Overview and Status of the Lunar Laser Communication Demonstration

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ABSTRACT

The Lunar Laser Communication Demonstration (LLCD), a project being undertaken by MIT Lincoln Laboratory, NASA's Goddard Space Flight Center, and the Jet Propulsion Laboratory, will be NASA's first attempt to demonstrate optical communications between a lunar orbiting spacecraft and Earth-based ground receivers. The LLCD space terminal will be flown on the Lunar Atmosphere and Dust Environment Explorer (LADEE) spacecraft, presently scheduled to launch in 2013. LLCD will demonstrate downlink optical communications at rates up to 620 Mbps, uplink optical communications at rates up to 20 Mbps, and two-way time-of-flight measurements with the potential to perform ranging with sub-centimeter accuracy.

We describe the objectives of the LLCD program, key technologies employed in the space and ground terminals, and show the status of development of the several systems.

Keywords: Free-space optical communications, deep space communications, photon counting receiver

1. INTRODUCTION

Optical communications offers many potential benefits for future space missions. Larger aperture gains and smaller diffraction losses at optical wavelengths, as compared to radio-frequency (RF) wavelengths, have the potential to enable higher data rate forward and return links with reduced size, weight, and power (SWaP) burden on a spacecraft and smaller ground terminals on the Earth. Moreover, the 10's of THz of available spectrum in the optical bands is unregulated, and, commercially-available optical transmitter and receiver technologies provide for efficient utilization of >40 GHz of optical bandwidth, again potentially enabling higher data rate links that are much more received-power-efficient than those that might be achieved using the narrower bandwidths available for RF links. For these reasons, NASA has identified optical communications as an important technology for the future of deep space communications[1]. The Lunar Laser Communications Demonstration is intended to be a first step toward developing an operational optical communications capability for future manned and robotic missions.

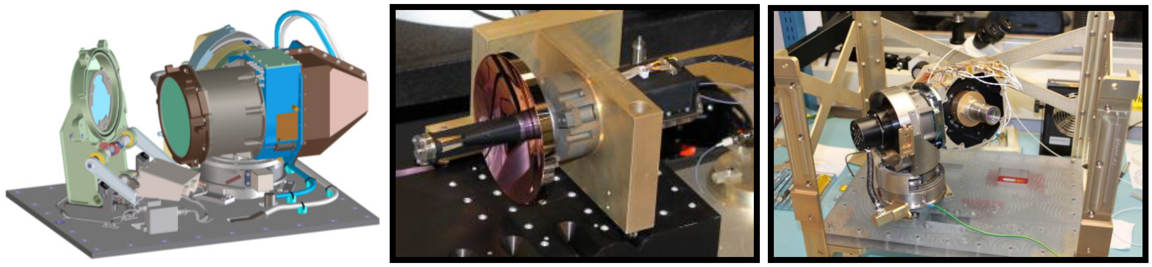
The primary objective of the LLCD is to demonstrate duplex optical communications between a space terminal on a lunar orbiter and an Earth-based ground network. The system is designed to support downlink data rates (from the space terminal to one of the ground terminals) of up to 620 Mbps and uplink data rates (from a ground terminal to the space terminal) of up to 20 Mbps. The system will also demonstrate a time-of-flight measurement technique that utilizes the high-bandwidth signals on the uplink and the downlink and could enable sub-cm ranging between the space and ground terminals. The LLCD comprises 4-elements: the Lunar Lasercom Space Terminal (LLST), the Lunar Lasercom Ground Terminal (LLGT), and the Lunar Lasercom Operations Center, -- all of which are being designed, built, tested, and operated by MIT Lincoln Laboratory -- plus a recently-added element, the ground-based Lunar Lasercom OCTL Terminal (LLOT) being configured by the Jet Propulsion Laboratory at their Optical Communications Telescope Laboratory (OCTL). The LLCD Mission is being managed by NASA's Goddard Space Flight Center.

The Lunar Lasercom Space Terminal will fly on NASA's Lunar Atmosphere and Dust Environment Explorer (LADEE) spacecraft. The LADEE spacecraft is being designed and assembled by NASA's Ames Research Center. The LADEE mission, currently scheduled for launch in 2013, aims to investigate the fragile lunar atmosphere prior to further human disturbances and to assess the likely effects of electro-statically transported dust grains on future lunar exploration missions[2]. The orbiter carries three science payloads which will be operated primarily during the ~100-day science phase of the mission while the spacecraft is in orbit at an altitude of a few 10's of km above the lunar surface. The LLST payload will be operated for a total of 16 days during the 1-month commissioning phase which precedes the science phase. During the commissioning phase, the spacecraft will be in a ~2-hour orbit at an altitude of approximately 250 km above the lunar surface. Power limitations and thermal considerations on the spacecraft limit the duration of LLST operations to about 20 minutes per orbital pass. Since the ground terminal must be in view for communicationsoperations to take place, each day will provide opportunities for 3-5 laser communications orbits.

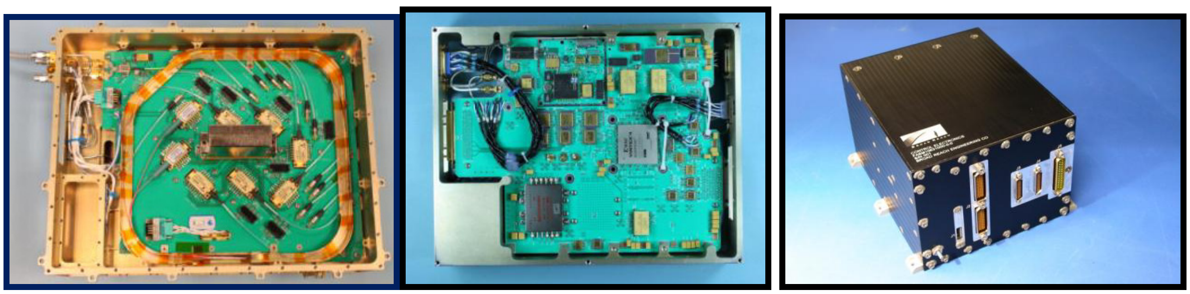
The ground segment comprises a transportable ground terminal, the Lunar Lasercom Ground Terminal (LLGT) plus a fixed ground terminal, the Lunar Lasercom OCTL Terminal (LLOT,) which resides at Table Mountain, in southern California. As of the writing of this paper, the location of the LLGT is still undecided. The activities of the LADEE spacecraft, the LLST, plus the LLGT and LLOT will be coordinated via the Lunar Lasercom Operations Center (LLOC) residing at MIT Lincoln Laboratory in Lexington, MA in collaboration with the LADEE Science Operations Center at Goddard Space Flight Center along with the LADEE Mission Operations Center at Ames Research Center.

2. SPACE TERMINAL OVERVIEW

The Lunar Lasercom Space Terminal comprises three modules, shown in Figure 1: an optical module, a modem module, and a controller electronics module. The optical module is situated on the exterior of the LADEE spacecraft payload module, while the modem and controller electronics modules are mounted on the interior of the spacecraft. The LLST payload weighs ~30 kg and operates at average powers of ~50-140 W.



a) Optical Module Telescope and Small Optics Gimbal with MIRU



b) Laser Board Digital/FPGA Board c) Controller Electronics

Figure 1. The Lunar Lasercom Space Terminal comprises three modules: a) the optical module, here shown in a CAD rendering plus during integration in the clean room at MIT Lincoln Lab. Shown are the the optics module consisting of the telescope with its back-end optics plus the gimbal with its MIRU stabilization unit[3]; b) the modem module, showing two of its four slices, about to be integrated; and c) the flight controller electronics module, ready for terminal integration.

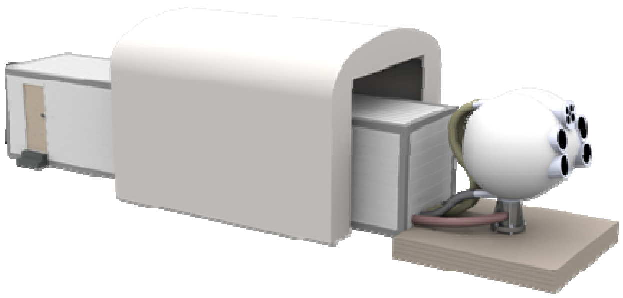
The optical module is a 10-cm Cassegrain telescope on a two-axis gimbal that enables optical link operation over a wide range of spacecraft orientations[3]. The telescope and backend optics are inertially stabilized using a magnetohydrodynamic inertial reference unit (MIRU) that rejects high-frequency disturbances from the spacecraft interface. A wide field-of-view InGaAs quadrant detector is used for spatial acquisition and coarse tracking of the optical uplink. Transmit and receive signals are coupled to and from the telescope via single-mode optical fibers. These fibers are mounted to piezoelectric actuators that are used to provide a point-ahead capability between the transmit and receive fibers and error signals for low bandwidth fine spatial tracking of the optical uplink signal. The optical transmitter and receiver are contained in the modem module[4], which is fiber coupled to the optical module. Digital electronics in the modem aggregate the various downlink data sources (including science data from the LADEE spacecraft, high-rate LLST telemetry, and loopback of the optical uplink) and encode the data using a high-efficiency half-rate code[5]. The encoded data are modulated onto an optical carrier using a high-bandwidth pulse-position modulation format (slot rates up to 5 GHz) and amplified to 0.5-W average power in an Erbium-doped fiber amplifier prior to transmission on the downlink. An optically preamplified direct-detection receiver based on a low-noise EDFA is used for the uplink receiver. A near-optimum hard-decision pulse-position modulation demodulator based on a previously demonstrated binary PPM demodulator[6] demodulates the uplink waveform prior to decoding of the uplink signals in a high-density SRAM-based field programmable gate array.

The controller electronics module, a custom avionics module based on a single-board computer, provides closed-loop control of the various actuators in the optical module. It also provides command and telemetry interfaces for the LLST payload to the LADEE spacecraft and configures and controls the modem.

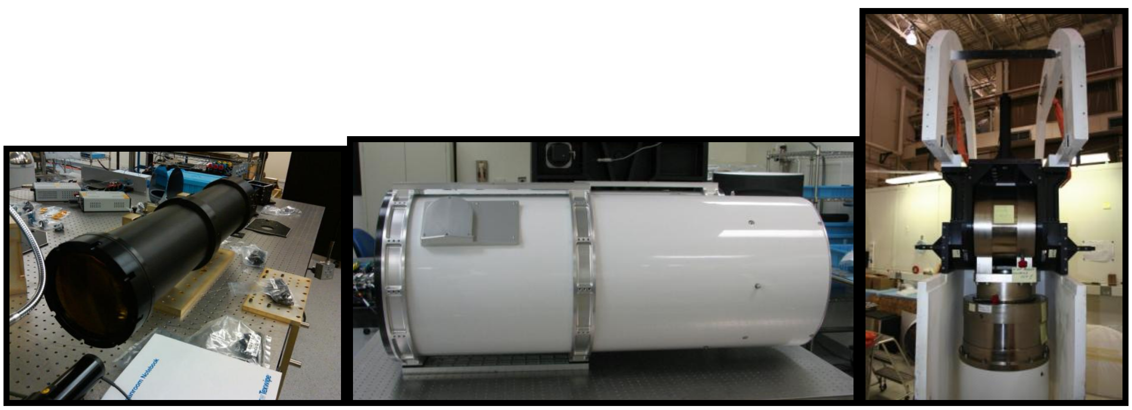
3. GROUND TERMINAL SEGMENT

Over the past year, it became evident that, if the spacecraft launched in the early summer, then a terminal in the US southwest desert would likely face daily cloud cover, further shortening the already brief period of operations. Thus, the program decided to include a second terminal – based on the existing Optical Communications Telescope Laboratory, built and operated by JPL at Table Mountain north of Pasadena – in addition to the planned, transportable Lunar Lasercom Ground Terminal (LLGT) which can be placed at a nearly arbitrary site with good weather independent from OCTL. As of the writing of this report, the final location for the LLGT is still undecided. Possibilities include other locations in the Southwestern continental US plus Pacific Ocean locations.

The Lincoln Lab-built Lunar Lasercom Ground Terminal (LLGT), shown in Figure 2, consists of an array of transceiver and receiver telescopes and a control room[7]. The telescope arrays are used to demonstrate a scalable and cost-effective approach for providing large-aperture transmitters and receivers[8,9]. They also provide spatial diversity which helps mitigate the deleterious effects of atmospheric turbulence on the optical uplink and downlink signals. Four 15-cm refractive telescopes are used for the optical uplink and four 40-cm reflective telescopes are used as collectors for the optical downlink. Each telescope is fiber-coupled to the control room where the optical transmitters and receivers reside. All 8 telescopes are mounted on a single elevation over azimuth gimbal. The gimbal provides coarse pointing for all of the telescopes with near-hemispherical coverage. The back-end optics for each telescope include a focal plane array and a fast-steering mirror for high-bandwidth tracking of the optical downlink and correction of any relative pointing biases between the telescopes on the gimbal. While mounting all of the telescopes on a single gimbal is not required for the arrayed transmitter/receiver concept, it simplifies the process of time-aligning the transmitted and received waveforms over the range of pointing required to support the optical links. The telescopes are housed in a fiberglass environmental enclosure which maintains a suitable environment for their operation. Photographs of some of the components of the LLGT are shown in Figure 2.



CAD rendering of the gimbaled telescopes in their enclosure, the control room holding the electronics and office, and the weather-protection-tent.

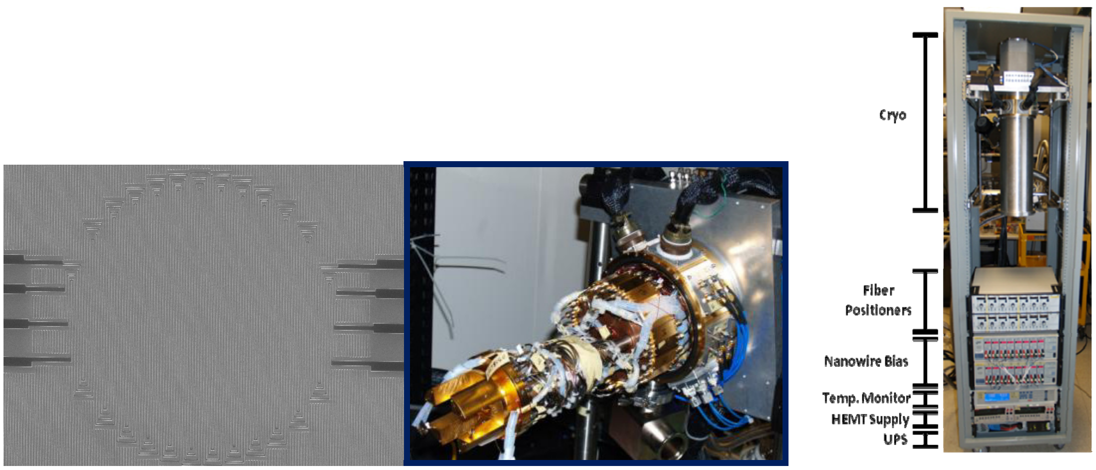


Uplink telescope   Downlink telescope   Gimbal with partial frame

Figure 2. The Lunar Lasercom Ground Terminal (LLGT).

The control room houses all of the electronics to control the gimbal and telescopes as well as the ground terminal modem electronics and optics. Four EDFA-based 10-W optical transmitters generate the pulse-position modulated signals for the optical uplink. Each transmitter is fiber coupled to one of the transceiver telescopes via a polarization maintaining single-mode fiber. The wavelengths of each of the transmitters are slightly detuned to allow for low-power penalty non-coherent combining of the signals at the space-terminal receiver.

The optical downlink receiver is based on photon-counting superconducting nanowire arrays[10]. These detectors operate at cryogenic temperatures, provide very high photon detection efficiencies, and have been previously used to demonstrate high data rate optical communications with receiver efficiencies exceeding 1 bit / detected photon[11]. In order to achieve good coupling efficiency in the telescopes in the presence of atmospheric turbulence while preserving the polarization of the downlink signal, a custom multi-mode polarization-maintaining fiber is used to couple the receiver telescopes to the SNDAs[12]. Custom FPGA-based digital electronics in the control room interface to the various data sources and destinations, generate the waveforms for the optical uplink, and demodulate and decode the detected signal on the optical downlink. Photographs of some of the systems are shown in Figure 3 during integration at MIT Lincoln Lab.



Intertwined 4-nanowire   Cryo assembly   Cryo in rack

Figure 3 LLGT Receiver Components

The LLGT is designed to be transportable. After initial assembly, the ground terminal will be deployed near MIT Lincoln Laboratory in Lexington, MA for calibration and performance characterization. Several months prior to launch of the LADEE spacecraft, the ground terminal will be transported to its operational location.

The JPL-designed Lunar Lasercom OCTL Terminal is being designed and built using the existing 1-meter telescope at the Optical Communications Telescope Laboratory [13] at the Table Mountain Facility near Wrightwood, CA. Although it will not provide an uplink data signal, it will provide an uplink beacon for the LLST to track on, and will include a PPM receiver based on hybrid photo-multiplier tubes[14] capable of receiving, demodulating, and decoding the downlink at rates up to 311 Mbps. OCTL is shown in Figure 4.

Figure 4 The Optical Communications Telescope Laboratory

The present plan of operations is to have the LLOC coordinate a link between the LLST and the LLGT if its local weather is clear, and between the LLST and the LLOT otherwise. If both are clear, the system will likely attempt “handing over” from one terminal to the other (in a break-before-make manner.)

The decision on the LLGT location is a complex one. Seasonal cloud cover, local ease of integration, operations considerations, and non-correlation of weather at the several sites are all being taken into account.

4. SUMMARY

The Lunar Laser Communications Demonstration (LLCD) aims to be NASA's first demonstration of optical communications at lunar ranges and will demonstrate a number of critical technologies for future missions, including a low-SWAP space terminal suitable for near-Earth (from low Earth orbit to the Lagrange points) missions, a ground network capable of selecting one of two terminals with clear weather, a scalable, low-cost ground terminal based on telescope arrays, a low-cost ground terminal based on an existing telescope infrastructure, and photon-counting-based ground receivers for high-efficiency high-data-rate return links . The Space Terminal is in its final phases of fabrication and testing, as is the transportable Ground Terminal. The LLOT, having started later and not required for another year, is still in the detailed design phase of development. Integration of the Space Terminal with LADEE is scheduled for fall of 2012.

REFERENCES

[1] NASA Space Communication and Navigation Architecture Recommendations for 2005-2030, Final Report. Space Communications Architecture Working Group (SCAWG), 15 May 2006.

[2] Lunar Atmosphere and Dust Environment Explorer, National Space Science Data Center, http://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=LADEE

[3] J. M. Burnside, S. D. Conrad, C. E. DeVoe, A. D. Pillsbury, "Design of an Inertially-Stabilized Telescope for the LLCD", Proc SPIE 7923 (2011).

[4] L. E. Elgin, S. Constantine, M. L. Stevens, J. A. Greco, K. Aquino, D. A. Alves, B. S. Robinson, "Design of a High- Speed Space Modem for the Lunar Laser Communications Demonstration", Proc SPIE 7923 (2011).

[5] B. Moision and J. Hamkins, "Coded Modulation for the Deep-Space Optical Channel: Serially Concatenated Pulse- Position Modulation", IPN Progress Report, 42-161 (2005).
[6] M. L. Stevens, D. M. Boroson, D. O. Caplan, "A Novel Variable-Rate Pulse-Position Modulation System with Near Quantum Limited Performance", IEEE Lasers and Electro-Optics Society Annual Meeting, 301-302 (1999).
[7] D. Fitzgerald, "Design of a Transportable Ground Telescope Array for the LLCD", Proc. SPIE 7923 (2011).
[8] D. M. Boroson, R. S. Bondurant, and D. V. Murphy, "LDORA: A Novel Laser Communications Receiver Array Architecture", Proc. SPIE 5338, 56-64 (2004).
[9] J. A. Mendenhall, L. M. Candell, P. I. Hopman, G. Zogbi, D. M. Boroson, D. O. Caplan, C. J. Digenis, D. R. Hearn, R. C. Shoup, "Design of an Optical Photon Counting Array Receiver System for Deep-Space Communications",
Proc. IEEE, 95, 2059-2069 (2007).
[10] E. A. Dauler, B. S. Robinson, A. J. Kerman, J. K. W. Yang, E. K. M. Rosfjord, V. Anant, B. Voronov, G. Gol'tsman, K. K. Berggren, "Multi-Element Superconducting Nanowire Single-Photon Detector", IEEE Trans. Appl. Supercond., 17, 279-284 (2007).
[11] B. S. Robinson, A. J. Kerman, E. A. Dauler, R. J. Barron, D. O. Caplan, M. L. Stevens, J. J. Carney, S. A. Hamilton, J. K. Yang, K. K. Berggren, "781-Mbit/s photon-counting optical communications using a superconducting nanowire detector", Opt. Lett., 31, 444-446 (2006).
[12] M. E. Grein, " Design of a fiber-coupled superconducting nanowire detector array system for the LLCD", Proc. SPIE, 7923 (2011).
[13] K. E. Wilson, N. Page, J. Wu, and M. Srinivasan, "The JPL Optical Communications Telescope Laboratory Test Bed for the Future Optical Deep Space Network", IPN Progress Report 42-153, May 15, 2003
[14] Kevin Birnbaum, William Farr, Jonathan Gin, Bruce Moision, Kevin Quirk, Malcolm Wright, "Demonstration of a high-efficiency free-space optical communications link," Proc. SPIE, 7199 (2009).

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