SpaceOps Conferences
5-9 May 2014, Pasadena, CA
SpaceOps 2014 Conference

10.2514/6.2014-1685

The NASA Lunar Laser Communication Demonstration—Successful High-Rate Laser Communications To and From the Moon

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The Lunar Laser Communication Demonstration (LLCD) is NASA's first demonstration of the use of free-space optical communications for high-rate duplex communications between a lunar spacecraft and an Earth ground station. The LLCD system comprised a space terminal on the Lunar Atmosphere and Dust Environment Exploration (LADEE) spacecraft and three ground terminals developed by NASA and the European Space Agency. The primary mission occurred during the fall of 2013 and successfully demonstrated reliable data delivery over optical data links operating at rates as high as 20 Mbps on the uplink and 622 Mbps on the downlink.

I. Introduction

IN October 2013, shortly after the insertion of NASA's Lunar Atmosphere and Dust Environment Explorer (LADEE) spacecraft into lunar orbit, a duplex high-rate optical communications link between the Moon and a ground station on Earth was established for the first time as part of the NASA's Lunar Laser Communication Demonstration (LLCD). The LLCD program[1] served as a pathfinder to demonstrate key technologies needed for future near-Earth and deep-space optical communications links. Free-space optical communication offers many potential advantages over existing radio-frequency (RF) link technologies. Optical wavelengths are thousands to tens-of-thousands of times shorter than RF wavelengths, leading to diffraction link losses that are millions to hundreds-of-millions of times less than the corresponding losses in an RF link. Consequently, optical terminals can be smaller and require less power than an RF terminal operating at the same data rate. The high-directivity of optical signals also decreases interference between transmitters, reducing or eliminating the spectrum congestion problems that RF systems face. The extremely high frequency of the optical carrier (>190 THz) also allows for very large modulation bandwidths, enabling power-efficient modulation formats and link data rates that are unachievable with RF technologies. In spite of all of these potential advantages, which have been recognized for many decades, optical communication is not used operationally for space missions today due to the immaturity of optical

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This work is sponsored by National Aeronautics and Space Administration under Air Force Contract #FA8721-05-C-0002. Opinions, interpretations, recommendations and conclusions are those of the authors and are not necessarily endorsed by the United States Government.

communications systems and widespread perceptions about the challenges of engineering and operating such links in a way that ensures reliable delivery of mission data.

The LLCD mission aimed to address some of the key issues that keep today's space missions from selecting free-space optical communications for delivery of mission data. The primary objectives of the mission were to:

- develop a small, capable optical space terminal for near-Earth missions (~geosynchronous orbits to Lagrange points)
- demonstrate a robust spatial acquisition scheme for a space-to-ground optical link
- demonstrate a duplex wide-band optical communications capability between a ground terminal on Earth and a lunar orbiting spacecraft with downlink rates up to 622 Mbps and uplink rates up to 20 Mbps
- demonstrate the use of duplex wideband optical communications links for making accurate (<200 ps) two-way time-of-flight measurements
- demonstrate a photon-counting ground-based receiver capable of high-efficiency high-rate deep-space optical communications
- demonstrate a scalable, transportable ground terminal architecture for space-to-ground optical communications links

The LLCD space terminal was developed and operated as a technology demonstration on NASA's LADEE mission[2]. As such, the success of the optical links was not critical to the success of the LADEE science mission and the primary LLCD operations were limited to the commissioning phase of the LADEE mission, concluding in November 2013. During the brief period of its operations, the LLCD mission demonstrated complete success in achieving its primary objectives. Beyond that, the LLCD mission demonstrated the utility of free-space optical links to future missions by demonstrating robust and reliable optical communications through the Earth's atmosphere, including the downlinking of the entire LADEE science data buffer in minutes on multiple occasions as well as demonstrating other mission critical communications functions such as delivery of telemetry, transfer of files, streaming of real-time high-definition video, time-of-flight measurements for ranging, and commanding over the optical uplink.

II. System Overview

The LLCD system is shown in Figure 1. The Lunar Lasercom Space Terminal (LLST) is on the LADEE spacecraft in lunar orbit. The primary ground terminal, the Lunar Lasercom Ground Terminal (LLGT)[3] is installed at White Sands, NM. Alternate ground terminals, the Lunar Lasercom Optical Communications Telescope Laboratory (OCTL) Terminal (LLOT)[4] and the Lunar Lasercom Optical Ground Station (LLOGS)[5] were developed using NASA Jet Propulsion Laboratory's OCTL telescope at Table Mountain, CA, and the European Space Agency's OGS telescope in Tenerife, Spain. The alternate ground terminals provided geographic diversity for

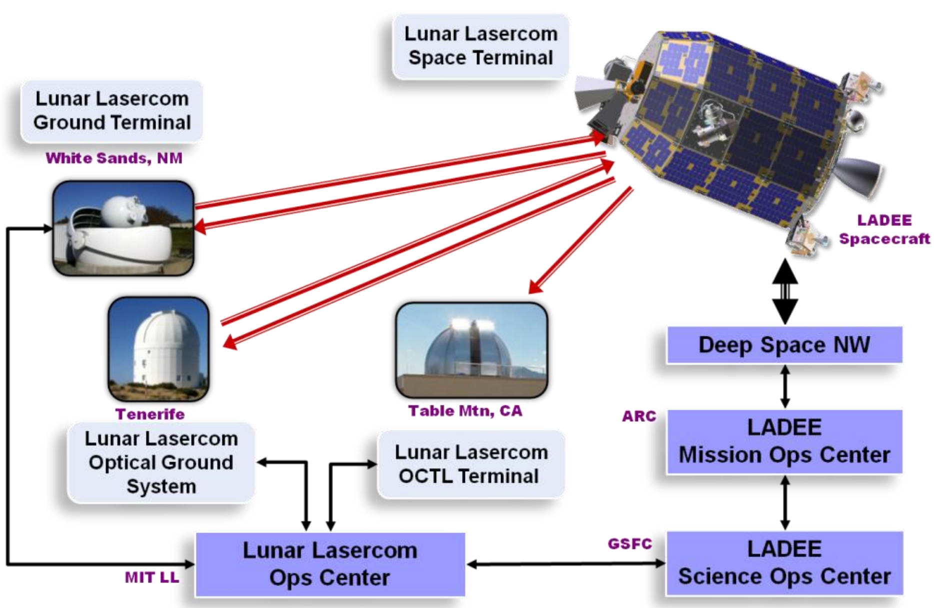

Figure 1. The LLCD System.

mitigation of weather outages during the demonstration and allowed for extended daily operations due to the longer duration when the Moon was visible by at least one terminal (the Moon rises at Tenerife approximately 6 hours before it rises at White Sands). They also allowed demonstration of alternate receiver architectures and detector technologies.

The Lunar Lasercom Operations Center, at MIT Lincoln Laboratory in Lexington, MA, controlled all operations of the LLST. Ground data and voice networks connected the LLOC to each of the ground terminals for coordination of laser communication operations. The LLOC was also connected to the LADEE Science and Mission Operations Centers, at the NASA Goddard Space Flight Center (GSFC) in Greenbelt, MD, and the NASA Ames Research Center (ARC) in Mountain View, CA, for coordination of spacecraft activities. S-band RF command and telemetry connections to the LLST were provided by the Deep Space Network via the LADEE Mission Operations Center for real-time control and health-monitoring of the LLST during all lasercom operations.

A. Space Terminal

The LLST, shown in Figure 2, comprises three modules: the optical module, the modem module, and the controller electronics. The optical module is an inertially stabilized 10-cm telescope[6] mounted to the exterior of the LADEE spacecraft via a two-axis gimbal. Tracking sensors in the back-end optics are used to spatially acquire and track a low-flux optical uplink signal from the ground terminal for rejection of pointing biases and low-frequency mechanical disturbances from the spacecraft. Downlink and uplink optical signals are exchanged between the modem module and the optical module via single-mode optical fibers. Closed-loop control of the various pointing mechanisms in the optical module is provided by the controller electronics, which also provides telemetry and control interfaces to the LADEE spacecraft and the modem module.

The modem module generates the optical downlink signal and processes the received optical uplink. It provides high-speed data interfaces to the controller electronics and the LADEE avionics for transmitting data over the optical downlink. Prior to transmission, the data are encoded using a ½-rate serially concatenated turbo code[8]. The encoded data are modulated using 16-ary pulse position modulation (PPM). The resulting symbols are interleaved with a ~1-second convolutional channel interleaver prior to being amplified to a nominal 0.5-W for transmission on the optical downlink. The combination of this powerful forward error correction code with channel interleaving enables reliable error-free communication through the turbulent Earth atmosphere with >1 received bit per detected photon, as shown in Section III below. The modem also processes the received uplink signal. This signal is amplified with a low-noise Erbium-doped fiber amplifier prior to detection. The uplink utilizes 4-PPM with the same serially concatenated code as the downlink for reliable efficient uplink communications.

The LLST weighs ~30 kg and consumes ~90 W during laser communications operations. The modem module[7] and controller electronics are mounted on the interior of the LADEE spacecraft. During the LLCD mission, thermal constraints associated with this mounting location along with the energy constraints of LADEE spacecraft limited LLST operations to ~20-30 minutes per ~2-hour orbit of the LADEE spacecraft. At its peak downlink rate of 622 Mbps, the LLST could downlink up to ~140 GBytes in each orbit.

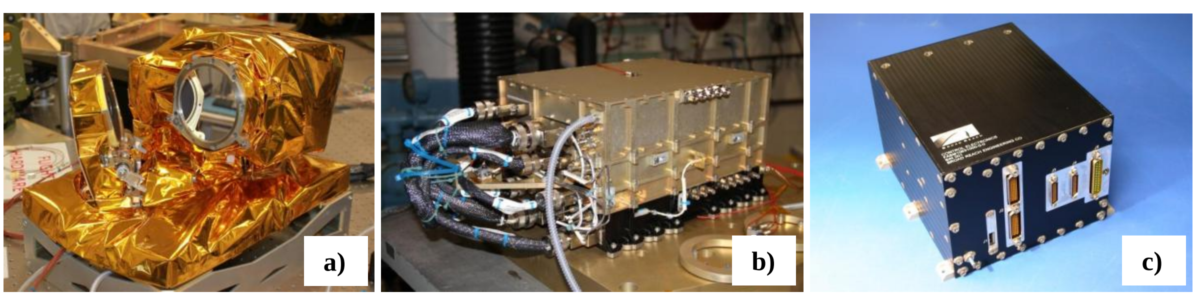

Figure 2. The Lunar Lasercom Space Terminal: a) optical module, b) modem module, and c) controller electronics.

B. Ground Terminals

The LLGT, shown in Figure 3, is the primary ground terminal for the LLCD system. This highly-capable, low-cost, transportable ground terminal was developed and first deployed at MIT Lincoln Laboratory in Lexington, MA, prior to being transported to White Sands, NM, for operations during the LLCD mission. The downlink receiver[9] consists of four commercial 40-cm telescopes mounted on a single gimbal. This multi-aperture receiver architecture is easily scaled to support future optical downlinks from distances beyond lunar orbit, such as the Earth Lagrange points. The array of relatively small optical receive telescopes is also capable of operating with very small sun angles. Indeed, during LLCD operations, the LLGT demonstrated operation with the LLST within 3 degrees of the Sun with no degradation in link performance. The downlink signal collected by each telescope is coupled to a custom polarization-maintaining multi-mode fiber[9]. The output of the multi-mode fiber is then coupled to a photon-counting array of cryogenically-cooled NbN superconducting nanowire detectors. These high-detection-efficiency low-jitter detectors[10] enable error-free downlink communications at the 40-622-Mbps downlink rates demonstrated by LLCD. The multi-mode multi-aperture receiver architecture provides efficient collection from a moderate-sized aperture and mitigates the effects of atmospheric turbulence on the downlink signal.

Figure 3. The Lunar Lasercom Ground Terminal gimbals and telescopes.

The LLGT uplink transmitter consists of four 15-cm refractive telescopes mounted to the same gimbal as the downlink receive telescopes. Each aperture is coupled to a 10-W 4-PPM transmitter[11,12] that provides the 10-20 Mbps uplink signal. The signals from the four uplink transmitters are non-coherently combined at the LLST receiver prior to detection, providing mitigation against atmospheric scintillation for the uplink. The LLGT also compares the timing of the transmitted uplink to the timing of the received downlink signal to measure the two-way time-of-flight between the LLGT and the LLST. Because of the wide-band nature of these signals, the synchronization required for reception of the optical communications signals ensures that the measured two-way time-of-flight is accurate to <200 ps.

As mentioned above, the LLOT and LLOGS alternate ground terminals are designed to extend the duration of LLCD mission operations, provide mitigation against weather, and demonstrate alternate receiver architectures and technologies. These terminals are based on existing ~1-m telescopes operated by NASA JPL and ESA which are retro-fitted with LLCD-compatible modems. Each of these terminals utilizes a photon-counting receiver capable of operating at downlink rates of up to 80 Mbps. The LLOGS terminal is also capable of providing an uplink signal at 10- and 20-Mbps and performing time-of-flight measurements.

III. Mission Operations and System Performance

The LADEE spacecraft launched from NASA's Wallops Flight Facility on Wallops Island, VA on 6 September 2013 and commenced a 1-month transfer orbit to the Moon consisting of 4 phasing orbits around the Earth prior to lunar orbit insertion. Shortly after launch, the LLST performed its initial aliveness test and post-launch alignment operations. Near the apogee of third phasing orbit, when the spacecraft was close to lunar distances, the LLST performed its initial spatial acquisitions, first with the LLOT and then with the LLGT. These initial acquisitions were used to calibrate the post-launch biases in the LLST telescope pointing relative to the spacecraft attitude control system. The spacecraft entered lunar orbit on 6 October 2013.

As a technology demonstration on the LADEE mission, the primary LLCD operations occurred during the LADEE spacecraft commissioning phase, with the spacecraft in a ~250-km near-equatorial orbit at the Moon. LLCD operations took place on lunar days, measured relative to moonset at the LLGT in White Sands, NM. During the LADEE commissioning phase, 4 consecutive days of LLCD operations were alternated with 3 days of spacecraft instrument check out activities. A total of 15 days of LLCD operations occurred between 17 October and 20 November 2013. Because the Moon orbits the Earth in approximately 27 days, this span of operations allowed LLCD to demonstrate laser communication operations during day time and night time, new moon and full moon, large and small sun angles, high and low elevations as viewed from the ground terminal, and close and far lunar ranges.

During the commissioining phase, the LADEE spacecraft was viewable from Earth for ~85 minutes of every ~2-hour orbit. LLST operations during this view period were restricted to ~20-30 minutes due to the thermal and energy constraints on the LADEE spacecraft discussed above. Moonrise at LLOGS occurred approximately 6 hours before moonrise at LLGT each day. Moonrise at LLOT occurred ~45 minutes after moonrise at LLGT. During each LADEE view period, a primary and secondary terminal were selected for operations, based on weather conditions and other availability considerations at each of the ground terminals.

Each laser communications operation began with a spatial acquisition process wherein the space- and ground-terminals initiated the closed-loop tracking required to accurately point their narrow optical beams and establish communications. On the LADEE spacecraft, the star-trackers used for attitude control and pointing knowledge were mounted on the upper radiator deck of the spacecraft, some distance away from the LLST optical module which was mounted to the side of the spacecraft. This led to ~mrad-class pointing uncertainties for the LLST. In contrast, the ground terminals could typically point to the LLST with <50-μrad uncertainties. For this reason, the acquisition protocol employed by the LLCD system requires the ground terminal to first illuminate the space terminal with its uplink signal. The space terminal detects this signal with a wide field-of-view acquisition sensor and then points back to the ground terminal to establish the link. Both space- and ground-terminals were designed to scan their uncertainty region during this initial acquisition. However, after initial post-launch pointing calibrations, it was found that both the LLGT and the LLST were able to repeatedly acquire over the course of the mission without scans, enabling near-instantaneous acquisition times, limited only by the pull-in time of the LLST and the round-trip time between the Moon and the Earth.

Link performance for a typical pass with the LLGT is shown in Figure 4. During this pass, the uplink was operated at 20 Mbps and the downlink was operated at 311 Mbps. Both uplink and downlink communications were established immediately after spatial acquisition. On this particular link, the uplink had an average power margin of ~9 dB over the required power for error-free operations at 20 Mbps. Note that uplink power monitor data shown in this plot is filtered at ~5 Hz, so the instantaneous received power fluctuations into the receiver were likely larger than those shown. Neverthess, the uplink data remained error free, even when the LLGT uplink tracking loops were opened at ~02:56, reducing the effective margin on the received uplink power at the LLST. The LLST downlink transmitter was operated at 250 mW during this pass, half the nominal downlink transmit power. This gave an average power margin of <3 dB at the 311 Mbps downlink data rate for the duration of the pass. Instantaneous received count rates measured on the downlink were often very close to the average-power threshold for error-free operations. Yet, like the uplink, the downlink remained error free for the duration of the link. After 26 minutes of error-free operations, 3.8 GBytes of data were received by the LLST uplink receiver and 30.8 GBytes of data were received by the LLGT downlink receiver. The error free operation of these links, even when operated with small link margins, as demonstrated in this particular pass, illustrates the effectiveness of the forward error correction coding and interleaving techniques employed in the LLCD system at mitigating atmospheric and other dynamic channel effects, thereby providing reliable high-rate data delivery over the optical link. During 54 links with the primary ground terminal, the LLCD system uplinked a total of 118 Gbytes of data and downlinked at total of 1.6 Tbytes of data.

The robust, error-free physical-layer data links provided by the LLCD system enabled high-rate delivery of a wide range of mission data during the demonstration. The 1-Gbyte LADEE science data buffer was successfully downlinked on numerous occasions during the mission. The data interface between the LADEE science data buffer and the LLST operated at a maximum data rate of 40 Mbit/s. Thus, the downlink of the entire buffer typically lasted <4 minutes. Error-free delivery of this data was demonstrated even in the most stressful atmospheric conditions encountered during the demonstration, with the link operating at <4 degrees above the Earth horizon. The optical downlink was also routinely used to deliver real-time ~5-Mbps LLST telemetry that could not be delivered via the LADEE RF downlink. The optical uplink was used as an alternate command path to the LLST, demonstrating that

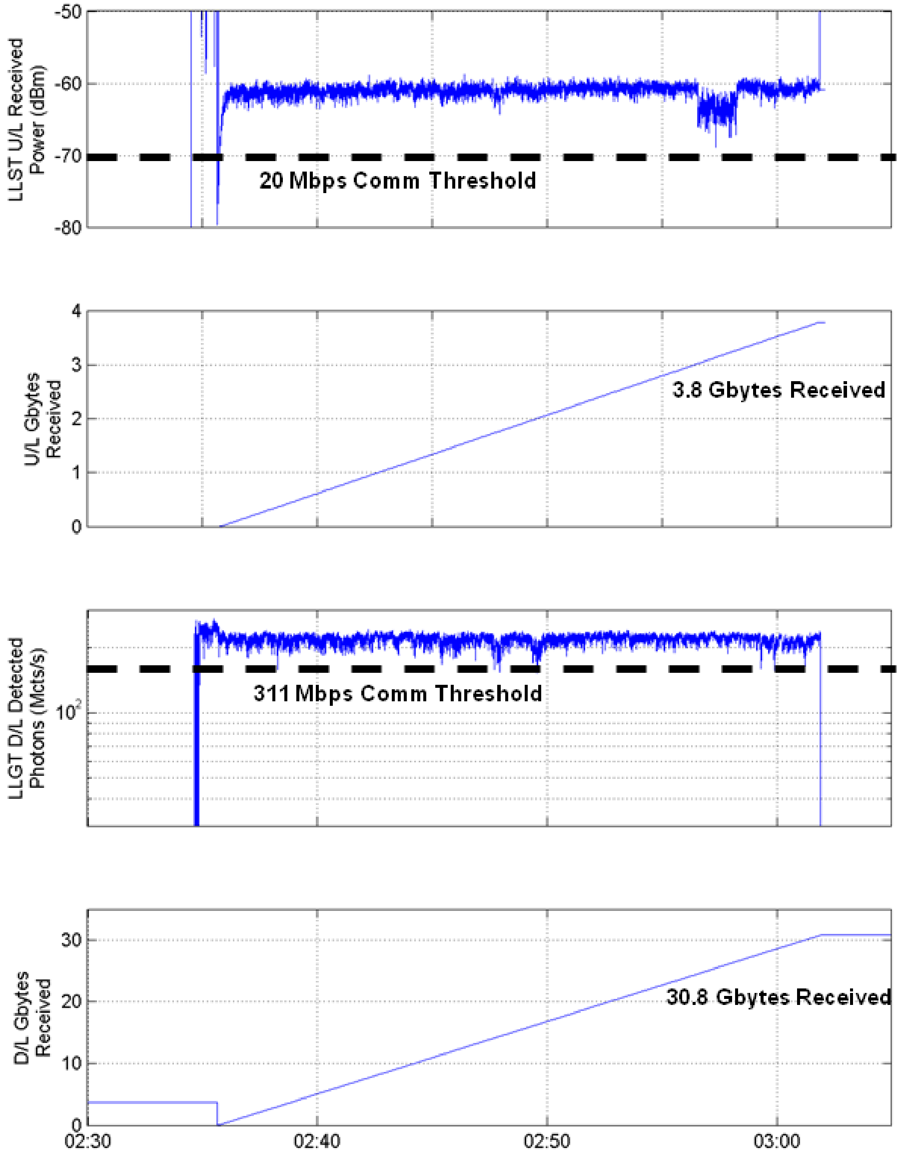

Figure 4. LLCD Link Performance on 19 November 2013.

the optical link could be established and operated even in the absence of a RF link to the spacecraft. File transfers between the LLST and the LLGT were demonstrated on both the optical uplink and downlink. Finally, during all link operations, all of the data received on the uplink was looped back onto the downlink. This loopback capability was used to demonstrate transmission of multiple live high-definition video streams to and from the Moon. The loopback was also used to demonstrate novel network data protocols, such as Delay/Disruption Tolerant Networking, which can further enhance the deep space data delivery capabilities of a laser communication link, even in the presence of partial clouds which could lead to intermittent connectivity[12].

IV. Conclusion

The LLCD mission accomplished all primary objectives in its 15 days of operations. A high data rate duplex optical communication link between the Moon and the Earth was established for the first time, the longest optical communication link ever demonstrated. A small, capable optical space terminal was integrated and operated on the LADEE spacecraft. This same terminal design will soon be modified for optical communications from geosynchronous orbit as part of NASA's Laser Communication Relay Demonstration[13] and may eventually be used for missions extending to Earth's Lagrange points or beyond. A transportable, scalable ground terminal architecture was demonstrated. The high-rate high-sensitivity photon-counting receiver technology developed for LLCD will enable future optical communications links to deep space where diffraction losses are much greater than those experienced in the LLCD links.

The LLCD mission demonstrated the utility of optical communications for high-rate delivery of data to and from a spacecraft. The 622-Mbps downlink data rate demonstrated by LLCD is more than six times faster than the fastest state-of-the-art Ka-band RF link from the Moon that was recently demonstrated on NASA's Lunar Reconnaissance Orbiter[14]. The 20-Mbps demonstrated optical uplink datarate is more than 1000 times faster than previously demonstrated RF lunar uplinks. Most importantly, over the course of the LLCD mission, these links were demonstrated to be reliable and robust, enabling error-free transmission of data to and from the LADEE spacecraft. These advances in the state of the art should now allow optical communications technology to be a mission-enabling capability for future space exploration missions.

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