Experimental Results from Integrated LCRD Low-Earth Orbit User Modem and Amplifier Terminal (ILLUMA-T) Program

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ABSTRACT

The National Aeronautics and Space Administration's (NASA) Integrated LCRD Low-Earth Orbit (LEO) User Modem and Amplifier Terminal (ILLUMA-T) payload was launched and installed on the International Space Station's (ISS) Japanese Experiment Module - Exposed Facility (JEM-EF) in November 2023. ILLUMA-T was the first space-based user to communicate with NASA's Laser Communications Relay Demonstration (LCRD) using free space optical communication to transfer data from the ISS at return rates to Earth of up to 1.244 Gbps and forward rates from Earth of up to 155 Mbps. A 6-month long Experiments Program on ILLUMA-T concluded in June 2024, after which the payload was removed from the ISS and is currently de-orbiting. The Experiments Program was carefully designed to understand and characterize the Pointing, Acquisition, and Track (PAT) process with the new Modular, Agile, Scalable Optical Terminal (MAScOT), optical modem performance, and end-to-end relay performance. [2]

Keywords: free-space optical communication, laser communication, lasercom, human space exploration

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1. INTRODUCTION

NASA's Integrated LCRD Low-Earth Orbit (LEO) User Modem and Amplifier Terminal (ILLUMA-T) recently completed its mission to demonstrate the first space-based LEO user for NASA's Laser Communications Relay Demonstration (LCRD) [1]. The ILLUMA-T payload was installed on the International Space Station's (ISS) Japanese Experiment Module (JEM), known as "Kibo," in slot 3 in November 2023 and operated from / by the NASA Goddard Space Flight Center (GSFC) until June 2024. The payload was a joint effort between MIT Lincoln Laboratory (MIT LL), NASA GSFC, and a number of industry suppliers [2]. The goal of the mission was to operationalize relay-based laser communications compatible with the needs of human exploration, as a precursor to potential optical relays at the Moon [1] and Mars [3], [4]. ILLUMA-T was also the first space demonstration of the Modular, Agile, Scalable, Optical Terminal, or MAScOT [5], which will also be used for the Orion Artemis II Optical (O2O) mission launching next year [6] as part of NASA's Moon to Mars program to return humans to the Moon and beyond. Finally, ILLUMA-T demonstrated the first multi-hop laser communications data delivery to ground [7], providing a forward communications link at 51 and 155 Mbps and a return communications link at 155, 311, 622, and 1244 Mbps.

The ILLUMA-T mission was funded for approximately six months as an experimental testbed. The experiments were designed to develop better understanding of the MAScOT terminal, physical optical link, end-to-end system performance, and networking performance. In this paper, we give an overview of the mission and describe selected experiments and show performance results.

2. SYSTEM OVERVIEW

2.1 The System

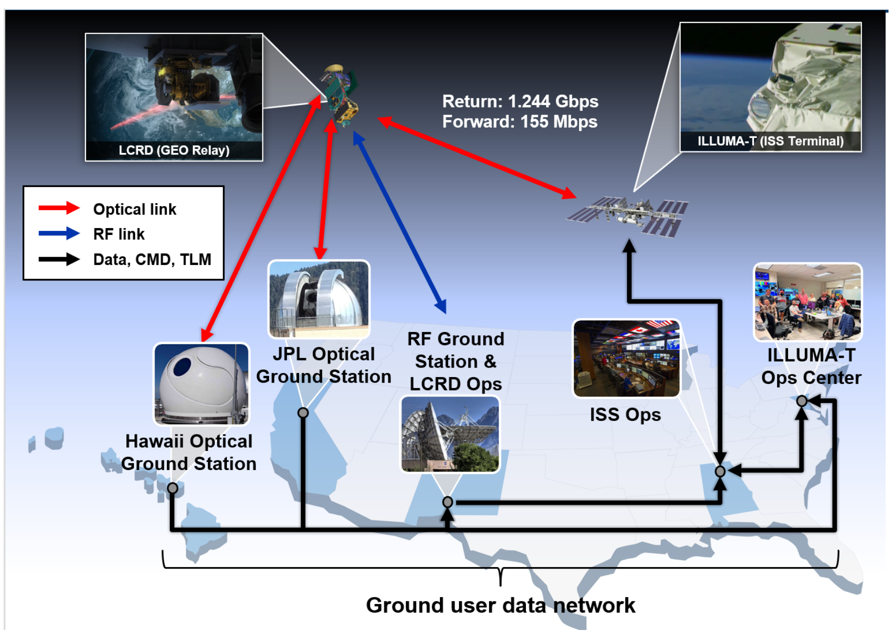

Figure 1: System diagram for ILLUMA-T mission.

The ILLUMA-T space terminal payload was designed to facilitate communications between the ISS and the ground via NASA's Laser Communications Relay Demonstration (LCRD) relay satellite in GEO [8], as shown in Figure 1. ILLUMA-T has 100 Mb /1 Gb Ethernet interfaces for user data on the ISS side and it receives / transmits and decodes / encodes a free space optical forward / return link signal from the remote terminal, LCRD. The LCRD relay is unique in that it demodulates and remodulates the optical data but does not decode / encode the user data; it simply passes the user data on to one of three ground stations, two optical and one Radio Frequency (RF) (return link) or to ILLUMA-T (forward link). [8],[9] The return link user data is then sent via fiber network to an end user at a NASA facility.

2.2 Space Terminal Payload

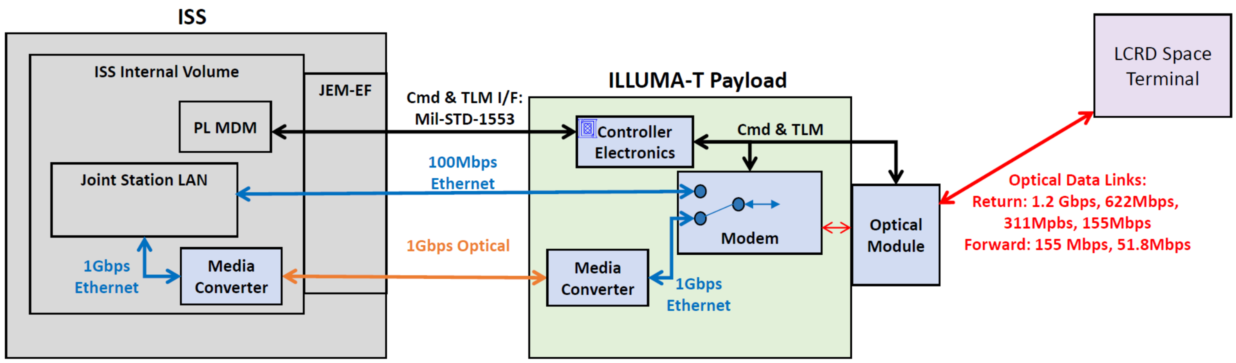

Figure 2: ILLUMA-T payload and interfaces. PL MDM = Payload Multiplexer Demultiplexer which manages data and commands for ISS payloads. TLM = Telemetry. CMD = Command.

Figure 2 shows a block diagram of the space side of the ILLUMA-T architecture with key interfaces labelled. The ILLUMA-T payload includes two data interfaces from the Modem Module (MM). One interface is 1 Gbps Ethernet via a Media Converter within the ILLUMA-T payload. There is also a 100 Mbps Ethernet interface which goes directly to the ISS. A standard MIL-STD-1553 is used for command and telemetry. The payload also has thermo-mechanical and power interfaces to the ISS (not shown), compatible with Kibo, all built by a combination of MIT Lincoln Laboratory, NASA GSFC, and industry partners. Figure 3 shows photos of the ILLUMA-T payload.

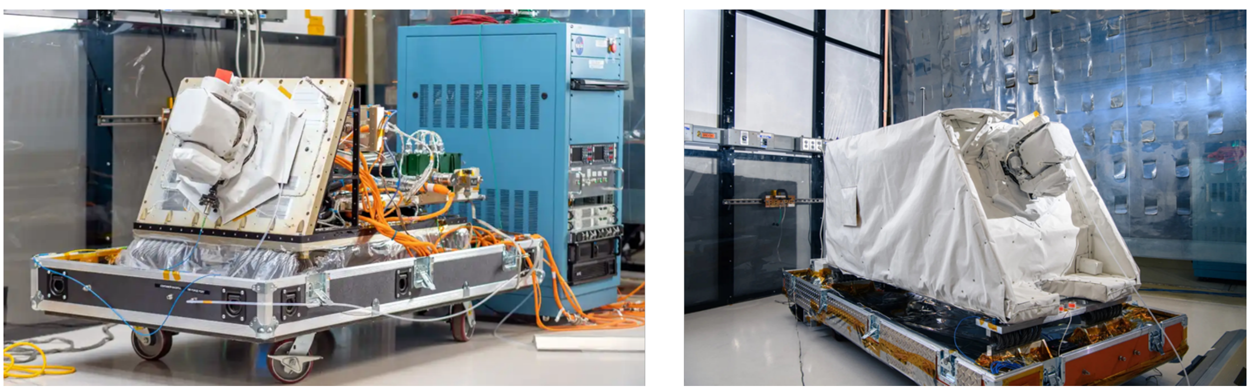

Figure 3: ILLUMA-T payload photos (courtesy of NASA).

A key subassembly in the ILLUMA-T payload is the space terminal assembly. The space terminal assembly is comprised of a MAScOT Optical Module (OM), MM, Controller Electronics (CE) Module, and Power Converter Unit (PCU), without the final outer space terminal structure and thermo-mechanics. The space terminal subassembly was integrated and tested by MITLL [11]. The final assembly and test of the entire space terminal payload was performed by GSFC.

The MAScOT OM is a gimballed 10-cm telescope [5] with a full hemispherical Field Of Regard (FOR). The FOR was restricted operationally in order to avoid pointing at any ISS structure. The OM gimbal is latched before launch to prevent contamination to the telescope and optics. The MM transmits up to 3 Watts of power at 1.5 microns in the form of a communications signal and a beacon signal (in various ratios). The MM communications signal is a Differential Phase Shift Keying (DPSK) format compatible with the LCRD modem as described in Ref. [12]. The beacon signal is a modulated signal, also compatible with LCRD, used in the cooperative Point, Acquisition, and Track (PAT) process. The MM connects to the OM via optical fibers [5]. The resulting transmitted free-space beam for communications is approximately diffraction limited but the beacon beam is defocused to have a fixed, wide divergence of ~ 260 μrad.

2.3 Relay and Ground Terminals

ILLUMA-T was designed to work in conjunction with LCRD, a lasercom relay payload. The LCRD payload was launched aboard the STPSat-6 on Dec. 7, 2021. The LCRD payload consists of two Optical Space Terminals (OST), each with its own OM and MM, along with an RF terminal, and a switching unit. The original demonstration for LCRD was to employ an optical ground station on Earth emulate a LEO user and send data to the LCRD satellite as a "return" link. The LCRD satellite then relays the user data back down via optical link to either Table Mountain, CA (Optical Ground Station (OGS)-1) or Maui, HI (OGS-2). In addition, data could also be relayed to earth via radio frequency (RF) to White Sands. The system also works in reverse for a "forward" link, from ground user back to a LEO user. Once ILLUMA-T was launched and commissioned, the LCRD architecture could be used to relay data from ILLUMA-T on the ISS via and optical link to the LCRD satellite followed by an optical or RF link to one of three ground stations.

3. MISSION TIMELINE

3.1 Launch and Installation

The ILLUMA-T payload launched on SpaceX's Commercial Resupply Mission 29 (CRS-29) at 01:28 UTC on Nov. 10, 2023 (calendar date Nov. 9, 2024). It docked to the International Space Station at 10:23 UTC on Nov. 11, 2023. The payload transferred from the SpaceX Dragon trunk via the Special Purpose Dexterous Manipulator (SPDM) and JEM Remote Manipulator System (JEMRMS) arms to its final position on the JEM beginning on Nov. 14 at 15:11 UTC and ending by 21:20 UTC.

3.2 Operations

The operations center for the ILLUMA-T mission was located at NASA GSFC. Since there were several additional parties involved in the end-to-end demo (ISS, LCRD satellite, LCRD ground stations in New Mexico, Hawaii, and California), daily coordination meetings were held. Further, operations occurred on (East Coast) weekdays and working hours were typically 8-12 hours per day. Due to the orbital geometry of the ISS-Earth system and working hour constraints, there were four to six 20–30-minute passes per day. However, there were days when ILLUMA-T operations were not possible due to ISS activities (launches of vehicles coming to the ISS and docking/undocking of vehicles) or LCRD availability (working with other experiments, antenna maintenance) or ground terminal availability (working with other experiments, weather, and also fire and earthquakes). Additionally, since command and control of the ILLUMA-T payload was initially performed real-time over RF using Tracking and Data Relay Satellite System (TDRSS), RF comm outages could affect ILLUMA-T operations. Happily, after some development work on the ground side, it became possible to set up a laser communications pass before an RF outage so that the communications pass could run automatically even if RF command/telemetry was unavailable.

3.3 Commissioning

The ILLUMA-T commissioning phase took place over several weeks. The first two of four commissioning phases involved just the payload and the last two activated the PAT and comm and thus required the involvement of the remote LCRD terminal. The phases for commissioning are shown and described in Table 1. First light occurred on Dec. 4, 2023.

Phase No.	Title	Overview	Dates (2023)
1	ISS Interface Checkout	Activated and tested ISS/JEM interfaces for power, thermal management, command/telemetry, file transfer, and user Ethernet data	Nov.14 - 17
2	Payload Activation and Test	Performed self-test performed to check the transmit-receive-acquisition boresight; released telescope launch latch; exercised gimbal over its full range of azimuth and elevation	Nov. 16, Nov. 21
3	Pointing, Acquisition, and Tracking Checkout	Pointed and transmitted modulated beacon towards remote terminal; scanned beacon position until acquired and tracked by remote terminal; received and tracked on signal from remote terminal; updated ISS to payload transformation matrix for attitude calculation (see [13])	Nov. 27 - 30, Dec. 1, Dec. 4 - 8
4	Communications Checkout	Transmitted and received all data rates and combinations of data rates for forward and return links from user terminal to / from remote terminal	Dec. 11 - 15

Table 1: ILLUMA-T payload commissioning steps and timeline.

4. EXPERIMENTS

Once commissioning was complete, the ILLUMA-T mission carried out a series of experiments, starting on Dec. 18, 2023 and ending on Jun. 27, 2024. The experiments were both at the physical and networking layers. Physical layer experiments were carefully designed to understand and characterize the physical optical link, as well as compare predicted vs. actual performance. The experiments were sub-divided into three categories: basic, exploring margins, and networking. Both basic and exploring margins experiments were considered primarily physical layer experiments.

4.1 Basic Experiments

Basic experiments were designed to characterize the ILLUMA-T payload and verify the system was performing as intended at the physical layer and met Level 1 requirements. As such, no attempt was made to optimize any part of the system. Table 2 shows the tests included, along the with planned number of dedicated passes (min and max) for each test. Summing the minimum and maximum numbers in the right most column indicates that 36 – 96 passes were allocated for basic testing. Assuming an average of 4 usable passes per day, working 5 days per week, the basic test plan was to take approximately 2-5 weeks to complete.

No.	Title	Overview	Planned No. of Dedicated Passes Min - Max
B01	All-Optical Return Link Test	155, 311, and 622 Mbps from ILLUMA-T space terminal Tx → LCRD space terminal Rx → LCRD space terminal Tx → OGS Rx	15 - 30
B02	All-Optical Forward Link Test	51 and 155 Mbps from OGS Tx → LCRD space terminal Rx → LCRD space terminal Tx → ILLUMA-T space terminal Rx	4 - 20
B03	All-Optical Loopback Test	155 Mbps from ILLUMA-T space terminal Tx → LCRD space terminal Rx → LCRD space terminal Tx → ILLUMA-T Rx	3 - 10
B04	All-Optical High-rate Return Link, ILLUMA-T Transmits Beacon	Operation of 1.244 Gbps return from ILLUMA-T space terminal Tx → LCRD space terminal Rx → LCRD space terminal Tx → OGS Rx	1 - 2
B05	LCRD Fine Tracking, ILLUMA-T does not Transmit Beacon	After LCRD has acquired and tracked on ILLUMA-T's beacon and a comm link established, the ILLUMA-T beacon transmission is shut off	3 - 6
B06	All-Optical High-rate Return Link, ILLUMA-T does not Transmit Beacon	Operation of 1.244 Gbps return from ILLUMA-T space terminal Tx (beacon is shut off after acquisition and coarse track have completed) →LCRD space terminal Rx → LCRD space terminal Tx → OGS Rx	2 - 4
B07	Optical to RF to Ground Test	622 Mbps from ILLUMA-T space terminal Tx → LCRD space terminal Rx → LCRD RF space terminal Tx → LCRD RF ground terminal Rx	2 - 4
B08	Ethernet Tests for Forward Links	Ethernet frames transmitted and frames received are compared	3 - 10
B09	Ethernet Tests for Return Links	Ethernet frames transmitted and frames received are compared	3 - 10

Table 2: ILLUMA-T basic experiments plan.

Note that all of the basic tests assume a working PAT process. Furthermore, these tests were designed to be simple enough to give system operators a chance to learn how to operate the basic system. The intent was to not have to change any major system parameters, just to characterize the system as designed and tested on the ground.

In Experiments B05 and B06 (operation tests), LCRD's space terminal first acquires and coarse tracks on ILLUMA-T's transmitted beacon. However, once LCRD's space terminal begins to fine track, ILLUMA-T's beacon transmission is shut off and all the transmitted optical power is put towards the communications signal. These experiments were devised were so as to be able to achieve the 1.244 Gbps return link with an adequate margin for the ILLUMA-T to LCRD / space-to-space link. Initial (pessimistic) calculations showed little margin on this 1.244 Gbps link with the beacon simultaneously transmitting. Since the MM architecture shares the High-Performance Optical Amplifier optical power between the beacon and the comm transmit beams, having the beacon transmitting meant power was taken away from the comm link. However, LCRD can continue to track without receiving a beacon as the fine tracking relies on fiber power (nutation) measured at LCRD's Modem.

4.2 Exploring Margins Experiments

Once basic performance was verified, the next step was to characterize and understand the system performance by varying parameters, hence the name "Exploring Margins." Again, this was mainly at the physical layer. In some cases, during this process, an optimization was discovered and, in these cases, sometimes it was decided to make a permanent change to the system parameters. Selected exploring margins experiments are shown in Table 3. Summing the minimums and maximums of right most column in this table indicates that it would take approximately 240 – 335 passes, or approximately 3-4 months, to complete the exploring margins test campaign.

No.	Title	Overview	Planned No. of Dedicated Passes
EM01	Forward Link Relay Curve	Vary transmit power on both legs of forward relay link: OGS Tx → LCRD Rx → LCRD Tx → ILLUMA-T Rx	40-60
EM05	Return Link Relay Curve	Vary transmit power on both legs of return relay link: ILLUMA-T Tx → LCRD Rx → LCRD Tx → OGS Rx	160-200
EM06	Return Link λ Optimization	Vary the transmit wavelength for the ILLUMA-T → LCRD Rx link and characterize performance variations	10-20
EM08A	Characterize Acquisitions	Using data collected, analyze effect of gimbal angle on acquisition performance	*
EM08B	Open Loop Pointing Optimization	Update/correct rotation matrices between space craft and payload to improve open loop pointing performance	5-10
EM15	Sun Exclusion Angle Test	Vary gimbal angle so that Sun angle changes and measure background light entering telescope	10-15
EM14	Tracking Bandwidth Optimization	Vary tracking gain parameters and characterize performance variation	10-20
EM14A, B, C	PAT State Transitions	Take high-rate data during PAT state transitions to understand more about tracking loop performance	5-10

Table 3:Selected ILLUMA-T exploring margins experiments plan. The '*' indicates that telemetry recorded during other tests was to be used to analyze this, not dedicated passes.

Note that all exploring margins tests with the exception of EM15, "Sun Exclusion Angle Test," require a working PAT process. Experiment EM08, "Characterize Acquisitions," was meant to involve examining performance data and suggesting additional experiments if necessary. Experiments EM14, EM14A, B, C were experiments on the tracking system which did not require an end-to-end link with the ground.

4.3 Networking

The networking experiments consisted of gradually building up services and applications over the various hops through the network. Ultimately the goal of the networking experiments was to show Delay Tolerant Networking (DTN) and a scalable communications network including multiple different nodes [7]. Generally, networking experiments could mostly be performed concurrently with physical layer basic experiments.

5. EXPERIMENTS RESULTS

In total, 36 experiments were successfully completed during the ILLUMA-T mission experiments campaign. Selected experimental results are discussed in this section. Note that Experiments EM08B and EM15 will be discussed extensively and exclusively in Refs. [13] and [14], respectively.

5.1 Tracking Bandwidth Variation

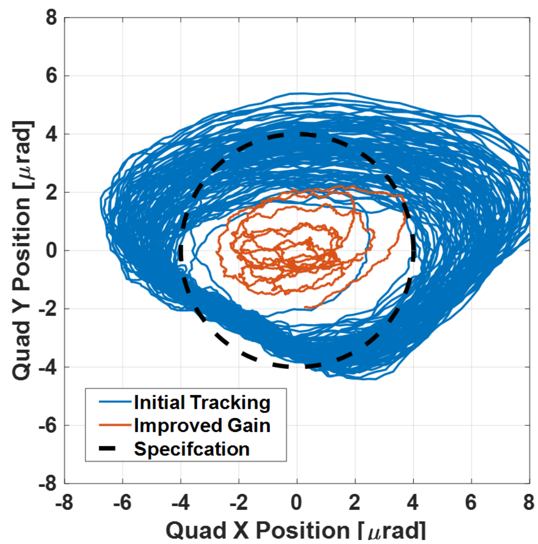

Figure 4: High-rate telemetry data showing ILLUMA-T quad cell position (x vs. y) over time. The blue curve is data with the original tracking parameters, the red curve is post optimalization, and the black dashed curve shows the requirement.

Experiment EM14, "Tracking Bandwidth Optimization," was a study performed during the Exploring Margins phase of the Experiments and involved characterization of system performance while varying ILLUMA-T's tracking gain and hence tracking bandwidth. Both the fast-steering mirror and the gimbal azimuth and elevation motors are part of the control system that stabilizes the beam. The tracking bandwidth parameters are directly tied to the jitter performance of the system, i.e., the stability of the communications signal that is received in the optical fiber interface to the modem module. In order to understand this, it is necessary to first understand the PAT process for the link which is integral to creating a bidirectional free space optical communications link. Each terminal must go through the entire PAT process and the process is collaborative between the terminals.

Step one of PAT is open loop pointing during which ILLUMA-T transmits a wide, modulated beacon beam towards LCRD (in GEO). To open loop point correctly, ILLUMA-T must know the attitude, position, and velocity of itself as well as of its target, LCRD. There are many subtleties involved in this process and the interested reader is referred to Ref. [13]. PAT step two is acquisition. During this step, the LCRD GEO terminal detects the beacon signal on its acquisition sensor, a quad cell. The detected signal must endure long enough so that LCRD can acquire it, that is pull in to the center of the quad cell and begin to track on it. Note, at this time, the ILLUMA-T terminal has not yet received any signal from LCRD. Once acquisition at LCRD has occurred, it moves to tracking step of the PAT process. Tracking comes in two sub-steps: coarse tracking and fine tracking. Coarse tracking at LCRD is done using LCRD's quad cell. Once the LCRD is coarse tracking, it is able to properly point its narrow communications signal back to ILLUMA-T. Once ILLUMA-T receives this communications signal on its quad sensor, it is able to coarse track and improve the pointing of its own beacon. Once LCRD is able to receive enough power from ILLUMA-T in its fiber nutator, it can begin fine track and communications. The ability to fine track allows LCRD to lay additional light on ILLUMA-T's quad sensor and being to fine track. ILLUMA-T's fine tracking loop is what combats ISS spacecraft jitter.

ILLUMA-T was designed to support a fine tracked residual jitter of 4 µrad. This jitter performance was verified prior to launch using a free space optical testbed called the MAScOT Optical Test Set (MOTS) [11]. Using the MOTS, the free space beam from the 10-cm fast-steering mirror was used to emulate spacecraft jitter and the tracking loop gains were tuned to give the proper residual jitter under operational conditions. The tracking loop gain parameters were kept in an on-board calibration file which could be updated on-orbit.

To understand jitter performance, high-rate telemetry was collected on-orbit while ILLUMA-T was tracking LCRD. Results are shown before and after gain loop optimization in Figure 4. The performance with the original calibrated tracking loop parameters is shown in blue and it can be seen that the performance was greater (worse) than the requirement (shown as the black, dashed circle). While it was found that this degraded tracking performance did not result in communication errors, it was important to understand if it could be improved during the experiment. It was found that lowering the loop gain for the OM improved performance indicating that the disturbance was self-excitation, rather than externally sourced. After several data points were taken, it was concluded that a 30% loop gain reduction resulted in the best performance, as shown by the red curve in Figure 4. Since this experiment took place interspersed with other experiments, it was decided to wait until other experiments finished before making this loop gain change permanent since it was not causing overall issues. The loop gains were updated in the calibration file on Apr. 10, 2024.

5.2 1.244 Gbps Communications Link

The key component that the ILLUMA-T mission brings to the end-to-end data delivery experiment is the ILLUMA-T to LCRD space terminal link since LCRD has been in operation for > 1 year demonstrating the space-to-ground communications links, before ILLUMA-T was launched. Experiment B06 examines the most interesting optical link: the 1.244 Gbps DPSK return link from ILLUMA-T to LCRD. This link is the most challenging with the least margin and potentially a measurable error rate. During the initial experiments planning, it was decided that it was best to operate the 1.244 Gbps return link without transmitting the beacon so that the entire 3 Watts of available optical power from ILLUMA-T could be used for communications (Experiment B06). As part of Experiment EM05, the ILLUMA-T transmit power was varied (reduced) to trace out error rate curves, as shown in Figure 5. Even though the data is not decoded at LCRD, LCRD reports bit error rate on fill frames since fill frames are uncoded, always transmitted/received, and are refreshed at each optical demodulation over the end-to-end link. A fill frame error rate of approximately 1.E-3 [16] is required to ultimately achieve error-free end-to-end performance. Each point in the curve represents an average power and fill frame error rate over at least 2-minute intervals. We found that performance matched expectations.

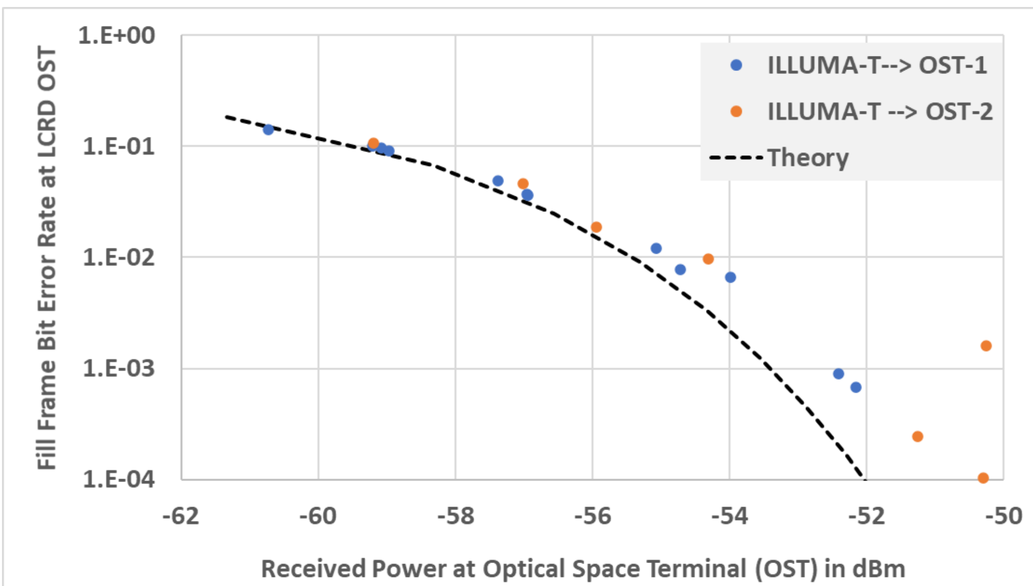

Figure 5: Received optical power vs. fill frame bit error rate for ILLUMA-T to LCRD optical link at 1.244 Gbps. Blue markers indicate Optical Space Terminal (OST)-1 and orange markers indicate OST-2.

5.3 End-to-End Performance

In order to obtain network connectivity, it is necessary to move beyond point-to-point physical links. Delay Tolerant Networking (DTN) is a networking protocol which can help obtain network connectivity despite high latencies of long optical links and multiple hops, whether optical or RF. DTN differs from a terrestrial network by including the capability to store and forward data. Although the latencies in the ILLUMA-T demonstration are small, the DTN principle is easily extendible to planetary distances. In fact, DTN has been previously demonstrated over Lunar distances in 2013 [15]. During our experiment campaign, a multi-hop video demonstration was shown (see Figure 6) while weather conditions in Ohio were cloudy and the airplane to NASA GRC (Glenn Research Center) was intermittent. During the video demonstration (which was also a NASA public relations event), a pet (as in cats and dogs!) video was transmitted featuring Astrid the Beagle along with ISS astronauts' pet photos (see Figure 7) [7]. The success of these experiments showed the effectiveness of operational use of lasercom links as part of a NASA communications network.

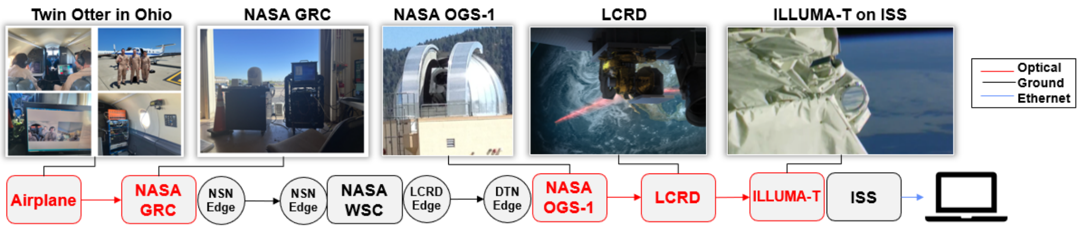

Figure 6: One direction of end-to-end video stream demo over LCRD and ILLUMA-T. Video was transmitted from airplane to ISS, looped back at ISS and transmitted back through same path and viewed at airplane. NSN=Near Space Network.

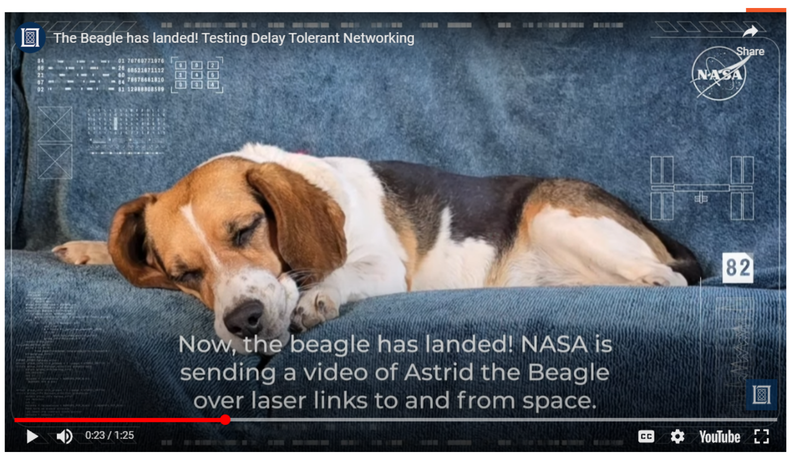

Figure 7: ILLUMA-T allowed NASA to send their first two-way, end-to-end laser relayed pet photos to and from the ISS. Delay Tolerant Networking (DTN) allows data to be reliably transmitted over networks which inherently have long delays and/or disruptions in communications. See https://youtu.be/VhWNefPyARE .

6. SUMMARY

In summary, the ILLUMA-T mission launched in November 2023 and showed successful end-to-end, multi-hop laser communications via the LCRD relay. Thirty-six experiments were performed over six months covering basic performance, margin exploration, and networking. The mission proved out the utility of laser communications for future Moon and/or Mars laser communications.

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