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Citation: Boroson, Don M., and Bryan S. Robinson. "The Lunar Laser Communication Demonstration: NASA's First Step Toward Very High Data Rate Support of Science and Exploration Missions." Space Sci Rev 185, no. 1–4 (December 2014): 115–128.

As Published: http://dx.doi.org/10.1007/s11214-014-0122-y

Publisher: Springer Netherlands

Persistent URL: http://hdl.handle.net/1721.1/105850

Version: Author's final manuscript: final author's manuscript post peer review, without publisher's formatting or copy editing

Space Sci Rev (2014) 185:115–128
DOI 10.1007/s11214-014-0122-y

The Lunar Laser Communication Demonstration: NASA's First Step Toward Very High Data Rate Support of Science and Exploration Missions

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Received: 29 September 2014 / Accepted: 19 November 2014 / Published online: 3 December 2014

Abstract Future NASA missions for both Science and Exploration will have needs for much higher data rates than are presently available, even with NASA's highly-capable Space- and Deep-Space Networks. As a first step towards this end, for one month in late 2013, NASA's Lunar Laser Communication Demonstration (LLCD) successfully demonstrated for the first time high-rate duplex laser communications between a satellite in lunar orbit, the Lunar Atmosphere and Dust Environment Explorer (LADEE), and multiple ground stations on the Earth. It constituted the longest-range laser communication link ever built and demonstrated the highest communication data rates ever achieved to or from the Moon.

This report will summarize the main achievements of LLCD and put them in context of the near-term and long-term communications goals of NASA space missions.

Keywords Free-space optical communications · Laser communications · Lasercom · Photon counting receiver · Lunar laser communications demonstration · Moon · Lunar

1 Introduction

The highest resolution maps to date of Mars are based on thousands of photographs taken by orbiting American and European spacecraft. These have resolutions of 20–100 meters per pixel. There are also a number of photographs of surface features taken by, for example, the HiRISE camera on the Mars Reconnaissance Orbiter, which can resolve details down to 0.3 meters. A quick calculation, though, indicates that, even with the recently demonstrated

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

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6 Mbps data delivery from Mars (Shambayati et al. 2006) (which was not at the max range), an 8 bit map of the entire Martian surface at that 0.3 meter resolution would take over 60 years to transmit back.

There is a similar story for manned space exploration. The in-development Orion Multi-Purpose Crew Vehicle will carry humans to the Moon, asteroids, and perhaps even Mars. Although it could conceivably also carry communications equipment similar to the large science relay satellites, mass and size constraints keep its links to a very few megabits per second up and down, from the Moon, Bergin (2009) with R^2 losses keeping data rates much lower as the distances grow. There is no question that high definition and perhaps even 3-D video will be desired for these missions' downlinks, with good video uplinks, as well as near-continuous web-like connectivity for the astronauts and the mission.

For over thirty years, NASA has been developing free-space optical communications technologies to try to achieve the kinds of high duplex data rates that will be needed, as well as keeping space hardware with low SWaP (Size, Weight, and Power).

As a first major step, NASA designed, built, and demonstrated the Lunar Laser Communication Demonstration (LLCD). This system consisted of a space terminal, the Lunar Lasercom Space Terminal (LLST, Robinson et al. 2011), and a primary ground terminal, the Lunar Lasercom Ground Terminal (LLGT, Fitzgerald 2011), a transportable system which was stationed at White Sands, NM for the mission. In order to increase the amount of time of operations in the face of the short LLCD mission (one month) and the possibility of clouds, the program also included two alternate terminals, the Lunar Lasercom OCTL Terminal (LLOT, Wilson et al. 2012), residing at the NASA Jet Propulsion Laboratory's Optical Communications Telescope Laboratory at Table Mountain Facility in California, and the Lunar Lasercom Optical Ground System (LLOGS, Sans et al. 2012), residing at European Space Agency's OGS on Tenerife, the Canary Islands. The space terminal was a payload on the Lunar Atmospheric Dust and Environment Explorer (LADEE) spacecraft (Elphic et al. 2014). The operation of the space and ground terminals were all coordinated from the Lunar Lasercom Operations Center (LLOC) which resided at the MIT Lincoln Laboratory in Lexington, MA. The LLST, LLGT, LLOC, and overall LLCD system were all designed, built, and operated by teams from the MIT Lincoln Laboratory. The LLOT was designed and operated by the Jet Propulsion Laboratory and the LLOGS was designed and operated by the European Space Agency. The entire LLCD program was overseen by NASA Goddard Space Flight Center, and the LADEE spacecraft was designed, built, and operated by the NASA Ames Research Center.

The LLCD system was highly successful in meeting its goals of performing reliable high-rate links both up and down, plus demonstrating that system needs for operations of such a system were essentially the same as those of radio links, and that the large delivered data volumes were useful.

2 Brief Introduction to Lasercom

Optical communications (also known as free-space optical communications, laser communications, or just lasercom) is the use of the optical frequencies of the electromagnetic spectrum instead of the radio frequencies. These can be with wavelengths as short as ultraviolet or visible, as long as 2–10 microns, or, more typically, in the near- and short-wave infrared bands between 1 and 1.5 microns, where the fiber telecom industry has developed much relevant technology. Such terrestrial technology includes the very high-speed modulation that is possible in these optical bands.

There are direct optical analogs for every part of a communication system: a telescope instead of an antenna (possibly duplex), waveguides for carrying the signal (optical fibers), optical amplifiers and pre-amplifiers, sources, modulators, low-noise receivers, and so on. The big difference is the width of the beam, which, for a fixed aperture size, is known to have a diffraction-induced width proportional to the wavelength. Thus, lasercom beams can be as much as 10,000 times narrower than radio beams. This is good from the point of view of efficiently delivering power, but creates an engineering task of pointing and stabilizing the beams. After many years of working on these problems, however, the industry has devised a number of successful approaches.

Unlike the radio bands, the optical bands are unregulated, although care must be taken if the lasers are bright and they aim near airplanes or satellites with optical sensors. Thus, if adequate power can be transmitted and if modem hardware is adequately capable, extremely high data rates can be achieved. The other possible tradeoff would be to achieve the same data rates as radio systems, but design the terminal to be much smaller. Typically, lasercom systems try to achieve a little of each.

LLCD was designed to achieve higher data rates from lunar orbit than ever achieved before, while keeping both the space and ground terminals somewhat smaller than even much less capable radio systems.

3 LLCD System Overview

3.1 The System (see Fig. 1 and Table 1)

The LLCD lasercom links operated in the 1.5 micron band, and supported 4PPM (pulse position modulation) uplinks at 10 and 20 Mbps; 16PPM downlinks at selectable rates from

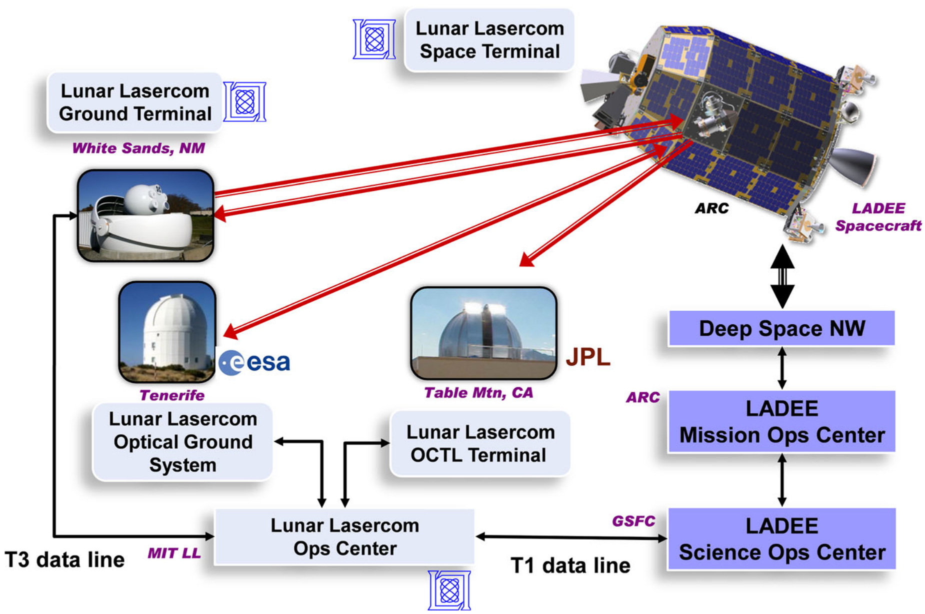

Fig. 1 LLCD system block diagram

Table 1 LLCD system block diagram

System	
Uplink data rate	10 or 20 Mbps
Uplink format	4-ary PPM
Downlink data rate	622, 311, 155, 78, 39 Mbps
Downlink format	16-ary PPM
Space terminal	
Total mass	~ 30 kg
Total power	~ 90 W
Telescope	10 cm, duplex
Uplink receiver	Pre-amplified direct detection
Downlink transmitter	0.5 W EDFA amplifier
Gimbal	2-axis
Tracking sensors	Inertial sensors plus nutating fiber comm receiver
Ground terminal	
Uplink	4 @ 15 cm
Downlink	4 @ 40 cm
Uplink transmitter	4 @ 10 W
Downlink receiver	Superconducting nanowire single photon detecting arrays

39 Mbps up to 622 Mbps; an uplink acquisition signal square-wave modulated at 1 Khz; and the capability to measure the round-trip Time of Flight (TOF) continuously with instantaneous errors somewhat less than 200 psec. As in most free-space lasercom systems, each of the two terminals of LLCD used the position of the received beam from the other terminal as its pointing reference.

3.2 Lunar Lasercom Space Terminal

The LLST has been described in detail in Robinson et al. (2011), Elgin et al. (2011), Boroson (2012), and Boroson et al. (2014). It consisted of an optical module mounted on an external panel of LADEE (See Figs. 1 and 2) and two electronics modules, the modem and the Controller Electronics (CE). The optical module was based on a duplex 10 centimeter reflective telescope that produced a ~ 15 μrad beam. Optical fibers coupled the optical module to the modem where nominally 0.5 W downlink transmitted optical waveforms were generated and uplink received optical waveforms were processed (Robinson et al. 2011). Control for the optical module and modem as well as command and telemetry interfaces to the spacecraft were provided by the CE. There was also a 40 Mbps interface between the LADEE data buffer and the downlink side of the modem, as well as data connections from the modem to the CE.

3.3 Ground Terminals

The primary ground terminal, the LLGT, has been described in detail in Fitzgerald (2011) and Boroson (2012). Its main features were its array of four 15 cm uplink telescopes, each transmitting a 10 W replica of the uplink which was delivered via single-mode fiber (Caplan et al. 2012) and tracking the downlink; its array of four 40 cm downlink telescope (Boroson et al. 2004), each coupled via multi-mode, polarization-maintaining fiber (Grein 2011) to an array of superconducting nanowire single photon detectors (Dauler et al. 2007; Willis et al. 2012); a single gimbal carrying all 8 telescopes in an environmentally-controlled enclosure; and a nearby control room containing the cryogenic nanowire systems, the rest of the modem electronics and opto-electronics, the various control computers, and the local operations center.

The LLGT was capable of performing all the uplink, downlink, and TOF functions in the LLCD system in real time. Its design and performance were described in more detail in Murphy et al. (2014). Its form factor allowed it to be transportable, and it was ultimately brought to White Sands. (See Fig. 3.)

The LLOT was based on the OCTL system with its 1 meter-diameter telescope (Wilson et al. 2012). It included uplink acquisition signals from 6 subapertures, with a total of 60 watts average power, and coupled its downlink via multi-mode fibers to a superconducting nanowire photon-counting array. The terminal was capable of supporting uplink acquisition and tracking, and could receive downlink rates up to 78 Mbps with software post-processing. Its design and performance were described in more detail in Biswas et al. (2014). (See Fig 4.)

The LLOGS was based on the OGS system with its 1 meter-diameter telescope (Sans et al. 2012). It included uplink acquisition and communications signals from 3 outrigger telescopes with a total of 60 watts average power, and coupled its downlink via multi-mode

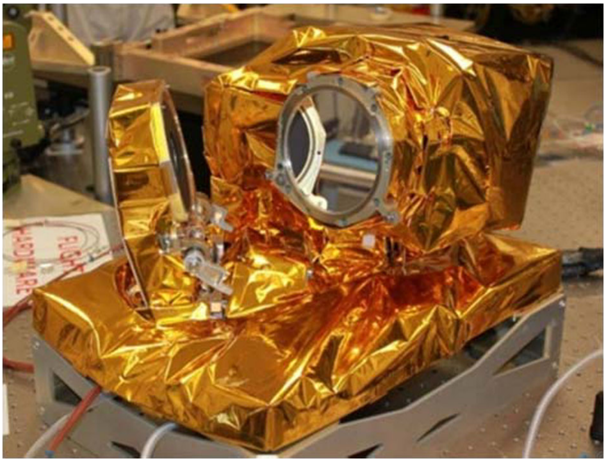

Fig. 2 The Lunar Lasercom Space Terminal, optical module. For scale, the aperture diameter is 10 centimeters

Fig. 3 The Lunar Lasercom Ground Terminal at site (White Sands, NM). The four smaller uplink telescopes can be seen grouped above the four 40 cm downlink telescopes

Fig. 4 The Lunar Lasercom OCTL Terminal (OCTL, at Table Mtn, CA)

Fig. 5 The Lunar Lasercom OGS Terminal (OGS, at Tenerife, Spain)

fibers to a photo-multiplier tube array. The terminal was capable of supporting uplink acquisition and tracking plus communications, and could receive downlink data at 39 Mbps with a hardware post-processor. Its design and performance were described in more detail in Sodnik et al. (2014) and Arnold et al. (2014). (See Fig. 5.)

3.4 Operations Center

The LLOC resided at MIT Lincoln Laboratory, and consisted of over one dozen desktop computers performing functions of command and control for the LLST, of monitoring telemetry from the LLST either over the RF path or the high-rate optical downlink path, of monitoring selected health and performance signals from each of the ground terminals, of monitoring weather conditions and predictions for the 3 sites, and monitoring telemetry and orbital information from LADEE. The computers and voice services were connected via ground lines to each of the ground terminals, to the LADEE Science Operations Center at Goddard Space Flight Center and to the LADEE Mission Operations Center at Ames Research Center.

4 Preparations, Launch, and Cruise

The LLST was designed, fabricated, integrated, tested, and space qualified at MIT Lincoln Laboratory. Integration onto LADEE, the launch, the phasing loops, and insertion into lunar orbit have been described elsewhere in this special issue (Elphic et al. 2014).

Near the apogees of loops 2 and 3, LLCD was provided a short window for checkout. Power up and internal checkouts plus the ground control infrastructure all operated correctly. The LLCD team was even able to attempt an initial pointing and acquisition session during one of the opportunities. Since the LLGT was partly cloudy during that period, the LLOT was used, and its uplink was successfully acquired and tracked. A downlink beam was similarly acquired and tracked. No lasercom data transfer was attempted. The primary spacecraft-to-LLST post-launch pointing biases, although reasonably small, were learned and subsequently compensated for on all the in-orbit passes.

5 Orbit, Conditions, and Operations Planning

The first month of the on-orbit LADEE mission took place in a near-circular low-inclination retrograde orbit approximately 250 km above the surface and lasting about 2 hours. This first month was divided into an alternating set of 4 and 3 day blocks. Each “4 Lunar Day Block (4LDB—a Lunar Day defined to be the time duration between moon rises)” was dedicated to LLCD operations during the approximately 19 hours that LADEE was visible by at least one of the 3 ground terminals. The 19 hour day started approximately one hour later each subsequent day as the Moon traveled in its monthly orbit around the Earth. In between the 4LDB’s were 3-day periods dedicated to the checkout and commissioning of the LADEE science payloads. At the end of this month, LADEE was lowered to approximately 50 km and was dedicated solely to its main science mission. The LLCD mission’s total duration ended up being 15 Lunar Days (Robinson et al. 2014).

The geometry of the orbit was such that LADEE was in front of the Moon for a little over an hour each orbit. The LADEE navigation team kept an up to date orbit model upon which LADEE in-view periods from Earth were predicted. Outputs from this orbital model were also sent regularly to the three ground terminals for their open-loop pointing needs. LADEE had allocated a (conservative) 39 watt-hours per orbit of energy usage for the LLST, since its battery was only being recharged about half of each orbit. Pre-launch calculations predicted that amount of energy would be able to power nominal LLST operations for 20–25 minutes. Thus, the joint LLCD/LADEE team had a certain freedom in the placement of the 25 minute pass time somewhere in the approximately one hour in-view time.

6 Pointing, Acquisition, and Tracking

The detailed design and operations of the LLCD pointing, acquisition, and tracking (PAT) systems and protocols have been described elsewhere (Burnside et al. 2011).

Using the most recent LADEE orbit knowledge, the ground terminal would transmit its beam to follow the moving spacecraft starting a few minutes before the LLST was to be powered up. The LLST used its knowledge of the location of the selected ground site plus one-second updates of attitude information sent to it by LADEE in order to initially point its telescope. Its acquisition detector was thus ready to detect an uplink if it were there.

As suggested above, after the very first (phasing loop) pass where the initial pointing bias was learned and corrected, the LLST was able to detect and pull in the uplink beam as soon as its gimbal had slewed to the proper position. Although conservative protocols had been devised and tested before launch in case either the ground terminal or the LLST were not able to point as well as hoped, it was found that both the ground terminals’ uplinks (with appropriate pre-pass star calibrations and appropriate beam-width selections) and the space terminal's pointing (even though it was mounted some distance from the LADEE star trackers) were good enough to produce instantaneous uplink detection and acquisition once the LLST gimbal completed slewing, and then, after a 1.3 seconds moon-Earth propagation time, instantaneous downlink detection and lockup. Once the ground terminal locked onto and tracked the downlink, it further refined its uplink pointing.

7 Communications and Ranging Functions

The LLCD data signals, both uplink and downlink, were constructed by multiplexing so-called transfer frames from multiple subchannels into a single time-division multiplexed (TDM) frame. These were block-encoded with data interleaved over approximately one second. The pairing of channel data interleaving with powerful coding (rate ½) has been found to be a highly robust means with which to combat even deep fading due to atmospheric turbulence (Boroson 2008; Barron and Boroson 2006).

Uplink streams were completely demodulated and decoded in the LLST modem (Stevens et al. 1999, 2014). The uplinks came from a combination of LLST terminal commands which were created at the LLOC (and were then passed by the LLST modem to the CE,) an arbitrary data stream from an Ethernet user port which was connected to the LLOC, and pseudonoise patterns to fill up the link.

Both the LLGT and LLOGS could transmit uplink data at either 10 or 20 Mbps. LLGT could send arbitrary data and the LLOGS could send a repeated fixed frame which was adequate for demonstrating the quality of the link by monitoring the LLST-measured and telemetered uplink Codeword Error Rates. The LLOT transmitted the uplink acquisition wavelength only. (The LLOGS and LLOT joined the LLCD program too late to be able to include all the functions.)

The downlink data sources included: the 2.7 Mbps LLST telemetry stream multiplexed with the data received on the uplink user channel and which provided a loop-back configuration for various demonstrations; a 38.55 Mbps stream from the LADEE buffer, which could be configured by LADEE to download arbitrary data partitions; and the rest of the downlink which was filled with encoded and framed pseudonoise patterns for assessing the performance of the entire link. The downlink could thus be selected to include 1, 2, 4, 8, or 16 parallel subchannels (corresponding to 39, 78, 155, 311, and 622 Mbps), with the lower data rates able to operate in even the poorest link conditions.

The LLGT had the capability to receive the entire downlink at any rate and decode any four selectable subchannels in real time using an FPGA implementation. The LLOT could receive either of the two lowest rates and could decode them off-line in a software-based system. The LLOGS could receive the lowest rate and could decode it off-line in a hardware-based system.

Thanks to the uplink and downlink rate designs being multiples of each other, the LLST modem used the derived uplink slot and frame clock as the reference for the downlink timing. Thanks to this feature, a ground terminal with both an uplink and downlink communications capability could measure the time delay between each uplink frame and the paired downlink frame that returned approximately 2.6 seconds later. This continuous (at 20 Khz) measurement of two-way Time of Flight (TOF) was a novel use of such a high-rate duplex link for Deep Space (or any) satellites. With the proper processing (removing the various known system biases) this measurement can produce knowledge of the position and orbit details of the spacecraft to a centimeter or better. Although LADEE did not make real-time use of this capability, the measurements were taken whenever there was a duplex link running.

8 Demonstrations and Performance

Of course, a major goal of LLCD was "just" to demonstrate that lasercom could be done from a lunar spacecraft to the ground. This was accomplished the first time it was attempted and on nearly all the passes through the month.

However, the real goal of LLCD was to show that lasercom had the following useful properties:

1. An optical space terminal can be integrated on and then flown on an operational spacecraft, and then provide useful services.
2. Lasercom can deliver high data rates from the Moon and beyond.
3. Optical beams can be acquired and tracked regularly, quickly and in many orbital and atmospheric conditions.
4. Optical links can be run error-free, on both the uplinks and downlinks through the turbulent atmosphere.
5. Optical links can be run error-free, on both the uplinks and downlinks, in daytime and nighttime, near the sun, as well as high and low in the sky.
6. Optical link operations can be run with a very small team.
7. Clouds can be dealt with operationally by preparing and coordinating a ground terminal network.
8. Intermittent clouds can be defeated by using a fast-re-acquiring system that uses a repeat-request protocol such as Disruption Tolerant Networking.
9. A capable optical ground terminal can be built from an array of small telescopes that can be transportable.
10. Highly-efficient high data rate optical reception can be achieved, even through turbulence, using high-speed photon-counters with error-correction codes and channel data interleavers.
11. Multiple error-free HD video streams can be carried over such links, in addition to data files.
12. Optical links can be used to carry command, control, and telemetry signals for the lasercom system itself.
13. Optical links can be brought up, operated, and reconfigured without the need for radio connectivity.
14. High-speed lasercom signals can be used to make continuous, real-time ranging estimates with centimeter-class accuracy.

All of these goals were achieved with LLCD.

1—Although LADEE was a completely new, very small satellite with only moderate capabilities for power and thermal control, the LLCD Space Terminal was successfully designed to fly on it. Its modularity allowed it to be placed throughout LADEE, aiding in balancing. It survived the launch and multiple rocket firings on the way to lunar orbit. It was successfully operated in the tough thermal environment of low lunar orbit, and was able to sustain links for 20–30 minutes per orbit on battery power.

2—The LLCD system regularly achieved error-free uplinks at either 20 Mbps or 10 Mbps, and also regularly was able to achieve downlinks at 622 Mbps, although many "passes" were operated at 311 Mbps so as to preserve energy by running the laser transmitter at half power. Lower data rates were sometimes used in particularly turbulent conditions. Such performance had been predicted in pre-launch modeling. The alternate terminals were successful in demonstrating their lower data rates.

3—After the first very few passes where pointing biases were learned and where a few space-ground (LLGT) configuration details were refined, then after acquisition, the system locked up every time with error-free performance both up and down. In most cases, with the uplink already illuminating the spacecraft, the Space Terminal was powered up and then slewed to its calculated position. Immediately upon reaching that position, the uplink was detected and locked up, and the duplex link was operational within seconds after that. (The one-way time of flight of the beam was about 1.3 seconds.)

4—With the primary ground terminal, uplinks and downlinks ran error free in nearly all atmospheric conditions. That is, the links were established and, 20 minutes later or so, when the links were powered down, the error totals on both the uplink and downlink showed zero counts. These counts were available because the decoders knew whether they had succeeded or not with extremely high probability.

5—With the primary ground terminal, links were error free at all times of the day and night. In fact, during the one pass with the sun near the Moon in the sky, links were preserved with Sun-Earth-Probe angles as low as 3 degrees. (There was essentially only one chance during the month when geometries were such that such a test could be run.) Also, the link continued to work as the Moon got lower and lower in the sky, with one pass down to 3.8 degrees elevation.

6—During the first several passes, many people from the Ground and Space Terminal teams—mechanical and thermal engineering, electrical engineering, and communications—stayed in the Operations Center to assist with any necessary initial debugging efforts. However, after only a few days, the operations had become so routine that only two operators at the LLGT and three operators (Director plus liaisons with the spacecraft team and the LLGT) in the LLOC were required. There is no doubt that operations could have been done with even fewer.

7—With the potential for cloud cover during the short one-month mission, the LLCD program added two alternate ground terminals, as described above. The times when both the LLGT and the LLOGS could see LADEE were limited, but of those, the availability of two terminals definitely increased the number of possible passes. The LLGT and LLOT had near complete time overlap, and so several times every day, there was the opportunity to choose, at the last minute, the terminal with better cloud conditions.

On several occasions during the month, it was found that cloud conditions changed during the pass. Thus, with only a modicum of warning to the terminal on standby, the Space Terminal was commanded to drop the link being clouded out, slew to the new terminal, and successfully lock up and operate, all in seconds. This demonstrated break-before-make handover will be important in future space-to-ground systems with capable ground networks.

8—Near the end of the month, a team from Goddard SFC plus the MIT Lincoln Laboratory programmers created the capability to send files from Goddard to the LLOC to the LLGT, up over the Moon, and back to Goddard, using end-to-end Delay/Disruption Tolerant Networking. The details of this demo were given in Israel and Cornwell (2014), but we can say here that the demonstration was quite successful in pushing files over the link. In fact, one of the passes selected for this demo experienced scattered clouds over White Sands. Although the link came and went, the DTN protocol successfully pushed the data through whenever the links were up. There is no doubt that such a capability will make some kinds of future laser communication functions be successful even in the face of partial clouds.

9—The LLGT was designed with an array of transmit telescopes and an array of receive telescopes, all configured on a single gimbal. The non-coherent uplink transmissions and multi-mode fiber-coupled photon-counted downlinks worked very well (and as predicted by theory and modeling) in achieving these high data rates, especially with the very small space transmitter. This was all designed so that it could be taken apart and reassembled quickly, making it fully transportable. Future ground infrastructures will likely be a combination of fixed-location terminals and transportable ones.

10—LLCD demonstrated what had been known through theory and simulation—that a powerful, medium-rate code paired with a long channel-data interleaver would allow error-free performance even through appreciable fading due to turbulence. In addition, the ground terminals used photon-counting detectors behind multi-spatial-mode collectors, allowing operation through turbulence without adaptive optics. Error-free performance was demonstrated in nearly all conditions.

11—Using the error-free, high-rate up and downlinks, LLCD was able to transmit arbitrary signals (via an Ethernet port) up to the Space Terminal, and then to loop the demodulated bits back to the ground. The 20 Mbps uplink was thus able to carry up to four HD video signals and loop them back. Although future systems will likely not use the loop-back configuration of this demonstration, the achievement showed the ability to send error-free HD videos either up or down. Both pre-recorded and live videos were sent in this fashion, to the great amusement of visitors to the LLOC.

The fast links were also used to demonstrate error-free transmission of large data files both on the uplink (to the Controller) and on the downlink. In fact, the downlink was used to transmit the entire 1 GB LADEE buffer on a number of occasions during the month, taking only minutes instead of the 2–3 days it would have taken had LADEE tried to accomplish this using its radio link. This data was found to be very useful, especially after anomalies occured.

12—Operating the Space Terminal was possible by sending it commands and by monitoring its telemetry. The system was able, of course, to do both of these using the radio links (through the LADEE systems). However, the Space Terminal was configured to send downlink telemetry (a much more complete set) at a rate about 50 times that of the radio link, as well as accept optical uplink commands sent in real time directly from the LLOC to the LLGT. After the first several sessions where all configurations were performed using the radio links, the LLCD team used instead the optical links to do all terminal commanding and configurations throughout the month of passes. That included being able to change the rate and format details of the uplink, with much care, during the sessions. It also made feasible (and demonstrated) the uploading of files including patches to the on-board software.

13—Usually, LLCD requested LADEE to send the power-up commands to the Space Terminal in real time when the ground terminal and planning were announced to be ready. However, on several passes, previously-configured command scripts had been uploaded to LADEE. Then, at a pre-defined time, LADEE autonomously powered up the Space Terminal which then acquired and locked up with the Ground Terminal. This allowed the entire session to be started, run, reconfigured, and shut down with no radio links required. Only pre-loaded "Absolute Time Sequences" and optical links were used. Such capability will greatly simplify future mission operations.

14—As described above, the primary terminal was able to make continuous two-way Time of Flight measurements with high accuracy whenever both the up and down lasercom links were running. This data was processed off-line for LLCD and LADEE and shows the predicted performance—at least as good as the sporadic ranging done by the radio system. It is very likely that future real-time details will be able to be tweaked to give even an order of magnitude (if not more) better than radio performance in future systems.

9 The Meaning of LLCD for Future Science and Exploration Mission

LADEE was a relatively short mission, and had an even shorter period allocated for LLCD operations. However, the approximately 100 total passes, spread out over a wide variety of day/night, orbital, and atmospheric conditions, plus three different ground terminals, were more than adequate to demonstrate the capability, robustness and reliability of the high-rate LLCD lasercom system.

In the past, science or exploration mission managers have been wary about employing this new technology for a number of reasons. It is hoped that the specific achievements listed in the last section will go a long way to giving confidence to future system designers for including lasercom in order to increase their data return, as well as meet new uplink needs.

Certainly, this exact system could be useful for lunar trunk lines, carrying large amounts of science or mission ops data in both directions. We should point out that the exact same space terminal hardware, if it were to be reprogrammed, could quadruple the downlink capability (if paired with a larger ground telescope). Similarly, the uplink could quadruple its capability with more on-board decoders. (It used a ¼ duty cycle uplink that could be filled in the future, and was already designed with plenty of signal margin.)

A manned exploration mission might not need all this demonstrated data rate capability, and so it is easily envisioned to create an even smaller space terminal that could still greatly outperform a radio system of the same SWaP.

Either of these systems would require the development of a set of ground terminals around the world, for increased availability due to both the rotation of the Earth and clouds.

The same space design, with an enhanced space transmitter amplifier and larger ground telescopes (2–3 meters, say), is predicted to be able to even deliver high capability on missions out to the Lagrangian points or possibly even some asteroids.

Of course, lasercom is highly relevant to planetary missions as well. Their huge distances, though, (hundreds to tens of thousands of times farther than the lunar link) would require a somewhat larger space telescope, an appreciably (though available) higher power space transmitter, and a very much larger ground collector (Boroson et al. 2004; Hemmati et al. 2012).

10 Summary

The LLCD mission was a great success. All the functions operated as predicted or better. PAT was robust and nearly instantaneous. Useful data services were demonstrated and found to be dependable. A rudimentary multi-site ground terminal network was developed and demonstrated. Operations with the NASA spacecraft were made routine. It was demonstrated that optical links could be set up without special hands-on interactions, and ground station handovers were demonstrated. Many lasercom system design approaches were validated, including specifying and validating the spacecraft-terminal interface, building the lasercom links to work through turbulence, operating lasercom as part of an ongoing science mission, employing multi-mode photon-counting receivers, using ground telescope arrays on both the uplink and downlink, employing an inertially-stabilized space telescope, including high-accuracy ranging as a by-product of the lasercom links, and so on.

LLCD has been the world's first successful two-way lasercom link from lunar orbit to the ground, has set the record for highest data rates ever accomplished to or from the Moon using any means, and has been NASA's first lasercom system. It is expected that next-generation science and exploration missions will begin to tap the great potential of optical communications.

Acknowledgements At this point, the two authors of this report would like to acknowledge the many dozens of people who designed, built, integrated, and operated the various parts of the LLCD system. These talented and highly dedicated teams were led by: Dr. Dennis Burianek and Dr. Daniel Murphy of MITLL, who led, respectively, the LLST and LLGT efforts; Dr. Farzana Khatri and Marilyn Semprucci of MITLL, who led the LLOC effort; Abhijit Biswas of JPL who led the LLOT effort; and Dr. Zoran Sodnik of ESA who led the LLOGS effort. Also special acknowledgements and thanks go to Dr. Donald Cornwell of NASA who was the tireless and talented Mission Manager, and to John Rush of NASA's Space Comm and Nav office, whose vision and energy led to the creation of this program, to its all-important inter-organizational arrangements, and to its continued strong support throughout.

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