Challenges, Lessons Learned, and Methodologies from the LCRD Optical Communication System AI&T

Bernie Edwards
NASA/GSFC Code 580
Greenbelt, MD 20771
301-286-8926
bernie.l.edwards@nasa.gov

Trisha Randazzo
NASA/GSFC Code 450
Greenbelt, MD 20771
301-286-9443
trisha.randazzo@nasa.gov

Nidhin Babu
NASA/GSFC Code 450
Greenbelt, MD 20771
301-286-0167
nidhin.babu@nasa.gov

Kendall Murphy
NASA/GSFC Code 450
Greenbelt, MD 20771
301-286-4062
kendall.t.murphy@nasa.gov

Shane Albright
NASA/GSFC Code 582
Greenbelt, MD 20771
301-286-7916
shane.a.albright@nasa.gov

Nick Cummings
NASA/GSFC Code 581
Greenbelt, MD 20771
301-286-4864
nick.cummings@nasa.gov

Javier Ocasio-Perez
NASA/GSFC Code 568
Greenbelt, MD 20771
301-286-7812
javier.ocasio-perez-1@nasa.gov

William Potter
NASA/GSFC Code 493
Greenbelt, MD 20771
301-286-5343
william.j.potter@nasa.gov

Russell Roder
NASA/GSFC Code 596
Greenbelt, MD 20771
301-286-3436
russell.roder-1@nasa.gov

Sharon A. Zehner
NASA/GSFC Code 460
Greenbelt, MD 20771
301-286-9403
sharon.a.zehner@nasa.gov

Ricardo Salah
NASA/GSFC Code 451
Greenbelt, MD 20771
301-286-6956
ricardo.salah@nasa.gov

Jonathan Woodward
NASA/GSFC Code 451
Greenbelt, MD 20771
301-286-8119
jonathan.r.woodward@nasa.gov

***Abstract* -The Laser Communications Relay Demonstration (LCRD) is a space flight technology demonstration mission, led by the National Aeronautics and Space Administration (NASA) Goddard Space Flight Center (GSFC) in Greenbelt, Maryland and sponsored by NASA's Technology Demonstration Missions (TDM) Program and Space Communications and Navigation (SCaN) Program Office. The LCRD payload is hosted on the Department of Defense (DoD) Space Test Program (STP) Satellite-6 (STPSat-6) space vehicle and will operate in geostationary orbit (GEO). Launching in late 2021, the mission will conduct a minimum of two years of communication experiments with optical terminals at NASA's Jet Propulsion Laboratory (JPL) Table Mountain Facility, in Hawaii, on the International Space Station in LEO, and via a high bandwidth radio link to White Sands Complex (WSC), New Mexico. This paper focuses on the assembly, integration, and test (AI&T) campaign spanning more than four years, using multiple test facilities, and involving multiple partner collaborations.**

Table of Contents

1 Introduction

Launch in December 2021, the LCRD payload flies aboard the Department of Defense (DoD) STPSat-6 space vehicle operating in GEO orbit at 112 W longitude. In addition to optical communications with the Optical Ground Station (OGS-1) in California and OGS-2 in Hawaii, LCRD communicates with STPSat-6's radio frequency (RF) ground station at White Sands Complex (WSC) in New Mexico and will communicate with an optical terminal on the International Space Station, once said terminal is deployed. This architecture (see Figure 1-1) fulfills the NASA demonstration requirements [1] for:

- Demonstrating optical relay communication architectures
- Demonstrating simultaneous and bidirectional direct optical communication services between Earth and GEO.
- Demonstrating bidirectional optical communication services between LEO and GEO
- Demonstrating pulse position modulation (PPM) services up to 311 Mbps
- Demonstrating differential phase shift keying modulation (DPSK) services up to 1.244 Gbps
- Measuring and characterizing the system performance through the life of the demonstration

The LCRD technology demonstration will inform any future space optical communication systems. While future relay systems may consist of multiple terminals, the LCRD demonstration includes two optical space terminals (OSTs) which are sufficient for the demonstration objectives (see Figure 1-2).

This paper presents the LCRD design description, current status, some unique methodologies (or techniques) used in the optical communication payload assembly, integration and testing.

2 LCRD's Design

The LCRD payload consists of two OSTs. Each OST includes an optical module, a controller electronics (CE) unit, and a modem. Between the OSTs is a Space Switching Unit (SSU) which is the high-speed data router for user data and serves as the command and telemetry handling subsystem for the payload. See figures 2-1 ad 2-4 for a mapping of LCRD boxes, which are also photographs of the final product before delivery to the space vehicle.

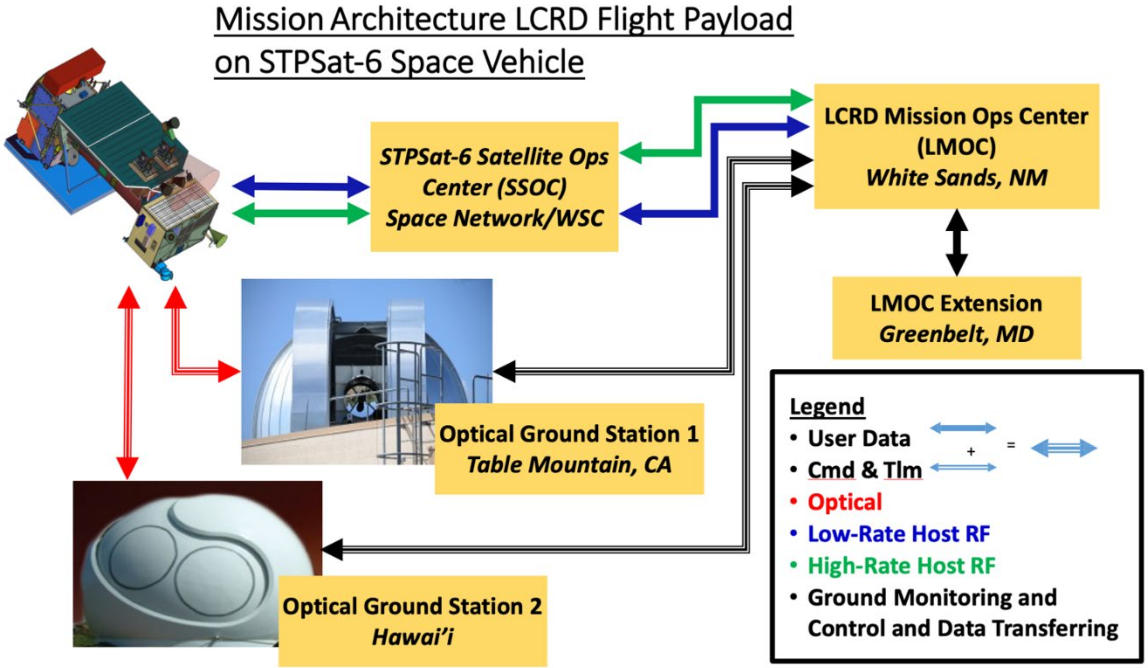
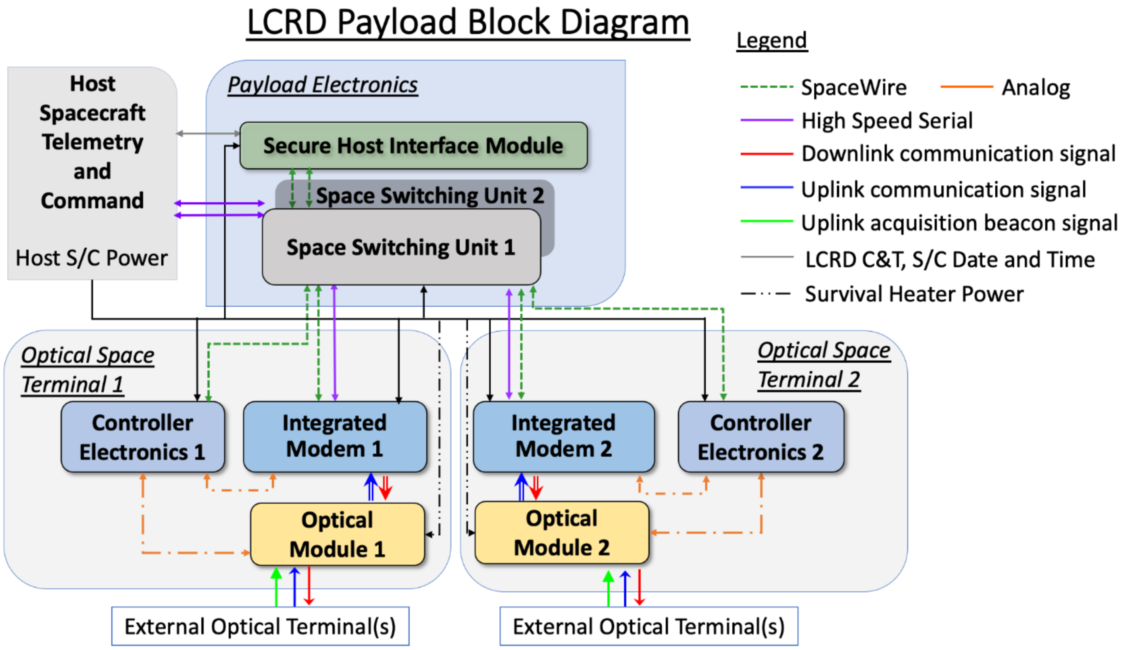


Figure 1-1. LCRD mission architecture. CMD & TLM = command and telemetry

Figure 1-2. LCRD architecture and functional block diagram. C&T = command and telemetry, S/C = spacecraft.



Lastly, the Secure Host Interface Module (SHIM) is the secure communication interface between the LCRD payload and the host space vehicle. The LCRD payload boxes are described in Figure 2-1 and mounted on a flat, honeycomb structure panel with embedded thermal heat pipes for thermal control of electrical and optical components. This ensures compatibility with the STPSat-6 space vehicle mechanical and thermal systems.

Historically space vehicle communication systems utilized various radio frequency (RF) modulations, such as Binary Phase Shift Keying (BPSK). LCRD has the ability to operate with two types of modulations: Differential Phase Shift Keying (DPSK) and Pulse Position Modulation (PPM). Photon counting PPM is typically specified for deep-space missions because it provides extremely high performance in a power limited communications channel, but due to limits in technology it can't be used for extremely high data rates (limited to a few Gbps). DPSK, on the other hand, requires more power (photons per bit) but it can be implemented at extremely high data rates (up to 100's of Gbps) making it ideal for near-space missions.

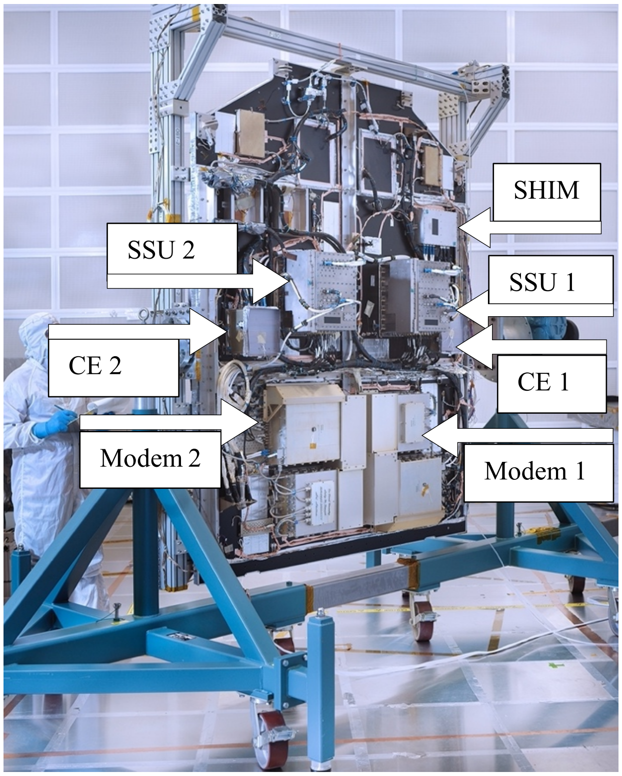


Figure 2-1. LCRD Flight Payload Graphic with Box Annotation

2.1 Flight Subsystem Descriptions

2.1.1 Modems

Each OST contains an optical modem (see Figure 2-2), which was assembled and tested by NASA at Goddard Space Flight Center. The modems support two modulation formats and can transmit and receive at uncoded symbol rates between 72 Mbaud and 2.88 Gbaud. With Forward Error Correction (FEC) coding, the user data rates are between 2Mbps and 1.244Gbps. The FEC encoding and decoding algorithms were developed by JPL and are implemented at the LCRD optical ground stations, for an edge-coding architecture capable of decoding errors imparted on both the uplink and downlink of the communications signals.

The modulation formats supported by the LCRD modems are DPSK and PPM. DPSK has superior noise tolerance and is suited to higher data rate operations, e.g. for near-space applications. It also supports communications when the Sun in the field of view. PPM is highly photon efficient (few signal photons required per bit at the receiver) and is suited for deep space operations, where data rate is reduced as efficiency is increased.

LCRD leverages an MIT Lincoln Laboratory (MIT LL) risk-reduction modem design based on the DPSK waveform and hardware implementation. The PPM waveform was developed by GSFC to run on the existing modem design.

2.1.2 Controller Electronics

The Controller Electronics (CE) unit is part of the very accurate system for Pointing, Acquisition and Tracking (PAT) to the ground stations or LEO satellites (e.g., International Space Station). The primary function of the Controller Electronics (CE) unit is to interface with the various sensors and actuators of the Optical Module and to process the closed-loop PAT algorithm within the Single Board Computer (SBC). The CE also receives a laser receiver power signal from the Modem that is critical for fine tracking. The Controller Electronics was designed and delivered by Moog Broad Reach in Gilbert, Arizona.

2.1.3 Space Switching Unit

The LCRD Space Switching Unit (SSU) connects the two Optical Space Terminal services and the space vehicle High Date Rate (HDR) system. The SSU uses the required decoding and deinterleaving for command frames while all other frames are routed between the OSTs and the space vehicle HDR system. The Space Switching Unit was delivered by SEAKR Incorporated in Denver, Colorado. The SSU software leverages code developed by MIT LL as part of high data rate communications during risk-reduction activities.

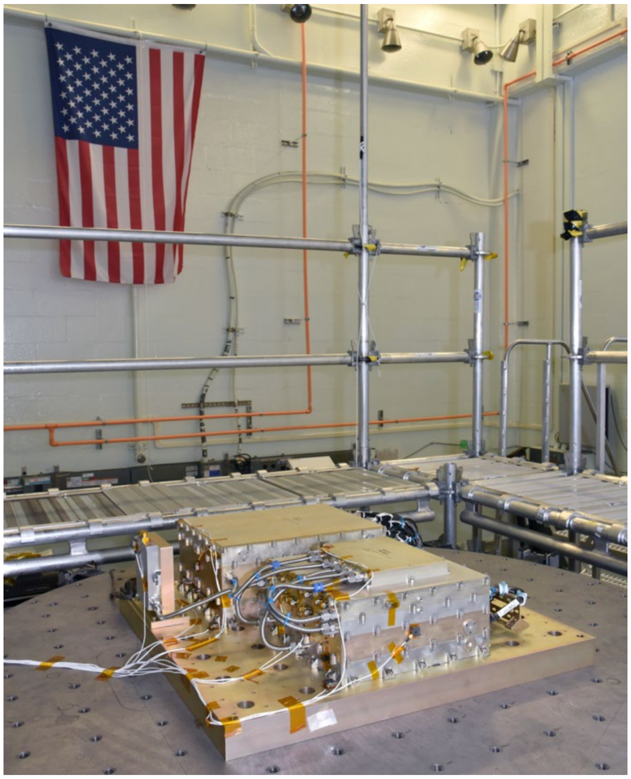


Figure 2-3. LCRD flight modem before integration onto payload panel.

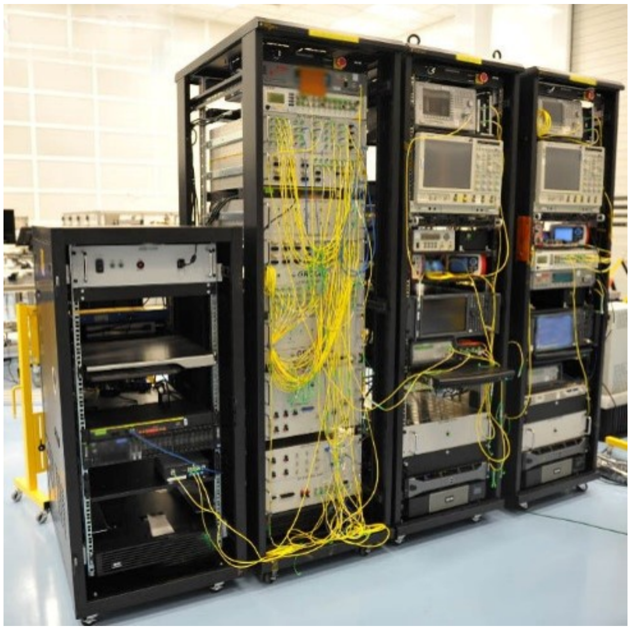


Figure 2-4. LCRD ground modem and supporting equipment

2.1.4 Optical Module

The Optical Modules (OMs) consist of six distinct subassemblies – the Optical Assembly (OA), the Inertially Stable Platform (ISP), the Gimbal & Latch Assembly (GLA), the Solar Window Assembly (SWA), the Boresight Assembly (BA) and the Radiator Assembly (RA). The BA and RA were assembled at GSFC. The other four subassemblies were procured from commercial vendors, in line with the goal of commercializing optical communication technology, and they were based on risk-reduction designs from MIT Lincoln Laboratory. The subassembly vendors included Harris (OA), Applied Technology Associates (ISP), Sierra Nevada Corporation (GLA), and L3-SSG (SWA). Each optical module includes a 4-inch reflective telescope that produces a ~15 microradian downlink beam. Each OM also houses a spatial acquisition detector, which is a simple quadrant detector, with a field of view of approximately 2 milliradians. The quad detector is used both for detection of a scanned uplink signal, and as a tracking sensor for the initial pull-in of the signal. The telescope is mounted to a two-axis gimbal via a magnetohydrodynamic inertial reference unit (MIRU). Angle-rate sensors in the MIRU detect angular disturbances, which are then rejected using voice-coil actuators for inertial stabilization of the telescope. Optical fibers couple the optical module to the modems where the transmitted optical waveforms are processed.

2.1.5 Secure Host Interface Unit (SHIM)

The secure host interface module (SHIM) isolates the LCRD flight payload, in an Information Assurance (IA) point of view, from the host space vehicle. Its purpose is to prevent unauthorized access, use, disclosure, disruption, modification, inspection, recording, or destruction of information within the LCRD flight payload. IA gets the right information to the right people at the right time while protecting that information from eavesdropping or corruption [3]. The SHIM was designed and delivered by L3 Harris in San Diego, California.

Electromagnetic interference and compatibility (EMI/EMC) of Optical Module Subsystems and Payload System utilized the OTS. The OTS isn't mobile, (see figure 2-5) so subsystem (EMI/EMC) had to be conducted in the cleanroom (see figure 2-6). To accomplish the test, a unique tent surrounding the OM and the Controller Electronics was designed and implemented to isolate the flight hardware from the ambient electromagnetic environment. A hole in the clean tent allowed the OM to look out, into the OTS, so any degradation or interruption of the optical link could be observed.

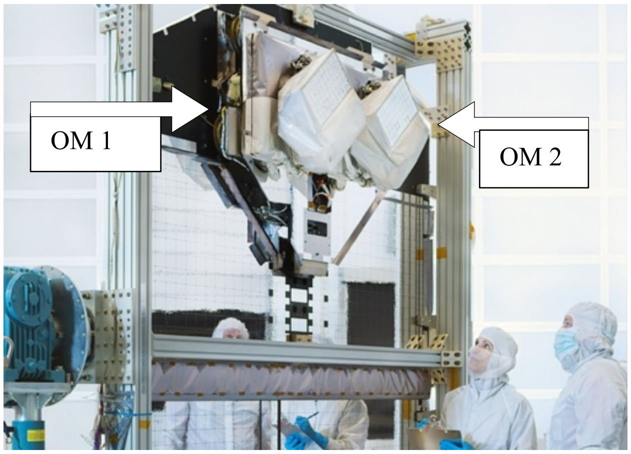


Figure 2-5. LCRD Flight Payload: final checks before delivery to space vehicle.

Figure 2-5. Photograph of the Optical Test Set (OTS).

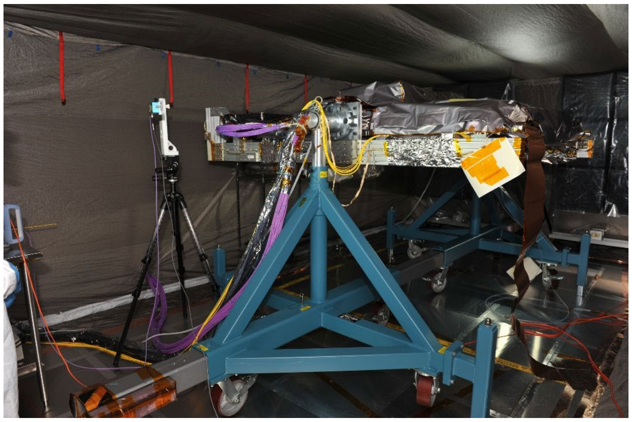


Figure 2-6. Payload Level EMI/EMC Test Set-up

OM thermal vacuum (TVAC) testing also took place in the cleanroom, using a temporary chamber, once again allowing for use of the OTS. See Figure 2-7.

Figure 2-7. Optical Module Level TVAC Test Set-up

2.1.6 Laser Safety Methodology

Integration and Testing with lasers necessitates specific safety measures and personnel training. A majority of the optical development occurred at Goddard, which has strict guidelines for projects utilizing lasers in an I&T campaign. LCRD personnel worked with the GSFC Radiation Protection Office to develop an appropriate laser safety plan. Typically, a laser safety plan is written per location, and due to the multiple facilities utilized in the I&T campaign, multiple laser safety plans were written for each location and were required to be read and signed by test personnel. The personnel commanding the lasers were required to undergo supervised on-the-job training before operating lasers unsupervised.

2.1.6.1 Ensuring Safety of Personnel When Utilizing a Remote Control Room

The main laser safety danger to I&T personnel existed when the lasers were operated remotely by the I&T team or the mission operations team (MOT). Without proper precautions, remote commanding could easily lead to a control room unknowingly activating a laser while cleanroom personnel are not wearing PPE. This was addressed procedurally thrice; in the commanding System Test Operations Language (STOL) scripts, the Test Procedures, and the Work Order Authorization (WOA), by requiring positive confirmation between the personnel working in the cleanroom and the personnel commanding the lasers. Before lasers are turned on, the Test Conductors (TCs), MOT members, and cleanroom personnel used headsets to verify cleanroom personnel had donned their laser safety PPE and that the warning signs in the cleanroom and the gowning area were illuminated. After positive confirmation was received, TCs and the MOT proceeded to turn on the lasers. As an extra safety measure, commands that turned on lasers generated a pop-up window, with a reminder to make sure that cleanroom personnel were ready. Advancing beyond the pop-up window required typing the word “SAFE”, so someone couldn’t accidentally click “Ok” before cleanroom personnel were ready.

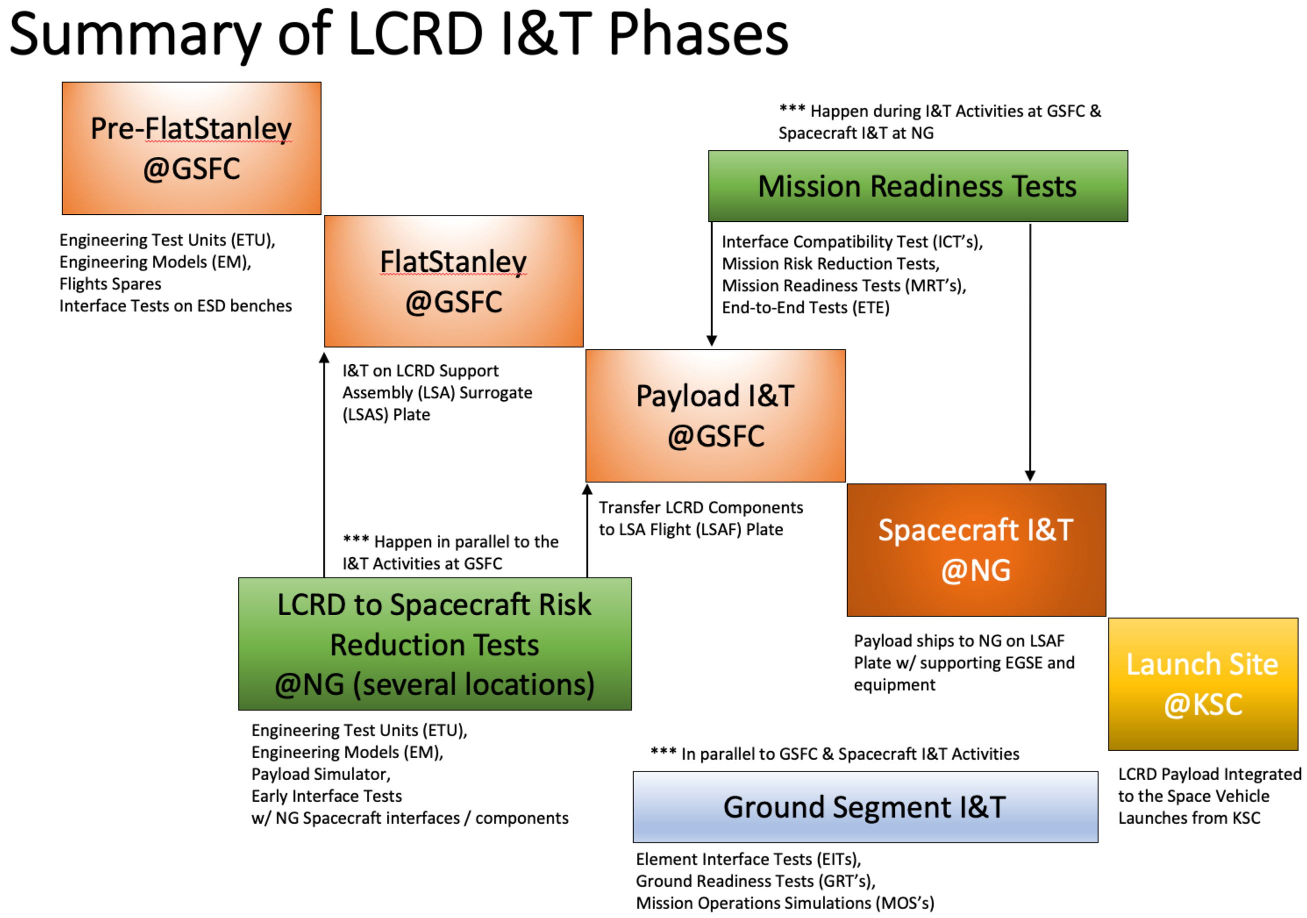


Figure 2-8. High level I&T flow for LCRD, starting with pre-FlatSat, phased through spacecraft I&T.

3 SV and LV AI&T

3.1 Overview

During the space vehicle (SV) I&T campaign the LCRD payload was mechanically and electrically integrated to the STPSat-6 Space Vehicle. Post-delivery standalone tests, limited performance tests, environmental tests and end-to-end tests were conducted in the space vehicle I&T phase.

Five space vehicle bus components were installed on the LCRD payload panel after delivery to the space vehicle: flight Protocol Coupler Router (PCR), Star Tracker Assembly (STA), the Coarse Sun Sensors (CSS), Tuned Mass Damper (TMD), all associated power and signal cables/harnesses, and a signal interface field-joint bracket (HL02). These completed the final installations of the LCRD payload flight configuration. Figure 3-1 shows the LCRD panel in its final configuration on the STPSat-6 space vehicle.

The emphasis during SV integration was for zero loss of data transmitted via the high data rate system and through all the functional units of LCRD. One of these tests lasted over 17 hours and showed 63,356,162 data frames (4.1E12 data bits) were relayed error-free.

At the Launch Vehicle (LV) level of AI&T, The LCRD I&T team executed various activities at the launch site: LCRD close-out activities, (blankets close-outs, cleaning, pre-ship inspections), shipment of LCRD GSE to the launch processing site (Astrotech, Titusville, Florida), post-ship inspections, Remove Before Flight (RBF) cover removals, and successful execution of the Launch Site Integrated System Test (LIST).

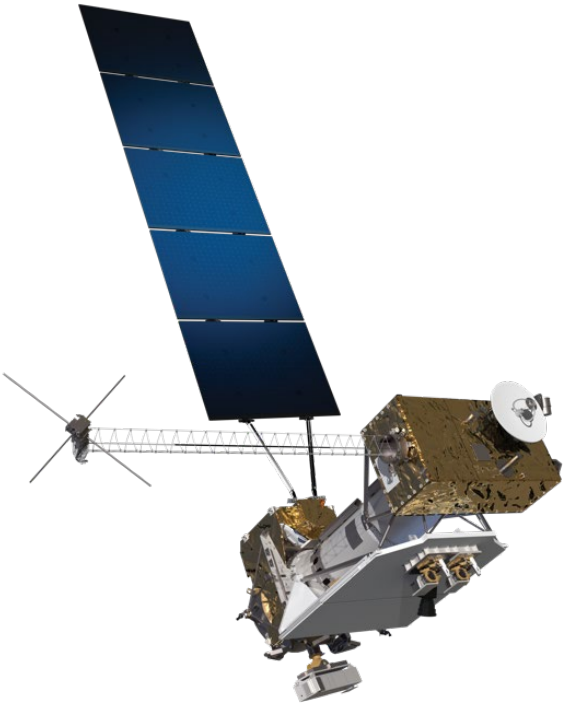


Figure 3-1. STPSat-6 Image

3.1.1 *Optical Communication Contamination Control Mitigation Methodology*

Optical Module latches were closed for nearly all of SV and LV I&T to preserve the cleanliness of the OM optics. The system performance was verified through Limited Performance Tests (LPT), leveraging the payload's built-in self-test functionality. This did not require the SV or LV integration facilities to implement expensive contamination protocols and did not require an expensive optical test set (OTS).

Figure 3-2. Image of Spacecraft Provided Subsystems as they are located on the LCRD payload.

LPTs consisted of boresight alignment (checks through the optical modules utilizing a retroreflector mounted on the launch cover), modem loopback performance tests, and data relay tests. The LCRD LPTs were successful during every SV and LV test.

3.1.2 *Early Space Vehicle Communication System Testing with LCRD Methodology.*

Open Panel testing (similar to FlatSat testing, but with flight hardware) was the first time the LCRD payload interfaced with Payload Ground Link Terminal (PGLT) through the ground high data rate (HDR) modem and the host space vehicle. The term "Open Panel" testing refers to Northrop Grumman's methodology to test the space vehicle in an unassembled configuration, thus allowing anomalies to be identified rapidly and corrected while mechanical access is easily available. This phase of space vehicle testing reduced risk to the interface between the HDR system and the LCRD payload while also providing engineers experience using the critical ground link hardware in a flight-like manner.

Figure 3-3. Image of STP-3 Integrated Payload Stack

3.1.3 *COVID-19 Response Methodology*

While not unique to optical communication, the COVID-19 pandemic posed a significant challenge to LCRD AI&T campaign. Medical Personal Protective Equipment (PPE) (disposable gloves, face masks, face shield, disinfecting wipes, and hand sanitizer) became scarce and team members were not permitted onsite by law. The LCRD team developed a strategy to maintain mission operations and continue mission critical activities leveraging tele-networking technology. NASA's computer networking systems enabled personnel to rapidly pivot to home-based work and maintain a significant fraction of their previous working efficiency. LCRD was one of the first missions to obtain approval from NASA's GSFC management to continue development and testing on-site.

On a volunteer-only basis, LCRD personnel developed I&T COVID-19 safety practices. These included keeping track of medical Personal Protective Equipment (PPE), such as face masks and face shields, cleaning supplies, hand sanitizers, in addition to social distancing in the control rooms and integration areas, and limiting the number of personnel per room. The team worked together to come up with clever solutions for remote collaboration, system monitoring, and system analysis using communication platforms like Microsoft Teams. This allowed for the health and safety of flight hardware to be continuously monitored while personnel remained isolated.

4 Ground Segment AI&T

4.1 Overview

Ground Segment Assembly, Integration and Test (AI&T) consisted of developing new architecture and integrating existing systems into the new architecture. Separate from the LCRD Project, the Optical Ground Stations were developed in California and Hawai'i. Similarly, the STPSat-6 Space Vehicle Operations Center (SSOC) was developed by the NASA Advanced Communications Capabilities for Exploration and Science Systems (ACCESS) Project and the Space Test Program at the White Sands Complex. The many different organizations and systems presented complex challenges to the AI&T campaign.

4.1.1 Logistics of Multiple Organizations Methodology

The logistical challenge of developing and integrating such interwoven, diverse, and complex systems was difficult when the technical team was separated across the country and by three time zones. Complex hardware and intricate software were initially developed, tested, and released at separate NASA centers. By utilizing regular weekly meetings outside normal business hours, the team designed, built, shared, and tested the disparate parts into one cohesive system. Especially when difficulties, misunderstandings, and performance challenges arose, the weekly meeting tempo encouraged collaborative solutions from the team.

4.1.2 Clear Performance Requirements Methodology

Mutual agreement of the performance requirements is essential to counter mission scope creep, in addition to full engagement and continuous support from the Principal Investigator (PI) when interpreting all requirements. With this close collaboration between the design and PI team, the implementation of requirements in a design was achieved. One example of this is the original assignment of requirements that, for a given average irradiance from the flight terminal at the ground receiver, a certain amount of light must be coupled into the single-mode fiber back to the ground modem system. This initial requirement wording missed the subtleties of uplink and downlink fade statistics that can have significant effects on maintaining and servicing a particular link. The Mission Team worked together to clarify and revise the requirement, and implement a feasible hardware system.

4.1.3 Virtualization and Automation Methodology

The LCRD Mission Operations Center (LMOC) is responsible for operation of the LCRD payload, control of the LCRD ground stations, and for coordinating communications experiments using the LCRD communications system, built-in user simulators, and external assets. The LMOC comprises the mission operations center at the White Sands Complex (WSC) and an LMOC Extension (LMOC-E) at Goddard Space Flight Center (GSFC). The LMOC-E facilitates remote viewing of real-time telemetry and archival data by subject matter experts and the experimenters.

The LMOC design uses a virtualization-based approach, where all subsystems are instantiated as software running on VMWare virtual machines (VMs). These VMs are run on redundant servers, enabling reliable operation through a failure of any single server with automatic failover. Configuration of the virtual machines is largely automated using Ansible and Gitlab.

The combination of virtualization and automation allows the LMOC to host multiple "rails" of the LMOC software: isolated functional units each providing a complete instantiation of the LMOC functions. Using this approach, the LMOC hosts an operations rail with the verified operational configuration of the software, as well as multiple test rails which support test activities (e.g., the testing of new software versions prior to deployment to the operations rail) concurrent with operations. The test rails also include ground station and payload simulator VMs, hosting software which simulates some of the command and telemetry functions of these other mission elements.

Based on the resource phasing of payload and ground system development for LCRD, development of the LMOC architecture and software occurred concurrently with the integration and test of the LCRD payload and integration with the STPSat-6 space vehicle, creating both technical difficulties and resource conflicts. The use of virtualization to provide multiple, functionally complete and independent rails of software was key to overcoming these difficulties, providing the technical capability to support multiple activities at once. Utilizing remote access to some of our test rails allowed us to share duties of supporting these concurrent activities across staff from both WSC and GSFC, which mitigated the staffing conflicts.

4.1.4 Multi-branches for Inherited Software Updates Methodology

The LMOC software for the Payload Telemetry and Command (PT&C) subsystem was informed by a risk-reduction code package from MIT LL. Customization by NASA was necessary in order to make it compatible with the LCRD payload, with continuing refinement to this customization throughout I&T. However, there were also new upstream releases of the risk-reduction software during the I&T campaign, sometimes incorporating changes to items that had already been customized. In order to be able to make use of these upstream updates in the LCRD setting, it was advantageous to keep a branch of these upstream changes in a Git repository alongside the master branch for Goddard's customized configuration. By doing this, upstream updates could be captured in the upstream branch for reference and then merged to the customized master branch, with the built-in Git 3-way merge features automating most of the merge (to prevent accidental reversion of earlier customizations) while identifying actual potential conflicts between customization and upstream changes. This approach greatly reduced the level of effort that would otherwise have been involved in taking these updates.

4.1.5 Distributed Version Control Systems Methodology

During the development, integration, and test of LCRD, the same code or configuration files have been needed in disparate environments, including development environments at GSFC, WSC, JPL as well as a separate Payload I&T environment at GSFC. Due to combinations of practical limitations and security requirements, these disparate environments did not generally have direct, real-time access to the same version control system repositories to facilitate unified configuration management of source code and configuration files.

Distributed version control systems (DVCSs) have proved to be a very useful tool to deal with these challenges. Specifically, we used Git and Gitlab to control source code and configuration file revisions. As a DVCS, Git is designed to address the use case of multiple environments without direct, real-time access to a central revision control repository, so revisions can be moved between environments using intermediary systems and even files containing change sets (which can be transported by email or, if needed, physically). Moreover, since the tracking of revisions is primarily based on hash functions, even in a situation where it is entirely impossible to move change sets from one environment back upstream, it is possible to manually reproduce the changes and, by comparing hashes, verify that the exact changes have been reproduced upstream where they can be recorded, retained, and deployed elsewhere.

While these additional capabilities are invaluable, this flexibility comes at the cost of complexity. A DVCS like Git requires the user to engage with the topics of branches and merges even for relatively basic use cases as well as nuances regarding what aspects are pushed to remote repositories (e.g., tags). Therefore, making use of a DVCS generally requires higher degree of fluency in version control concepts by the users, necessitating more training. After the planning phase, execution of tests occur starting at the component level and moving up through the subsystem, segment, system and finally on-orbit testing. As the mission progressed through design and into implementation, a few deviations from the model were warranted and prudent to stay within budget and on schedule. However, LCRD was able to stay true to the spirit of the model for most of V&V.

5 Summary

The communications link bandwidth between space and Earth has long been a critical space mission systems driver. Information from a scientific or exploration mission must be returned to Earth, and the more data that is received per second directly increases the science return. The Laser Communications Relay Demonstration (LCRD) mission provides a space-based technology demonstration of these critical techniques, utilizing existing systems and minimal modifications to existing flight systems to fully characterize high data rate optical communications in a space flight environment.

During the LCRD Mission assembly, integration and test (AI&T) campaign many methodologies were used to complete the LCRD Optical Communication System qualification for space flight.

In summary these included:

- Early use of Pre-FlatSat and FlatSat
- Ground station equipment use in flight AI&T
- Centralized Optical Test Set (OTS)
- Three layers of laser safety protocol
- Telescope launch covers closed for majority of SV and LV AI&T mitigating contamination risk
- Open panel verification testing of SV communication interface
- Clear communication logistics
- Continuous Principal Investigator support for requirement interpretation

- Virtualization and automation of system ground software system deployment
- Multi-branches for Inherited Software Updates methodology
- Distributed version control systems

These unique approaches to preparing the LCRD optical communication system for spaceflight make it possible to launch in 2021. LCRD will provide at least two years of continuous high data rate optical communications in an operational environment, demonstrating that optical communications can meet NASA's and other agencies' growing needs for higher data rates and by enabling lower power, lower mass communications systems on future science and exploration space vehicles.

6 REFERENCES

[1] John McDougal and Randy Lillard. "Program Level Requirements Appendix (PLRA) for the Laser Communication Relay Demonstration Project, Marshall Space Flight Center, Huntsville, Alabama, 2013.

[2] Israel, David J., Bernard L. Edwards, and John W. Staren. "Laser Communications Relay Demonstration (LCRD) Update and the Path towards Optical Relay Operations." IEEE Conference, Big Sky, Montana, USA, 2017.

[3] Israel, David J., Bernard L. Edwards. "Update on NASA's Laser Communication Relay Demonstration Project, International Conference on Space Operations, Marseille, France 2018.

7 Acknowledgements

The work described in this paper was carried out at NASA's Goddard Space Flight Center; at Lincoln Laboratory, Massachusetts Institute of Technology; and at the Jet Propulsion Laboratory, California Institute of Technology, under contract with NASA. It is funded and supported by NASA's Technology Demonstration Missions (TDM) Program and Space Communications and Navigation (SCaN) Program Office. Additionally, Dr. John Moores at Massachusetts Institute of Technology Lincoln Laboratory provided expertise for this paper.