NASA'S LASER COMMUNICATIONS RELAY DEMONSTRATION EXTENDED EXPERIMENT PROGRAM: RECENT RESULTS

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ABSTRACT

The National Aeronautics and Space Administration's (NASA) Laser Communications Relay Demonstration (LCRD) project has been an experimental program, operating since June 2022. The LCRD geosynchronous payload includes two laser communications terminals, and an RF communications link provided by the host satellite, STPSat-6. The terminals are interconnected via an onboard electronic switch. The payload can relay information between any of three ground stations. Optical ground stations are located in California and Hawai'i, and an RF ground station is located in New Mexico.

Experiments to date have included collection of telemetry characterizing the performance of laser communications links, including the impacts of the daily and seasonal variation of optical turbulence, while systematically varying link parameters such as data rate, uplink/downlink transmit power levels and channel interleaver depth. Other activities have included optical relay links connecting the International Space Station with ground terminals, use of an optical link to command and telemeter the LCRD payload instead of a traditional RF link, emulation of user data service scenarios, and characterization of optical space telescope (OST) pointing performance. This paper provides an overview of the experiment program, highlights of recent experiments, and a short description of future activities.

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

Keywords: Free Space Optical Communications (FSOC), lasercom, communications relay, Delay Tolerant Networking (DTN), channel interleaver, laser beam profile characterization, atmospheric optics

1. INTRODUCTION

The National Aeronautics and Space Administration's Laser Communications Relay Demonstration completed its initial two-year experiment program in June 2024. Since then, it has been operating in an extended experiment phase, continuing long-term trending experiments, and supporting new experiments.

A summary of the two-year experiment campaign was published previously [1]; this paper provides an updated summary to include the experiments performed during the extended experiment campaign.

Experiments to date have included collection of telemetry characterizing the performance of laser communications links, including the impacts of the daily and seasonal variation of optical turbulence, while systematically varying link parameters such as data rate, uplink/downlink transmit power levels and channel interleaver depth. Other activities have included optical relay links connecting the International Space Station with ground terminals, use of an optical link to command and telemeter the LCRD payload instead of a traditional RF link, emulation of user data service scenarios, and characterization of optical space telescope (OST) pointing performance. This paper provides an overview of the experiment program [2], highlights of recent experiments, and a short description of future activities.

2. LCRD ARCHITECTURE AND MISSION

The LCRD mission architecture comprises flight and ground segments (see Figure 1). The flight segment is hosted by 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), OST-1 and OST-2, 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, at Table Mountain, California, and Optical Ground Station 2, or OGS-2, at Haleakalā, Hawai'i), and a radio frequency ground station (RF GS) at NASA's White Sands Complex (WSC) in New Mexico.

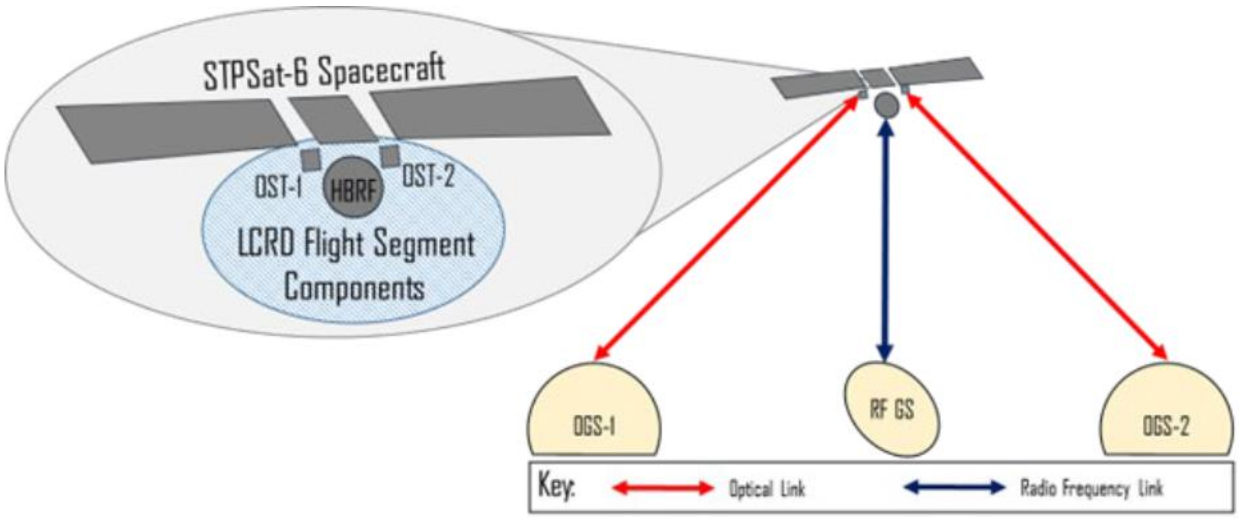

Figure 1. The LCRD mission architecture consists of a flight segment and a ground segment that have demonstrated two simultaneous bidirectional optical links, and three simultaneous bidirectional physical links (two optical and one RF).

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3. LCRD CAPABILITIES AND EXPERIMENTS

The LCRD payload facilitates laser communication with its use of two OSTs, a switch, and an RF communication link (provided by the host vehicle). Each of these physical communication links can multiplex multiple user data streams, providing a communication trunkline capability. A trunkline is a shared physical link for multiple independent data streams running in parallel. Each OST can be pointed independently to perform laser relays between two targets, be they low-earth orbit (LEO) user platforms or ground stations. The user data streams run in parallel along the laser link, each with their own parameters.

LCRD is also able to support experiments at different layers of the Open Standards Interconnection (OSI) stack. In addition to Layer 1 and 2 point-to-point laser link tests, networking tests can be run as overlays. As an example, traffic between DTN nodes has flowed over LCRD links while physical and data link layer tests were being run. The DTN traffic has no impact on the lower layer tests. The lower layer tests impact the DTN tests only insomuch as any packet losses on the physical links are mitigated by the DTN suite of protocols.

The design of LCRD has facilitated multiple experiments that leverage its unique capabilities. Some of these experimental configurations are outside the realm of nominal communications relay configurations but can generate test data not available otherwise.

The following are some experiments that have been performed with LCRD:

- **Artificial Star:** Using the LCRD OSTs to provide a reference light source to a ground terminal or astronomical observatory (ORCAS [3], RINGSS [4])
- **LCRD OST Performance:** Characterization over time of LCRD OST performance (Section 5.3 Downlink Beam Characterization)
- **Interleaver Diversity:** Characterizing the impact of channel interleaver depth on communication performance over the varying relevant atmospheric conditions and signal level. (Section 5.1 Interleaver Diversity)
- **Delay Tolerant Networking (DTN)**: Establishing the use-case of a space network service provider by forming a network between the International Space Station (ISS), the LCRD ground station network, a cloud-borne gateway, several NASA field centers, and an aircraft. (DTN Experiment [5])
- **Optical Link Margin**: Operating at the lower bounds of link budget to find minimum thresholds for acquisition and to induce physical layer errors to test error correction (well below nominal transmit power levels) (Section 5.3 Downlink Beam Characterization; Section 5.1 Interleaver Diversity; DTN experiments [6])
- **Modulation Diversity**: Performing physical layer experiments with asymmetric link modulations (e.g. Differential Phase-Shift Keying (DPSK) modulation uplink and Pulse-Position Modulation (PPM) downlink)
- **Multicast data services:** Forward user data services send a single set of user data to the LCRD payload, with identical copies of the user data are sent to two ground stations. (Section 6, Upcoming EXPERIMENTS and future Plans)
- **Optical In-band Commanding**: Using an optical link instead of a RF link to command and receive telemetry from the LCRD payload (Section 5.4 Optical In-band Commanding Experiment)
- **Non-LCRD Optical Ground Terminals**: Testing optical ground terminals beyond OGS-1 and OGS-2 which include the SaberGT [7], Low Cost Optical Terminal (LCOT) [8] and will include in the near future Arizona State University (ASU) and General Atomics (GA) ground terminals (Section 6, Upcoming EXPERIMENTS and future Plans)

Some of the experimental test configurations were not envisioned in the original operational concepts, highlighting the flexibility of the design.

4. EXPERIMENT STATISTICS

LCRD schedules experiment sessions two weeks in advance, capturing all configuration parameters and the timing of the experiments. LCRD operations are normally scheduled for five days a week, eight hours a day. LCRD evaluates weather impacts to the schedule daily and utilizes contingency schedules to allocate experiment sessions to available ground stations or experiments more tolerant to weather conditions.

During experiment sessions, the LCRD experiment team records the timing and duration of the communication links and whether the session completes successfully. Experiments typically require multiple sessions to collect enough data to complete the experiment goals.

The current LCRD experiment catalog includes 39 experiments, of which, 19 are currently underway, 13 are complete, and 7 are in development. At the same time, the LCRD Experiment Program remains open to new experiments, and the team is regularly evaluating new candidate experiments on an ongoing basis.

4.1 Experiment Statistics

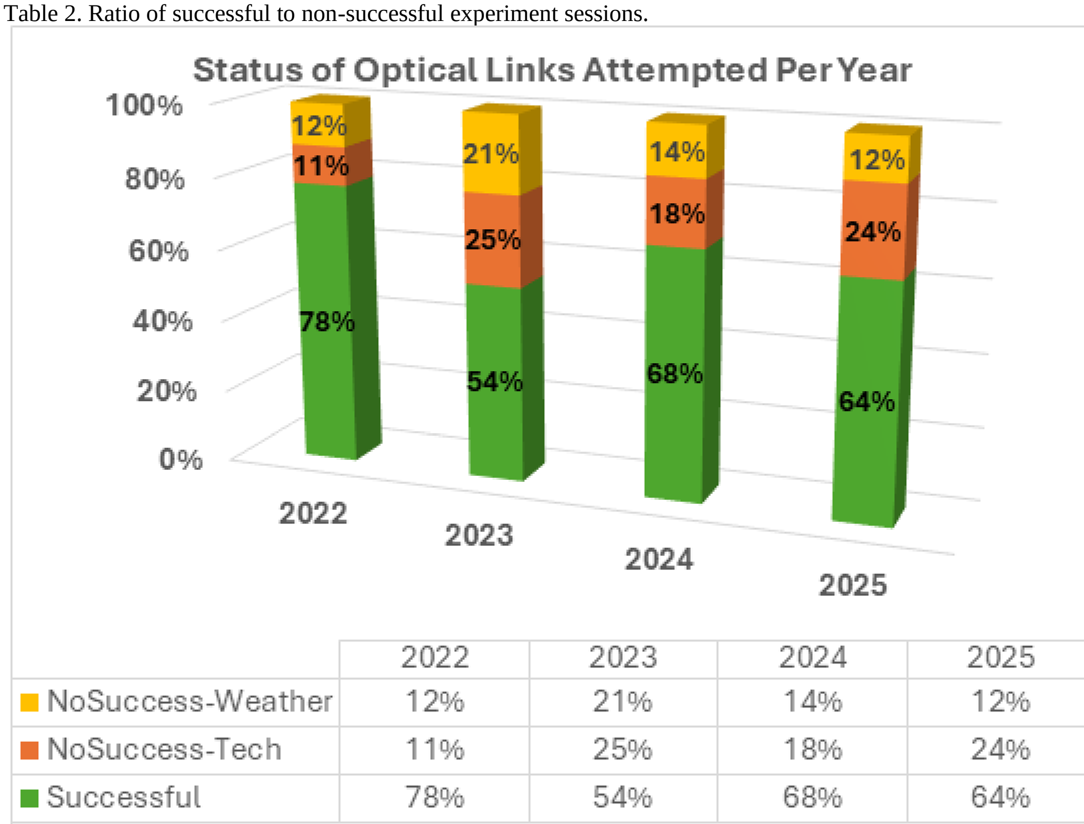
As of December 4th, 2025, LCRD has scheduled 3426 experiment sessions and successfully completed 2198. Table 1 denotes the yearly number of experiment sessions. Success is defined as collecting at least 10 minutes of continuous experiment data during the session. If a session is not successful, the reason is recorded as either technical- or weather-related.

Table 2 shows the relative percentage of successful experiment execution status to non-successful experiment sessions by year.

Table 1. LCRD Experiment Session Statistics

Year	Successful	NoSuccess-Tech	NoSuccess-Weather	Total Sessions
2022 (starting June 23)	345	47	51	443
2023	576	267	228	1071
2024	800	211	160	1171
2025	477	178	86	741
Total	**2198**	**703**	**525**	**3426**

Table 2. Ratio of successful to non-successful experiment sessions.



Looking at the number of experiments scheduled each year one can see that LCRD was able to increase the total number of experiments scheduled in 2023 and 2024 by ~10% relative to the previous year. This increase reflects some efficiencies and proficiencies in the planning and scheduling of experiments, including better contingency plans to work around weather and site outages.

In 2025, however, there is a decrease in number of experiments of ~25% relative to 2024. This is in part due to the impact of increased maintenance outages at OGS-2, decreased operational funding at OGS-1 when compared to previous years, and station conflicts with other lasercom missions.

5. UPDATES ON LCRD EXPERIMENTS

5.1 Interleaver Diversity

The LCRD communication system can operate with variable optical channel rates using DPSK burst modulation from 2880 to 72 uncoded Mb/s and PPM modulation from 720 to 240 uncoded Mb/s. LCRD uses Digital Video Broadcasting -Second Generation Satellite (DVB-S2) error correcting scheme based on Low-Density-Parity-Check [9] coding with a code rate of approximately 50%. Once the optical channel rate is selected, the LCRD communication system architecture can multiplex up to three separate encoded data services onto the optical channel. Multiplexed services can have the same or different data rates; however, the overall data rate of the services must be compliant with the channel data rate.

Services are physically associated with modem "paths,"; i.e. service #j is associated with modem path #j, where j is an integer from 1 to 3. Each path independently encodes, interleaves and frames the user service data before the frames are multiplexed onto the optical channel.

The LCRD system can characterize the quality of the link by different telemetry products [10] such as the rate of coded bit correction, codeword error rate, and max number of iterations needed by the soft-decision decoder over some period of time.

In addition to data services, the LCRD communication system sends (uncoded) fill frames that can provide further information on the optical channel and quality of the link with the telemetry of the (uncoded) bit error rate (BER).

Another significant characteristic of the LCRD communication system is the ability to improve the robustness of the data communication link using interleaving. During a relay (or loopback) link, a convolutional interleaver [11] reorders encoded bits during data transmission (i.e. uplink path) to mitigate (decorrelate) the effects of signal fading due to the optical channel [12]. At the receive end of the link (i.e. downlink path), a de-interleaver restores the sequence of received symbols for the DVB-S2 decoder. The interleaver depth (the amount of temporal diversity or spreading of codeword symbols) can be selected from a maximum of ~1 sec to a few milliseconds depending on the service rate.

LCRD provides the unique possibility to set different interleaver depth per service when multiple services are transmitted. This capability suggests running several experiments to validate the effectiveness of interleaving to improve the quality of communication links, and to assess the minimum interleaver depth needed to meet performance targets, as a function of time of day and other factors that influence the turbulence strength. For example, it is possible to compare the effects of different interleaver depths on services of the same modulation and of the same data rate over the identical optical channel conditions. As an example of this activity, some results from an experiment run on September 8, 2025, at OGS-1 are described next.

During the experiment, the link was configured as a "loopback," where the OGS-1 uplink user data directed towards the LCRD terminal was re-transmitted back to OGS-1 via the downlink. The selected optical channel rate was 2880 uncoded Mb/s that supported three multiplexed data services, each having data rate of 311 Mb/s. Three distinct interleaver depths (pairwise delay between neighboring codeword symbols) were selected for the services: ~1 sec for modem path 1 (service 1), ~0.1 sec for service 2, and ~50 msec for service 3. The experiment lasted approximately seven hours, and during this time the uplink comm beam power was decreased in discrete steps from the initial nominal average of 8W down to 0.5 W. This procedure was done to test the link quality under different conditions of signal strength. At the same time**,** for each setting of uplink power, the downlink average power of the transmitting laser at the GEO space terminal was set to 0.5 W (nominal value) and then 0.25 W. While it is not the intention of this paper to describe the complete data set collected during the entire experiment, the results are summarized here from the most stressing cases, when the uplink transmitting power was reduced to 0.5 W causing the worst signal-to-noise ratio for the uplink signal at the spacecraft payload receiver. Moreover, for sake of conciseness, only the data related to service 1 (largest interleaver depth and service 3 (shortest interleaver depth) are discussed here. During the experiment session when the uplink power was set to 0.5 W, uplink and downlink experienced the same optical turbulence conditions due to the nature of the loop-back link being within the isokinetic angle despite pointahead. The uplink beam was corrected by a tip/tilt compensation to correct the effects of uplink beam wandering. During the experiment, at OGS-1, the downlink atmospheric coherence length was measured around 5 cm, using the convention of specifying at zenith and 500 nm even though it was measured in the 1550nm band. The elevation angle of the ground-to-space link was approximately 48 degrees.

Figure 2 depicts the ground modem received optical power (or the downlink signal injected in the single-mode-fiber in front of the ground receiver). Modem power is reported at a cadence of 1 Hz. The link lasted approximately 90 minutes, where during the first thirty minutes the downlink transmit power was set to 0.5 W and then was scaled down to 0.25 W. This change of downlink power is clearly captured in Figure 2 where a sharp transition of is seen, from -52 dBm to -55 dBm.

Figure 3 depicts the BER performances vs. time for service 1 (interleaver depth of ~1 sec for the downlink. The uncoded BER values are the blue circles, and the codeword-error-rate (CWER) is represented by the red diamonds. Specifically, the average uncoded BER values over two seconds are reported, while CWER values are averaged at 1 Hz. CWER values below 10^{-15} are essentially error-free and are plotted as approximately 10^{-15} to limit the ordinate range. The figure shows an uncoded downlink BER of approximately 10^{-3} when the transmitted downlink power is 0.5 W, with CWER approximately zero all the time (except for a couple of bursts). When the downlink power is reduced to 0.25 W, the uncoded BER increases approximately to 10^{-2}, but nonetheless, the CWER is still mostly zero.

In contrast, the results for service 3 are quite distinct, with a large set of CWER values larger than 10^{-4} during the entire duration of the link, as captured in Figure 4. Service 1 and service 3 had the same data rate, error correcting code, code rate, and atmospheric optical channel, differing only in the interleaver depth: ~1 sec for service 1 and ~50 msec for service 3. It is evident that the experiment demonstrates how the larger interleaver duration in service 1 can offset the effects on the communication link of the signal fading, while the much shorter interleaver of service 3 is not adequate to mitigate the effects of the fading under these atmospheric conditions.

A more direct comparison of the interleaver effects is also shown in Figure 5 and Figure 6. Figure 5 is the cumulative distribution function (CDF) of the CWER of service 1 (red) and service 3 (blue). Error free CWER probability is approximately 89% for the interleaver of ~1 sec duration with respect to 39% for the shorter interleaver duration of ~50 msec.

Figure 6 compares how the modem Low-Density Parity-Check (LDPC) decoder performs for service 1 (red) and service 3 (blue). Particularly, this figure describes the cumulative distribution function for the maximum number of decoder iterations, measured at a cadence of 1 Hz. The LCRD decoder is set to have maximum iteration number to 80. This means that after 80 iterations, the decoder halts, and the entire codeword is dropped because the decoder cannot produce a code word error-free within the real-time time constraints. The red curve clearly demonstrates that the decoder can converge more rapidly to an error-free codeword in service 1 with respect to service 3. For example, considering the benchmark of 50 iterations or less, 50% of the codewords have been decoded for service 1, in contrast to only 20% for service 3. At the same time, the figure shows how the decoder cannot correct approximately 19% of the codewords in service 1 while 68% of the codewords are dropped in service 3 because the decoder is unable to correct the received codewords due to the shorter interleaver duration.

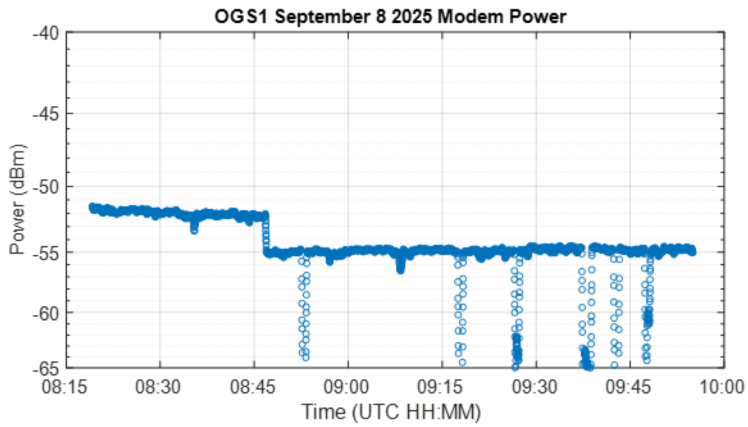


Figure 2. OGS-1 September 8, 2025. Ground modem received power. The reduction of the power of approximately 3 dB after 8:45 is caused by the reduction of downlink transmit power from 0.5 W to 0.25 W.

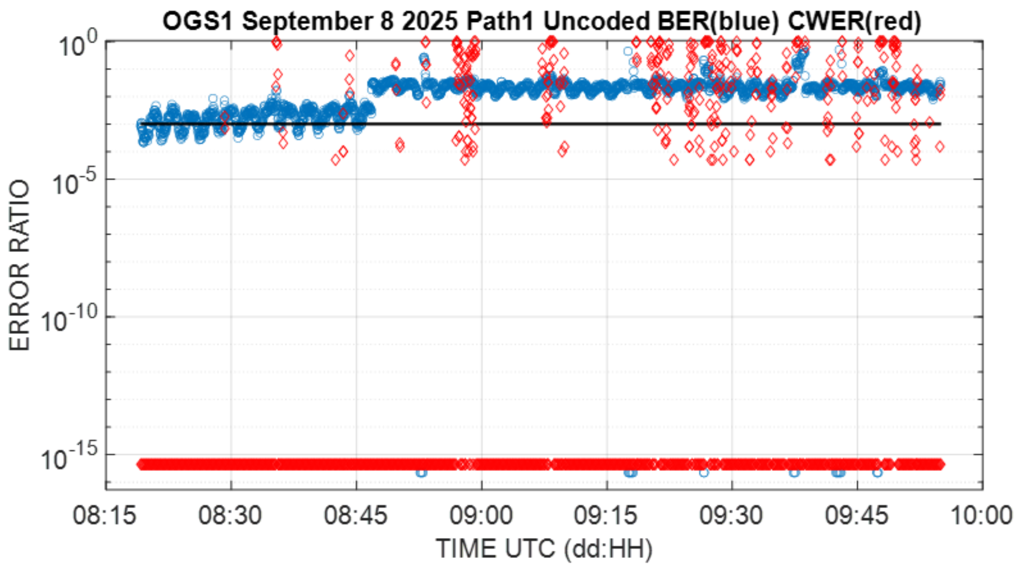


Figure 3. OGS-1 September 8, 2025. CWER (red) of service 1 during the link. The interleaver depth was set to ~1 sec.

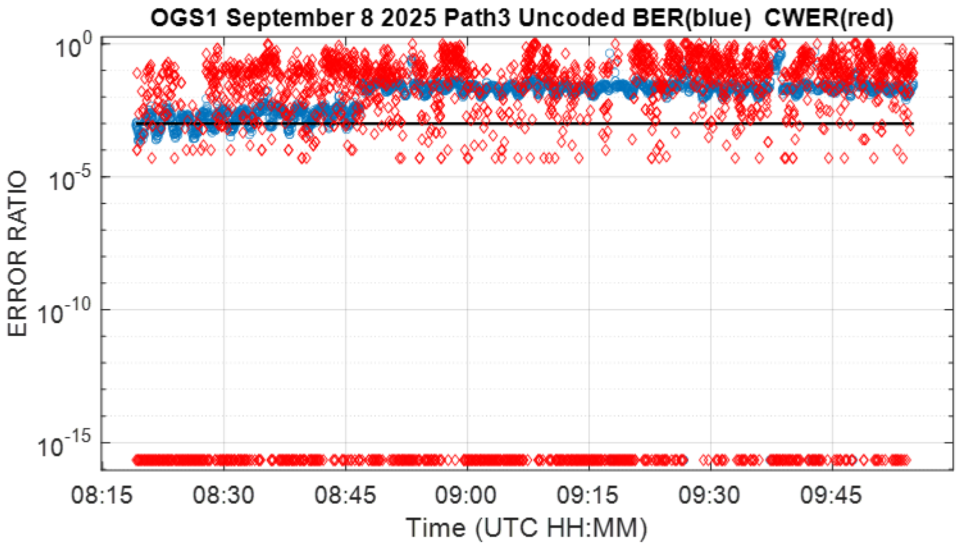


Figure 4. OGS-1 September 8, 2025. CWER (red) of service 3 during the link. The interleaver depth was set to ~50 msec.

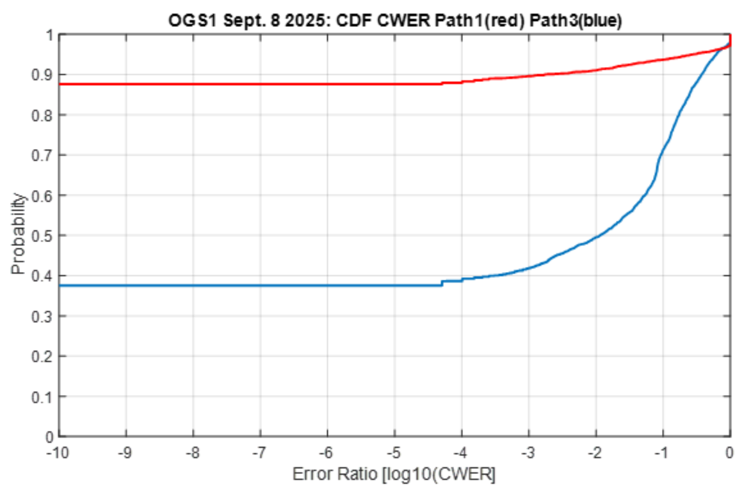


Figure 5. OGS-1 September 8, 2025. CWER CDF comparison for service 1 and service 3. Larger interleaver duration greatly increases the quality of the link. Error free CWER probability is approximately 89% for the interleaver of ~1 sec duration with respect to 39% for the shorter interleaver duration of ~50 msec.

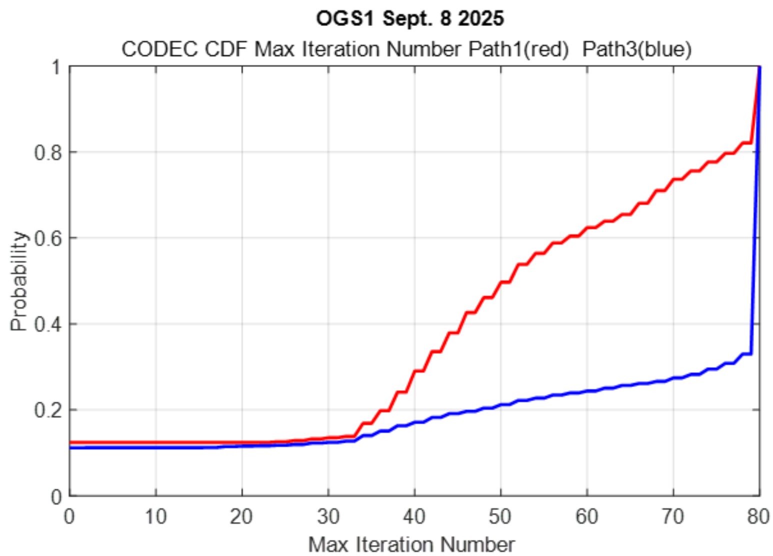


Figure 6. OGS-1 September 8, 2025. Max iteration number CDF comparison for service 1 and service 3. At larger interleaver duration, service 1 (red curve), the decoder converges more rapidly to decode a codeword, while at the shorter interleaver the decoder fails to decode most of the codewords.

5.2 LCRD Uplink Signal Characterization

During LCRD operations, the ground stations can transmit a beacon uplink and a communication uplink signal toward the LCRD GEO satellite. Both beacon and comm uplink beams use wavelengths in the range of 1550nm.

To engage a communication link, in the first phase of link establishment, the uplink beacon illuminates the satellite in such a way that the flight terminal Pointing Acquisition and Tracking (PAT) system detects the signal and reaches a status of 'coarse track'. The 'coarse track' PAT status corresponds to a stabilization of the flight gimbals that enables the flight terminal to point its comm beam at the ground terminal. With both terminals illuminating each other, the terminals can advance to the next PAT state of 'fine track', which is conducive to the establishment of the data communication exchange between ground station and space terminal.

Particularly, at OGS-1, the uplink beacon system was designed to compensate possible pointing errors generated by ground telescope initial blind pointing and errors in the two-line element (TLE) set describing the orbital elements of the LCRD spacecraft. To accomplish this, the overall uplink beacon full beam divergence diameter was designed to go beyond 200 μrad. Moreover, a multibeam system of four beams is used to reduce uplink fading in the presence of optical turbulence. Each beam wavelength slightly differs by several gigahertz so that the beat frequencies are beyond the bandwidth of the quadcell to avoid interference when each transmitter irradiance is summed at the space terminal [13].

Several experiments were conducted at OGS-1 to characterize the uplink beacon and to validate the flight terminal optical tracking system under different conditions. Sample data from an experiment run in April 2025 are presented next.

At OGS-1, the nominal uplink beacon transmit power is 7 W when using four uplink beams. During the experiment, the uplink power and the number of uplink lasers were scaled as indicated in Table 3. Overall, the experiment consisted of nine different steps of a duration of approximately 20 minutes for each step. In steps 1 to 3, the total power of the four lasers was reduced from 7 W to 1.02 W. Particularly, on step 3, each of the four lasers was transmitting a reduced power of approximately 0.25 W. Next, the number of transmitting lasers was reduced from four to one, with a final transmit power of 0.24 W for a single laser (step 6). Finally, the number of lasers was increased one by one to reach the final overall transmit power of 1.02 W over four lasers (note: transmit power in step 9 equal to transmit power in step 3).

During this experiment the uplink main target was the LCRD OST-1 that transmitted back to OGS-1. No uplink comm beam was used. The uplink beacon signal is detected by a quadcell detector able to discern the beacon angle of arrival of the beam and to provide pointing information to the PAT system for the downlink beam.

Figure 7 presents the variations of the average received quad power during the different nine steps of the experiment. Overall, the experiment duration was approximately three and a half hours. The flight telemetry were collected at a rate of 5Hz.

The detected OST-1 Quad power decreased along the transmitted power to a minimum average level of -79 dBm in step 6 for a single uplink laser. After that, when the power of other uplink lasers was added, OST-1 quad power went back to the level of -73.47 dBm for four beams, the same measured in step 3, as expected.

During this experiment, the OST-1 receive system experienced a power change of almost 16 dB with increasing fading due to the fact that the number of uplink beams was reduced. Figure 8 a) depicts the variation of the normalized variance, or signal scintillation, during the experiment. Clearly, the signal scintillation is the largest on step 6 when a single beam was used. It is important to note that in accordance with the theory [13] it was verified that the normalized variance of the overall uplink beam is: a) constant with the number of beams despite the different overall transmitted power; and b) it increases with lower number of beams (it is approximately four times the normalized variance for a single transmitting beam).

Concerning the OST-1 tracking performance during the experiment, Figure 8 b) indicates the PAT states. LCRD codifies the PAT state with an identification number that goes as high as 30 for the condition of fine track. During the experiment the conditions of fine track could not be achieved because the uplink comm signal was absent. However, during the experiment, the PAT state was between 20 and 23 that is associated with coarse track, including step 6 of the test configuration which is the worst-case scenario tested (largest signal scintillation and lowest uplink beacon power).

Table 3. Sequence of uplink beacon illumination at OGS-1: Number of Beams; Transmitted Power; Received Power. Experiment run on April 10, 2025.

Step	Tx Power(W)	Number Beams	Quad (dBm)
1	7.04	4	-63.58
2	3.4	4	-67.57
3	1.02	4	-73.47
4	0.75	3	-75.91
5	0.48	2	-77.37
6	0.24	1	-79.13
7	0.48	2	-77.37
8	0.75	3	-75.9
9	1.02	4	-73.47

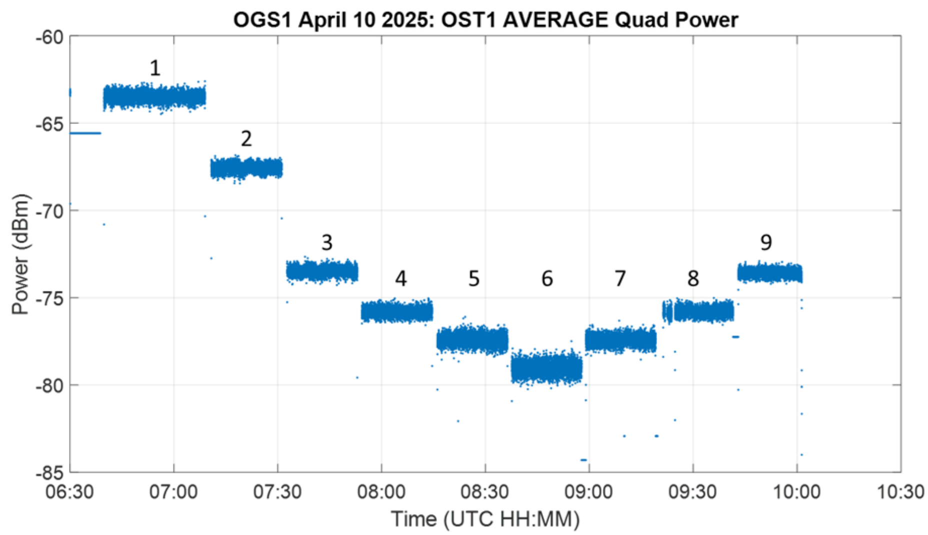


Figure 7. Experiment run on April 10, 2025, at OGS-1. Beacon power received at OST-1 when illuminated by a beacon of variable power and variable number of beams. Levels of ground transmitted power and number of beams are indicated in Table 3.

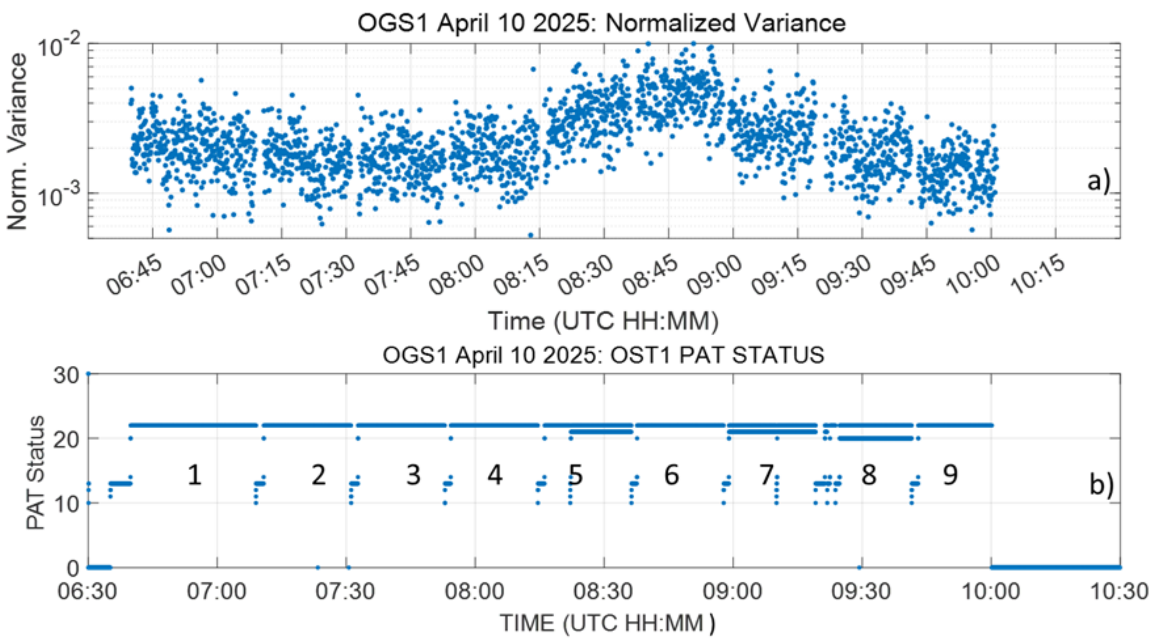


Figure 8. a) Experiment Run on April 10, 2025. a) Normalized variance of the beacon power at OST-1. b) Pointing, Acquisition, and Tracking (PAT) status at OST-1: values between 20 and 23 indicate a status of coarse track. Levels of ground transmitted power and numbers of beams are indicated in Table 3.

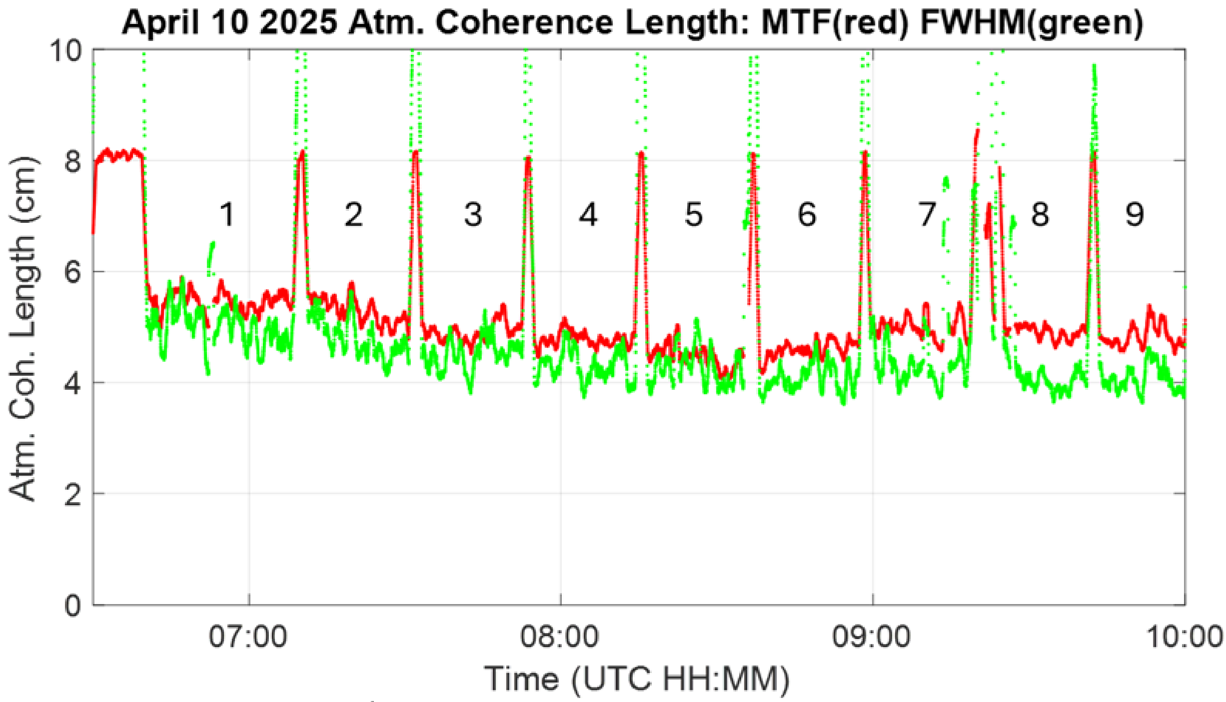


Figure 9. Experiment run on April 10, 2025, at OGS-1. Atmospheric coherence length measured using the Full-Width-Half-Maximum (FWHM) focal plane spot size (green) and the Modulation Transfer Function (red). Data are smoothed over 30s; spiked values are an artifact due to discontinuity of the data acquisition. The atmospheric coherence length is referred at 500nm at zenith.

Concerning the condition of optical turbulence, it must be pointed out that during the duration of the experiment, the measured atmospheric coherence length at OGS-1 was between 5 and 6 cm, indicating the effects of the optical turbulence were approximately the same during all nine steps, Figure 9. The atmospheric coherence length values are referred to 500 nm and at zenith. At OGS-1, the atmospheric coherence length was evaluated by two different algorithms based on the point spread function (PSF) measured by a dedicated acquisition camera. The first algorithm is based on the determination of the FWHM of the long-term PSF; the second algorithm is based on the modulation transfer function (MTF) of the PSF [14].

5.3 Downlink Beam Characterization

The LCRD flight payload is composed of two laser terminals, each with a telescope having an aperture of approximately 10 cm diameter. For each flight terminal, the laser transmitter physical characteristics were designed to have the same optical performance in terms of transmitted power and with downlink gaussian (approximately) beam divergence close to the diffraction limit.

Understanding that the transmitting laser power may change during the years of operation, at regular intervals the downlink beams from each space terminal are tested. The transmit powers and beam full divergences are measured. To do so, an automatic pointing routine was implemented, where the optical terminals were instructed to illuminate OGS-1 at different offset angles along two orthogonal directions. The offset pointing angles were comprised in an interval from -18 μrad to +18 μrad in each direction in 3 μrad steps. The corresponding downlink irradiance at OGS-1 and pointing loss were recorded and, using antenna theory, the downlink beam's full beam divergence was reconstructed for OST-1 and OST-2 using an optimization routine. In addition to the full beam divergence, during this procedure the pointing bias offset for OST-1 and OST-2 and the difference of on-axis irradiance between the terminals were measured.

Figure 10 compares data between the last characterization of OST-1 (November 6, 2025) and OST-2 (October 24, 2025), reconstructing the downlink beam patterns. It is important to notice that for OST-1 a full beam divergence of approximately 29 μrad was measured, while the full beam divergence of OST-2 was approximately 26 μrad. The difference of gaussian beam divergence is also the reason that the measured on-axis irradiance of OST-2 is approximately 1 dB larger than OST-1. During the pre-launch phase of integration and testing, the full gaussian beam divergence for the optical terminals was approximately 27 μrad. Finally, static pointing bias error of approximately 2 μrad was measured for both terminals.

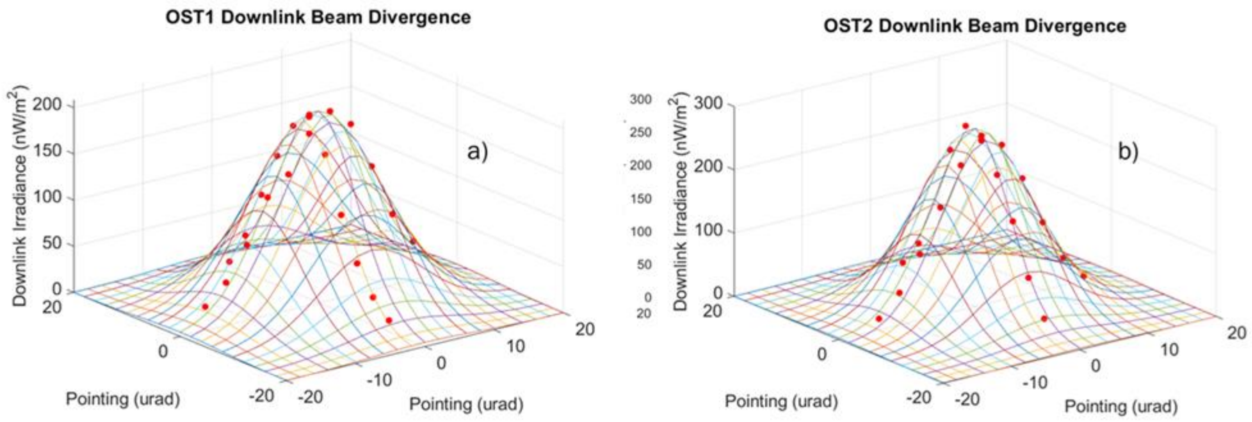


Figure 10. a) OST-1 Downlink illumination pattern at OGS-1 measured on November 6, 2025; b) OST-2 Downlink illumination pattern at OGS-1 on October 24, 2025.

5.4 Optical In-band Commanding Experiment

The LCRD payload is usually commanded with an RF system routed through the host vehicle, STPsat-6. RF commanding is performed through the RF ground station located at White Sands, NM. However, for LCRD, laser links can be an alternate command path. Therefore, an experiment was performed by routing telemetry from the payload down a laser link and routing commands up through an optical ground station via a similar laser link. The actual command path for this experiment was from White Sands, NM to OGS-2 in Hawai'i directly to the LCRD payload.

During the experiment, the team evaluated LCRD payload health & safety using the telemetry in the new laser link configuration. This procedure was then followed with an evaluation of command latency by sending more than a hundred "No-Operation" commands to characterize the overall performance of the laser command link. Each accepted command to the payload increases the command count by 1. However, there was a loss of signal when clouds were in the optical path, but the system was able to automatically re-acquire the link after the dropout, allowing the test to continue. Standard CCSDS [15] command re-transmits were enabled during the duration of the test. Overall, no commands were dropped and there were no telemetry dropouts due to link quality other than when the link was blocked by the presence of clouds. Figure 11 describes the dynamics of the experiment test session performed on June 16, 2025.

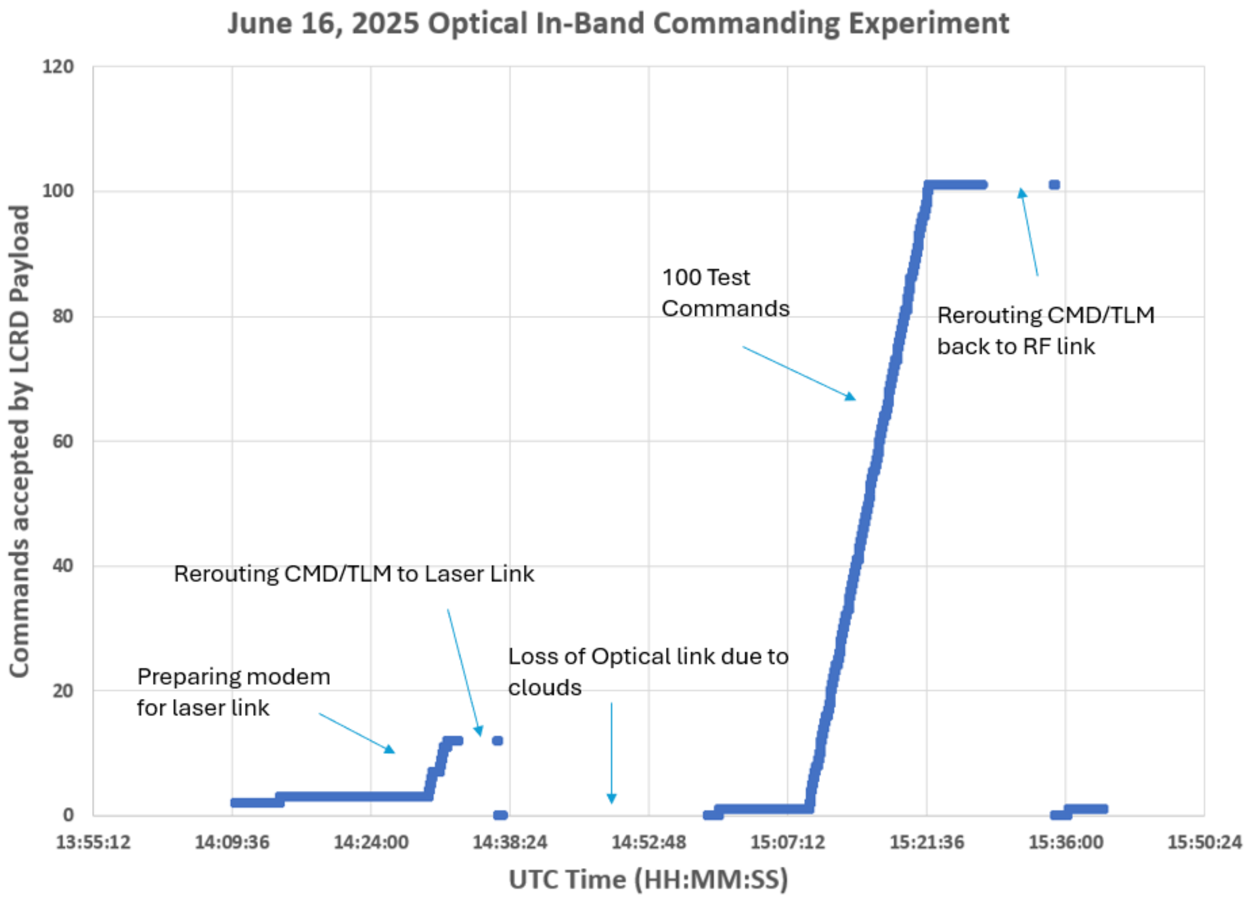


Figure 11. LCRD Payload command sent on June 16, 2025, during the Optical In-band commanding experiment

Command latency is a general metric to compare optical to RF command performance. Command latency is the trip time between a ground system and when it is received and processed by the flight processor.

Overall, optical path command latency compared favorably with RF path latency. In fact, on average, command latency was 1.0 seconds less with optical path commanding. This may be explained by the fact that RF commands travel through multiple layers of RF and spacecraft systems before they reach the LCRD payload, which causes significant latency. At the same time, optical commands experience a delay due to the terrestrial network transit time between WSC (NM) and OGS-2 (HI), but the overall command latency is less.

The LCRD system can multiplex user services with command and telemetry on the same laser link. In the near future, the LCRD mission plans to validate this capability by performing optical experiments while commanding the LCRD payload via laser link.

To our knowledge, this was the first time a free space laser communication system used laser links for both command and telemetry.

5.5 Handover Testing

In satellite communication, a handover takes place when a platform breaks a link with one partner terminal and initiates a new link with a different terminal. For example, a satellite that requires near-continuous communications with terrestrial assets may have to perform a handover from one ground terminal to another, either because of a weather blockage or changing ground station visibility. LCRD has demonstrated handovers, as described below.

Early handover experiments involved a link between the LCRD payload and OGS-1 using data generated onboard the payload. This link was then handed over to OGS-2 by slewing the OST and re-establishing the link with the new ground station. LCRD handovers and day in the life activities were described in a previous paper [16].

A noteworthy set of handover experiments was performed between the LCRD payload, ground terminals, and the Integrated LCRD LEO User Modem and Amplifier Terminal (ILLUMA-T) lasercom system on the ISS in low-earth orbit in 2024 [17]. Experiments with ILLUMA-T have been the only set of LCRD activities to date with relays involving another on-orbit asset. During these experiments, one LCRD OST established and maintained a laser link with ILLUMA-T on the ISS, while the other OST linked with an OGS. The transfer of user traffic used DTN nodes on the ISS and on the ground.

After the ILLUMA-T relay links were established, a handover was performed, where the link between the payload and OGS-2 (HI) was broken, then the OST slewed over toward OGS-1 (CA) and a new relay link was established with OGS-1. The total outage time (time when user data was not flowing between LCRD and the ground) was less than two minutes, which included the time to slew, the time for spatial acquisition of the laser link, and the time to achieve clock recovery and frame lock of the user data. During the handover, it was necessary to switch the terrestrial data connection to the alternate OGS. User data resumed flowing after both the new laser link and terrestrial links were established. Figure 12 displays the initial optical relay configuration and the post-handover configuration.

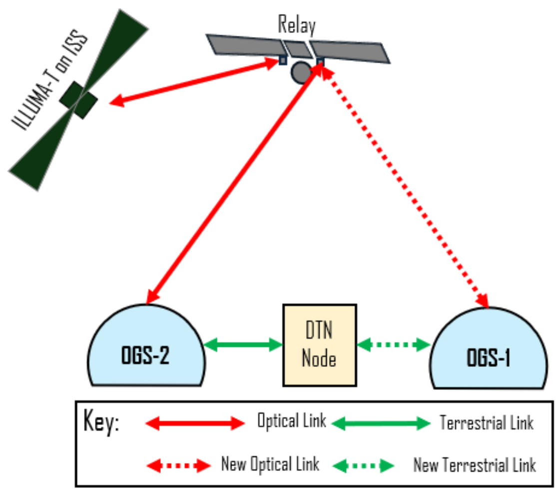


Figure 12. Optical relay configuration during handover experiment and the post-handover configuration. Bidirectional user data is established between ILLUMA-T and OGS-2 via the LCRD payload. Post handover configuration has bidirectional user data established between ILLUMA-T and OGS-1 via the LCRD payload.

During a second test session, the relay link to the ground was transitioned from OGS-2 to OGS-1 and back to OGS-2 within the same pass with ILLUMA-T. This activity is illustrated in Figure 13.

Overall, handovers were performed three times during the ILLUMA-T experiment campaign, and six times in alternate configurations using the two OGSs and the RF-GS.

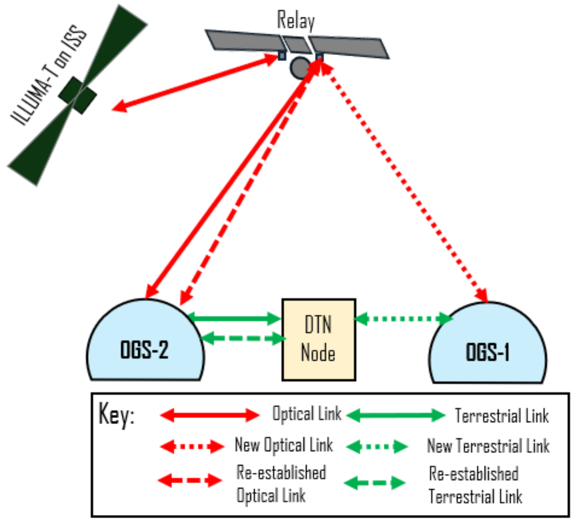


Figure 13. Optical relay configuration during handover experiment and the post-handover configuration. Bidirectional user data is established between ILLUMA-T and OGS-2 via the LCRD payload. After the first handover, the configuration has bidirectional user data established between ILLUMA-T and OGS-1 via the LCRD payload. Final configuration is bidirectional user data between ILLUMA-T and OGS-2 via the LCRD payload.

5.6 LCRD and LCOT

The Low-Cost Optical Terminal at NASA's GSFC Geophysical and Astronomical Observatory (GGAO) is a research and development ground terminal designed with optical and quantum communications in mind. It features a commercially available receiver telescope, state-of-the-art adaptive optics system, novel high-power laser amplifiers, and other innovative subsystems to facilitate laser communications. LCOT is designed in a modular fashion such that it can be quickly reconfigured to support different laser communication missions, but its initial configuration was designed for operation with TeraByte InfraRed Delivery (TBIRD), LCRD, and the Orion Artemis II Optical Communications (O2O) Missions.

LCOT successfully linked with LCRD 66 times from June 2024 through November 2025. Although LCOT has not yet made use of LCRD's relay capability, LCRD is the workhorse satellite for LCOT testing, enabling the new ground station to move through all primary phases of integration and testing. Links regularly last many hours, limited only by scheduling, weather, and the sun separation angle (must be >27 degrees).

With LCRD, LCOT typically transmits equal power of beacon, filler, and unmodulated uplink communication wavelengths. The filler signal is present to ensure the amplifier always has a seed even during the off period of the beacon's square wave signal to avoid self-lasing damage. The filler also prevents gain dynamics from filtering the modulation. The filler is filtered out at the space terminal. Even unmodulated, the presence of the comm wavelength allows LCRD to enter a fine track state, providing LCOT with a more stable downlink signal.

LCOT has a bistatic configuration. The LCOT receive configuration is a 70 cm Planewave RC-700 telescope with a rotating tertiary mirror, allowing received light to be directed to one of two optical benches mounted on each side of the telescope, named starboard and port benches. Initially, only the port bench was mounted, and the starboard bench was installed in the summer of 2025. In the first phases of testing, a temporary single channel transmit optical assembly was used for the uplink; the final four-channel transmit optical assembly was integrated in summer 2025. LCRD provided the space terminal source for the four integration and testing phases of LCOT:

1. **First light with the port optical receive bench + temporary transmit optical assembly:**
   Starting in June 2024, LCOT saw first light and began regular linking with LCRD. In this phase, a preliminary and custom built, low-cost, single off-axis parabolic transmit telescope provided the uplink source. It did not have tracking and was only used to transmit beams with large (but changeable) divergence at a total output power ~7 W. It was mounted on a first iteration robotic piggyback mount on top of the main telescope, which provided live pointing compensation from flexure between the transmit and receive optical axes with elevation changes. The port optical bench – which carries the adaptive optics (AO) capability – was installed, but the AO path was bypassed and only a simple tracking loop was engaged. Links between June 2024 – Jan 2025 demonstrated LCOT's operational ability and enabled a host of initial testing and characterization: PAT sequence, received power, throughput, fine alignment, transmit power and beam characterization, uplink divergence tuning, and thermal management studies. A full summary of the tests during this phase is discussed here [8]. Many of the data taken during these initial months informed the ongoing construction and testing of the next systems to be installed.

2. **Adaptive optics system characterization and RealTOR testing:**
   After initial alignment and capabilities were understood, the AO system was brought online in the Port Optical Bench. The system re-images the telescope pupil to a deformable mirror, in loop with a wavefront sensor, to provide live wavefront correction. The AO system was built by General Atomics and their team was involved with the on-sky characterization of the system with LCRD. The AO system -provides significant correction to the turbulence-induced pointing and wavefront error and enabled higher coupling of LCRD's downlink beam into fiber. During this time, a team from NASA Glenn Research Center (GRC) made multiple trips to GSFC to test their Real Time Optical Receiver (RealTOR) system. RealTOR is a high-speed, low-cost photon counting optical communications ground receiver system, consisting of the fiber device, COTS Superconducting Nanowire Single-Photon Detectors (SNSPDs), and FPGA-based receiver. These tests with LCRD at the LCOT facility progressed their system from TRL 5 to TRL 8 [18], enabling readiness for Australian National University's use for a demonstration with O2O. For testing of both the AO system and the RealTOR system, the ability to link reliably for hours, multiple days in a row, enabled large amounts of data to be collected across a range of turbulence, thermal, and background noise conditions, significantly improving real world understanding and model comparison capabilities.

3. **Starboard optical receive bench + temporary transmit optical assembly:**
   Starting June 2025, the Starboard Optical Bench was installed and characterized on sky with LCRD. Lessons learned with LCRD during the installation and alignment of the Port Optical Bench were implemented for the new bench and dramatically reduced the initial alignment time. The bench is now fully aligned, and measurements are ongoing to fully characterize coupling into fiber over various turbulence conditions.

4. **Transmit optical assembly and full system characterization**
   Starting August 2025, the final four-channel Transmit Optical Assembly delivered by University of Arizona was installed, along with additional lasers and amplifiers and an improved robotic piggyback mount featuring upgrades driven by the first year of testing. The Transmit Optical Assembly features tracking loops, improved beam quality and control, and thermal mitigation. Four channels quadruple the output power, providing ~27 W total on the uplink. After initial alignment on the moon and stars, LCOT transmitted its first uplinks with the new system to LCRD and was able to link. Since then, LCOT has successfully linked dozens of times with LCRD and is undergoing testing to characterize the uplink assembly (fade rates, far field measurements, link statistics, atmospheric scintillation measurements, thermal impact); more details are planned for an upcoming paper.

LCRD regularly provides support and data to LCOT during these and all other testing. Although the LCOT project has now ended, the optical communication test ground terminal at GGAO is now operating regularly in its final planned configuration to help the O2O project and will continue to work with LCRD to help O2O related testing.

6. UPCOMING EXPERIMENTS AND FUTURE PLANS

ASU/Azora

Current optical communications downlink systems at 1550 nm use either photodiodes or other linear detectors for high data rates or non-linear "Geiger-mode" single photon counting detectors for low light, “photon-starved” applications. ASU is developing semiconductor and superconductor-based linear detectors that potentially can provide an improved combination of high speed and sensitivity compared to the current state of the art. ASU is using LCRD to test these detectors coupled to low cost, small optical receivers to benchmark SNR vs. commercial devices. The combination of low-cost multi-aperture ground-based optics and high-speed detectors with close to single photon sensitivity will enable Gbps data rates from the moon and deep space compared to the current Mbps rates using radio-based systems. This experiment has just begun, and the LCRD project looks forward to seeing the results.

This experiment is being performed by Arizona State University and Azora Inc using the LCRD payload.

Multicast Experiment

The multicast experiment utilizes a functionality provided by the LCRD payload. Namely, a single user data stream can be sent to the relay, and two identical data streams, copies of the uplink stream, can be downlinked from the relay. Any of the available downlink paths (subject to bandwidth limitations) are destination options.

The LCRD project will be using this functionality to test multicasting with the two laser-links and single RF link, and for direct data comparisons between the two downlink data streams.

Uplink Beam Divergence Characterization

This experiment characterizes the actual far-field beam profile of both the uplink beacon and uplink communication lasers from OGS-1. The experiment uses a pre-defined pattern of off-pointing of the uplink beams and LCRD payload signal strength readings to map the beam.

General Atomics ElectroMagnetic Systems (GA-EMS) Optical Ground Station

This planned experiment is a collaborative effort between GA-EMS and NASA/GSFC to demonstrate an AO-enabled OGS capability currently in development at GA and perform loopback laser links and atmospheric effects characterization. The experiment will test GEO-to-ground FSO link quality to better understand current limitations on data rates and optical signal recovery. It will also demonstrate bidirectional data transfer between the GA-EMS OGS and one of the existing LCRD OGSs.

Future LCRD DTN Testing

Current and planned LCRD DTN experiments are furthering the ability to architect and manage space networks, which have high latency and intermittent communication links. These experiments are about deploying Kubernetes over DTN. Kubernetes is an open-source system for automating deployment, scaling, and management of containerized applications that is widely used for cloud computing [19].

In lab environments, Kubernetes can operate over DTN with the high latency associated with space networks; this experiment aims to demonstrate this approach empirically under the real-world conditions of the LCRD laser communications network in a variety of configurations to ensure its practicality for future Earth-to-space asset deployments using this industry standard approach.

Additional future experiments involve expanding the DTN protocol suite to include functionality for management of complex software systems over space networks, including time synchronization over DTN. Time synchronization has been studied and prototyped for DTN and has been tested in simulation [20]. Therefore, the LCRD communication network will be used to test these functionalities.

7. FINAL REMARKS

LCRD is a unique on-sky testbed, supporting a diverse set of tests and experiments since mid-2022. Use of an on-orbit asset enables testing and verification of emerging laser communication terminal technologies and ground systems up to TRL 7+. LCRD can help support developments towards future lunar and Martian laser communication networks.

The LCRD payload and ground system continue to be healthy and operating within nominal parameters, and the experiment program is alive and well.

The LCRD Guest Experiment Program remains open. Interested researchers are encouraged to take advantage of this unique experiment opportunity. More information about the LCRD experiment program is available in the document, "Laser Communications Relay Demonstration: Introduction for Experimenters," available from https://ntrs.nasa.gov/citations/20170006243.

LCRD's testing pipeline remains full. Upcoming experiments include testing of multiple guest ground terminals, detectors, additional characterization of the optical link budget margin, including beam divergence explorations, continued studies of laser beam propagation in the atmosphere, and further optimization of AO systems for laser communication. Finally, LCRD experiments will continue to identify and demonstrate methods for optimizing the performance of networking and laser communications links emulating future application scenarios. The results of these activities will provide data for the specifications and designs for future user missions and communications provider systems.

8. ACKNOWLEDGMENTS

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