Laser Communications Relay Demonstration (LCRD) Update and the Path towards Optical Relay Operations

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Abstract—**This paper provides a concept for an evolution of NASA's optical communications near Earth relay architecture. NASA's Laser Communications Relay Demonstration (LCRD), a joint project between NASA's Goddard Space Flight Center (GSFC), the Jet Propulsion Laboratory - California Institute of Technology (JPL), and the Massachusetts Institute of Technology Lincoln Laboratory (MIT LL). LCRD will provide a minimum of two years of high data rate optical communications service experiments in geosynchronous orbit (GEO), following launch in 2019. This paper will provide an update of the LCRD mission status and planned capabilities and experiments, followed by a discussion of the path from LCRD to operational network capabilities.**

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1. INTRODUCTION

NASA is expanding its communications capability to include an optical relay as part of a next generation communications and navigation architecture [1]. NASA's past success with the Lunar Laser Communications Demonstration (LLCD) will be followed-up by the Laser Communications Relay Demonstration (LCRD) Project. LCRD is scheduled to launch in 2019 and will provide at least two years of optical communications services in an operations environment. LCRD consists of two optical communications terminals and associated electronics carried as a payload on a geosynchronous satellite. Bidirectional user data rates up to 1.244 Gbps are expected. Two optical ground Stations will function as both ground stations for optical relay trunklines and as simulated optical relay users.

There have been significant changes in the LCRD mission. The flight payload will now fly on Space Test Program Satellite 6 (STPSat-6). The change in spacecraft has allowed for other changes, including the addition of high bandwidth Ka-Band RF links and relocation of spacecraft operations. In addition to these changes, the second optical ground station, known as Optical Ground Station 2 (OGS-2) has been relocated to Hawaii. The new LCRD Mission Architecture Diagram is seen in Figure 1.

Some of the motivation for the changes to LCRD are the evolving strategy for a future space communications relay architecture. This paper will describe the changes to LCRD in more detail and conclude with a description of the LCRD role in a proposed future evolution to an operational space relay system.

2. A CHANGE IN SPACECRAFT

A big change for LCRD is the spacecraft host. The LCRD Project worked very closely with Space Systems Loral (SSL), a leading provider of geostationary commercial satellites, since the project's inception. SSL was a great partner with extensive knowledge and experience; their engineers were a pleasure to work with to determine how best to accommodate the LCRD payload on a SSL built satellite. However, sometime after the project's Preliminary Design Review (PDR), the decision was made to make LCRD more than just a technology demonstration of optical communications from GEO; the decision was made to increase the fidelity of LCRD's demonstration of technologies and operations critical for a future operational relay system. One important area that wasn't originally incorporated into LCRD is Information Assurance (IA). IA is critical for future operational relay satellites. Mission critical communications have to be protected to ensure that the integrity and confidentiality of the end-to-end system is maintained; this is particularly true for NASA's human exploration missions such as the future Orion Crew Exploration Vehicle. A key component of IA is encryption technology. NASA HQ made the decision that LCRD deploy a particular type of

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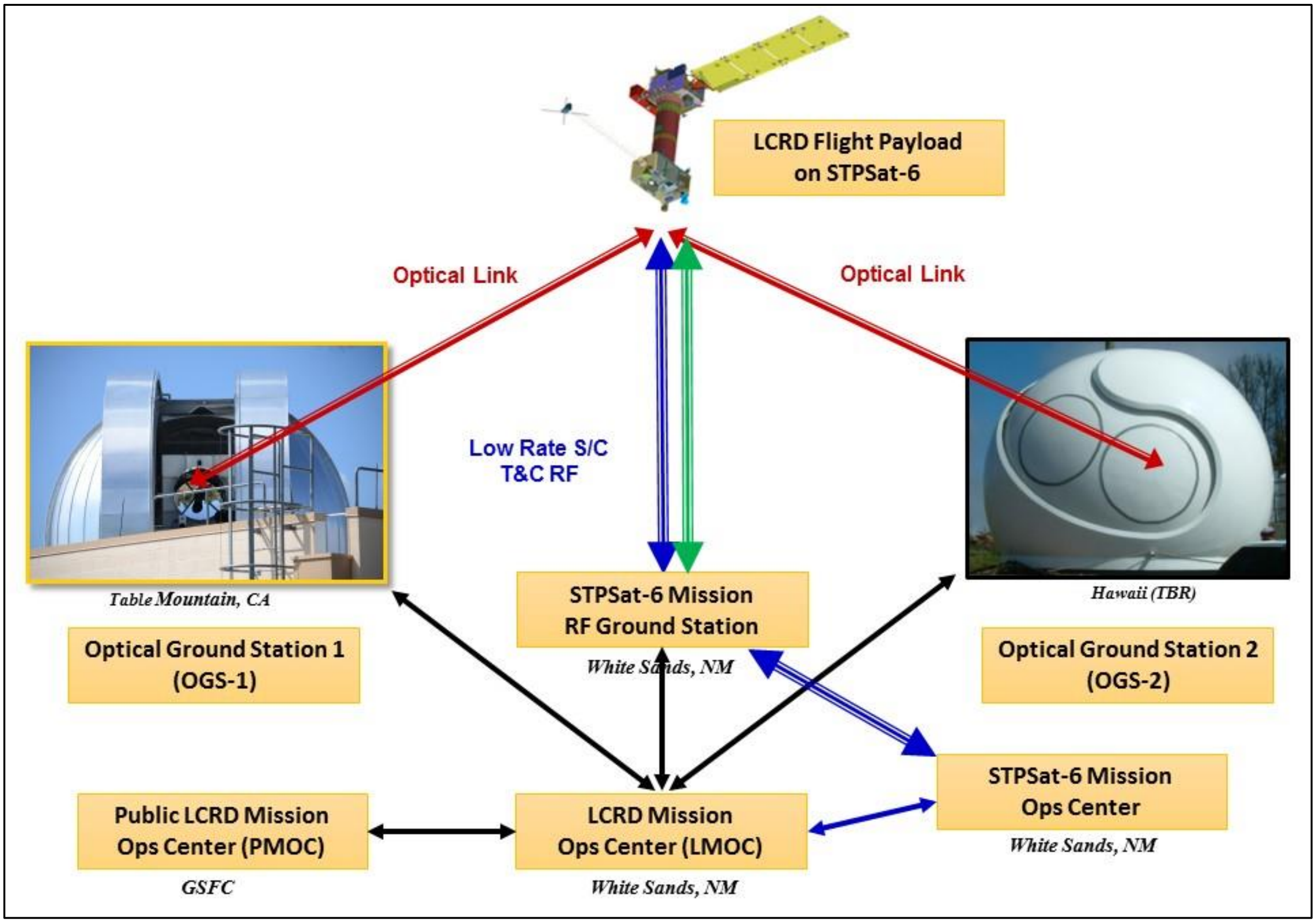

Figure 1. LCRD Mission Architecture

cryptography instead of a more common commercial technology. While the more stringent encryption technology is not really needed on LCRD since none of the LCRD data requires this level of protection, LCRD was chosen to demonstrate the IA concept needed in a future operational relay that could be hosted. SSL worked diligently to accommodate LCRD with the new IA requirements, however given the increased schedule and cost risks, NASA chose to find another spacecraft provider for LCRD.

Following a search for alternate rides, LCRD found a good match with Space Test Program Satellite (STPSat-6). STPSat-6 will be the latest in a series of spacecraft developed under a Defense Department program to field space capabilities quickly in response to emerging national needs. STPSat-6 is scheduled to launch in 2019 and is managed by the Space Test Program office.

While STPSat-6 is a DoD satellite, it should be noted that LCRD will demonstrate IA technologies and concepts as if it was flying on a commercial satellite. It has not been determined if future operational NASA relay satellites will be wholly owned by the government as is the case with the current TDRS satellites. In the not so distant future, NASA may decide to deploy an operational relay network where some of the nodes are provided by commercial spacecraft hosting a NASA provided RF and/or optical payload. Thus LCRD will demonstrate that concept, even though it is now flying on a government owned spacecraft.

3. ADDITION OF HIGH BANDWIDTH RF LINKS

In the original design, the LCRD baseline contained only two optical space terminals and two optical ground stations, with one station acting as the user and one station receiving the optical trunkline [2]. This would allow LCRD to simulate an optical to optical relay prior to the launch of an orbiting relay. One of the major benefits of an optical to optical relay is that it allows the trunkline to carry the same bandwidth as the link between the relay and the user. Though this is the ideal scenario, in the real world an optical relay would need to contend with the inevitable cloud. If a cloud was present, the optical trunkline could either wait for clouds to pass, or could switch to a different ground station that has a cloud free line of sight; however, both of these options create a link outage.

A high bandwidth RF trunkline has been added to the LCRD architecture. Additional cost and complexity results from placing a RF system aboard the relay; however, this allows the RF and optical capabilities to complement each other. The optical link can deliver a higher data volume than the RF link and the RF link allows for the delivery of data when an optical link would be compromised due to clouds. [Fig. 2].

The assumption is made that some user data can tolerate the latency of an outage. For example, science instrument files, housekeeping files, software uploads, etc. can often be delayed as long as it is completely delivered. However, most missions also have requirements for real-time or very low latency delivery such as commanding, telemetry, science alerts, voice, video, etc. [3].

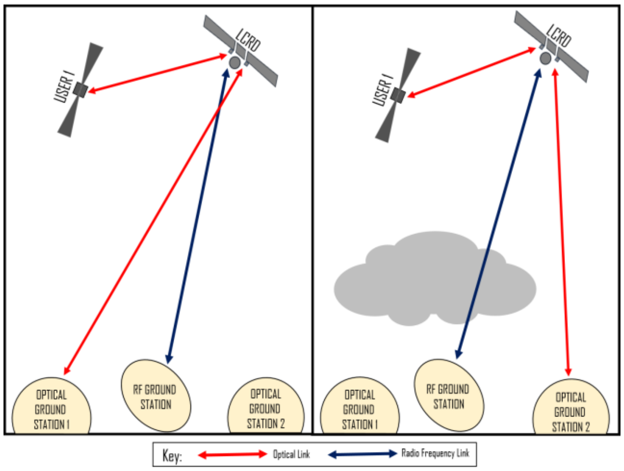

Figure 2. RF Trunkline Enables Transmission of Critical Data during Cloud Cover

Up to 64 Mbps uplinks and up to 622 Mbps at Ka-Band can be supported with the LCRD High Bandwidth RF (HBRF). The STPSat-6 Tracking Telemetry and Command (TT&C) links will be supported by a separate antenna and ground equipment than the LCRD HBRF, while co-located at White Sands, New Mexico. The same user gateway and user simulator capabilities will be used on both the LCRD RF ground station and the optical ground station, providing the ability for the same user data services and experiments to be supported over both trunklines, though at differing data rates. Switching data to be relayed over the RF links or optical links will be performed on the LCRD payload on a frame by frame basis. Various concepts for the utilization of the combination of RF and Optical trunklines will be examined during the two years of LCRD on-orbit experiments and demonstrations. [4]

4. SPACECRAFT OPERATIONS CENTER AT WSC

The STPSat-6 spacecraft operations center and TT&C RF ground station will be also be located at the White Sands Complex. Co-location with the payload operations and high bandwidth RF ground systems provides not only cost savings, but this arrangement will also allow NASA to gain insight into the operations of a spacecraft with an optical relay capability. The continued separation of the payload operations in the LMOC from the spacecraft operations will allow the development of operations concepts that will not preclude future relay capabilities flying as hosted payloads.

5. OGS-2 IN HAWAII

Another change to the high level LCRD architecture is the location of Optical Ground Station 2. A significant objective of LCRD is to demonstrate advance relay operations on the GEO spacecraft. LCRD will enable a wide variety of relay operations through the Space Switching Unit that connects the two onboard optical terminals and the high data rate RF modem. To be an optical relay demonstration, LCRD will create a relay connection between one optical ground station (acting as a data source) and the high data rate RF ground station, or between two optical ground stations. Before the decision was made to add the high data rate RF link to the spacecraft, there was considerable concern at NASA HQ about the availability of each optical ground station from a cloud free line of sight (CFLOS) and atmospheric disturbance perspective. The susceptibility to cloud cover, scintillation, scattering, and other atmospheric effects are known challenges associated with optical communication through the atmosphere. Initially there was a concern that both optical ground stations would need to be available to perform a relay demonstration in the absence of any “user terminals”; in other words, if only one optical ground station was available due to cloud coverage over the other then an optical relay demonstration could not be performed. Therefore the decision was made to perform a study to replace the original White Sands location with a location with better CFLOS statistics.

Each optical ground station must provide three functions when communicating with one of the two space optical communications terminals on the GEO spacecraft: receive the communications signal from the GEO space terminal, transmit a signal to the GEO space terminal, and transmit an uplink beacon beam so that the GEO space terminal points to the correct location on the Earth. The uplink beacon, transmitted from each Earth ground station, must provide a pointing reference to establish the GEO space terminal beam pointing direction.

Figure 3. Ground Station 1, OCTL Site, Table Mountain, CA

LCRD still plans to use the Optical Communications Telescope Laboratory (OCTL), managed and operated by the NASA Jet Propulsion Laboratory, as Optical Ground Station 1. The OCTL is located on top of Table Mountain in the San Gabriel Mountains of southern California and houses a 1-m f#75.8 coudé focus telescope; it is shown in Figure 3 above. The large aperture readily supports the high data rate Differential Phase Shift Keying (DPSK) and Pulse Position Modulation (PPM) downlinks from the LCRD space terminal with adequate link margin. Required to operate 24/7, in the presence of winds and as close as 5 degrees solar angles, the OCTL telescope shown in will be enclosed in a temperature controlled dome with a transparent window to allow laser beam and radar transmission [5].

LCRD's plans for Optical Ground Station 2 has changed since the project was baselined. Originally, LCRD was going to use a ground station deployed at White Sands, New Mexico, which was the site of the primary ground station for the Lunar Laser Communication Demonstration (LLCD) [6]. However, there was some concern with the availability of an operational ground station at White Sands during the late summer months. Thus at NASA's request, Northrop Grumman performed a study to look at the suitability of putting Optical Ground Station 2 at White Sands, on the Island of Hawaii (the Big Island), or on Maui. As can be seen from Figure 4 below, White Sands has much more variability in performance than the Hawaii sites.

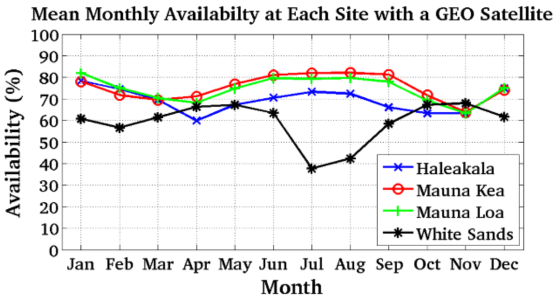

Figure 4. Mean Monthly Availability

Northrop Grumman found that the optical turbulence is typically much more benign on Maui than White Sands or at Table Mountain (location of Ground Station 1) in California; see Figure 4.

Figure 5 shows the Cumulative Distribution Function (CDF) of r0, the atmospheric coherence length, for Table Mountain, White Sands, and Haleakala. The CDF was referenced to zenith and 1550 nm. Haleakala has the most benign turbulence with a median r0 = 43.5 cm. White Sands and Table Mountain had similar statistics; median r0 was 22.8 cm for White Sands, and 20.0 cm for Table Mountain.

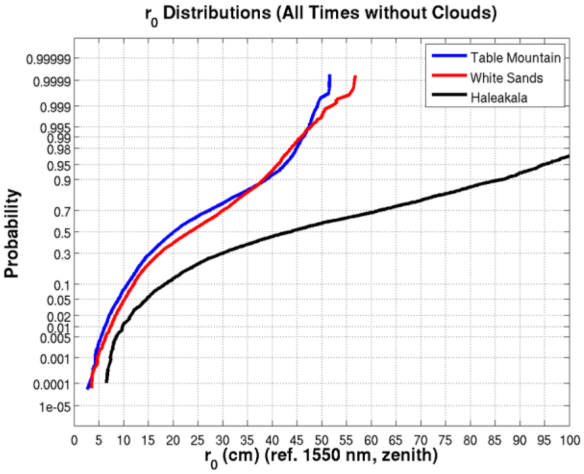

Figure 5. Comparison of Haleakala to White Sands and Table Mountain

When considering the total availability of a site to a satellite at 120 degrees west (being used just for analysis purposes), Table Mountain and White Sands resulted in an availability of 83.8% while Table Mountain and Haleakala resulted in an availability of 88.5%. Furthermore, as previously mentioned above, some of the experiments proposed for LCRD require that both ground stations be available simultaneously. For simultaneous cloud-free-line-of-site, Table Mountain and White Sands have a predicted availability of 37.1% while Table Mountain and Haleakala have a predicted availability of 48.2%.

Similar analysis is being done for both Mauna Kea and Mauna Loa on the Big Island. Mauna Loa is also being studied by NASA for a future home of a large deep space optical terminal; such a terminal would be much larger than the near Earth optical terminal being developed for LCRD's Optical Ground Station 2. While the exact location for Optical Ground Station 2 is still being decided by NASA HQ, the decision has been made to locate the terminal somewhere in Hawaii. Thus a new system that could be easily shipped to Hawaii and assembled on a mountain top had to be developed. Ideally, the ground station will eventually be located at a summit of one of the volcanoes there to get above the clouds and have excellent atmospheric seeing conditions. NASA is working with MIT Lincoln Laboratory to develop the necessary hardware and software to meet the project's requirements and goals. Optical Ground Station 2 will have a 60 cm receive aperture, a 15 cm transmit aperture, and be located within an approximately 5.5 meter diameter dome, Figure 6.

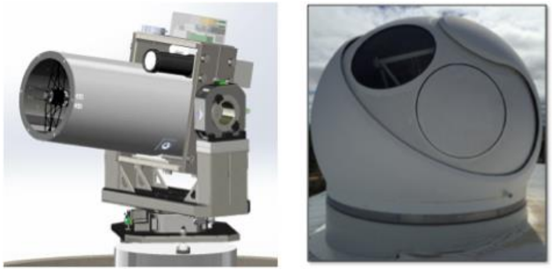

Figure 6. Optical Ground Station 2 Site Telescope and Dome

The laser subsystem consists of a custom photonics assembly that produces a low power (<10 mW) fiber-coupled optical signal, followed by a commercially obtained high-power optical amplifier. The fiber amplifier can produce up to 10 W of optical power but will be limited by software to a maximum power of 7.3 W during operation. After accounting for transmission loss of the transmit telescope and the window in the dome, the maximum power emitted into free space outside the dome is 5.4 W.

6. PATH TO OPERATIONAL SYSTEM

As NASA develops its strategy for the evolution of its space relay network, a leading candidate is to provide the relay services in a disaggregated approach. Instead of providing all services with each relay node, as is currently done with the TDRS satellites. The disaggregated approach would separate optical relay services from RF relay services, for example. This would allow the next generation relay architecture to be deployed in functional subsets, such that some services could be provided by commercial or industry partners. The replenishment of existing service capabilities can occur on a schedule decoupled from the insertion of new capabilities. The existing TDRS fleet will continue to provide RF service, as new optical relay payloads or spacecraft are placed into orbit. The RF capabilities can be continued as required by the health of the TDRS spacecraft, the user requirements, and the availability of other providers.

The addition of the LCRD HBRF system and a redundant onboard data switch will also provide a longer expected on-orbit operational capability for LCRD. If a single LCRD Optical Space Terminal fails, optical relay service will still be possible using the RF trunkline, though with reduced maximum data rates. LCRD may therefore provide an initial limited operational optical relay capability between the period of LCRD experiments and the launch of a first operational optical relay payload.

The LCRD experiments will inform the development of the performance requirements and operations concepts for the future optical relay system, as well as the decision to deploy the optical relay capability as a hosted payload or on a dedicated spacecraft.

7. SUMMARY

There have been many changes since the start of the LCRD project. The lessons learned are valuable experiment data in their own right, as NASA embarks on the deployment of a next generation relay system. LCRD has successfully completed a Critical Design Review in December 2016 and is well on its way to a 2019 launch.

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BIOGRAPHY

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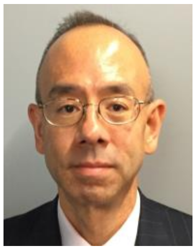

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