COMPLETION OF NASA'S TWO-YEAR LASER COMMUNICATIONS RELAY DEMONSTRATION (LCRD) EXPERIMENT PROGRAM

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Abstract

The National Aeronautics and Space Administration's (NASA) Laser Communications Relay Demonstration (LCRD) completed its two-year experiment program in June 2024. The LCRD geosynchronous payload includes two laser communications terminals interconnected via an onboard electronic switch. The payload relays data between two optical ground stations located in California and Hawaii and can also exchange data with an RF ground station in New Mexico. The addition of the Integrated LCRD Low-Earth Orbit (LEO) User Modem and Amplifier Terminal (ILLUMA-T) on the

International Space Station in 2023 enabled data relay demonstrations between a laser terminal in low Earth orbit and either one of the optical ground stations or the RF ground station.

The experiment program has included a variety of experiments originating within the LCRD project, NASA, and industry. The experiments have included measurements of the effects of the atmospheric optical channel (turbulence, weather) on the performance and availability of laser communications, adaptive optics characterization, demonstration of optimetrics techniques, and demonstration of Delay/Disruption Tolerant Networking (DTN). Furthermore, various future operational scenarios including robotic and exploration missions and various network service configurations have been emulated. This conference paper provides an overview and highlights of the LCRD experiment program with an emphasis on activities and results since the start of the ILLUMA-T testing in December 2023. A discussion of the expectations for the next phase of the LCRD mission, as well as how LCRD results may be applied to future applications is also included.

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).

INTRODUCTION

The National Aeronautics and Space Administration's (NASA) Laser Communications Relay Demonstration (LCRD) completed its two-year experiment program in June 2024. During this time, LCRD performed experiments focusing on characterization of laser communication links and the LCRD system, initial operations demonstrations, and, for the final six months, demonstrations with the International Space Station (ISS). 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 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, 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.

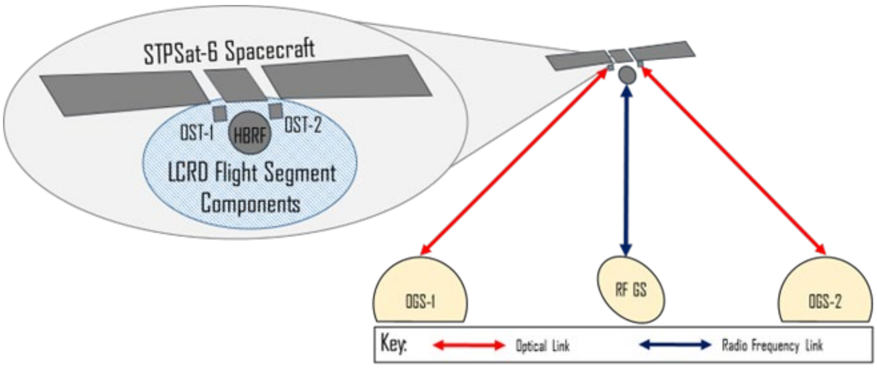

Figure 1. The LCRD mission architecture consists of a flight segment and a ground segment that have demonstrated two simultaneous bidirectional optical links.

A summary of the first 18 months of the two-year LCRD experiment program was previously published [2]; this paper provides an updated summary to include the last six months of the experiment program (a.k.a. the update period). The continued operation of LCRD has supplied additional data to update availability statistics. Most significantly, 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 [3]—launched and completed its mission during this update period.

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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. During execution, the LCRD experiment team 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. ILLUMA-T launched and was installed on the ISS in November 2023. Following ILLUMA-T's on-orbit commissioning, regularly scheduled experiments with ILLUMA-T were the primary activities executed during the daily LCRD operations periods.

As of July 14, 2024, the team had scheduled 2,221 experiment sessions and successfully completed 1,385. 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-related (Not Successful [NS] Weather) or technical (NS Technical) reasons. Experiment session success indicates that the experiment session was properly configured and data was collected. The first row of the table is the summary as of November 26, 2023. The second row provides the statistics for the subsequent six months, indicating overall improvement in the percentage of successful sessions from 59% to 69%. This improvement was due to a reduction in the number of experiments that could not be conducted for technical reasons and a significant reduction in weather outages during the update period.

Table 1. Experiment Session Statistics (June 10, 2022 – July 14, 2024)

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
Previous Summary Reported	6/10/22	11/26/23	161	330	535	1418	280	306	832	20%	22%	59%
Update Period Summary	11/27/23	7/14/24	331	196	231	803	98	152	553	12%	19%	69%
Total Since Operations Started (6/10/22)	6/10/22	7/14/24	161	196	766	2,221	378	458	1,385	17%	21%	62%

Table 2 breaks down the availability for elements of the LCRD experiment architecture, independent of weather-related outages. The improvement in optical ground station availability is clearly seen as the contributing factor that improved experiment session success. Note that some experiments require use of a specific ground station due to some differences in ground station capabilities.

Table 2. LCRD Element Availability Over Experiment Phases

Element	Availability 6/10/22 – 11/26/23	Availability 11/27/23 – 7/14/24	Total Availability 6/10/22 – 7/14/24
Payload	99.3%	100.0%	99.5%
OGS-1	57.8%	76.0%	65.0%
OGS-2	40.5%	85.1%	56.6%
RF Ground Station	99.2%	97.4%	98.7%

ILLUMA-T Experiments

Most of the experiment sessions during the last six months of the LCRD experiment program were dedicated to supporting ILLUMA-T. Even so, the LCRD team was able to continue activities such as gathering data for ongoing atmospheric trending experiments, and refining operations concepts for ground station and data service handovers.

On November 9, 2023, ILLUMA-T was launched and integrated with the ISS. Together, LCRD and ILLUMA-T constituted NASA's first end-to-end laser communications relay system with an orbiting user (see Figure 2).

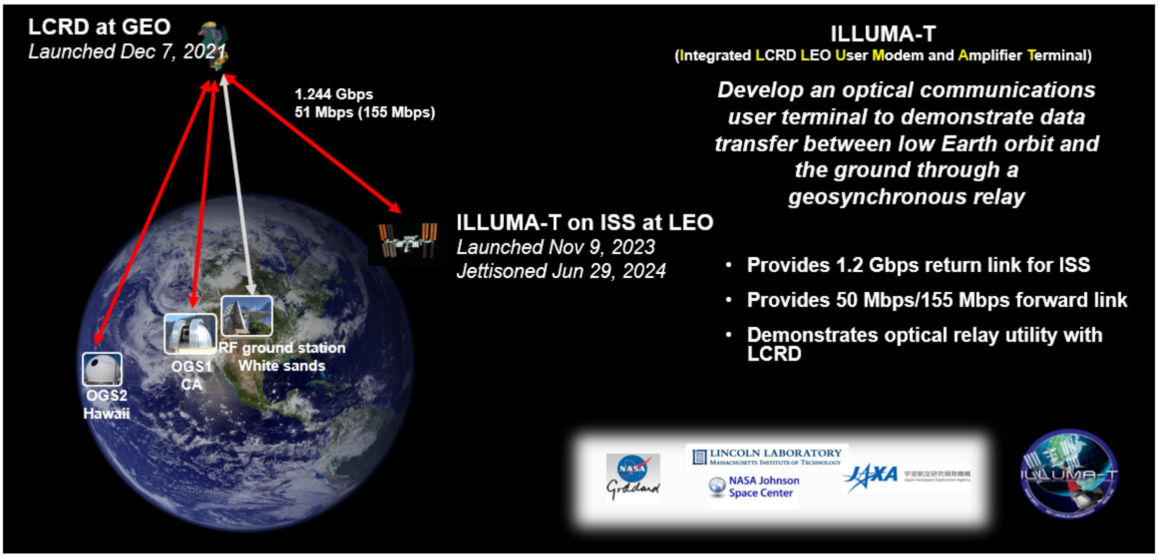

Figure 2. LCRD and ILLUMA-T Optical Communications Relay System.

LCRD and ILLUMA-T successfully achieved their “first light” connection on December 5, 2023 and conducted a six-month experiment campaign designed to explore physical layer performance, pointing and acquisition performance, operational parameters, networking, and user data flows. The ILLUMA-T experiment concluded when the ILLUMA-T payload was jettisoned from the ISS on June 29, 2024.

The ILLUMA-T experiments were categorized into two groups: physical layer experiments and networking experiments. The physical layer experiments focused on all aspects of the laser links, including pointing, acquisition, and tracking (PAT); link margin; and laser communication link performance. The networking experiments focused on the routing of data to and from the ISS using Delay/Disruption Tolerant Network (DTN) protocols [4].

The baseline physical layer experiments demonstrated the ability of the ILLUMA-T and optical terminal and LCRD optical terminals to acquire and track each other, and to relay data. The maximum data rate goals for all links were achieved: 155 Mbps forward link to the ISS and 1.244 Gbps return link from the ISS. The ISS orbit allowed for an average of five LCRD contacts during each daily LCRD eight-hour operations period. A series of experiments to explore the margins on all the laser links, acquisitions, and link budgets was completed following the initial baseline experiments. The data from these experiments are being analyzed and results will be published in early 2025.

The final month of ILLUMA-T experiments included an increasingly complex set of networking experiments. The High-rate DTN (HDTN) experiment laptop was launched and installed onto the ISS at the same time as ILLUMA-T. This laptop was installed onto the ISS Joint Station LAN (JSL) and configured to be a source and destination for networking data flows. The architecture for the networking experiments is seen in Figure 3.

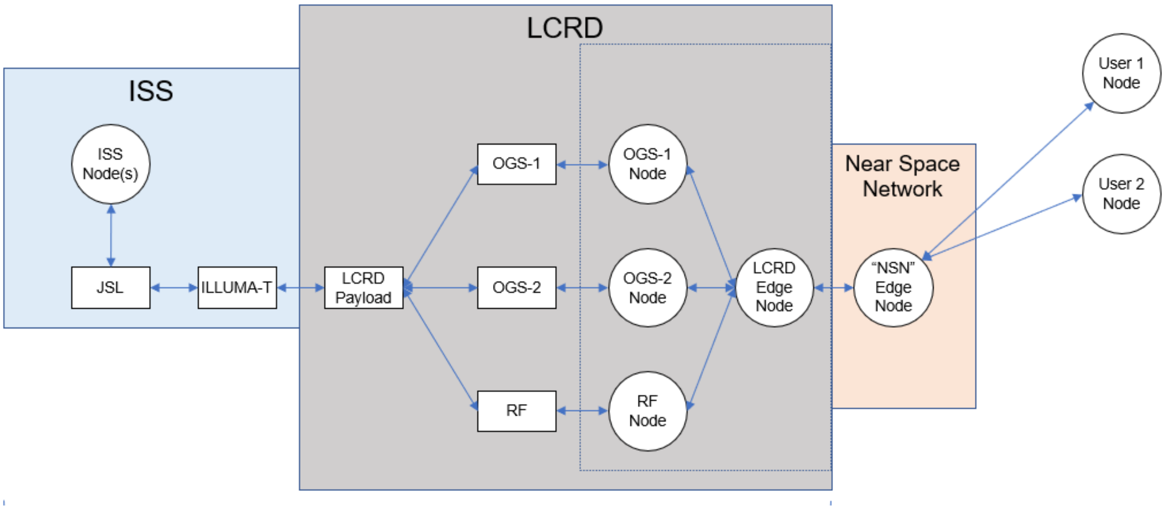

Figure 3. LCRD/ILLUMA-T Networking Experiment Architecture

The initial demonstrations flowed data between the ISS and an LCRD Edge Node that was co-located with the RF ground station at the White Sands Complex (WSC) in New Mexico. From the ISS perspective, all data flowed through the laser communications link with LCRD and no a priori knowledge about the trunkline used (i.e., OGS-1, OGS-2, or RF) was necessary. Only the LCRD Edge Node needed to know which trunkline path was active so it could route data to the correct trunkline uplink. This capability is critical for future network operations, since the ground stations used for a particular relay link could change at any time, including during an active event, due to weather or other circumstances. Using this configuration, LCRD and ILLUMA-T demonstrated the capability of the DTN protocols to provide reliable data transfer at the maximum data rates, including when trunkline handovers occurred in the middle of contacts.

Following the successful data exchange with the LCRD Edge Node, the data flows were extended out to terrestrial user nodes. In these experiments, a cloud-based node performed the role of a Near Space Network (NSN) Edge Node. A NSN Edge Node allows the terrestrial nodes to have a single connection into the NSN, while the NSN may route data to/from multiple providers. During these experiments, only the LCRD system was available as a provider, but future experiments will include other provider connections to the NSN Edge Node. This configuration allowed the demonstration of LCRD's capability to deliver networked data end-to-end between ISS and the ILLUMA-T operations center at the NASA Goddard Space Flight Center, the Huntsville Operations Support Center at the NASA Marshall Space Flight Center, and to the NASA Glenn Research Center. The Glenn Research Center extended the network further over an air-to-ground laser communications link using an airplane in flight. All these successful demonstrations and experiment results are described in more detail in another paper presented at this conference [5].

The ILLUMA-T experiment campaign was a complete success. LCRD verified and characterized a laser communication relay's capabilities to support an orbiting user, and ILLUMA-T verified and characterized a laser communications terminal for users. The LCRD and ILLUMA-T operations teams documented a series of lessons learned that are presented in other papers at this conference [6][7]. The experiments conducted and lessons learned from these tests will inform future operational developments for laser communications. The LCRD and ILLUMA-T systems, combined with the ground infrastructure, demonstrated successful laser communications links in the context of a larger communications network.

Conclusions

The two-year LCRD experiment program is complete, but the LCRD project is continuing with an extended experiment phase. The flight payload and the ground systems are all performing well, and a continuation of the forty hours of experiment time per week is planned. Future experiments will include the ongoing characterization of link performance in relation to atmosphere and weather conditions, additional operational and networking scenarios, and demonstrations with other ground-based terminals.

The LCRD architecture continues to be a testbed capable of supporting a diverse set of experiments. Use of an on-orbit system allows demonstrations of developing laser communication terminal technologies and ground systems. The inclusion of networking expands the possible set of experiments beyond those focused on laser communications links to experiments concerning space communications architectures. The next phase will continue to identify and demonstrate methods for optimizing the performance of networking and laser communications links within scenarios analogous to future applications, such as lunar science orbiters, lunar relays, and earth observation satellites. The results of these activities will provide data for the specifications and designs for future user missions and communications provider systems.

The LCRD Guest Experiment Program will remain open. More information about the LCRD experiment program is available in the Laser Communications Relay Demonstration: Introduction for Experimenters [1].

ACKNOWLEDGMENTS

The success of these experiments would not have been possible without the efforts of the many individuals who built the flight and ground segments, launched and installed them, and now operate them.

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