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Overview and Status of The Lunar Laser Communication Demonstration

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***Abstract*—The Lunar Laser Communication Demonstration represents NASA's first attempt to demonstrate optical communications from a lunar orbiting spacecraft to an Earth-based ground receiver. A low SWAP optical terminal will be integrated onto the Lunar Atmosphere and Dust Environment Explorer (LADEE) spacecraft, presently scheduled to launch in 2013. LLCD will demonstrate duplex optical communications between this small space terminal and a multi-aperture photon-counting ground terminal at downlink data rates of up to 622 Mbps and uplink data rates of up to 20 Mbps. As of the time of this conference, the Lincoln-built ground terminal is being operated at a temporary site near Lincoln Lab, the space terminal is being integrated onto the spacecraft, and the two alternate ground terminals – being built by JPL and ESA – are in preparation.**

Keywords-Free-space optical communications, lasercom, photon counting receiver, lunar laser communications demonstration

I. Introduction

NASA has been developing free-space optical communications technology in order to support projected data return requirements for future space missions. Free space optical communications offers the promise of higher data rates than current radio-frequency communications capabilities, with reduced user burden in terms of required size, weight, and power (SWAP) for transmit and receive terminals. As an example, from lunar orbit, a ~10-cm transmit aperture transmitting a 0.5-W optical signal to an Earth-based 0.8-m collection aperture can support a data rates in excess of 500 Mbps using existing technologies. By comparison, on a recent lunar mission, the Lunar Reconnaissance Orbiter, a state-of-the-art radio frequency system designed to support data rates of 100-Mbps downlink rates used a 75-cm transmit aperture transmitting a 40-W Ka-band signal to an 18-m collection aperture on the Earth. In addition to reduced user burden, transmission in the optical bands offers access to large amounts of unregulated spectrum. Bandwidths in excess of 40 GHz can be utilized with existing electronic and electro-optic technologies.

In order to demonstrate these potential benefits of free-space optical communications for future deep space missions, NASA's Lunar Laser Communications Demonstration (LLCD) has been designed to demonstrate many of the potential benefits of free-space optical communications for future deep space missions [1]. LLCD will demonstrate high-rate duplex optical communications between a space terminal in lunar orbit and an Earth-based ground terminal. The LLCD system consists of a space terminal, the Lunar Lasercom Space Terminal (LLST), and a primary ground terminal, the Lunar Lasercom Ground Terminal (LLGT), which is designed to be transportable, but which will reside at White Sands, NM for the mission. In the past two years, the program has also added two alternate terminals, the Lunar Lasercom OCTL Terminal (LLOT), residing at JPL's Optical Communications Telescope Laboratory at Table Mountain Facility in California, and the Lunar Lasercom Optical Ground System (LLOGS), residing at ESA's OGS on Tenerife, the Canary Islands. The space terminal will be operated as a payload on the Lunar Atmospheric Dust and Environment Explorer (LADEE) spacecraft [2]. The operation of the space and ground terminals will be coordinated by the Lunar Lasercom Operations Center (LLOC) which resides at the MIT Lincoln Laboratory in Lexington, MA.

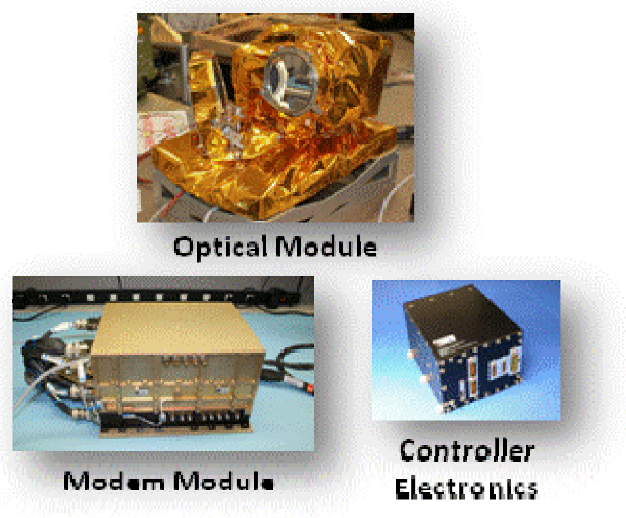

Figure 1. The Lunar Lasercom Space Terminal (LLST)

II. Terminal Overview

A. Lunar Lasercom Space Terminal

The LLST consists of an optical module and two electronics modules, the modem and the controller electronics, shown in Fig. 1. The optical module is based on a 10-

centimeter reflective telescope that produces a ~15 μrad downlink beam. The telescope is mounted to a two-axis gimbal via a magneto-hydrodynamic inertial reference unit (MIRU) [3]. Angle-rate sensors in the MIRU detect angular disturbances which are then rejected using voice-coil actuators for inertial stabilization of the telescope. Optical fibers couple the optical module to the modem where downlink transmitted optical waveforms are generated and uplink received optical waveforms are processed [4]. Control for the optical module and modem as well as command and telemetry interfaces to the spacecraft are provided by the Controller Electronics.

B. *Ground Terminals*

One of the goals of the LLCD is to demonstrate techniques for aggregating multiple small- to moderate-sized apertures in order to create an equivalent large-aperture for transmission and reception of optical signals [5-7]. Thus, the LLGT consists of an array of eight telescopes mounted on a single elevation-over-azimuth gimbal, as shown in Fig. 2. The gimbal provides coarse pointing for the entire telescope array. Each individual telescope includes a wide field-of-view focal plane array detector and a fast steering mirror for fine pointing corrections and tracking the received downlink signal. Four transceiver telescopes are used for transmitting the uplink signal. These ~15-cm refractive telescopes generate a ~10-urad focused beam for transmission. Four 40-cm reflective telescopes are used for the downlink collection aperture.

A control room housed in a 12-meter shipping container provides control for the telescopes and gimbal. The control room also houses the modem electronics and the uplink transmitter and downlink receiver electro-optics. The uplink transmitters and downlink receivers are coupled to the transceiver and receiver telescopes, respectively, via optical fibers.

The alternate terminals each include a single, 1-meter telescope with a coude path where the uplinks, receivers and trackers reside. Designs for these systems are being finalized as of the writing of this report.

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III. Operations

The Lunar Laser Communications Demonstration will operate during the commissioning phase of the LADEE mission. During this phase, the LADEE spacecraft will be in a ~2-hour equatorial orbit around the moon. When the moon is in view of the LLGT, there will be a ~65-minute window in each orbit when the LADEE spacecraft is in view of the LLGT and LLCD operations can occur. Power and thermal constraints on the spacecraft limit LLST operations to 15-30 minutes during this window. In each of these short operations periods, then, the terminals will spatially acquire each other and demonstrate uplink, downlink and time-of-flight operations.

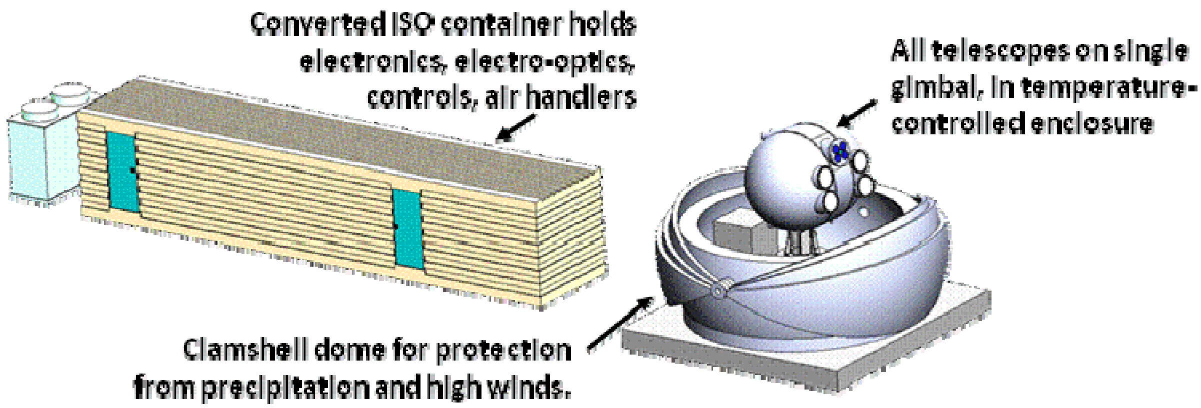

Figure 2. The Lunar Lasercom Ground Terminal (LLGT)

A. *Spatial Acquisition and Tracking*

Prior to initiation of communications, the various pointing and position uncertainties of the LLST and LLGT are sufficiently large so that neither terminal can accurately point its narrow communications beam at the other terminal. Thus, a coordinated spatial acquisition process is required to point the uplink and downlink beams at their respective receivers. During this process, a defocused ~45-μrad beam from the LLGT uplink transceiver telescopes is scanned over the uncertainty region of the ground terminal pointing. At each step in the scan, the LLGT dwells sufficiently long for the LLST to detect the uplink signal on its wide field-of-view quadrant detector. Once this uplink signal is detected, the gimbal and MIRU actuators on the LLST are used to point the downlink beam back at the LLGT by centering the detected uplink signal on the quadrant detector. Because of the relative motion of the terminals, a point ahead angle is required between the received uplink signal and the transmitted downlink signal. This point ahead angle is implemented using a piezo-electric actuator on the downlink transmitter fiber in the LLST optical module.

The downlink beam is then detected by the LLGT using wide-field of view focal plane array detectors in each of the transceiver and downlink telescopes. While the LLGT gimbal provides coarse pointing for all of the telescopes, a fast steering mirror in each telescope is used for fine pointing corrections as determined by tracking the downlink signal on each of the focal plane arrays. Once tracking of the downlink is initiated, the uplink beam is focused to ~10-μrad. This delivers sufficient uplink signal power to the LLST to initiate fine tracking of the uplink using a nutation tracker on the LLST receive fiber.

The two alternate ground terminals work similarly, and thus, their point/acq/track sequences are the same as for the LLGT. As of the writing of this report, however, they include beacon but no comm. signals on the uplink.

B. Downlink Communications

The downlink communications signal is generated by the LLST modem. Data from multiple sources are multiplexed onto the downlink waveform, including high-rate LLST telemetry (~5 Mbps), high-rate spacecraft data (up to 40 Mbps), and a loopback of the received uplink signal (up to 20 Mbps). Pseudo-random binary sequences are added to the multiplexed data to generate source data rates up to 622 Mbps for transmission. The data from each of these sources are framed and encoded using a 1/2-rate serially-concatenated turbo code which was developed for high-efficiency deep space optical communications [8]. A deep memory buffer (1-2 seconds) is used to interleave the encoded data symbols, providing temporal diversity to help mitigate the effects of atmospheric turbulence on the downlink communications channel. After encoding and interleaving, the symbols are modulated onto the optical carrier using 16-ary pulse position modulation. The downlink data rate is selectable by varying the pulse-position modulation slot frequency from 5 GHz down to 311 MHz. The modulated signal is amplified to 0.5 W using an erbium-doped fiber amplifier. This amplified signal is coupled via single-mode optical fiber to the LLST optical module for downlink transmission.

The downlink signal is collected by the LLGT using the four 40-cm downlink receive apertures. The collected signal in each telescope is coupled into a multimode polarization maintaining fiber for transport to the downlink detectors [9]. Superconducting nanowire detector arrays are used to detect the downlink signal. These single-photon detectors provide high detection efficiency (>60%), low-jitter (<50 ps), low noise (<50 kHz dark count rate), and fast detector response (<10 ns reset time), as required for the high-data rate downlink [10-11]. Each telescope is coupled to a 4-element SNDA. The outputs from each of the SNDAs are digitized and aggregated using high-speed digital electronics. The resulting high-speed digital signal is deserialized and input into a field-programmable gate array (FPGA)-based digital receiver for synchronization, demodulation and decoding.

C. Uplink Communications

The optical communications uplink is designed to operate at 10- and 20-Mbps source rates. Two data sources are transmitted on the uplink: commands to the LLST (up to 80 kbps) and high-rate user data for loopback (up to 20 Mbps). These data sources are framed and multiplexed in the LLGT digital electronics. The multiplexed data are encoded and interleaved using the same serially-concatenated turbo code and interleaver that is used for the optical downlink. The uplink uses a 4-ary pulse-position modulation format with 311-MHz slots. Dead time between the transmitted symbols is selected to be 12 or 28 slots to generate the two uplink data rates. Four optical transmitters modulate the encoded data onto optical carriers. The wavelengths of each of the four laser transmitters are detuned by ~1-GHz so that they are incoherently combined at the LLST receiver with little power penalty. After modulation, each of the four transmitters then has its signal amplified to 10 Watts using an erbium-doped fiber amplifier. The amplifier outputs are coupled to the four transceiver telescopes via single-mode fibers. The use of four transmit apertures provides spatial diversity to mitigate the effects of atmospheric turbulence while also enabling the use of commercial amplifier technology to generate the 40-W total uplink transmit power.

The transmitted uplink signals are collected by the 10-cm LLST telescope aperture and focused into an optical fiber for processing by the LLST modem. A low-noise erbium-doped fiber amplifier amplifies the received optical signal. The output of the optical amplifier is filtered with a 10-GHz fiber-Bragg grating filter prior to direct detection. A near-optimum hard-decision PPM demodulator [12] demodulates the signal which is then decoded by the LLST modem digital electronics. LLST commands received on the optical uplink are relayed to the controller electronics for execution. These commands as well as the high-rate user data received on the uplink are also looped back on the optical downlink.

D. Two-Way Time-of-Flight Measurements

In addition to uplink and downlink optical communications, LLCD will demonstrate a technique for utilizing duplex optical signals to perform two-way time-of-flight measurements between the LLGT and the LLST. This is accomplished by linking the uplink and downlink clocks in the LLST and comparing the phase of the transmitted uplink frame clocks and the received downlink frame clocks at the LLGT. A 5-GHz voltage-controlled oscillator (VCO) is used to generate the recovered 311-MHz slot clock in the LLST uplink receiver. This same VCO is used to generate the 5-GHz slot clock for the optical downlink, thereby ensuring that the uplink and downlink slot clocks are phase-locked at the LLST. In order to make the time-of-flight measurements, the uplink and downlink frame clocks must also be synchronized. This synchronization is enabled via command after the LLST has acquired the uplink signal. After synchronizing the uplink and downlink clocks in this manner, the LLCD system is capable of measuring the ~2.5-s two-way time-of-flight between the LLST and the LLGT with <200-ps instantaneous accuracy at a 20-Khz update rate.

IV. STATUS

As of the writing of this report, the system hardware, software, and planning are entering their final phases.

The LLST is being delivered this fall to NASA Ames Research Center, where the LADEE spacecraft is being built and integrated. It will be tested there until the spring of 2013 when it will be shipped to Wallops Island, VA, for launch preparations. Launch windows occur in early fall of 2013.

The LLGT is being assembled at a site near Lincoln Laboratory, so it can be operated and calibrated for a number of months before it is taken apart, shipped on several flat-bed trailers, and re-assembled at White Sands, NM. The uplink and downlink signals from the LLGT and LLST have been tested together via fiber at MIT Lincoln Laboratory.

Both the LLOT and LLOGS are being designed and built to meet the LLCD system requirements. Each of them will see interface checkout sometime over the winter, using space terminal engineering units provided by MIT Lincoln Lab.

V. SUMMARY

NASA's Lunar Laser Communications Demonstration will demonstrate, for the first time, high-rate duplex optical communications between a terminal in lunar orbit and an several Earth-based ground terminals. It will also demonstrate the use of duplex optical communications signal for high-accuracy two-way time of flight measurements between the terminals. The space terminal will reside on the NASA's Lunar Atmosphere and Dust Environment Explorer, currently scheduled for launch in 2013.

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