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Overview of the Lunar Laser Communication Demonstration

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***Abstract*—For one month in late 2013, NASA's Lunar Laser Communication Demonstration (LLCD) successfully demonstrated for the first time duplex laser communications between a satellite in lunar orbit, the Lunar Atmosphere and Dust Environment Explorer (LADEE), and 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. The system included the development of a novel space terminal, a novel ground terminal, two major upgrades of existing ground terminals, and a capable and flexible ground operations infrastructure. This presentation will give an overview of the system architecture and the several terminals, basic operations of the system, and a brief discussion of the results.**

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

I. Introduction

For over thirty years, NASA has been developing free-space optical communications technologies 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 a first major step, for the past six years NASA has been designing and building the Lunar Laser Communication Demonstration (LLCD.) This system consists of a space terminal, the Lunar Lasercom Space Terminal (LLST, [1]), and a primary ground terminal, the Lunar Lasercom Ground Terminal (LLGT [2]), 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, [3]), residing at JPL's Optical Communications Telescope Laboratory at Table Mountain Facility in California, and the Lunar Lasercom Optical Ground System (LLOGS, [4]), residing at ESA's OGS on Tenerife, the Canary Islands. The space terminal was a payload on the Lunar Atmospheric Dust and Environment Explorer (LADEE) spacecraft [5]. 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.

II. ACKNOWLEDGMENTS

At this point, the lone author 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 Bryan Robinson of MIT Lincoln Laboratory, the LLCD System Engineer; 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.

III. System Overview

A. The System

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

B. Lunar Lasercom Space Terminal

The LLST has been described in detail in [1] [6], and [26].. (See Fig 1.) It consists of an optical module and two electronics modules, the modem and the Controller Electronics (CE). The optical module is based on a duplex 10-centimeter reflective telescope that produces a ~15 µrad beam. Optical fibers couple the optical module to the modem where nominally 0.5-W downlink transmitted optical waveforms are generated and uplink received optical waveforms are processed

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([1]). Control for the optical module and modem as well as command and telemetry interfaces to the spacecraft are provided by the CE. There is 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.

C. Ground Terminals

The primary ground terminal, the LLGT, has been described in detail in [2] and [7]. Its main features are its array of four 15-cm uplink telescopes, each transmitting a 10-W replica of the uplink which is delivered via single-mode fiber ([20]) and tracking the downlink; its array of four 40-cm downlink telescope ([22]), each coupled via multi-mode, polarization-maintaining fiber ([8]) to an array of superconducting nanowire single photon detectors ([9]); 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 are described in more detail in [10]. Its form factor allowed it to be transportable, and it was first set up and tested for several months near MIT Lincoln Laboratory, and then disassembled and transported to White Sands, where it resided since early summer, 2013. (See Fig 2.)

The LLOT was based on the OCTL system with its 1-meter-diameter telescope. ([3]) 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 are described in more detail in [11]. (See Fig 3.)

The LLOGS was based on the OGS system with its 1-meter-diameter telescope ([4]). 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 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 are described in more detail in [12] and [27]. (See Fig 4.)

D. Operations Center

The LLOC was constructed in an office 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 SFC and to the LADEE Mission Operations Center at Ames RC.

IV. PREPARATIONS, LAUNCH, AND CRUISE

The LLST was designed, fabricated, integrated, tested, and space qualified at MIT Lincoln Laboratory. The three modules were shipped to Ames by the very beginning of the calendar year 2013. There, they were integrated onto the spacecraft, and then spent the spring participating in spacecraft functional and qualification testing. The entire spacecraft was packed up and shipped and arrived at the launch facilities at Wallops Island, Virginia the beginning of June 2013.

LADEE was launched on a Minotaur V rocket . The completely successful nighttime launch was visible up and down the U.S. East Coast. LADEE was put into a series of four phasing loops, using short rocket bursts and gravity assists to increase the max distance each loop. 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.

Thanks to the LADEE Ames team, the spacecraft achieved lunar orbit on October 8.

V. 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)” 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 to be lowered to approximately 50 km and to be dedicated solely to its main science mission. Thus, the LLCD mission’s total duration was planned to be 16 Lunar Days.

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 appearance and disappearance times 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 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.

VI. Pointing, Acquisition, and Tracking

The LLCD pointing, acquisition, and tracking (PAT) systems and protocols had been designed to push much of the complexity off of the LLST and onto the ground terminal. Thus, the uplink included a separate wavelength for the acquisition phase and for the uplink communications phase. Both signals were on at fractional power during LLST tracking handover, and, in fact, could both be left on whenever there was adequate uplink comm received power as monitored from the real-time LLST telemetry. (We note here that the uplink was designed with plenty of signal margin.)

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 uplink beam was spread to between 45 and 100 urad (each ground terminal had its own design). The acquisition wavelength was square-wave modulated at 1 Khz which provided a background and detector noise immunity at its acquisition detector.

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 two-milliradian-wide acquisition quadrant 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. 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. These protocols had various patterns of uplink scanning and downlink scanning until acquisition was successful, and very worst case analyses had predicted as much as a few minutes for the sequence to finish. Instead, 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, 1.3 seconds later, instantaneous downlink detection and lockup. Once the ground terminal locked onto and tracked the downlink, it further improved its uplink pointing.

VII. Communications Functions

The LLCD data signals were constructed by multiplexing so-called transfer frames from multiple subchannels into a single time-division multiplexed (TDM) frame. Data bits from each sub-channel were first appended with ID, CRC, and termination bits to create a 7560-bit block. Each block was then encoded by a rate ½ serially concatenated turbo code ([15]). Encoded channel symbols from each sub-channel were then convolutionally interleaved with a total spread of up to one second. The pairing of channel data interleaving with powerful coding has been found to be a highly robust means with which to combat even deep fading due to atmospheric turbulence ([16]). Finally, each encoded and interleaved block of 15120 channel bits was appended with a 64-channel-bit fixed Frame Alignment Sequence (FAS).

The uplink was a fixed slot rate, variable dead time 4PPM signal that could carry either a 10 Mbps or 20 Mbps data stream.([20]) It multiplexed either 8 or 16 subchannels. The receiver for this was a novel, bit-wise hard decision architecture with noise figure set by an optical pre-amplifier and configured with a Fiber Bragg Grating (FBG) near-matched filter ([17]). Uplink streams were completely demodulated and decoded in the LLST modem. The uplink subchannels 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 rate. 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 was a 16PPM signal, with selectable slot rates from 311 MHz to 5 GHz. A single subchannel data rate was 38.55 Mbps and link data rates went from 38.55 Mbps up to 622 Mbps. Downlink TDM frames included 1, 2, 4, 8, or 16 subchannels. Subchannel 0 always included the 2.7 Mbps LLST telemetry stream multiplexed with the data received on the uplink user subchannel. This provided a loop-back configuration for various demonstrations. Subchannel 1 was a 38.55 Mbps stream from the LADEE buffer, which could be configured by LADEE to download arbitrary data partitions. The other subchannels were filled with encoded and framed pseudonoise patterns for assessing the performance of the entire link. Data paths and capabilities for the LLCD system are depicted in Figure 5.

The downlinks were received in all 3 ground terminals by coupling the light into multi-mode fibers which then fed photon-counting subsystems, as briefly described earlier. (Many more details are given in [10], [11], [12], and [27]). 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. Furthermore, the time delay between the receipt of an uplink TDM frame and the subsequent downlink TDM frames was calibrated before launch. 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) is a novel use of such a high-rate duplex link for Deep Space (or any) satellites. With the proper processing (removing the various known biases) it is expected that this measurement will produce knowledge of the position and orbit details of the spacecraft to a centimeter or better. Although LADEE did not make use of this capability, the measurements were made whenever there was a duplex link running, and future analyses will assess its utility. Laboratory measurements of the flight hardware had showed that the instantaneous time errors were to be on the order of 10s of picoseconds, set mostly by the lower-rate uplink.

VIII. Demonstrations and Performance

At the beginning of the month of LLCD operations, the LLST was programmed to start up at 155 Mbps down, 20 Mbps up, and only 0.25 W transmitted, with the plan to change rates and power during the passes as the team got more familiar with the performance. After the first very few passes 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. With real-time LLST commanding from the LLOC (plus paired instructions to the ground terminal,) rates could be changed, and thus all data rates were exercised, with similar error-free performance found throughout. It was found that 0.25 Watts sufficed for error-free downlink performance at all rates up to 311 Mbps, and, depending on the atmospheric conditions, sometimes also for 622 Mbps, although usually the team upped the power to 0.5 Watts for the 622 Mbps sessions. (Note: it had been found in ground testing that the 622 Mbps mode in the LLGT sometimes displayed a codeword error rate floor of about one error per minute, due to several hardware nuances. As of the writing of this report, it was planned to exercise in a possible final set of passes a very low overhead erasure-correcting end-to-end code, that will remove this floor.) The uplink was similarly error free at both data rates. The alternate terminals had similar quick lock-up, and have seen very good downlink performance as well. (Details on their performance are given in [11] and [12].

To exercise the links and show their utility, a number of demonstrations were run with the LLGT. Although LADEE provided only about 50 Kbps of real-time downlink RF telemetry, when the optical link was running, the LLST had the capability of sending 2.7 Mbps of high-rate telemetry on the optical link. This data was forwarded in real time to the LLOC, where the telemetry processing system (ITOS) simultaneously displayed and graphically plotted both its high-rate measurements and the lower-rate LADEE-delivered data. High rate signals such as the received uplink power and tracking corrections were viewed. All transmission of telemetry was delivered error-free throughout.

A number of times during the month, the LADEE 1 GB data buffer was also downloaded, error-free, and forwarded to the LADEE team for analysis.

Another use of the data links included the uplink user port. The nearly 20 Mbps was adequate for transmitting multiple simultaneous high definition videos, and then having those videos be demodulated and loop-back re-modulated onto the downlink. Once this capability was made to work, it was used continuously on all subsequent LLGT passes. Videos transmitted included professionally-created NASA videos of launches and shuttle operations and others. Also, many personal photos were compiled into a slide show which was looped up and back from the Moon.

Finally, a live HD video camera was set up in the LLOC, and operators plus visitors to the LLOC got to see their images go up over the Moon. Live video delays included the 2.6 seconds of the time of flight, a fraction of a second for the signal to twice traverse the country, about 2 seconds for the data interleavers on uplink and downlink, plus a final couple seconds for the delays required by the real-time video processing software used in the LLOC. Thus, viewers saw their activities about 7 seconds later. Needless to say, this was a very popular feature of the demonstration.

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, using end-to-end Delay/Disruption Tolerant Networking. The details of this demo are given in [18], 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.

The TOF measurements gave results as predicted. When a preliminary coarse translation from time to distance was calculated, the measurements followed the predicted ephemeris-derived range extremely well. Also, instantaneous errors were found to be only a few centimeters in the 20 Khz data, which suggests that the follow-on ranging exercise should be able to achieve sub-centimeter accuracy for orbit models. ([19]).

Due to scheduling details and some changes of plans, LLCD ended up with 15 Lunar Days of operations, the last 3 of which were in a slightly lower orbit. The LLGT took a total of 56 passes, the LLOT 22 passes, and the LLOT 15 passes, with 8 passes lost because no available terminal was cloud-free. They were usually used to perform LLST-internal functions. These numbers include links that were attempted even when there were partial clouds, and a number of passes were completely successful even in such conditions.

IX. SUMMARY

NASA considers the LLCD mission to have been 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 a ground station handover was 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.

REFERENCES

[1] B. S. Robinson, D. M. Boroson, D. A. Burianek, D. V. Murphy, "Overview of the Lunar Laser Communications Demonstration", Proc SPIE 7923 (2011).

[2] D. Fitzgerald, "Design of a Transportable Ground Telescope Array for the LLCD", Proc. SPIE 7923 (2011).

[3] K. E. Wilson, D. Antsos, L. C. Roberts Jr., S. Piazzolla, L. P. Clare, A. P. Croonquist "Development of the Optical Communications Telescope Laboratory: A Laser Communications Relay Demonstration Ground Station", ICSOS 2012.

[4] M. Sans, Z. Sodnik, I. Zayer, R. Daddato, Design of the ESA Optical Ground Station for Participation in LLCD", ICSOS 2012.

[5] Lunar Atmosphere and Dust Environment Explorer, National Space Science Data Center, +

http:// http://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=2013-047A

[6] 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).

[7] D.M. Boroson, "Overview and Status of the Lunar Laser Communication Demonstration", ICSOS 2012.

[8] M. E. Grein, "Design of a fiber-coupled superconducting nanowire detector array system for the LLCD", Proc. SPIE, 7923 (2011).

[9] 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).

[10] D. V. Murphy, R. E. Lafon, J. E. Kansky, M. E. Grein, R. T. Schulein, M. M. Willis, "LLCD operations using the Lunar Lasercom Ground Terminal", Proc SPIE 8971 (2014)

[11] A. Biswas, J. M. Kovalik, M. W. Wright, W. T. Roberts, K. Birnbaum, M. D. Shaw, M. K. Cheng, M. Srinivasan, K. J. Quirk, "LLCD operations using the Lunar Lasercom OCTL Terminal", Proc SPIE 8971 (2014)

[12] Z. Sodnik, H. Smit, M. Sans, I. Zayer, M. Lanucara, I. Montilla, A. Alonso , "LLCD operations using the Lunar Lasercom OGS Terminal", Proc SPIE 8971 (2014)

[13] B. D. Felton, P. D., Hayes, R. J. Alliss, "Improved atmospheric characterization for free-space link analysis using numerical weather prediction", Proc SPIE 8380 (2012).

[14] D. M. Boroson, J. J. Scozzafava, D. V. Murphy, B. S. Robinson, H. Shaw, "The Lunar Laser Communications Demonstration (LLCD)", Proc SMC-IT 2009.

[15] B. Moision and J. Hamkins, "Coded Modulation for the Deep-Space Optical Channel: Serially Concatenated Pulse-Position Modulation", IPN Progress Report, 42-161 (2005).

[16] R. J. Barron, D. M. Boroson, "Analysis of Capacity and Probability of Outage for Free-Space Optical Channels with Fading due to Pointing and Tracking Error", Proc SPIE 6105 (2006).

[17] 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).

[18] D. Israel, D. Cornwell, "Disruption Tolerant Networking Demonstrations over LLCD's Optical Links", IPNSIG Space Technology Innovations Conference, 24 Jan 2014.

[19] B. S. Robinson, "The LLCD Time of Flight System", SMC-IT 2014.

[20] D. O. Caplan, J. J. Carney, R. E. Lafon, and M. L. Stevens, "Design of a 40 Watt 1.55 um Uplink Transmitter for Lunar Laser Communications, Proc. SPIE, 8246 (2012).

[21] 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).

[22] D. M. Boroson, R. S. Bondurant, and D. V. Murphy, "LDORA: A Novel Laser Communications Receiver Array Architecture", Proc. SPIE 5338, 56-64 (2004).

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

[24] D.M. Boroson, "Overview and Status of the Lunar Laser Communication Demonstration", ICSOS 2012.

[25] M.M. Willis, A.J. Kerman, M.E. Grein, J. Kansky, B.R. Romkey, E.A. Dauler, D. Rosenberg, B.S. Robinson, D.V. Murphy, D.M. Boroson, "Performance of a Multimode Photon-Counting Optical Receiver for the NASA Lunar Laser Communications Demonstration, ICSOS 2012

[26] D. M. Boroson, B. S. Robinson, D.A. Burianek, D.V. Murphy,F. I. Khatri, J.M. Kovalik, Z Sodnik, "Overview and Results of the Lunar Laser Communication Demonstration",Proc SPIE 8971, (2014).

[27] F. Arnold, M. Mosberger,J. Widmer, F. Gambarara, "Ground Receiver Unit for Optical Communication between LADEE Spacecraft and ESA Ground Station", Proc SPIE 8971 (2014).

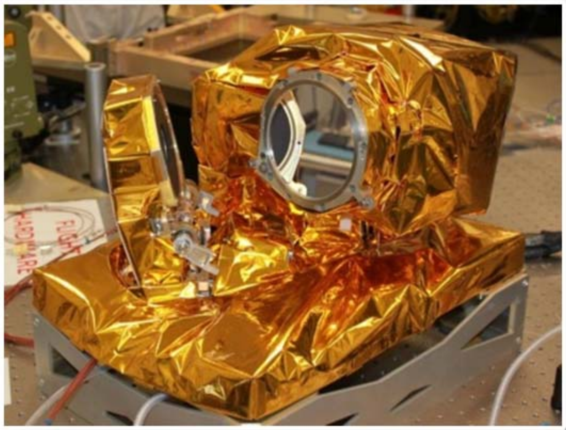

Figure 1 The Lunar Lasercom Space Terminal, Optical Module

Figure 2 The Lunar Lasercom Ground Terminal at site (White Sands, NM)

Figure 3 The Lunar Lasercom OCTL Terminal (OCTL, at Table Mtn, CA)

Figure 4 The Lunar Lasercom OGS Terminal (OGS, at Tenerife, Spain)

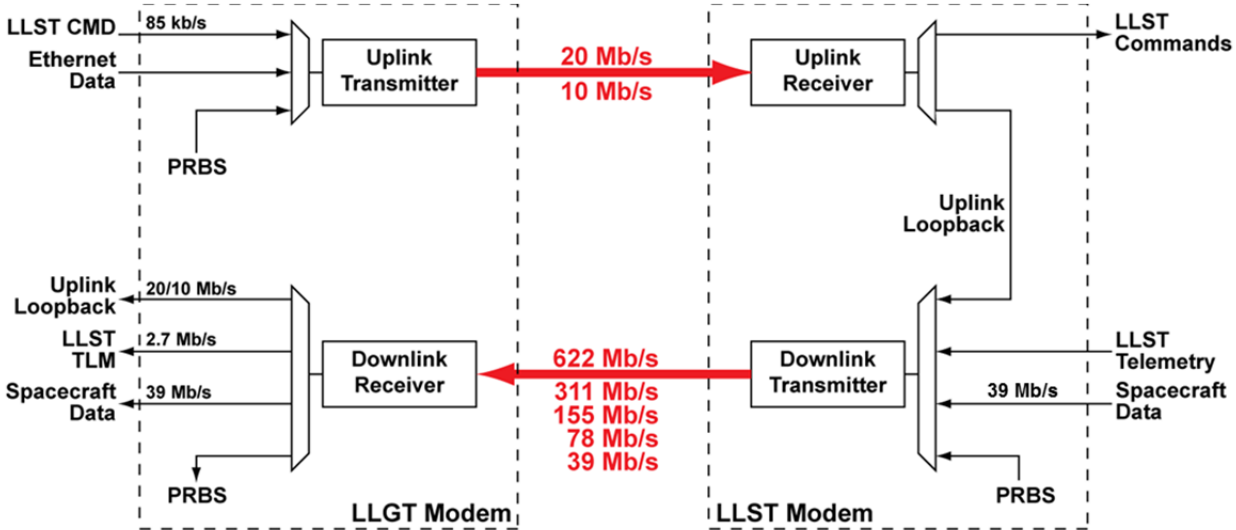

Figure 5 LLCD data paths