

Latest Changes to NASA's Laser Communications Relay Demonstration Project

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Abstract—Over the last couple of years, NASA has been making changes to the Laser Communications Relay Demonstration (LCRD) project, a joint effort spanning 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). The changes make LCRD more like a future Earth relay system that has both high-speed optical and radio frequency links, enabling LCRD to demonstrate a more detailed concept of operations for a future operational, mission-critical Earth relay. LCRD is planned to launch in June 2019 and is expected to be followed a couple of years later by a prototype user terminal on the International Space Station. LCRD's architecture will allow it to serve as a testbed in space, and this paper will provide an update of its planned capabilities and experiments.

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1. INTRODUCTION

NASA's Space Network (SN) provides space-to-space and space-to-ground bidirectional communications via a fleet of Tracking and Data Relay Satellites (TDRS) in geosynchronous orbit, along with associated ground stations and operation centers. The relay satellites are distributed around the equator to provide global coverage to users in low-Earth orbit or below. NASA is evaluating the expected life of the current fleet, and is targeting a next generation of relay capability on orbit before the end of the next decade.

Three generations of relay satellites are on orbit, and NASA is performing various architecture studies and technology pathfinders to help architect, plan and develop future space communications capabilities. One new type of service NASA is investigating for the future network is optical

communications [1]. Optical communications could provide substantially higher data rates and increased security for users, while reducing the user communications system's required mass, volume and power.

NASA successfully completed the Lunar Laser Communication Demonstration (LLCD) from lunar orbit in late 2013 [2]. The success of that technology demonstration led the way for the planned Laser Communications Relay Demonstration (LCRD) project. 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 gigabits per second are expected. Two optical ground stations will function as both ground stations for optical relay trunklines and as simulated optical relay users.

LCRD was originally intended to only demonstrate the technology like LLCD, but over time its requirements and capabilities were increased, enabling LCRD to not only serve as a technology demonstrator, but also as a bridge to NASA's future operational network. For example, LCRD's life expectancy has been increased so it can provide residual operational support to NASA missions after the initial two-year technology demonstration. In addition to the key redundancy added to increase its life expectancy, a high-bandwidth Ka-band radio frequency (RF) link was also added to demonstrate a future concept of operations for a relay satellite with both optical and RF services.

One motivation for the changes to LCRD is the evolving strategy within NASA in developing a future space communications relay architecture. The new LCRD mission architecture is depicted in Figure 1. This paper describes the changes to LCRD in more detail.

2. SPACE TEST PROGRAM SATELLITE 6

The LCRD flight payload will fly on the Space Test Program Satellite 6 (STPSat-6). Space Test Program satellites are a series of spacecraft developed under a Department of Defense (DoD) program to field space capabilities quickly in response to emerging national needs. STPSat-6, which is

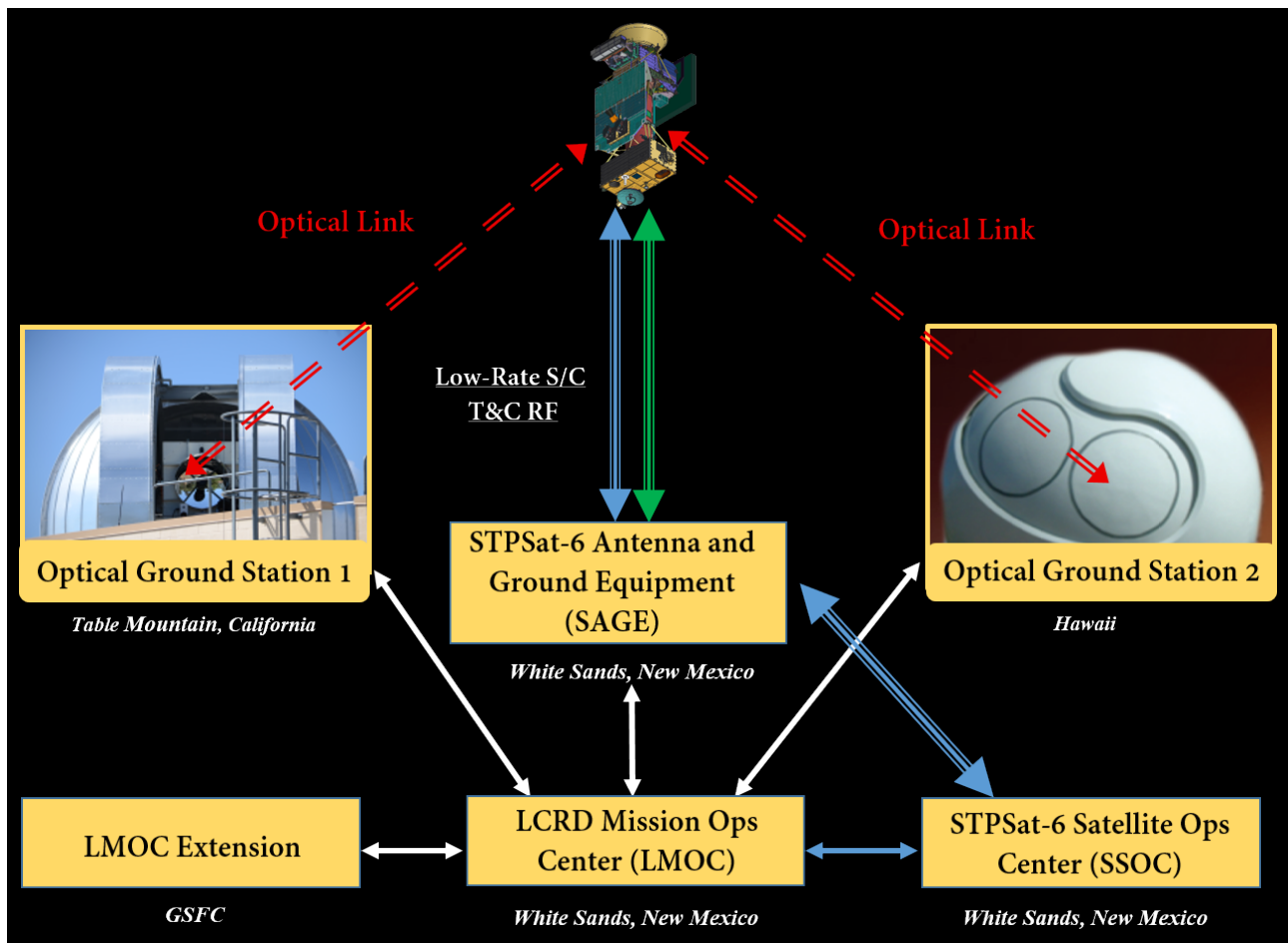


Figure 1. LCRD mission architecture

managed by the Space Test Program office at Kirkland Air Force Base in Albuquerque, New Mexico, is scheduled to launch in summer of 2019. The Space Test Program office is in the Advanced Systems and Development Directorate within the Space and Missile Systems Center of the U.S. Air Force. While the satellite is named STPSat-6, the entire mission is referred to as Space Test Program 3.

The STPSat-6 spacecraft bus, to be provided by Orbital ATK in Dulles, Virginia, is based on a partially assembled satellite in storage based on Orbital ATK's high-end modular A-500 bus. The satellite will be directly inserted into an orbit slightly above geostationary.

STPSat-6 will carry several experiments into orbit. The primary payload is the Space and Atmospheric Burst Reporting System 3 from the National Nuclear Security Administration, which provides nuclear detonation detection and space environment data, and is designed to complement nuclear detonation detectors currently in orbit. The satellite will also host seven Department of Defense Space Experiments Review Board payloads from the Space Test Program office.

3. INFORMATION ASSURANCE

As mentioned, LCRD's capabilities have been enhanced since the initial concept to demonstrate different technologies and operations critical for a future operational relay system. One enhancement is in the area of information assurance (IA). IA technology helps prevent the unauthorized access, use, disclosure, disruption, modification, inspection, recording or destruction of information.

At the beginning of the Space Age, NASA was less concerned with IA. Thus, many of its communications systems were designed either without IA technology, or the technology was grafted onto the architecture as an afterthought following development and deployment. In today's environment, IA is a critical need in space just as it is on Earth. IA gets the right information to the right people at the right time while protecting that information from eavesdropping or corruption. NASA's space communication links must be available when needed (e.g. be protected from a denial of service attack) and reliably transmit data (e.g. be protected from information manipulation). Some of NASA's communications, such as medical information and private astronaut communications, also need to be protected from eavesdropping. Thus IA is critical in preserving the integrity and confidentiality of future operational relay satellite

systems; 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. LCRD will deploy a National Security Agency-developed and -approved encryption solution to demonstrate the IA concept projected to be needed in a future operational relay that could be hosted by a non-U.S. provider, whether commercial or foreign government. In such a scenario, NASA must have complete faith in the integrity of the NASA payload. Thus, while STPSat-6 is a DoD satellite, LCRD will demonstrate IA technologies and concepts as if it were flying on a commercial satellite to demonstrate a potential future space communications architecture supporting a heterogeneous mix of government and non-government relays.

LCRD’s IA techniques protect the flight payload’s command, control and telemetry, as well as the location of the user terminal (pointing commands to the LCRD flight payload and corresponding telemetry are encrypted). Basically, in standard DoD parlance, LCRD acts as “black transport” with regards to the users. LCRD delegates to the users whether their mission data should be encrypted.

4. ADDITION OF HIGH BANDWIDTH RF LINKS

When LCRD was originally conceived and approved, the project contained only two optical space terminals and two optical ground stations. This was considered to be the minimum configuration that would allow NASA to experiment and learn about a geosynchronous-Earth orbit (GEO)-based optical communications relay service. With two ground stations, NASA could simulate a handover from one ground station to another; in a different configuration, one ground station could act as the user and the other could act as the “receiving” ground station (i.e. as the optical trunkline from the relay satellite) [3].

This minimum configuration was never considered ideal for proving the benefits of optical communications. Rather, it was recognized that a real operational demonstration required a user terminal in space communicating through LCRD to the ground to provide NASA with the most knowledge and experience in operating an optical relay service. Furthermore, the minimum architecture would suffer from cloud coverage at either optical ground station. A benefit 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. An actual optical relay would need to contend with inevitable cloud cover over one or both ground stations. The susceptibility to cloud cover, scintillation, scattering and other atmospheric effects are known challenges associated with optical communications. If a cloud were present, the optical trunkline could either wait for clouds to pass or 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 (HBRF) trunkline has been added to the LCRD architecture to provide more capability and alleviate concerns regarding lack of optical ground station availability due to cloud cover. Without an RF trunkline, 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, then an optical relay demonstration could not be performed. NASA expects that future operational GEO relay satellites will have both optical and RF services. Optical communications would be used for extremely high-data transfer in which some latency might be acceptable; RF would provide high availability of services, but lower data transfer. For example, science instrument files, housekeeping files, software uploads and more can often be delayed as long as they are completely delivered. But most missions also have requirements for real-time or very low-latency delivery, such as commanding, telemetry, science alerts, voice, video, etc. [4]. In this way, the capabilities complement each other, enabling both high-volume data delivery and reliable coverage. Thus, the addition of HBRF to LCRD makes the demonstration much more valuable to NASA in developing and experimenting with future concepts of operations. [Figure 2].

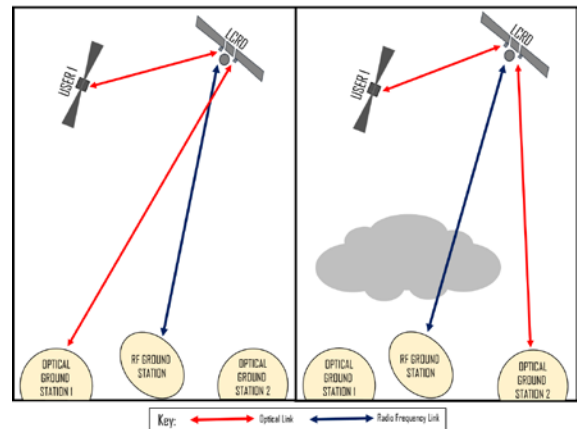


Figure 2. RF trunkline enables transmission of critical data during cloud cover.

With HBRF, LCRD can support up to 64 megabits per second (Mbps) uplinks and up to 622 Mbps at Ka-Band. The HBRF system is a full duplex communications system capable of simultaneous reception (uplink) and transmission (downlink). The HBRF system consists of one dual, circularly polarized high-gain antenna, one RF converter, one high-data-rate transceiver and one traveling wave tube amplifier per polarization. The system is also equipped to receive and transmit in single- or dual-polarization models at any time during its mission.

The STPSat-6 tracking, telemetry and command (TT&C) links, while co-located with the LCRD HBRF at White Sands Complex, New Mexico, will be supported by a separate antenna and separate ground equipment. The same user gateway and user simulator capabilities will be used on both the LCRD RF ground station and the optical ground station, enabling 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 or optical links will be performed on the LCRD payload on a frame-by-frame basis. Various concepts for utilizing the combination of RF and optical trunklines will be examined during the two years of LCRD on-orbit experiments and demonstrations [5].

5. SPACECRAFT OPERATIONS CENTER AT WSC

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

LMOC will have access to real-time and predictive atmospheric data from both optical ground stations. When only one optical ground station is required for a particular communications pass, LMOC will be able to allocate a ground station based on predictive performance. For example, an infrared cloud imager (ICI), ceilometer and weather station have recently been installed at Optical Ground Station 2 (Figure 3). The ceilometer is used in atmospheric attenuation measurements. Figure 4 shows the kind of data available to the LMOC to help determine if a site is initially available or if an optical handover from one site to the other should occur.

6. OPTICAL GROUND STATION 2

Optical Ground Station 2 has changed significantly over the course of the project. The design, location and even the utility of the second optical ground station were reexamined.

One significant objective of LCRD is to demonstrate advanced relay operations on 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 serve as an optical relay demonstration, LCRD will initially create a relay connection between one optical ground station (acting as a data source) and either the high-data-rate RF ground station or the other optical ground station. However, with the enhanced life expectancy of LCRD, NASA now expects to have optical user terminals on-orbit that will communicate through LCRD. For instance, NASA’s Goddard Space Flight Center is currently working with MIT Lincoln Laboratory to

deploy an optical user terminal on the International Space Station in 2021.



Figure 3. Installed Infrared Cloud Imager (7-11 um) with attached rain sensor

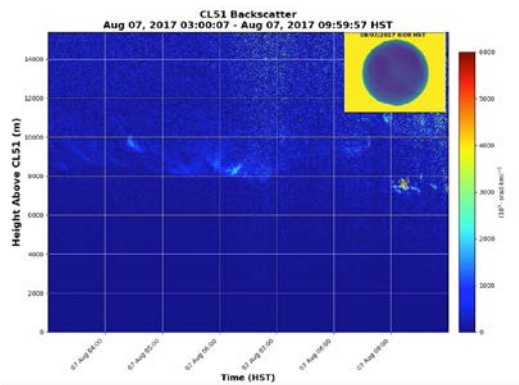


Figure 4. Example of data from Ground Station 2’s atmospheric characterization equipment

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 or transmit an uplink beacon beam so the GEO space terminal points to the correct location on Earth. The uplink beacon, transmitted from each Earth ground station, must provide a pointing reference to establish the GEO space terminal beam’s pointing direction.

NASA’s Jet Propulsion Laboratory Optical Communications Telescope Laboratory (OCTL) will be used as LCRD’s 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-meter, f/75.8 coude focus telescope (shown in Figure 5). 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 will be

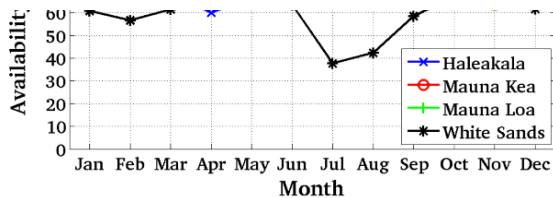


Figure 5. Ground Station 1, OCTL Site, Table Mountain, California

enclosed in a temperature-controlled dome with a transparent window to allow laser beam and radar transmission [6].

LCRD’s plans for Optical Ground Station 2 have 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) [7]. 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 is evident in Figure 6, White Sands has much more variability in performance than the Hawaii sites.

Figure 6. Mean monthly availability at each site with a GEO satellite



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

Figure 7 shows the cumulative distribution function (CDF) of r_0 , the atmospheric coherence length, for Table Mountain, White Sands and Haleakala. The CDF was referenced to zenith and 1550 nanometers. Haleakala has the most benign turbulence with a median r_0 of 43.5 centimeters. White Sands and Table Mountain had similar statistics; median r_0 was 22.8 centimeters for White Sands, and 20.0 centimeters for Table Mountain.

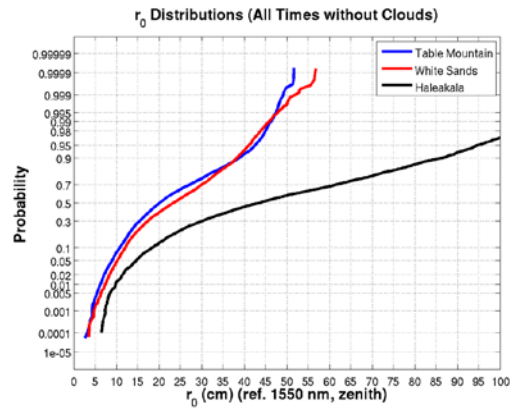


Figure 7. Comparison of Haleakala to White Sands and Table Mountain

When considering the total availability of a site to a satellite at 120 degrees West (used just for analysis purposes), Table Mountain and White Sands resulted in an availability of 83.8 percent, while Table Mountain and Haleakala resulted in an availability of 88.5 percent. Furthermore, as 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 percent, while Table Mountain and Haleakala have a predicted availability of 48.2 percent.

For this reason, NASA chose to install Optical Ground Station 2 at the U.S. Air Force’s Maui Optical and Supercomputing Space Surveillance Complex on top of Haleakala in Maui, Hawaii. Figure 8 shows the exact location of the NASA optical terminal relative to the rest of the facility.



Figure 8. Optical Ground Station 2 Location

Optical Ground Station 2 has a 60-centimeter receive aperture and a 15-centimeter transmit aperture; both are located within an approximately 5.5-meter-diameter dome on the roof (Figure 9). Elevation over azimuth gimbals support the two telescopes. The dome provides an enclosed, temperature-stabilized environment with a steerable window for day and night operations.



Figure 9. Optical Ground Station 2 Site Telescope and Dome

The laser subsystem consists of a custom photonics assembly that produces a low-power (<10 milliwatt), fiber-coupled optical signal, followed by a commercially obtained high-power optical amplifier. The fiber amplifier can produce up to 10 watts of optical power, but will be limited by software to a maximum power of 7.3 watts 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 watts.

7. LCRD EXPERIMENT PLANNING

After LCRD launch in 2019, the LCRD investigator team will carry out diverse experiments to test LCRD’s bidirectional optical communications links – including the use of heterogeneous (RF and optical) links – and associated communications tactics. To supplement experimentation, the LCRD investigator team is encouraging individuals from government, academia and industry around the world to propose experimentation ideas through the Guest Experimenters Program.

LCRD’s ground and flight elements can be leveraged in various ways to support different experiment configurations. For instance, to test the capability of optical relay providers to support user spacecraft requirements, such as particular data transmission rates, view periods and latencies, one of the optical ground stations could serve as the user, and the LCRD flight segment could serve as the optical relay. In Figure 10, for example, Optical Ground Station 1, functioning as the user spacecraft, would use its user platform simulator to model specific data types and volumes, view periods and data rates. The LCRD flight segment, functioning as the optical relay, would use one of its optical space terminals to communicate with the user spacecraft, and use its other optical space terminal to send data to and receive data from Optical Ground Station 2, which is functioning as the optical ground station. The LCRD flight segment could communicate with the RF ground station using its onboard HBRF terminal. The RF or optical ground stations could also function as user mission operations centers.

In such a configuration, experimenters can test the capability of optical relays using optical communications links to support various characteristics, such as data volumes and

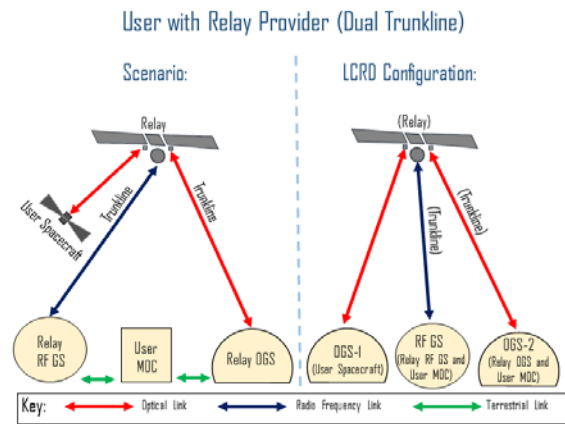


Figure 10. Example LCRD experiment configuration (on right) to simulate a scenario involving a single user spacecraft communicating with a relay provider (on left).

latency requirements. Experiments could be based on real-life scenarios; for instance, and experimenter could create a contact schedule around a particular mission’s expected orbit and subject that schedule to change based on weather and atmospheric conditions or limited space relay availability. Additionally, experimenters could leverage heterogeneous (RF and optical) links to test LCRD’s ability to respond to real-time data delivery requirements.

Potential experiment proposers can read about the proposal process and its requirements in the LCRD Introduction for Experimenters document at lcrd.gsfc.nasa.gov. Accepted experimenters will work with LCRD experiment coordinators to refine their proposals and determine all requirements [8].

8. PATH TO OPERATIONAL SYSTEM

The addition of critical redundant components, such as a redundant, onboard data switch and the high-bandwidth RF system, provide a longer expected on-orbit operational capability. For example, 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. With its increased life expectancy and NASA’s on-going development of a user optical terminal for the International Space Station, LCRD will provide NASA with an initial operational optical relay capability between the period of LCRD experiments and the launch of a future operational optical relay satellite. With the addition of the high-bandwidth RF system, NASA will learn how to operate a relay system that can provide both extremely high-data-rate transfer via an optical link and more conventional data transfer via the RF link. In fact, with the addition of this RF system, LCRD will more closely resemble the future operational GEO relay; the only real difference will likely be the data transfer rate, as NASA expects that future operational relays will operate at much higher data rates than will LCRD.

LCRD is a critical first step toward a future operational optical relay satellite. The demonstration will inform the development of the performance requirements and operations concepts for the future optical relay system. As a hosted payload on the STPSat-6 spacecraft, LCRD has already proven invaluable in helping NASA understand the advantages and disadvantages of hosted payloads versus dedicated spacecraft.

8. SUMMARY

Many changes were made since the start of the LCRD project. The current architecture more closely resembles what is expected in a future operational relay satellite. The lessons learned, especially in the area of information assurance, are valuable in their own right as NASA embarks on the deployment of a next-generation relay system. LCRD is well on its way to a summer 2019 launch, and NASA is looking forward to performing bidirectional optical communications demonstrations in Earth orbit. The value of LCRD will be further enhanced once an LCRD-compatible user terminal is installed on the International Space Station in 2021.

ACKNOWLEDGEMENTS

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BIOGRAPHY



David J. Israel is the architect for NASA's Exploration and Space Communications Projects Division, and the principal investigator for the Laser Communications Relay Demonstration (LCRD) at NASA's Goddard Space Flight Center. He has been working on various aspects of space communications systems since joining NASA in 1989. He received his bachelor's degree in electrical engineering from the Johns Hopkins University in 1989, and his master's degree in electrical engineering from the George Washington University in 1996. He has led the development of various Space Network/Tracking and Data Relay Satellite System (TDRSS) operational systems and has been the principal investigator for multiple communications technology activities concerning advanced space communications concepts and networking protocols, including the LPT CANDOS experiment on STS-107 and disruption-tolerant networking demonstrations on the Lunar Laser Communication Demonstration.



Bernard L. Edwards is the chief communications systems engineer at NASA's Goddard Space Flight Center. He received his bachelor's degree in electrical engineering in 1989, his master's degree in electrical engineering in 1991, and his master's degree in computer science in 1993, all from the Johns Hopkins University. He supports the NASA representative to the Interagency Operations Advisory Group (IOAG), and helps represent NASA in the Consultative Committee for Space Data Systems (CCSDS) in the area of optical communications. He has been involved in various NASA optical communication projects and technology developments since coming to NASA in 2000.



Seema K. Vithlani is a technical publications manager within the Exploration and Space Communications Projects Division at NASA's Goddard Space Flight Center. She received her bachelor's degree in multiplatform journalism from the University of Maryland in 2016, and began working at NASA in 2017. She has been involved in writing, editing and providing graphics support for a number of space communications and navigation-related technical papers.