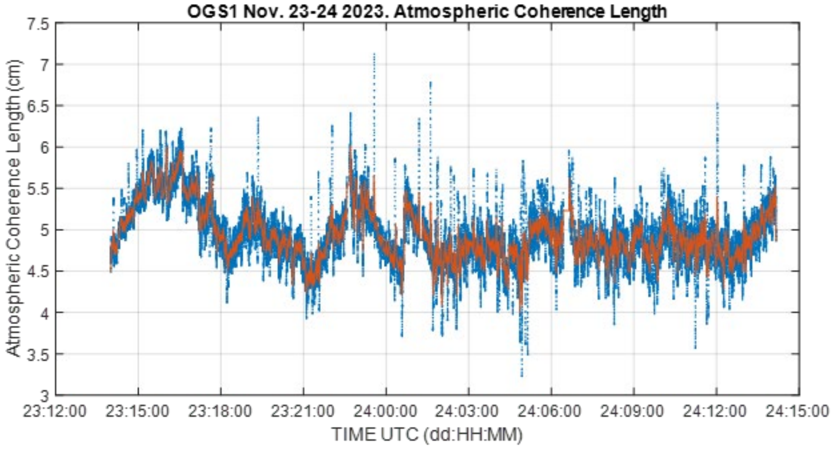


Figure 7. Atmospheric coherence length measured at OGS-1. The atmospheric coherence length is referred at zenith at 500 nm. Measurements were taken during LCRD's extended operation cycle and they cover approximately 24 hours. Measurement cadence is 1 Hz, but the figure shows 30-second (blue) and 120-second (red) averages.

5.2 Optimetrics (LCRDEX-20)

The optimetrics experiment seeks to use the optical communications link between the LCRD space terminal in geosynchronous orbit and OGS-1 at Table Mountain, California to perform precision, two-way ranging measurements. Full details of the experiment and results are described in a paper that will be presented at the 2024 Institute of Electrical and Electronics Engineers (IEEE) Aerospace Conference [10].

5.3 Adaptive Optics (LCRDEX-4)

The main metric used to characterize the adaptive optics (AO) system at LCRD optical ground stations is the system coupling efficiency, which is the measure of the downlink signal coupled into the ground modem's input SMF. For example, OGS-1's AO system experiences a large variation of the strength of the optical turbulence, with a Fried parameter as low as 2 cm (at 500 nm at zenith) during daytime around noon. Under these conditions of strong optical turbulence, it is very difficult for the OGS-1 AO system to provide constant and sufficient coupling efficiency. However, the AO system can be tuned to optimize the final optical signal coupling efficiency by changing its configuration parameters. For instance, the AO wavefront sensor consists of a near-infrared camera with a variable frame rate. The frame rate of the camera can be varied from a lower useful limit of 2 kHz up to a limit of 20 kHz. The LCRD team determined that in most cases a frame rate of 5 kHz or 10 kHz is adequate for the system to generate the optical compensation necessary to reduce the dynamical optical aberration generated by the optical turbulence. Generally, the coupling efficiency varied from a few tens of percent to a high of fifty percent, which may be reached in conditions of relatively benign optical turbulence that sometimes occur during nighttime operations.

5.4 Saber (LCRDEX-146)

The Saber optical ground-terminal (OGT) built by The Aerospace Corporation demonstrated an optical communication link with the OST without the assistance of any optical downlink signal (see Figure 8). Saber OGT pointing and data throughput was coordinated via online communications in real time and assessed via user data retrieved from the LCRD telemetry archive for post-pass analysis.

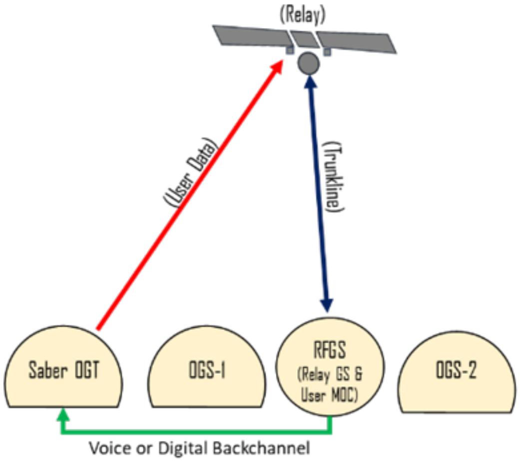


Figure 8. LCRD and Saber System Configuration.

Completed Saber test cases included the following:

- Open loop pointing, tracking, and illumination of the LCRD OST
- Transmission of frames from Saber to RF GS at data rates of 51.8, 155, 311, and 622 Mbps
- Characterization of the link via fill frames for 51.8, 155, 311, and 622 Mbps rates and user data BER for 51.8 Mbps rate (to date)
- Multiple 10- to 30-minute link engagements completed during a nominal four-hour window

- Link execution during the day and night

For a detailed description of the Saber experiment, see another paper presented at this conference [11].

5.5 Low-Cost Optical Terminal (LCRDEX-155)

A series of LCRD sessions involving the Low-Cost Optical Terminal (LCOT) built by GSFC have been planned. Phase 1—calibration with a far-field laser source—occurred this past fall. The LCRD OST open-loop pointed to LCOT and illuminated the ground station with the communications beam. LCOT team members used an infrared camera to capture video of the communications beam and achieve first light with LCRD (see Figure 9).

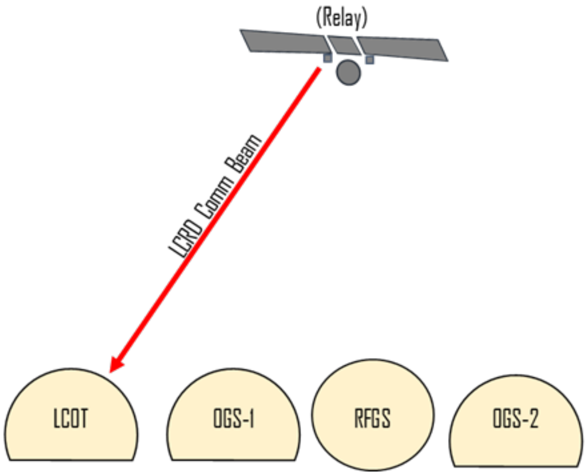


Figure 9. LCRD and LCOT System Configuration.

Planned follow-on activities include pointing characterization with the LCOT beacon subsystem and full bidirectional optical communications between LCOT and an LCRD ground modem.

5.6 Data Services Using Optical Links (LCRDEX-156)

This experiment is the first in a series of experiments that go beyond link investigations. The focus of this experiment is to operate the LCRD system as a lasercom relay service provider. The experiment sessions configure one of the optical ground stations as a simulated user, while another ground station supports a trunk line (see Figure 10). All the available selections for modulation and data rates are exercised. LCRD can support data services ranging from bitstream services to link layer frame services. These data services are also all exercised within this experiment.

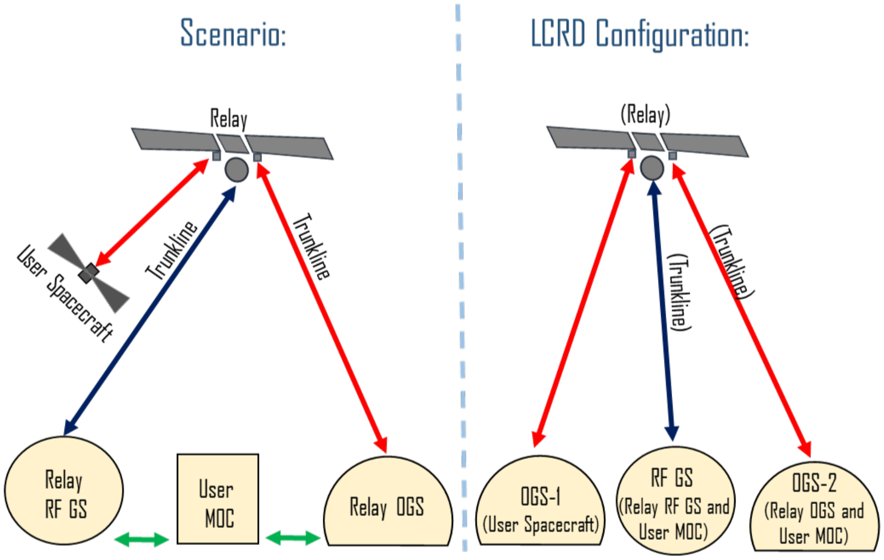


Figure 10. LCRD configuration for user relay simulations

Experiment sessions so far have been successful. Besides demonstrating the capability of all systems involved, these sessions have allowed the LCRD operations team to begin viewing the LCRD system as a service provider system and become more proficient in the service provider role. These sessions also identified parts of the system that were unused in previous experiments that must be available to determine service provider availability metrics.

5.7 LEO Simulation (LCRDEX-101)

This experiment simulates links with a satellite in low Earth orbit using one of the LCRD optical ground stations as a stand-in for the satellite. The goal of the experiment was to test tools, processes, and configurations for performing links with a simulated LEO target. One of the ground stations was configured as if it were the ILLUMA-T, and the duration of the links was based on orbital parameters of a representative low Earth orbit.

These experiment sessions have been successful and have proven to be excellent preparation for the support of ILLUMA-T. The operations team began to experience the rhythm of providing regular services to an orbiting user. Now that ILLUMA-T has launched, these experiments will continue with growing complexity to add multiple users into the schedule.

5.8 Delay/Disruption Tolerant Networking (DTN) (LCRDEX-60)

DTN is a suite of protocols designed to enable the Solar System Internet (SSI), analogously to the way the Internet Protocol (IP) suite enables the Internet [12]. Three major thrusts of NASA's DTN project are research, development, and as DTN matures, operations. LCRD is in a unique position to intersect with all three of these objectives.

Indeed, if LCRD were to be used as a relay between two networks using DTN as a networked communications solution, DTN must both be able to operate at LCRD's data rates (i.e., DTN must not be the bottleneck) and facilitate end-to-end network data services. These factors push the research and development of DTN in terms of performance and capability respectively, but are largely focused on point-to-point data delivery. To take this a step further, consider an external user (satellite) that uses LCRD and its three geographically diverse ground stations as a service provider; in this case, use of DTN means the user does not need to be aware of which ground station is scheduled (or used in a handover), thereby simplifying operations. A series of LCRD DTN experiments has been designed to build, test, refine, and operate such a network capability.

DTN exists as an overlay network, capable of uniting an extremely heterogeneous collection of nodes and underlying link protocols. The first LCRD DTN experiments used JPL's implementation of DTN, the Interplanetary Overlay Network (ION), to demonstrate DTN's ability to provide robust data transmission as shown in Figure 11. Here the operator at GSFC uses the Integrated Test and Operations System (ITOS) to control the flow of bundles (the primary unit of data in DTN) from Host 1 to Host 2. The data path involves LCRD in loopback mode communicating with OGS-1. The DTN hosts connect to the LCRD ground stations through a High-level Data Link Control (HDLC) Encapsulated Interface for Data Interchange (HEIDI), which provides bitstream compatibility with existing LCRD ground systems. These particular tests were conducted at local noon, when the noise is at its highest, to induce natural packet loss. Ultimately, DTN was able to provide reliability mechanisms over the intentionally lossy channel, resulting in 100% data delivery.

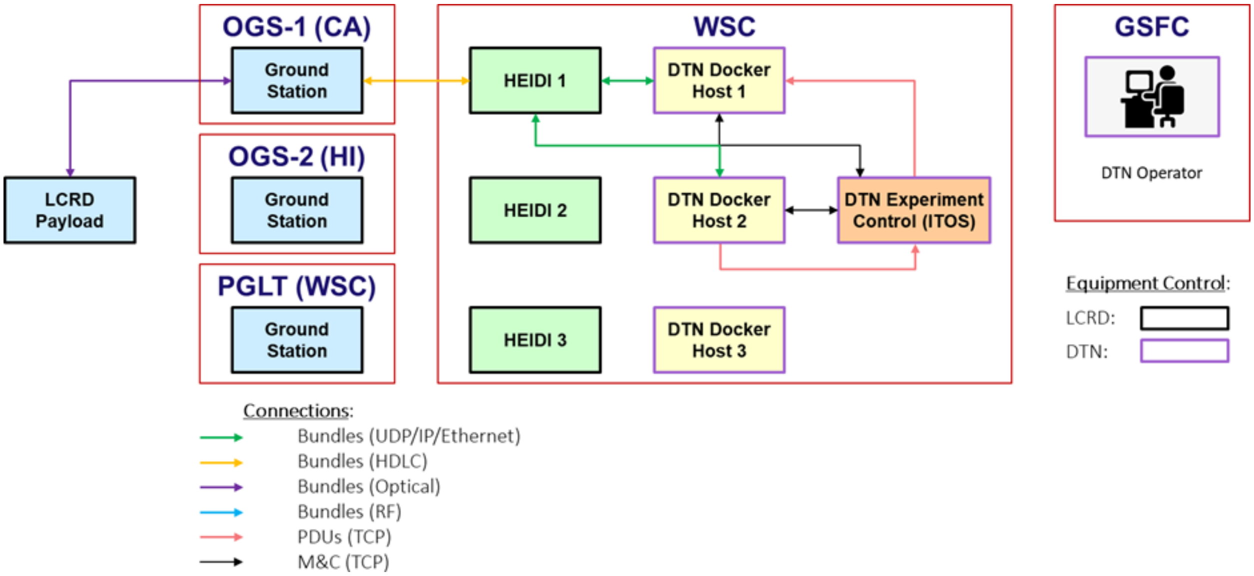
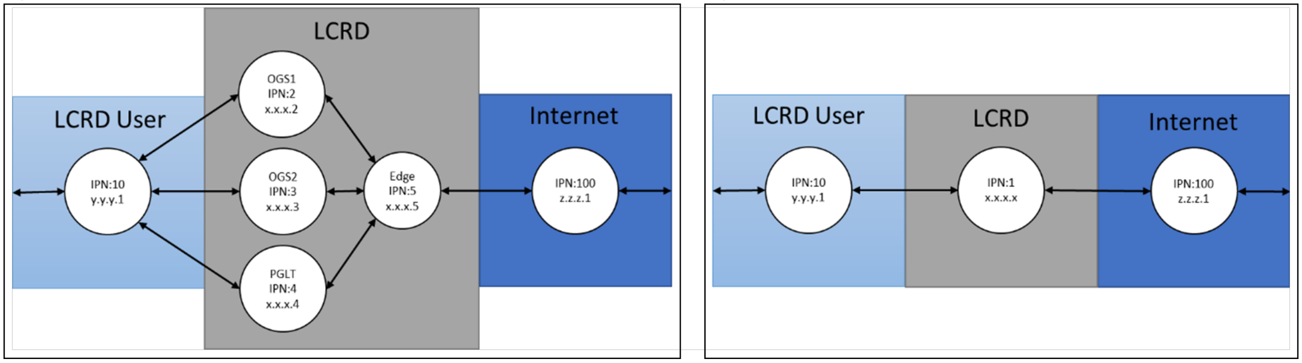


Figure 11. LCRD experiment environment.

Future DTN experiments to build on this success by using DTN implementations that are optimized for performance (i.e., High-rate DTN, or HDTN) are currently planned. These experiments will showcase high-rate DTN, Bundle Protocol security (BPsec), DTN video streaming, and increased reliability by using reliable transport. For detailed information on the experiments conducted and planned, see reference [13]. Once these point-to-point capabilities are proven, higher-scale experiments in the spirit of networked connectivity can be performed.



a) Link Schedule Details Distributed

b) Link Schedule Details Obscured

Figure 12. LCRD configuration options for DTN support

Consider a satellite user that wishes to make a connection to the Internet (a closed network with appropriate security controls). One approach using LCRD is to have a globally distributed, globally consistent link schedule that includes such details as which ground station will be used at what times (see Figure 12a). While this scenario would work, a more desirable configuration would be to obscure the particulars of the LCRD subnetwork from the user (see Figure 12b). In this scenario, the scheduled links and actual links (e.g., handover due to obscuration/weather) are immaterial to the user, which only needs to know details regarding its link with LCRD. The controls internal to the LCRD box in the diagram are based on available telemetry. Control of the systems along with necessary DTN functionality (i.e., routing) are currently under development to provide this type of service. LCRD provides an excellent test bed for supporting the test and demonstration of these capabilities.

6. A SAMPLING OF UPCOMING EXPERIMENTS

6.1 Large File Transfer with MIT Haystack Observatory (LCRDEX-171)

This experiment will explore transmitting real-world Very Long Baseline Interferometry (VLBI) data via lasercom. VLBI is a technique used in radio astronomy and geodesy that combines measurements from antennas located far away from each other. In the field of radio astronomy, VLBI was used to create the first image of a black hole by the Event Horizon Telescope (EHT). In the field of geodesy, VLBI is a key technique used to determine Earth's reference frame and orientation in space. Unlike many other types of data, VLBI data is uniquely tolerant to certain types of losses. This experiment will transmit data over a wide variety of weather and atmospheric conditions, and will explore turning off traditional error correction layers to achieve faster data transfer. The overall goal is to build up a database of performance vs. atmospheric properties and to push the limits of lasercom's potential speed and VLBI's loss tolerance.

In this experiment, data previously collected from geographically diverse antennas during the same time interval will be transmitted over the LCRD relay under various channel conditions. Data integrity will be evaluated, and correlations (fringes) between data sets from different locations will be compared to results obtained using traditional methods.

6.2 Handover Operations (LCRDEX-217)

Ground station spatial diversity will be a key enabler for operational atmospheric lasercom systems. LCRDEX-217 will demonstrate handovers where the relay transitions from sending and receiving data to/from one ground station to sending and receiving to/from another ground station. The experiment will involve not only exercising handovers, but also exploring ways to streamline and optimize handover operations. The first experiment configuration will involve the RF GS emulating a user and one of the OGSs providing the trunkline. The handover will transition the trunkline to the other OGS. The second configuration to be demonstrated calls for the user to be emulated by one OGS with two trunklines—one to the RF GS and the other to the other OGS. Due to the impact of weather on optical links, unplanned handovers are an expected part of future operations. Determining methods to execute handovers with minimal loss of user data is the primary goal of this experiment.

6.3 Link Budget Ver/Val (LCRDEX-195)

The LCRD mission can accommodate two kinds of modulations for optical communication: binary differential phase shift keying (DPSK) modulation with data rates from 2880 Mbps to 72 Mbps, and pulse position modulation (PPM) with data rates from 720 Mbps to 240 Mbps. LCRD also implements Digital Video Broadcasting Satellite Second Generation (DVB-S2) forward correction coding [14] for both modulations with channel interleaving to mitigate signal fading.

Before the LCRD launch, link budgets describing all the modulations and data rates were studied and defined using simulations of the atmospheric optical channel and laboratory test data. The initial assessment of the link budgets included transmitter and receiver performances for both uplink and downlink paths, code performances, and effects of the interaction between the propagating beams with the atmospheric optical channel, including fading and the quality of the correction of downlink signal using the OGS AO system [15].

Several experiments are planned to verify and validate existing LCRD link budgets for all modulation formats and data rates. One of the approaches to be used will examine varying the transmitter power of the uplink and downlink beams over time to test and verify the link margins. This approach will allow the receiver detection threshold to be assessed while the code performance is verified. To understand their impact on the links, the atmospheric optical channel will be carefully monitored by dedicated sensors, such as those in the atmospheric monitoring channel (ACM) deployed at OGS-1 [16]. Furthermore, the experiments will be performed at different times of the day to experience the different strengths of optical turbulence that occur during the diurnal cycle and the season.

The results from this set of experiments will improve the understanding of the optical communication performance of the LCRD mission and, in general, will be beneficial to the planning of future Earth-to-space-based optical communication missions.

6.4 ILLUMA-T (LCRDEX-27)

On November 9, 2023, the Integrated LCRD Low Earth Orbit User Modem and Amplifier Terminal (ILLUMA-T) was launched and integrated with the International Space Station (ISS) [17]. Together, LCRD and ILLUMA-T constitute NASA’s first end-to-end optical communications relay system (see Figure 13).

LCRD and ILLUMA-T successfully made their “first light” connection on December 5, 2023. LCRD and the ILLUMA-T terminal have begun a six-month experiment campaign designed to explore physical layer performance, pointing and acquisition performance, operational parameters, networking, and user data flows. Though the LCRD payload was designed to be able to communicate with an orbital user, this is the first opportunity to demonstrate that capability. The narrow beamwidths for both the LCRD and ILLUMA-T optical links make the pointing, acquisition, and tracking (PAT) extremely challenging.

Previous experiments simulating relay operations can be taken a step further with an orbiting user. The planned maximum data rates up to 1.244 Gbps on the return link from the ISS and a forward link to the ISS of up 155 Mbps have been demonstrated. Following further tests fully exercising and demonstrating the PAT and physical layer capabilities, a series of networking experiments is planned. These networking experiments will include both the use of Internet Protocol (IP) and DTN. Beyond demonstrating basic network functionality, demonstration of various applications communicating possibly with multiple terrestrial endpoints is being considered.

Figure 13. LCRD and ILLUMA-T Optical Communications Relay System.

7. CONCLUSIONS

The first year and a half of LCRD experiment operations has been busy and productive. As expected, operating a lasercom relay has yielded lessons that could only come from experience. The team has learned and adapted such that system availability is always increasing. The flight hardware has performed very well and continues to not contribute significantly to any losses in availability. In fact, the flight system has, in a lot of ways, proven to be the most reliable part of the overall mission architecture. It has become clear that more than two ground stations built for regular operations would be required to meet the >99% availability usually expected of a communications provider. Data analysis has begun with the goal of revising models, link predictions, and availability metrics.

The LCRD architecture has been proven to be a testbed capable of supporting a diverse set of experiments. A variety of experiments have been completed, generating papers on topics ranging from optical link performance to optimetrics and networking. The experiments performed are shifting from fundamental link and technology demonstrations to operational demonstrations. The most significant of these operational demonstrations will be the many experiments planned with the ILLUMA-T onboard ISS.

The two-year experiment phase ends in June 2024. Starting July 2024, the LCRD payload will continue to execute characterization and operations studies. The LCRD Guest Experiment Program will remain open. More information about the LCRD experiment program is available on the NASA Opportunities for Experimenters webpage [18].

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