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Citation: Boroson, D.M. et al. "The Lunar Laser Communications Demonstration (LLCD)." Space Mission Challenges for Information Technology, 2009. SMC-IT 2009. Third IEEE International Conference on. 2009. 23-28. © 2009 IEEE.

As Published: <http://dx.doi.org/10.1109/SMC-IT.2009.57>

Publisher: Institute of Electrical and Electronics Engineers

Persistent URL: <http://hdl.handle.net/1721.1/61673>

Version: Final published version: final published article, as it appeared in a journal, conference proceedings, or other formally published context

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The Lunar Laser Communications Demonstration (LLCD)

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Abstract - NASA is presently overseeing a project to create the world's first free-space laser communications system that can be operated over a range ten times larger than the near-earth ranges that have been demonstrated to date. To be flown on the Lunar Atmosphere and Dust Environment Explorer (LADEE), which is planned for launch by NASA in 2012, it will demonstrate high-rate laser communications from Lunar orbit to a transportable ground terminal on the Earth. To support up to 622 Mbps over the approximately 400 thousand kilometer link, the system will make use of a high peak-power doped-fiber transmitter, a hybrid pointing and tracking system, high efficiency modulation and coding techniques, superconducting photon-counting detectors, and a scalable optical collector architecture. It also will support up to 20 Mbps on the optical uplink, plus a highly accurate continuous two-way time-of-flight measurement capability with the potential to perform ranging with sub-centimeter accuracy to the moving spacecraft. The project is being undertaken by MIT Lincoln Laboratory (MIT/LL) and the NASA Goddard Space Flight Center (GSFC.)

I. INTRODUCTION

In the near future the National Aeronautics and Space Administration anticipates a significant increase in demand for long-haul communications services from deep space to Earth. Distances will range up to 40 AU (1 AU = 149.6 million kilometers,) with data rate requirements in the 1's to 1000's of Mbits/second. It has long been known that optical communications has several great advantages over RF systems: extremely wide bandwidth transmitters and receivers available for carrying high rate data, extremely high gain from small terminals, and unregulated spectrum. Although the use of optical communications techniques in space have been just out of reach

for many years, in the past decade several international successes have shown it to be a real technology that could be considered for NASA's needs. In the U.S., the GOLD demonstration and GeoLITE; internationally, the SILEX system; and collaboratively internationally, OICETS and TESat, have all demonstrated long-distance and space-based lasercom.

There have also been several recent NASA studies, investigating the potential for lasercom. "RF and Optical Communications: A Comparison of High Data Rate Returns From Deep Space in the 2020 Timeframe," a 2007 report from one study ([1]), showed that lasercom has the potential to deliver any data rate possible by RF systems, but with less mass and using much less power. Some high data rates, especially from very long distances, are not even feasible using RF, but are within sight of today's lasercom technology. (See, e.g. [2])

In 2003, NASA kicked off its Mars Laser Communications Demonstration, which was to have been the world's first truly deep space laser communications mission. This program's goal was to demonstrate 3-50 Mbps (depending on the distance) from a NASA satellite, the Mars Telecom Orbiter. The program, with the space terminal developed by MIT Lincoln Laboratory, one ground terminal based on the Hale Telescope developed by the Jet Propulsion Laboratory, and one ground terminal based on a novel telescope receive array developed by Lincoln Lab, would have demonstrated many firsts ([3], [4]): a lasercom duplex link with up to a 40 minute round trip, point-ahead angles of up to 100 beamwidths, a space terminal with high-bandwidth beam

This work was sponsored by the National Aeronautics and Space Administration under Air Force Contract F19628-00-C-0002. Opinions, interpretations, conclusions, and recommendations are those of the author and are not necessarily endorsed by the United States Air Force.

stabilization based on an inertially-stabilized reference, near-capacity-achieving rate $\frac{1}{2}$ coding with interleaving and turbo-decoding, a master-oscillator-power-amplifier (MOPA) – based 5-W transmitter supporting 64-ary PPM, and two separate technologies of photon-counting at the receivers – JPL’s hybrid photo-multiplier tubes (PMTs) and Lincoln’s Geiger-mode avalanche photo diode (APD) arrays.

Although the MLCD program had proceeded successfully through its Preliminary Design Reviews, the MTO, unfortunately, was cancelled in 2005. Without the ride, NASA was forced to cancel MLCD as well.

Since that time, however, NASA has continued to pursue the development of technologies that could enable high data rates from Mars and beyond. In addition, NASA has also been pursuing related technologies for servicing missions to the Moon. Although high data rates (up to and beyond 1 Gbps) are feasible using RF techniques from the Moon, lasercom once again has the *potential* to deliver these rates and more with much lower mass and power at the space terminal. Lasercom also has the potential to deliver many Gbps, far past the point where RF has run out of steam.

II. The LADEE and LLCD Programs

In the spring of 2008, a NASA program was kicked off to send a new, small craft into lunar orbit. This science mission was to make measurements of the composition of the lunar atmosphere and also to characterize the lunar exospheric dust environment. Soon after the kickoff, it was also realized that this small craft had enough capacity to carry one more small payload, and that this could be the perfect chance to perform a technology demonstration of lasercom. Thus, the Lunar Laser Communications Demonstration was born.

The science mission is called the Lunar Atmosphere and Dust Environment Explorer, or LADEE, ([5]) and is being run by the NASA Ames Research Center (ARC.) The small spacecraft, being designed and built by ARC, is based on their recently-developed modular bus design, shown in Figure 1. To be launched on a Minotaur V out of Wallops Island, VA in mid 2012, it is hoped that this small but capable craft will be the first of many relatively inexpensive

missions to travel to the Moon and possibly beyond.

The main goal of the Lunar Laser Communication Demonstration, or LLCD, is to demonstrate the feasibility of performing high rate lasercom from a small terminal at lunar distances. LLCD comprises three main components: the Lunar Lasercom Space Terminal, or LLST; the Lunar Lasercom Ground Terminal, or LLGT; and the Lunar Lasercom Operations Center, or LLOC. The MIT Lincoln Laboratory is engineering the link and the system, and is designing and building these three components. The program is being managed for NASA by the NASA Goddard Space Flight Center (GSFC,) who is also in charge of developing the three science payloads on the LADEE spacecraft.

III. The LLCD System

The main goal of LLCD is to transmit up to 622 Mbps on the optical downlink, and up to 20 Mbps on the optical uplink. To do this, the LLST, shown in Figure 2, comprises 3 modules: an Optical Module, a Modem Module, and a Controller Electronics Module. The fully-gimballed Optical Module resides on an outer face of the small spacecraft, and the two other modules reside inside. Connections are made via electrical and optical fiber harnesses. There are 3 wavelengths between 1550nm and 1570 nm.

The Optical Module comprises a 2-axis gimbal, based on COTS parts ([6]), a 10-centimeter reflector telescope, a spatial acquisition detector, and fiber-coupling optics. The acquisition detector is a simple quadrant detector, with a field of view approximately 2 mrad. It is used both for detection of a scanned uplink signal, and as a tracking sensor for initial pull-in of that signal. The receiver is a fiber-coupled detector with an optical preamplifier. Low-frequency tracking error signals are generated by physically nutating the fiber using piezo-electric transducers. The transmitter is also fiber coupled, and the two beams are combined/separated in small optics using a dichroic beamsplitter. The transmitter and receiver fiber can achieve Point-Ahead via a piezo-electric transducer holding the transmit fiber.

The complete set of optics is flexure-mounted to a device based on the

Magnetohydrodynamic Inertial Reference Unit (MIRU) built by the ATA Corp. This device was originally to be used on the MLC D space terminal. It is a small platform, with a centrally-mounted optic, that uses Angle Rate Sensors, based on magnetohydrodynamics, to sense changes angle. Feedback signals to voice-coil actuators keep the plate inertially stable, at least above about 5 Hz. The LLCD Optical Module design takes the MLC D concept and balances through its center a 10-cm telescope plus its optical back-end.

Traditionally, lasercom terminals have supported symmetric or near-symmetric links, all at high rate. Thus, there has usually been adequate power to use 10% or so of the incoming power to be measured on a spatial tracking sensor, which then is used to drive a fast steering mirror. It was learned in the MLC D mission that deep space missions, especially ones that use uplinks that go through the atmosphere, find it difficult to deliver as much power to the space terminal as might be required to use this approach in a wide-band tracking loop. Thus, an inertially-stabilized telescope allows a much lower power incoming signal to support a much lower-bandwidth tracker. On LLCD, frequencies above about 5 Hz are stabilized by the MIRU, and frequencies below about 5 Hz are stabilized using error signals from the fiber-nutation system.

The fiber-coupled transmitter is a 0.5-W Master Oscillator Power Amplifier design, using an external modulator to create multiple data rates of 16-ary PPM on a 5 Ghz slot clock. A Virtex-4 FPGA is used to format, encode, and interleave data at rates up to 622 Mbps. The same FPGA is also used to decode and further process the uplink, which is a 20 Mbps 4-PPM signal on a 311 Mhz slot clock. Variable dead times (very similar to the concept described in [7]) are used to vary the uplink data rate. Downlink data rates are varied by using multiple counts of the 5 Ghz clock per PPM slot.

The Optical Module is held and protected during launch with a cover and one-time launch latch.

The Modem Module includes the electro-optics of the PPM transmitter and receiver, the FPGA and high-speed digital electronics, and analog receiver front-end electronics.

The Controller Electronics includes a general purpose processor for interfacing with the spacecraft, as well as I/O for all the sensors and actuators in the Optical Module plus the digital control loops to run them.

The ground terminal, the LLGT, includes a transmit telescope array and a receive telescope array, plus several racks of electronics and electro-optics. Shown in Figure 3, it is planned to be transportable to the ground site in the Southwest US, where the telescopes will be stationed on a concrete pad.

The transmitter system comprises four 15-cm co-boresighted telescopes on a single gimbal. Each telescope transmits up to 10 Watts, and carries a dedicated camera for spatial acquisition and tracking. The beam comprises the sum of both the uplink communications wavelength and the spatial acquisition wavelength, whose power ratio can be varied.

The receiver system comprises four 40-cm telescopes, each with a multi-mode fiber coupling its received beam to the receiver, placed several meters away. Each of these telescopes sends a small amount of its incoming power at a tracking camera. The multi-mode fiber has been designed so that, even in poor conditions, the tracking system couples most of the received light into the fiber.

The receiver for the downlink is based on superconducting nanowire single photon detectors (SNSPDs) developed jointly by MIT Lincoln Laboratory and MIT. ([8].) These devices have a detection efficiency of 50%, and only about 30 psec of timing jitter, which means they have no trouble detecting pulses on the 5 Ghz clock. They each are sized to have a reset time of about 3 usec and so are used in small multi-element arrays of 8 detectors per telescope. ([9] See Figure 4.) The size of the array of detectors has been designed so that each multi-mode fiber can have its output easily coupled to it using simple optics.

Using data interleaving to combat various fading phenomena, along with a near-Shannon-capacity-achieving code with its turbo-coder ([10]), this system will be able to achieve an efficiency of approximately one bit per photon. Aggregating the counts from four such systems provides adequate photons to support up

to 622 Mbps, with 311 Mbps possible in even poor atmospheric conditions.

The entire LLCD system is coordinated from the LLOC, which will reside along with the GSFC-built Science Operations Center which coordinates the science payloads on LADEE.

IV. The LLCD Mission

The LADEE mission has been designed to be of short duration – only 4 months total. Thus, the LLCD goal will be to achieve nearly as much lasercom time as possible in the first month, with the vagaries of weather at the single ground station being the biggest variable. It is expected that there will be nearly 20 hours of operations, including pointing, acquisition, and communications experiments in conditions including daytime, nighttime, full moon, new moon, high elevation, low elevation, and all sorts of atmospheric conditions.

A final feature of the LLCD system is its time-of-flight measurement system. With such short pulses on both the uplink and downlink it was reasoned that a careful coordination of clocks could allow measurement of two-way time-of-flight to a small fraction of the pulse times. Since the uplink pulses are about 300 psec, LLCD is expecting to make instantaneous two-way measurements with much less than 150 psec total error. Averaged over even a short pass, such a capability could provide sub-centimeter ranging even while the system's range is varying at rates up to several Kilometers per second.

V. Conclusion

We have attempted to give a snapshot of the design of the upcoming LLCD system, to be launched in mid-2012. It is hoped that a successful mission will open up the possibility of achieving both extremely high data rates and very small space terminals for future NASA mission. Starting at the Moon, and then scaling up to Lagrange point missions, and ultimately, planetary missions, lasercom could revolutionize

data collection and mission strategies across the Solar System.

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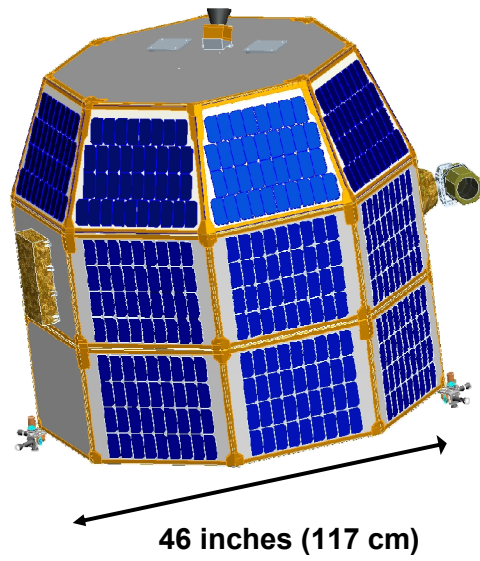


Figure 1. LADEE's modular "Common Bus" developed by NASA Ames Research Center.

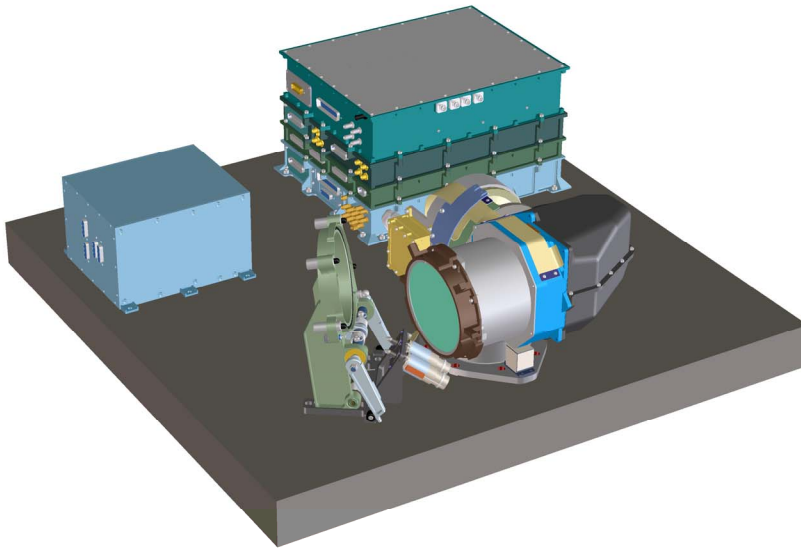


Figure 2. Lunar Lasercom Space Terminal.



Figure 3. Lunar Lasercom Ground Terminal telescopes and gimbal

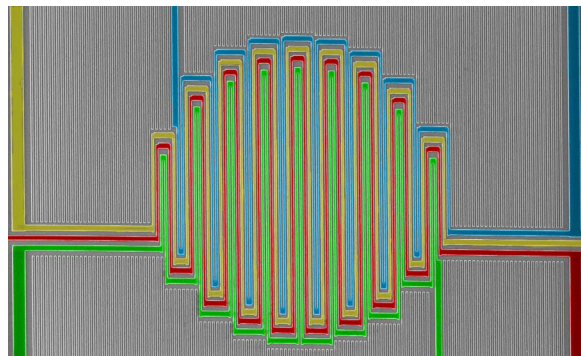


Figure 4. A four-element superconducting nanowire detector array.