SPACE COMMUNICATIONS AND NAVIGATION

Laser Communications Relay Demonstration:

Introduction for Experimenters

June 2017

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INTRODUCTION

DOCUMENT PURPOSE

This document provides guidance to individuals or groups considering proposing an experiment for the Laser Communications Relay Demonstration (LCRD) Experiment Program. For the purposes of this document, the term "experiment" refers to both experiments and demonstrations. The document's goals are: (1) to introduce potential experimenters to the LCRD mission, its purpose, and its system architecture; (2) to help them understand the types of experiments that are possible using LCRD; and (3) to provide an overview of the experiment proposal process and explain how and where to obtain further information about making a proposal.

LCRD BACKGROUND

Communications between observatories and Earth are often a limiting mission design factor for today's spaceborne science missions. Radio frequency (RF) communication systems are not keeping pace with the needs of the advanced instrumentation systems that can be flown in space today. Optical communications can provide missions with greatly improved communication capabilities that will increase scientific return and efficiently use mission resources. For example, an optical communications system can provide higher data rates than an RF system requiring the same mass and power. Similarly, an optical communications system will require less mass and power than an RF system to provide the same data rate. Furthermore, use of optical communications eliminates issues such as microwave spectral congestion, spectrum allocation, and constrained bandwidth that are commonplace with RF communications.

Optical communications will revolutionize space-based science and exploration capabilities by supplying data rates up to 100 times faster than current RF systems. New science will be enabled as missions become capable of hosting instruments that require substantial bandwidth, such as hyperspectral imagers and instruments with high definition in spectral, spatial, or temporal modes. Optical communications will make it possible to establish a "virtual presence" at a remote planet or other solar system body, enabling high-rate communications with future space explorers.

LCRD will provide a space-based technology demonstration platform for bidirectional optical communications, leveraging work done in the past for the National Aeronautics and Space Administration (NASA) and the Department of Defense. LCRD will utilize existing systems and designs with minimal modifications to gain operational experience while minimizing costs. LCRD will execute experiments for a minimum of two years, providing high data rate optical communications in an operational environment. LCRD experiments will

demonstrate that optical communications can both meet NASA's and other agencies' growing need for higher data rates and enable lower-power, lower-mass communications systems on spacecraft.

In addition, LCRD's architecture will enable it to serve as a developmental testbed for advanced communication techniques including adaptive optics, symbol coding, link layer protocols, and network layer protocols. LCRD's dual optical link system will allow it to serve as the first step in demonstrating optical communications for use in a next-generation space-based relay system and potentially provide early operational support for low Earth orbit (LEO) terminals. LCRD will also enable experimenters to characterize atmospheric effects on optical communications and validate atmospheric models. LCRD will advance optical communications technology toward infusion into both deep space and near-Earth operational systems, while growing the capabilities of industry sources to produce affordable optical communications systems and components for use on the ground and in space.

The LCRD flight segment consists of a payload on a geosynchronous Earth orbit (GEO) satellite—the Space Test Program Satellite-6 (STPSat-6). The LCRD ground segment consists of two optical ground stations, an RF ground station, an operations control center, and an additional facility for observation and monitoring of LCRD operations and experiments.
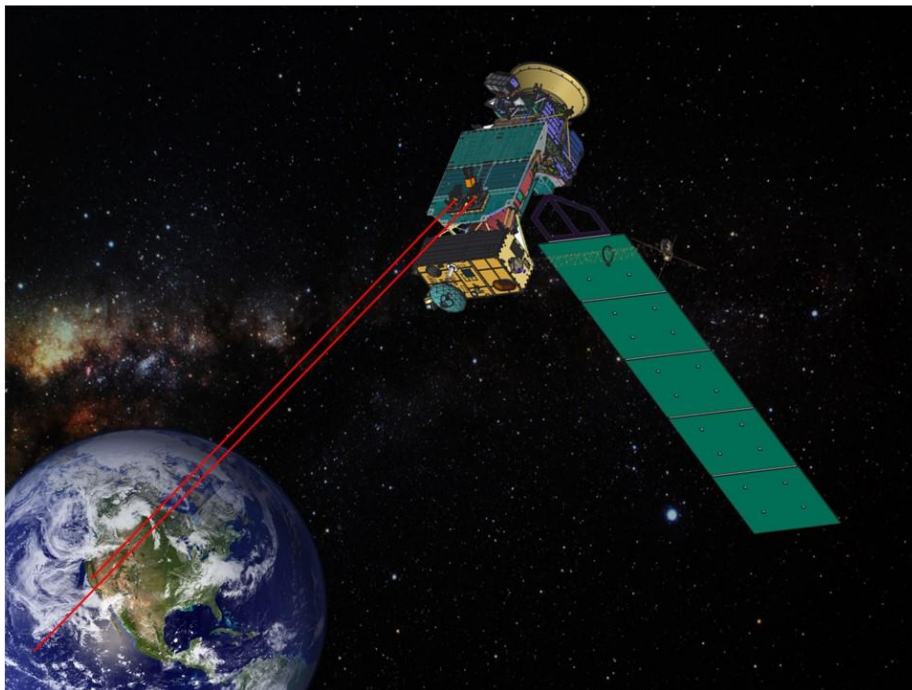

Figure 1. LCRD consists of a flight segment and a ground segment that will demonstrate two simultaneous bidirectional optical links.

The LCRD mission objectives are to:

- demonstrate bidirectional optical communications between geosynchronous Earth orbit (GEO) and Earth,
- measure and characterize the system performance over a variety of conditions,
- develop operational procedures and assess applicability for future missions,
- transfer laser communication technology to industry for future missions, and
- provide an on-orbit capability for test and demonstration of standards for optical relay communications.

During the two-year LCRD prime mission phase, NASA will execute a predetermined set of NASA experiments designed to achieve the mission objectives. The Agency may also supplement this predetermined set with experiments selected via the LCRD experiment proposal process. Proposers of such supplemental experiments may be internal or external to the LCRD Project, and may include individuals or groups from NASA, other government agencies, academia, or industry.

LCRD is funded by the NASA Space Technology Mission Directorate (STMD) and the Space Communications and Navigation (SCaN) Program, and is led by a Principal Investigator (PI). The project is a collaborative effort between NASA Goddard Space Flight Center (GSFC), the Jet Propulsion Laboratory (JPL), and Massachusetts Institute of Technology Lincoln Laboratory (MITLL). The LCRD Project Office resides at GSFC.

LCRD ARCHITECTURE

The LCRD mission architecture, depicted in Figure 2, is composed of flight and ground segments. The flight segment onboard the STPSat-6 spacecraft includes the LCRD flight payload and the spacecraft-provided High-bandwidth Radio Frequency (HBRF) terminal. The ground segment includes two optical ground stations (Optical Ground Station 1, or OGS-1, and Optical Ground Station 2, or OGS-2); an RF ground station (RF GS); and an LCRD Mission Operations Center (LMOC), which includes an LMOC Extension (LMOC-E). The following subsections in this report provide additional information about the elements and systems in these segments that are relevant to LCRD experiments.
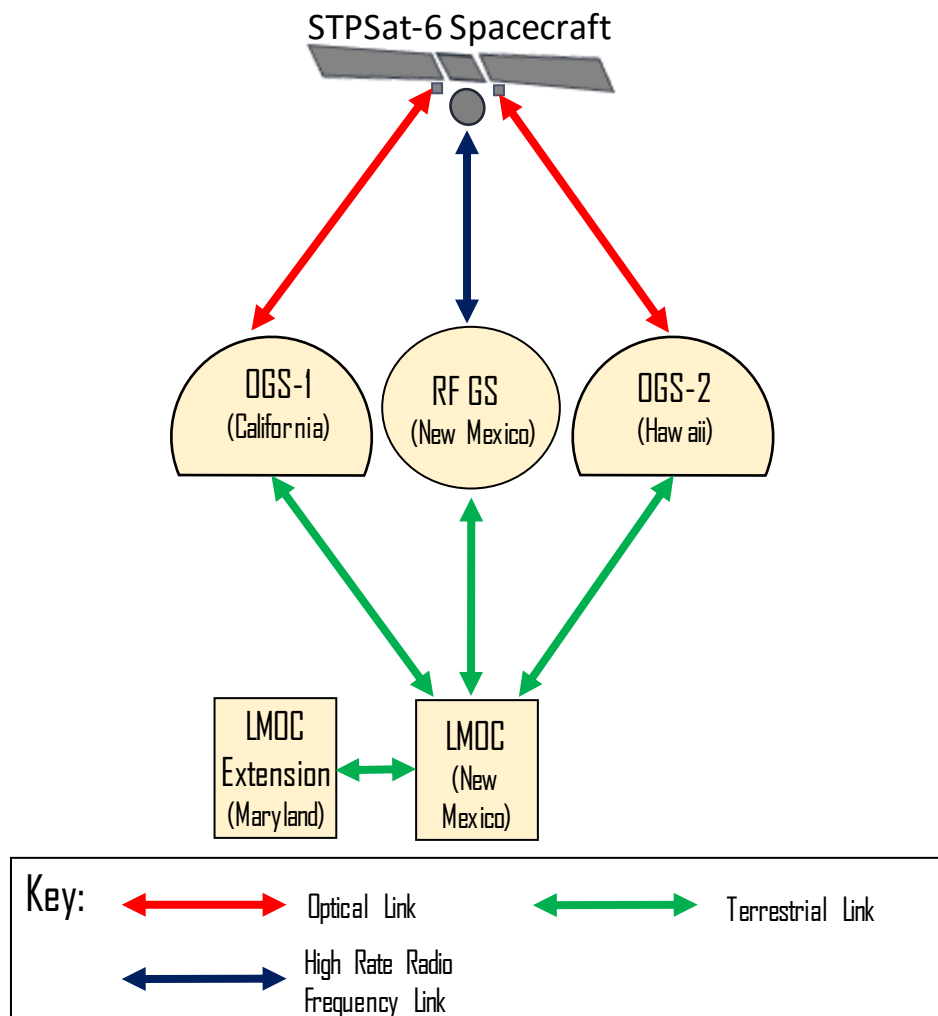

Figure 2. The LCRD mission architecture

FLIGHT SEGMENT

The LCRD flight segment, depicted in Figure 3, consists of the LCRD Flight Payload and the HBRF terminal.

Figure 3. The LCRD flight segment

LCRD FLIGHT PAYLOAD

Space Switching Unit

The Space Switching Unit (SSU) is the central controller for the LCRD Flight Payload. The SSU receives and switches incoming data according to the frame header, processes Payload commands, and accumulates and transmits Payload telemetry.

Optical Space Terminals

Each optical space terminal (OST) contains a telescope to collect and transmit laser signals, a modem that supports both Pulse Position Modulation (PPM) and Differential Phase Shift Key (DPSK) waveforms on the uplink and downlink, and controller electronics for pointing, tracking, and acquisition and thermal control.

The modem includes multiple Built-in Test (BIT) functions that enable simple calibrations and internal modem or payload loopback testing. The modem can also generate test pattern data frames for use in direct downlink return service.

HIGH-BANDWIDTH RF TERMINAL

The HBRF terminal supports LCRD Ka-Band communications. On the forward link, the HBRF terminal can support one or two users with an effective user data rate up to 32 Mbps for each user. On the return link, the HBRF terminal can support a single user with an effective user data rate up to 622 Mbps, or two users with effective user data rates up to 311 Mbps each. Data passing through the HBRF terminal can be a composite of data going to both optical space terminals (for return link) or coming from both optical space terminals (for forward link). The HBRF terminal is connected to the SSU so that data can be switched between the optical and RF links. The HBRF terminal is only used for space-to-ground trunklines; no RF space-to-space links will be supported.

GROUND SEGMENT

The ground segment includes the two optical ground stations, an RF ground station and an LCRD Mission Operations Center (LMOC), which includes an LMOC Extension (LMOC-E).

OPTICAL GROUND STATION

The primary LCRD optical ground station (OGS-1) is located at the JPL Optical Communications Telescope Laboratory (OCTL) facility in California. A second optical ground station (OGS-2) is located in Hawaii. LCRD optical ground station subsystems include an Optical Telescope Assembly, Ground Modem, Coder/Decoder (CODEC), User Services Gateway, User Element Simulators (a User Mission Operations Center [MOC] Simulator and a User Platform Simulator), and an Atmospheric Channel Monitoring system. Figure 4 illustrates the subsystems of an LCRD optical ground station. Both optical ground stations can communicate with either LCRD optical space terminal.
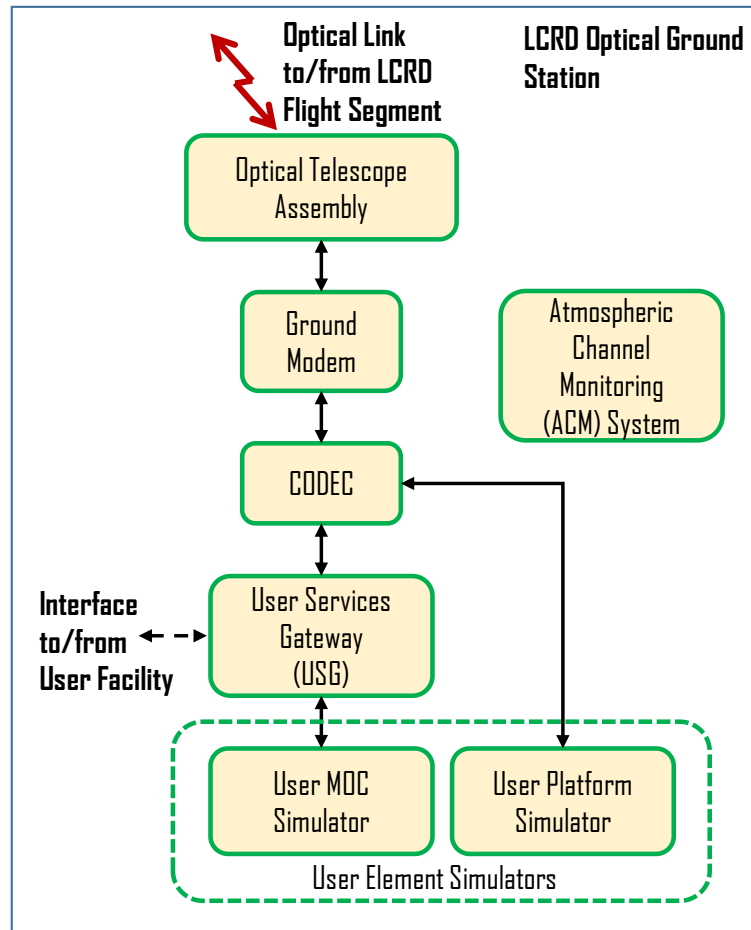
Figure 4. LCRD optical ground station subsystems.

Optical Telescope Assembly

The OGS-1 optical telescope assembly is comprised of a one-meter optical telescope with a coudé room for transmit and receive optics. The optical telescope assembly at OGS-2 is installed in a dome approximately 5.5 meters in diameter, and includes a 60-centimeter receive aperture and a 15-centimeter transmit aperture.

The receive systems of each telescope assembly use adaptive optics to collect efficient light at the downlink wavelength into a single mode fiber that is routed to the Ground Modem and CODEC. Both ground stations employ an uplink beacon to provide a reference beam that enables the optical space terminal to establish the pointing direction.

Ground Modem

The Ground Modem modulates the signal on the uplink side and demodulates it on the downlink side. The Ground Modem at OGS-1 enables use of both Pulse Position Modulation (PPM) and Differential Phase Shift Key (DPSK) modulation. The Ground Modem at OGS-2 enables use of DPSK only.

Coder/Decoder (CODEC)

On the uplink, the CODEC applies Forward Error Correction (FEC) and interleaving to Flight Payload command data and user service data (if requested) prior to modulation. Once data are encoded and interleaved, the correct logical path identifier (known as the "unique word") and physical layer header are added to the data to create a physical (optical) layer frame. Once the frame header is applied to the uplink data, the CODEC multiplexes the optical frames containing data into a single stream and forwards them to the Ground Modem. The CODEC executes the process in reverse on the downlink for return data and Payload telemetry.

User Services Gateway

The User Services Gateway (USG) serves as an interface point for multiple ground users exchanging data over an optical link with the Flight Payload. User MOCs connect with the USG to send forward service data and receive return service data for all services. The USG directs uplink data into the proper channels in the CODEC and distributes downlinked data to terrestrial User Mission Operations Centers (MOCs) or the LMOC. The USG also performs protocol processing for space or ground transport according to the user service being provided.

User Element Simulators

LCRD uses two types of user element simulators in support of demonstrations and experiments—a User MOC Simulator (UMS) and a User Platform Simulator (UPS). The UMS interfaces with the LCRD network through the USG and will provide and receive data that looks as though it was generated and received by an outside User MOC. The UMS also enables an interface for service planning and retrieval of service simulator data products.

The UPS simulates User Platform data. It receives forward service data from the Flight Payload over an optical link and transmits return service data to the Flight Payload over an optical link.

Atmospheric Channel Monitoring System

An Atmospheric Channel Monitoring (ACM) system at each optical ground station will collect data to characterize the weather at the site and to gauge the atmospheric effects on the optical links during experiments. Data will be available to experimenters for analysis. Such measurements may include:

- Weather (temperature, humidity, atmospheric pressure, wind speed, wind direction)
- Atmospheric transmittance
- Daytime sky radiance
- Strength of optical turbulence at the ground layer
- Daytime atmospheric coherence lengths (r_0)
- Cloud coverage
- Atmospheric coherence length (r_0) along the downlink path (during experiments)
- Downlink signal irradiance

RF GROUND STATION

The LCRD RF ground station is in White Sands, New Mexico. Figure 5 depicts the LCRD RF ground station subsystems. The RF ground station employs the same CODEC, user gateway, and user simulator capabilities (UMS and UPS) as the LCRD optical ground stations. It allows the same user data services and experiments to be supported over an RF trunkline as the optical trunkline, though at different data rates. The LCRD RF ground station also includes RF equipment (antennas, amplifiers, transmitters, receivers, and other data processing equipment) that is necessary to connect the LCRD high-rate RF data stream with the CODEC.
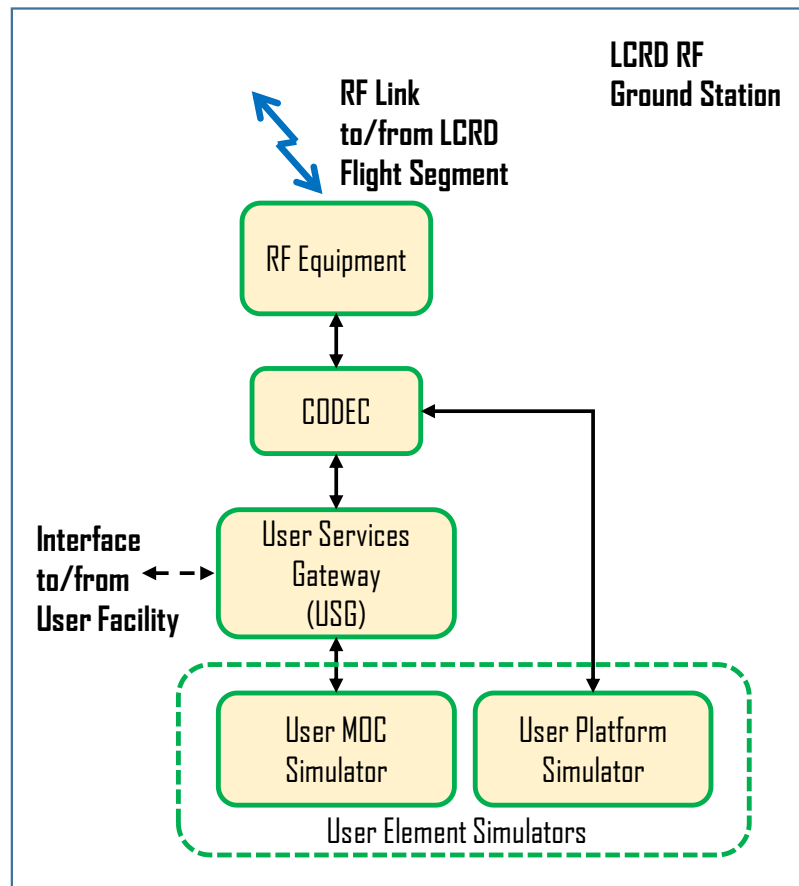
Figure 5. The LCRD RF ground station subsystems.
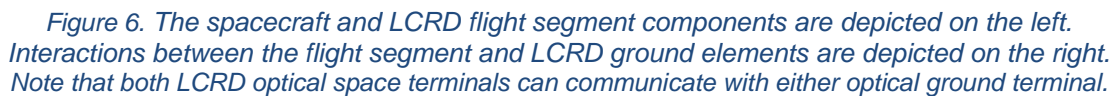
LCRD MISSION OPERATIONS CENTER (LMOC)

The LMOC is located at the White Sands Complex (WSC) in White Sands, New Mexico, and securely coordinates all LCRD operations, including the following functions:

- Mission Planning and Scheduling
- Payload Telemetry and Command
- Data Storage
- Data Analysis
- Central Operations Monitoring and Control
- Service Management
- Ground Station Remote Monitoring
- Experiment Operations

The LMOC is connected via terrestrial networks directly to each ground station supporting the LCRD mission.

An extension of the LMOC—the LMOC-E—is located at GSFC in Greenbelt, Maryland. During operations, the LMOC-E will support experiment operations and remote monitoring of LCRD health and safety. The LMOC-E can provide observers with a view similar to that experienced at a user MOC, including insight into the scheduling process and monitoring of experiment operations. The LMOC-E can also allow observations of LCRD operations from the viewpoint of the LCRD operator (LMOC). The LMOC-E will enable experimenters to monitor LCRD link performance during an experiment, analyze weather effects, etc. There are no network control or Payload command functions accessible from or located in the LMOC-E.

EXAMPLE EXPERIMENTS

LCRD is capable of simulating numerous optical communication scenarios, and LCRD experiments will involve elements both on the ground and in space (see Figure 6). Each LCRD element can perform several different functions, and the role each element plays depends upon the experiment being executed.

Figure 6. The spacecraft and LCRD flight segment components are depicted on the left. Interactions between the flight segment and LCRD ground elements are depicted on the right. Note that both LCRD optical space terminals can communicate with either optical ground terminal.

Primarily, the LCRD flight segment serves as a relay between a user employing optical communications links and a ground station on Earth. In this type of configuration, one LCRD optical space terminal (OST-1 or OST-2) provides the forward/return optical link to the user. An optical trunkline can be provided via a link between the other optical space terminal and one of the optical ground stations (OGS-1 or OGS-2). Alternatively, an RF trunkline can be provided via a link between the onboard HBRF terminal and the RF ground station.

The LCRD flight segment can also serve as an optical relay between user spacecraft. In this configuration, one LCRD optical space terminal provides a forward/return optical link to one of the user spacecraft, and the other optical space terminal provides the forward/return optical link to the other user spacecraft. In this user-to-user optical relay configuration, the onboard HBRF terminal can be used to exchange data (e.g., housekeeping, telemetry, etc.) with the RF ground station.

In addition, **the LCRD flight segment can function as a Direct-to-Earth (DTE) user**. To simulate a DTE user downlink, the LCRD flight segment receives simulated user-formatted data streams either via an optical uplink from one of the optical ground stations to an optical space terminal or via an RF uplink from the

RF ground station to the onboard HBRF terminal. Once the flight segment receives the simulated DTE user data, it sends the data to an optical space terminal for downlink transmission to an optical ground station, which is scheduled and configured to support a DTE downlink. An optical uplink from the optical ground station to the DTE user may also be simulated in an analogous way in the other direction.

An LCRD optical ground station can also function in multiple ways, depending on the type of experiment being executed. It can function as an optical ground station providing either optical trunklines in a relay configuration or sending uplinks and receiving downlinks for a DTE demonstration. Or to demonstrate a relay scenario, an optical ground station can simulate a user spacecraft by communicating with the LCRD flight segment via optical forward/return link with one of the optical space terminals. When simulating a user spacecraft in a relay scenario, an optical ground station will employ its user element simulators (UPS and UMS) to generate and receive user data to support return and forward optical links with LCRD flight segment. Finally, an optical ground station can employ its user element simulators to supply and receive simulated data via optical links with the LCRD flight segment to enable the flight segment to function as a DTE user.

The LCRD RF ground station can also function in multiple ways. It can function as a ground station to support RF trunklines to/from the onboard HBRF terminal. It can also provide simulated DTE user data via the HBRF to the LCRD flight segment to enable the flight segment to function as a DTE user. During certain experiments (e.g., those where it is desirable to use both optical ground stations for optical trunklines) the RF ground station can simulate an optical relay user spacecraft in a limited fashion by providing simulated relay user data to LCRD via the HBRF terminal. When simulating an optical relay user, the RF ground station simulates only the data portion of the link—not the optical modulation, wavelength, etc. User element simulators at the RF ground station will support all of these experiments.

The example scenario and experiment configuration in Figure 7 show how the LCRD elements could be configured to support an experiment demonstrating a user spacecraft communicating via a relay spacecraft to the ground. (Note that Figure 7 depicts an operational scenario on the left, and a potential corresponding LCRD experiment configuration on the right. Functions of LCRD systems in the experiment configuration are indicated in parentheses. This depiction method is employed throughout the remainder of this document.) In the scenario depicted on the left, the user spacecraft employs an optical link to communicate with the relay spacecraft, and the relay spacecraft uses an RF link to exchange data with the ground station. In the corresponding LCRD experiment configuration depicted on the right, one of the optical ground stations functions as the user spacecraft, using its user element simulators to generate and receive user data. The LCRD flight segment functions as the relay spacecraft. The RF link between the HBRF and RF ground station simulates the trunkline, and the LCRD RF ground station employs its UMS to function as the User MOC. All the links are bidirectional and it is possible

to independently control the data rates, coding, and modulation on each link; therefore, one could demonstrate a user with asymmetric data rates.
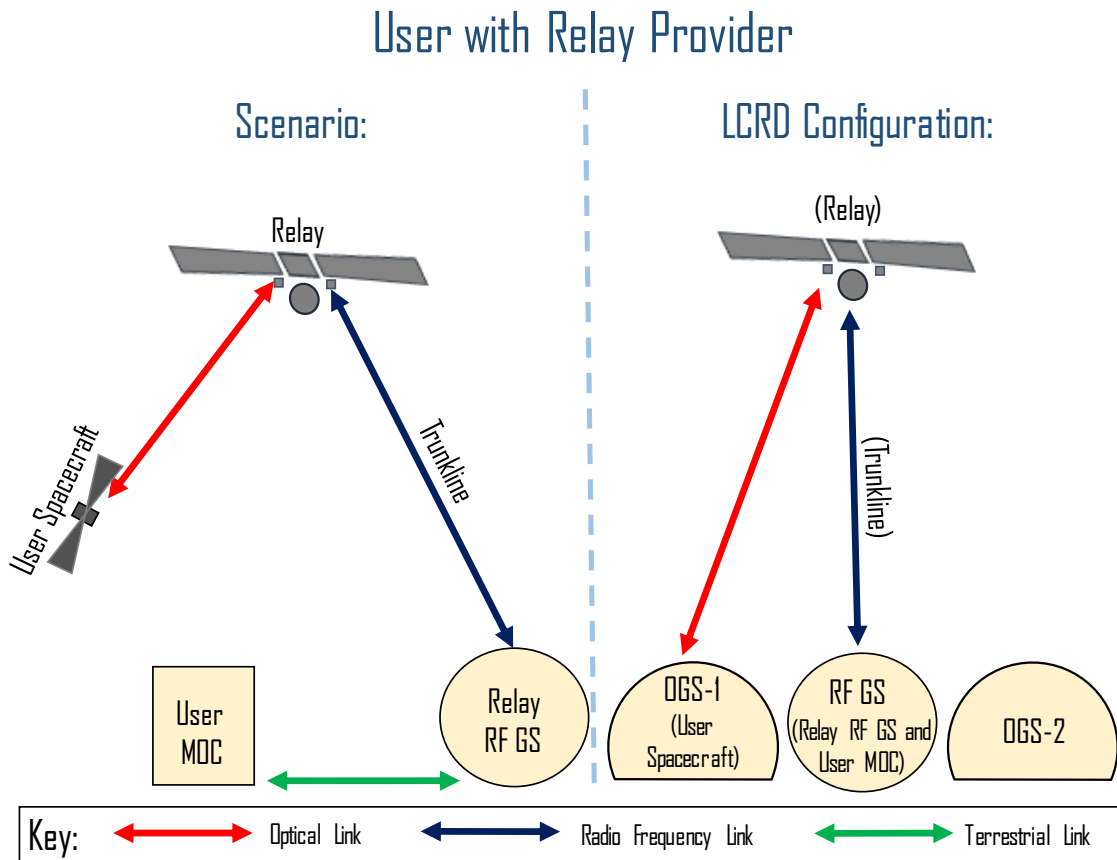
User with Relay Provider

Figure 7. Example LCRD experiment configuration (depicted on the right) to simulate a scenario involving a relay provider supporting a single user spacecraft (depicted on the left).

In another example, Figure 8 depicts one way the LCRD architecture could be configured to execute an experiment simulating a scenario where a user spacecraft employs an optical downlink to transmit data to a ground station (i.e., a DTE user). In the experiment configuration on the right, an LCRD optical ground station (OGS-1) enables the LCRD flight segment to simulate the user spacecraft by employing its UPS to generate the simulated user data and providing the data via optical uplink to one of the onboard optical space terminals. The LCRD flight segment functions as the user spacecraft and transmits the data via optical downlink from the other onboard optical space terminal to OGS-2, which acts as the receiving optical ground station. In addition, OGS-2 employs its UMS to function as the user MOC. Note that when executing the simulated user downlink to the ground, the LCRD flight segment can employ a modulation scheme that is different than that employed on the uplink to send the simulated user data from the ground to the LCRD flight segment.

Direct-to-Earth User

| Scenario: | LCRD Configuration: |

Key:
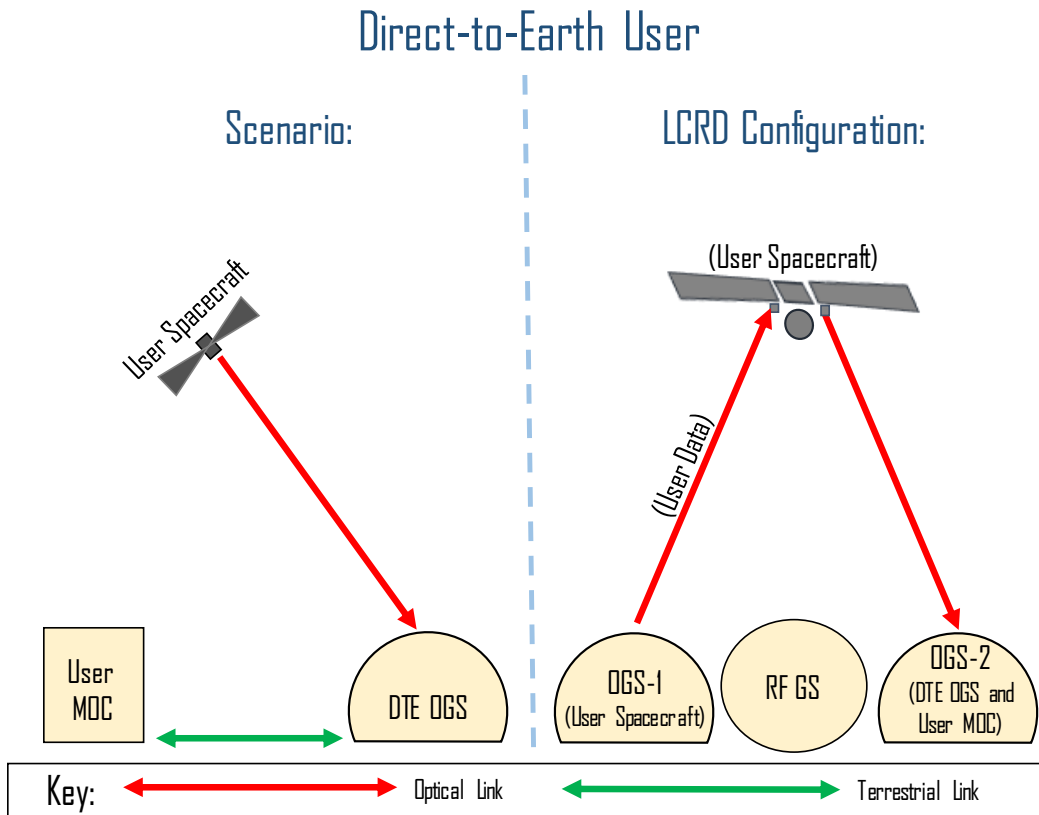← → Optical Link   ← → Terrestrial Link

Figure 8. Example LCRD experiment configuration (depicted on the right) to simulate a scenario involving a Direct-to-Earth user (depicted on the left).

In LCRD experiments, data can be exchanged between Earth and the LCRD flight segment via two pathways: (1) optical link between an optical space terminal and an LCRD optical ground station, and (2) RF link between the HBRF terminal and the RF ground station. These two methods have respective advantages and disadvantages. Using an optical link enables a high data rate, but the link can experience interference from weather and atmospheric factors. Data transfer via RF link occurs at a lower data rate, but the link is not affected by weather. Furthermore, experiment configurations that use the RF uplink to supply simulated data to the flight segment leave both optical ground stations available, enabling execution of experiments involving handovers from one optical ground station to another. The LCRD flight segment can also generate user data frames and insert them onto the optical link, eliminating the need for an uplink and the corresponding effect on performance.

LCRD experimenters will have access to the telemetry data collected during their respective experiments. In addition, they will have access to data collected by the atmospheric channel monitoring system at the optical ground station(s) used during the experiments. Experiments can be scheduled to run for any duration, any time of day or night, as the schedule permits. Experimenters will also be able to

connect their own equipment via multiple interface locations within the LCRD ground systems.

The following sections discuss the experiments that different types of potential LCRD experimenters may wish to conduct. This discussion of potential LCRD experiments is not intended to be exhaustive; instead, a sample set of typical experiments is reviewed to highlight LCRD capabilities. Experimenters are encouraged to propose additional experiments of interest, including those that demonstrate commercial applications.

RELAY PROVIDER

Providing communication services to customers using optical links is an emerging capability. In addition to technical challenges, optical communications relay providers will need to consider other factors that affect the optical link quality, such as weather conditions. Unlike RF communications, however, there is no historical optical communications data record from which to gather information about required equipment or to generate statistics regarding link performance, availability, etc.

LCRD will execute multiple types of experiments to establish such a data set for the optical communications community. Initial experiments will likely characterize provider performance, generating data that will enable providers to resolve the attributes of present systems and determine the service levels currently available. Additional experiments will help determine potential changes that can be made to optimize future optical communication systems and improve the level of service providers can guarantee to users. Relay providers will also be able to conduct experiments to determine the effectiveness of operational procedures and discern when automation can improve service provision.

The left side of Figure 9 depicts a communications scenario involving a relay provider serving multiple user spacecraft, while the right side of the figure depicts a typical LCRD experiment configuration designed to simulate that scenario. In this configuration, one LCRD optical ground station employs its UPS to function as one of the user spacecraft, exchanging data with one of the onboard optical space terminals via an optical link. The other optical ground station functions in an identical way as the second user spacecraft. The LCRD flight segment functions as a relay, exchanging data via an RF trunkline between the HBRF terminal and the RF ground station. In addition to functioning as a ground station, the LCRD RF ground station uses its UMS to function as the User MOCs of both spacecraft.

Relay Provider for Multiple Users
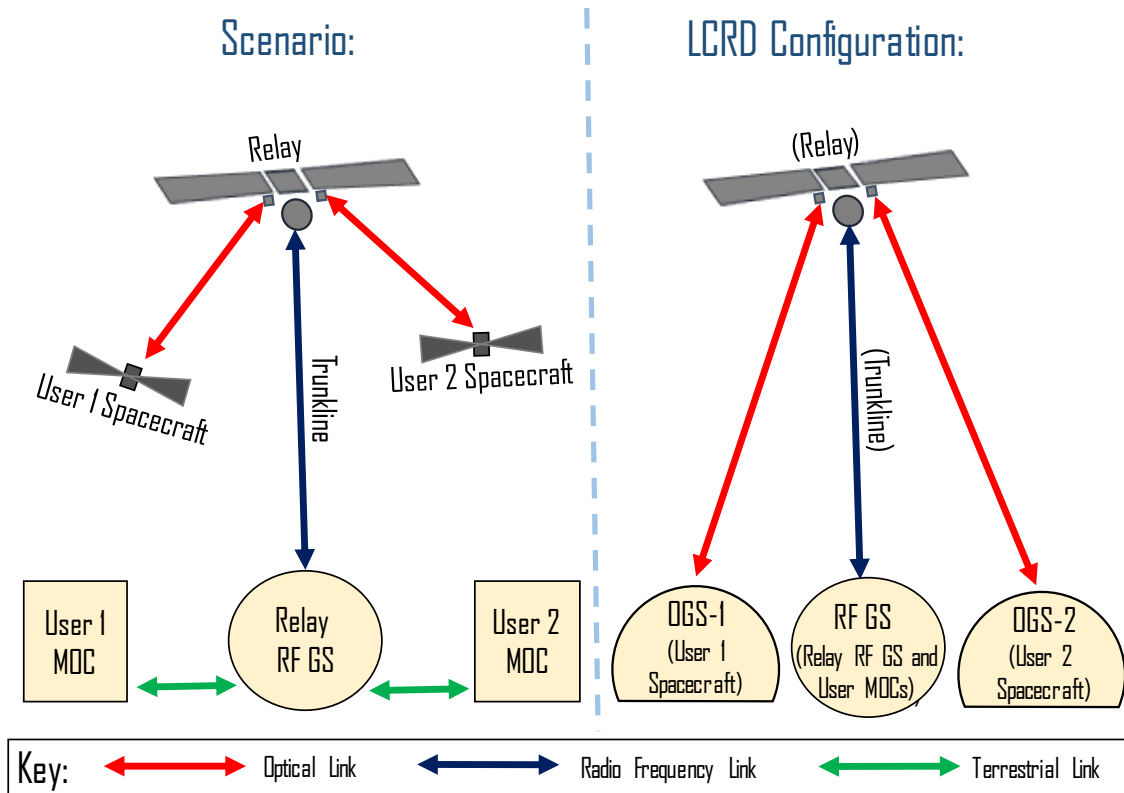
Scenario:

LCRD Configuration:

Figure 9. Example LCRD experiment configuration (depicted on the right) to simulate a scenario involving a relay provider supporting multiple user spacecraft (depicted on the left). Note that either LCRD ground station (OGS-1 or OGS-2) can simulate either user spacecraft.

Another potential operations scenario of interest to a relay provider is depicted on the left in Figure 10. A relay provider serving a single user spacecraft executes a station handover (i.e., the trunkline between the optical space terminal and the ground is transferred from one ground station to another). In the corresponding experiment configuration depicted on the right, the LCRD RF ground station functions as the optical relay user spacecraft, leaving the two LCRD optical ground stations available to function as ground stations so that a station handover can be executed. To simulate the user spacecraft, the RF ground station employs its UPS to simulate the data portion of the links and exchanges data with the flight segment via the HBRF terminal. The initial optical trunkline is established between an LCRD optical space terminal and OGS-1, which is simultaneously employing its UMS to function as the User MOC. To conduct the handover, the initial trunkline is terminated, and a new optical trunkline is established between the same optical space terminal and OGS-2. Once the new trunkline is established, OGS-2 functions as the relay optical ground station and the User MOC.

Relay Provider with Station Handover

Scenario:

LCRD Configuration:

Relay

Trunkline

User Spacecraft

Trunkline

Relay OGS-1

User MOC

Relay OGS-2

(Relay)

(Trunkline)

(Trunkline)

OGS-1 (Relay OGS-1 and User MOC)

OGS-2 (Relay OGS-2 and User MOC)

RF GS (User Spacecraft)

Key: | Optical Link | Radio Frequency Link | Terrestrial Link
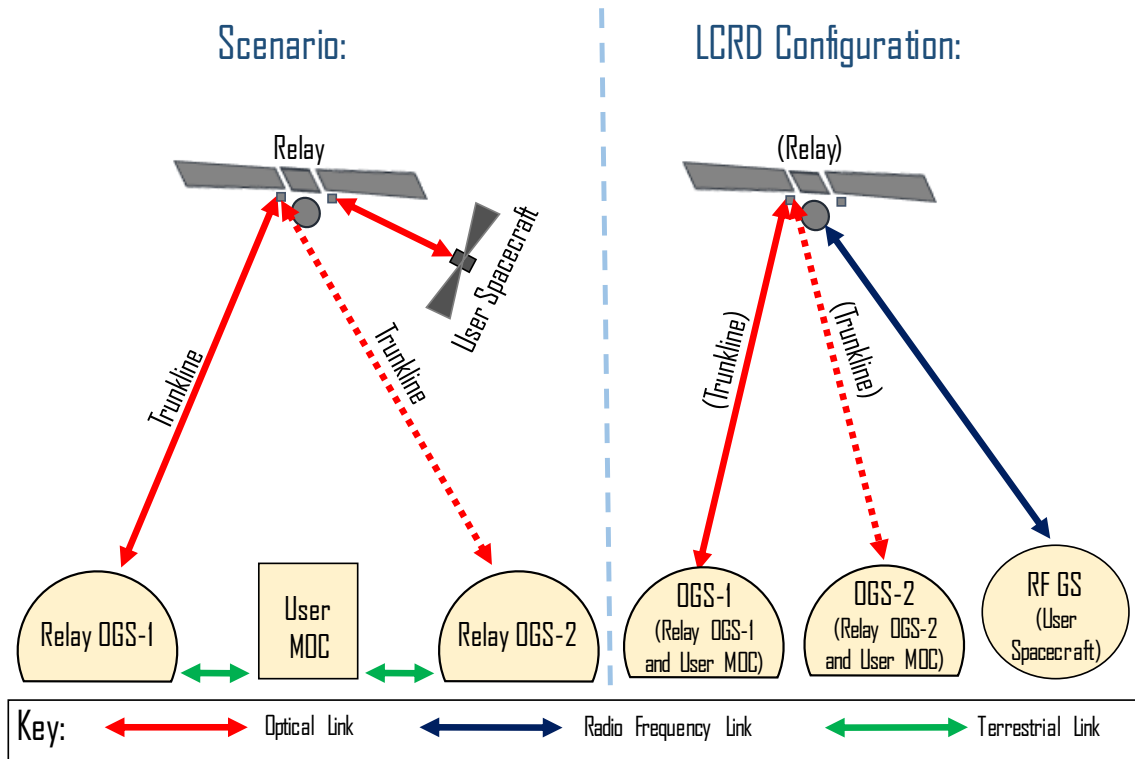
Figure 10. Example LCRD experiment configuration (depicted on the right) to simulate a scenario involving a relay provider executing station handovers (depicted on the left).

By using the RF link to simulate the user in this fashion, a relay provider could use this experiment configuration to characterize the process for handing over relay spacecraft communications from one optical ground station to another. A provider could conduct experiments that involve handovers with different simulated user configurations and in various weather conditions to determine how quickly the handover process can be executed. Given this information, the provider would be able to calculate how far in advance station operators must predict the need for a handover. Providers may also want to characterize the process used to determine when handovers are needed. To learn how effective handover need predictions are, a provider could conduct an LCRD experiment to establish a communications link, and then determine if it is possible to predict when the link will become disrupted by weather conditions, etc.

RELAY USER

Relay users may want to conduct LCRD experiments to demonstrate that optical communications can successfully meet specific operational needs of their spacecraft, including data rates, view periods, and maximum data latency requirements.

Figure 11 depicts an example experiment configuration simulating a scenario involving a user spacecraft supported by an optical relay provider. In the configuration depicted, OGS-1 functions as the user spacecraft, employing its UPS to generate data modeling the view periods, data rates, types of data, etc., specific to the user, and exchanging data with the LCRD flight segment via optical link with one of the onboard optical space terminals. The LCRD flight segment functions as a relay spacecraft and transmits data to/from the ground via an optical trunkline between the other optical space terminal and OGS-2, or via an RF trunkline between the onboard HBRF terminal and the RF ground station. In this configuration, when a ground station (optical or RF) provides a trunkline, it also employs its UMS to function as the User MOC. Note that the optical and RF trunklines can operate simultaneously, if desired, allowing this experiment configuration to support numerous scenarios. If an experiment involves simultaneous RF and optical trunklines, the UMS at the RF ground station and the UMS at the optical ground station will be coordinated as the experiment requires.
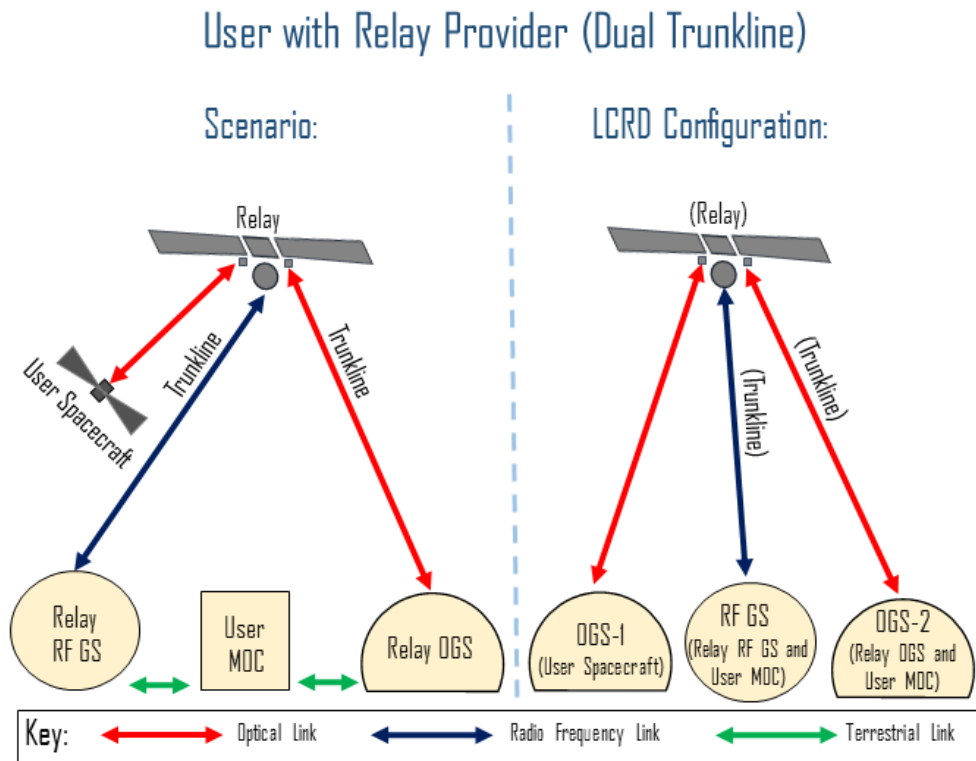

Figure 11. Example LCRD experiment configuration (depicted on the right) to simulate a scenario involving a single user spacecraft communicating with a relay provider (depicted on the left).

For example, this experiment configuration can be used to demonstrate that an optical relay using an optical trunkline could support a user spacecraft with specific characteristics. LCRD could simulate an Earth science mission expecting to generate a certain daily data volume by configuring the OGS-1 subsystems to simulate data from that particular user spacecraft. An optical trunkline would be established between an LCRD optical space terminal and OGS-2 (no RF trunkline is required in this particular experiment). To see if the required data volume can be achieved, the experiment would run for a given period of time, with the contact schedule determined by the expected orbit of the potential mission. In addition to determining the effects of weather on contact outages, the contact schedule could also be altered to show how the system behaves if the relay spacecraft is also supporting the communications needs of additional user spacecraft.

Another potential experiment that could be supported by the experiment configuration depicted in Figure 11 demonstrates whether the LCRD system can accommodate specific requirements for real-time data delivery. In this case, user data required in real time could be transported to/from Earth using the RF trunkline, while the remainder of the data is transported to/from Earth using the optical trunkline.

Potential relay users can also test optical communications systems—either in space or on the ground—to characterize their performance with the LCRD systems. During such an experiment, one of the LCRD optical space terminals would communicate directly with the user system, instead simulating the user with an OGS. (This scenario is not depicted in Figure 11.)

DIRECT-TO-EARTH (DTE) GROUND STATION PROVIDER

DTE ground station providers face the same challenges regarding space-to-ground optical links as relay providers, but for a DTE ground station provider the optical communication link is between the user spacecraft and the provider optical ground station. Like the relay providers, DTE providers will need to understand how factors such as the weather affect space-to-ground optical links, and will need to characterize the performance of their systems, determine how to optimize future systems, and determine the effectiveness of operational procedures.

To accomplish these objectives, DTE providers may wish to perform experiments similar to those described for relay providers, but instead of functioning as the relay spacecraft, the LCRD flight segment will function as the user spacecraft. In a DTE communications scenario, however, potential contacts with the user spacecraft are typically less frequent than in a relay scenario, and the length of time that the user spacecraft is in view of the ground station is quite short—usually on the order of minutes. An experiment configuration simulating a DTE ground station provider will feature a contact schedule that reflects the view periods typical of DTE users.

Figure 12 depicts one LCRD configuration that could be used to simulate a scenario where a DTE ground station provider is supporting more than one DTE

user spacecraft. In the scenario depicted on the left in Figure 12, the User 1 Spacecraft employs an optical link to exchange data with a provider's DTE optical ground station. As the User 1 Spacecraft moves out of view and the User 2 Spacecraft moves into view, the DTE optical ground station will conclude support to the User 1 Spacecraft and start providing support to the User 2 Spacecraft, according to a pre-defined contact schedule.

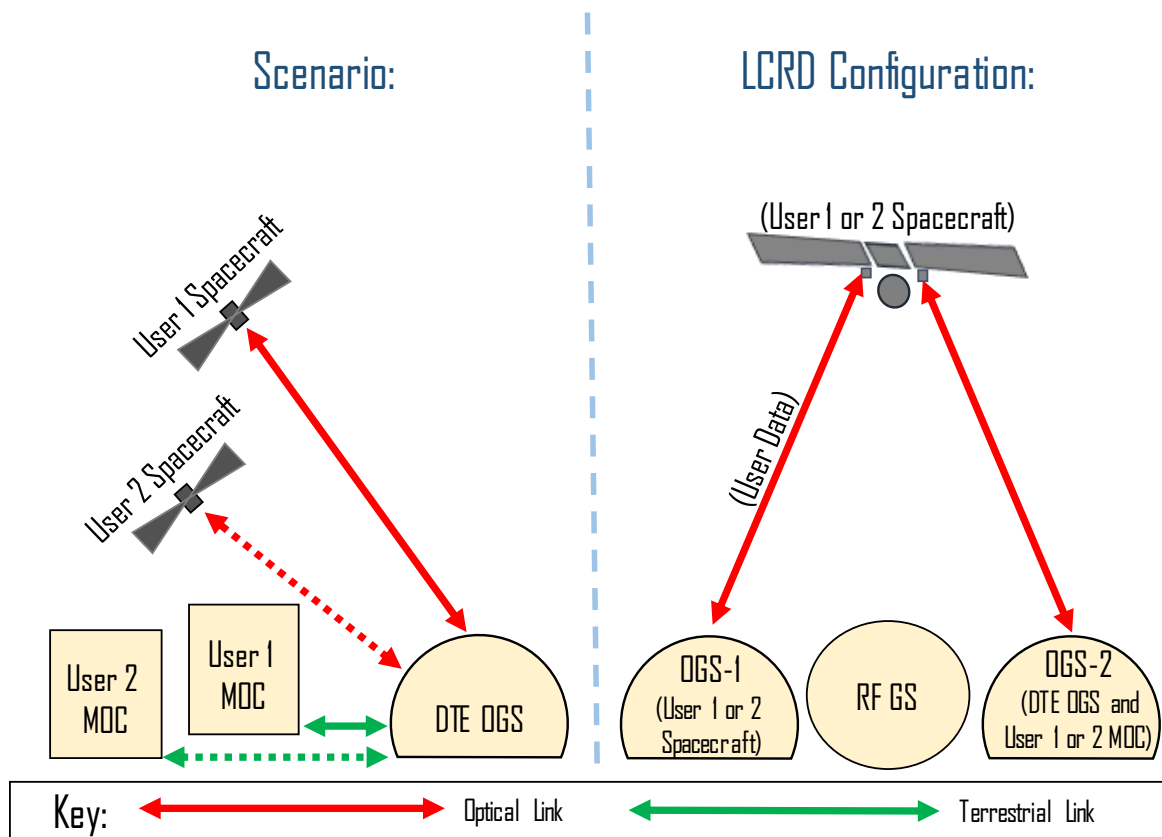## Direct-to-Earth Provider Supporting Multiple Users

Figure 12. Example LCRD experiment configuration (depicted on the right) to simulate a scenario involving a DTE ground station provider supporting multiple users (depicted on the left).

In the corresponding LCRD experiment configuration shown on the right, the user element simulators at the LCRD ground stations enable the LCRD system to simulate each user spacecraft and its MOC, according to an experiment contact schedule that includes support for both spacecraft. To simulate the scenario depicted on the left, the UPS at OGS-1 first generates simulated user data with the desired characteristics of the User 1 spacecraft. By exchanging data via optical uplink with one of the onboard optical space terminals, OGS-1 enables the LCRD flight segment to simulate the User 1 spacecraft. The LCRD flight segment uses

its other optical space terminal to exchange data via optical link with OGS-2, which functions as the provider's DTE ground station. OGS-2 also employs its UMS to function as the User 1 MOC. Then as the experiment's contact schedule dictates, the OGS-1 UPS stops generating User 1 Spacecraft data and starts generating data with the characteristics of the User 2 Spacecraft, enabling the LCRD flight segment to simulate the User 2 Spacecraft. OGS-2 continues to function as the provider's DTE ground station, but employs its UMS to function as the User 2 MOC.

In addition, if an experiment is independent of the data rate, DTE ground station providers may choose to execute an experiment configuration that employs an RF link between the onboard HBRF terminal and the RF ground station to exchange the data between the user and the ground. Such a configuration would enable one of the LCRD optical ground stations to be available for another purpose during the experiment.

As various experiments exercising different ground station subsystems are executed, the optical communications community will gain valuable data about optical DTE ground station operations that can be applied to future operations.

DTE USER

Like the relay user, the DTE user may wish to conduct experiments to demonstrate that optical communications can successfully be used for operations of a specific DTE user spacecraft. For example, a DTE user may wish to determine whether a mission with certain requirements (e.g., real-time data needs, etc.) can be successfully supported using two DTE provider ground stations. Although this experiment is limited, since the two LCRD optical ground stations are the only station locations available, the results may enable predictions about optical communications operations in similar situations.

The left image in Figure 13 depicts a scenario where two different optical ground stations are potentially available to support a DTE User Spacecraft. Either DTE OGS can support the DTE User, as long as an optical link is achievable and the station is available.

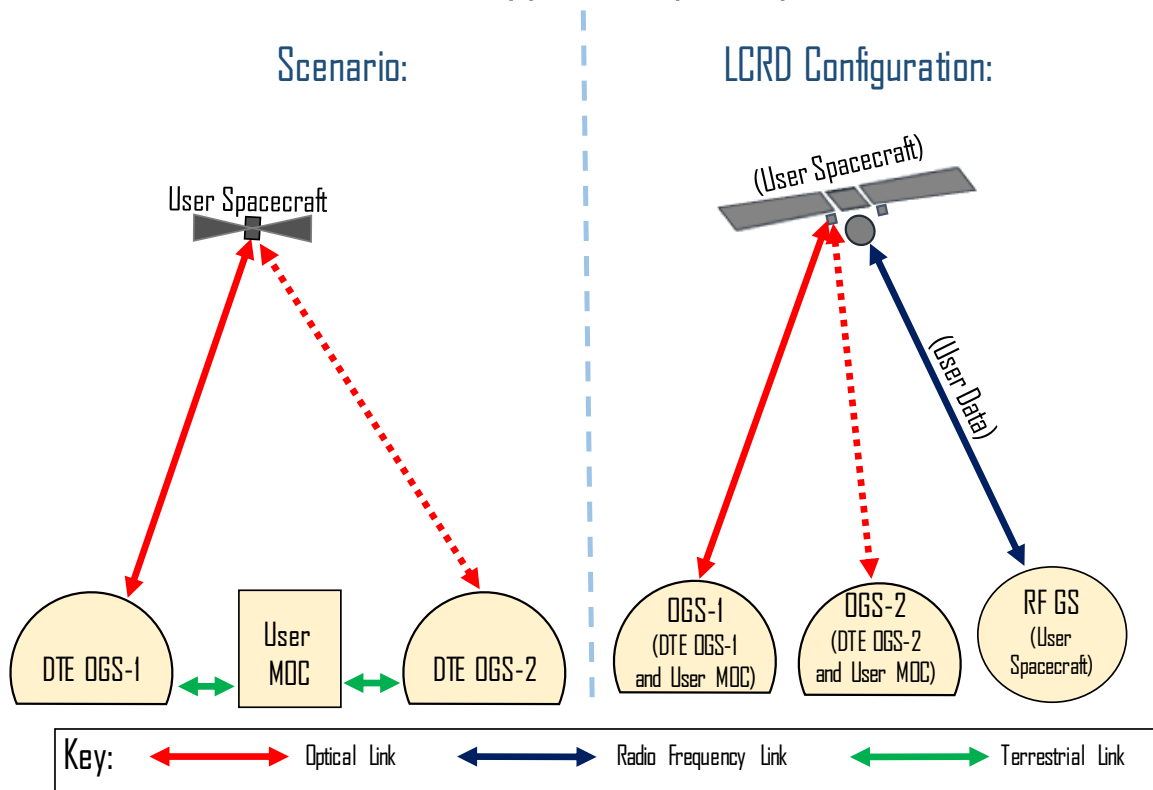# Direct-to-Earth User Supported by Multiple Ground Stations

Figure 13. Example LCRD experiment configuration (depicted on the right) to simulate a scenario involving a DTE user supported by multiple ground stations (depicted on the left).

In the corresponding LCRD experiment configuration shown on the right, the LCRD RF ground station enables the flight segment to function as the DTE User Spacecraft. The two LCRD optical ground stations provide support to the simulated DTE User Spacecraft according to the experiment contact schedule, which will depend on the available view periods, the predicted weather at each ground site, etc. To enable simulation of the DTE User Spacecraft, the UPS at the RF ground station generates simulated user data with the desired mission characteristics (view periods, data rates, types of data, etc.) and exchanges data via RF link with the onboard HBRF terminal. Functioning as the user spacecraft, the LCRD flight segment exchanges data via one of its optical space terminals with one of the optical ground stations (in this case, OGS-1), which functions as the DTE optical ground station. That optical ground station also uses its UMS to function as the DTE User MOC.

When the experiment contact schedule dictates support be provided by a different ground station, the LCRD flight segment exchanges data with the other LCRD optical ground station (in this case, OGS-2), which then assumes the roles of the DTE optical ground station and the DTE User MOC. To determine whether mission requirements can be successfully met using two stations in similar geographic

locations, a DTE user could run this experiment for a period of time, during which a typical variety of weather conditions could be experienced. The experiment contact schedule could also simulate a situation where one station is temporarily unavailable because it is committed to supporting other users.

LINK PERFORMANCE MODELER

LCRD will enable experimenters to determine how atmospheric parameters affect optical communications links. To investigate these effects, investigators can conduct experiments employing various LCRD configurations with different modulation schemes and data rates. During these experiments, the ACM system at an LCRD optical ground station will measure the relevant atmospheric observables, enabling experimenters to characterize the effects of atmospheric parameters on the optical links.

In addition to the LCRD relay and DTE experiment configurations previously described, experimenters can opt to use a loopback experiment configuration, as shown in Figure 14, to discern how atmospheric parameters affect optical links. In the loopback configuration, an LCRD OGS uses its user platform simulator to both generate and receive data, which is exchanged via optical link with an onboard optical space terminal.

Loopback Experiment

LCRD Configuration:

OGS-1   RF GS   OGS-2
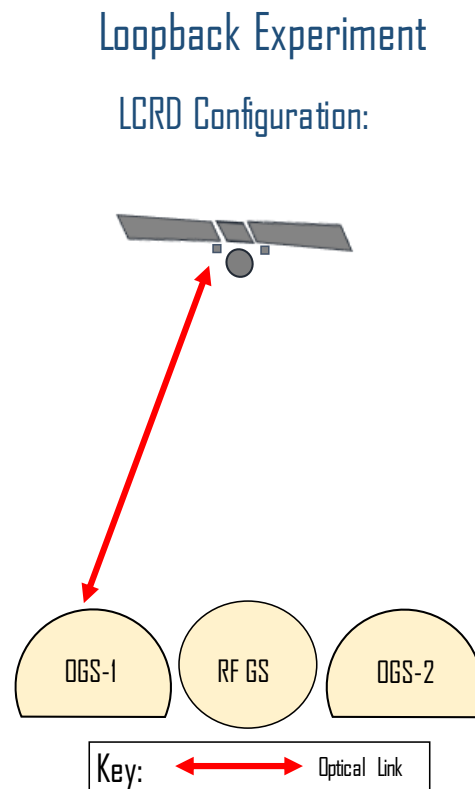
Key: ←——→ Optical Link

Figure 14. Example LCRD loopback configuration. The OGS-1 user platform simulator both generates and receives data, which is exchanged via optical link with an onboard optical space terminal.

LCRD experimenters will be able to investigate a wide variety of atmospheric effects by conducting experiments using the desired LCRD experiment configurations, modulation schemes, and data rates and then using data collected from the ACM system to correlate the network performance with the behavior of atmospheric parameters.

For example, to investigate the effect of optical turbulence on link performance, experiments can be conducted during daytime and nighttime and in different weather conditions to ensure a range of optical turbulence profiles are encountered. Using the ACM data collected during the experiments (e.g., r_0, wind speed, downlink fading), investigators can determine the effects of optical turbulence on the data reception at the optical space terminal and ground station.

In a similar manner, modelers could also investigate the effects of cloud optical depth on LCRD's optical links. For example, modelers could use time-stamped cloud optical depth obtained from ACM measurements and correlate the atmospheric attenuation of the optical signal with code word error rate (CWER).

Since ACM data are collected during any LCRD experiment, these types of experiments can be combined with other experiments that employ the desired LCRD experiment configuration, modulation scheme, and data rate.

OPTICAL COMMUNICATIONS TECHNOLOGIST

Experimenters may be interested in testing new hardware and software technologies in various LCRD experiment configurations (relay, DTE, or loopback) to determine how the technologies perform in an operational environment. Such experiments may include characterization of new or different coding schemes to determine their efficacy using a desired LCRD experiment configuration.

An Optical Communications Technologist could determine the effects of uplink beam parameters such as mispointing and divergence on CWER in various LCRD experiment configurations. To account for atmospheric variables during such an experiment, the experimenter could use data gathered by the ACM system. For example, the experimenter could cross-correlate CWER with the strength of the optical turbulence measured during intentional mispointing.

Likewise, experimenters could investigate the effects of modem hardware parameters (e.g., interleaver depths, adaptive optics update rate, bandwidth, etc.) on CWER. To account for interactions with the atmosphere along the optical channel during such an experiment, the experimenter could use data gathered by the ACM system. For example, the experimenter could cross-correlate CWER with optical turbulence measured while the interleaver depth is set to a minimum.

In addition, Optical Communications Technologists may wish to test interoperability and characterize the performance of systems or subsystems for future LCRD users or optical ground stations. For example, to test a user spacecraft modem design, an experimenter could install a candidate modem at an LCRD optical ground station to interface directly with the optical telescope

assembly (see Figure 4). Figure 15 depicts an example of such an experiment. The test modem is installed in OGS-1, which functions as the user spacecraft. OGS-1 employs its UPS to generate simulated user data, which is processed through the candidate user spacecraft modem on its way to/from the LCRD flight segment. The LCRD flight segment functions as a relay spacecraft and transmits data to/from the ground via an RF trunkline between the onboard HBRF terminal and the RF ground station. The RF ground station functions as the RF ground station and the user spacecraft MOC. To evaluate the performance of the candidate modem, an experimenter could execute the same experiment using the LCRD modem instead of the candidate modem and compare the results.

In addition, if an experimenter wishes to test the performance of an entire user platform (instead of a system or subsystem), a ground-based, air-based or spaceborne platform can function as the user spacecraft in the LCRD experiment configuration.

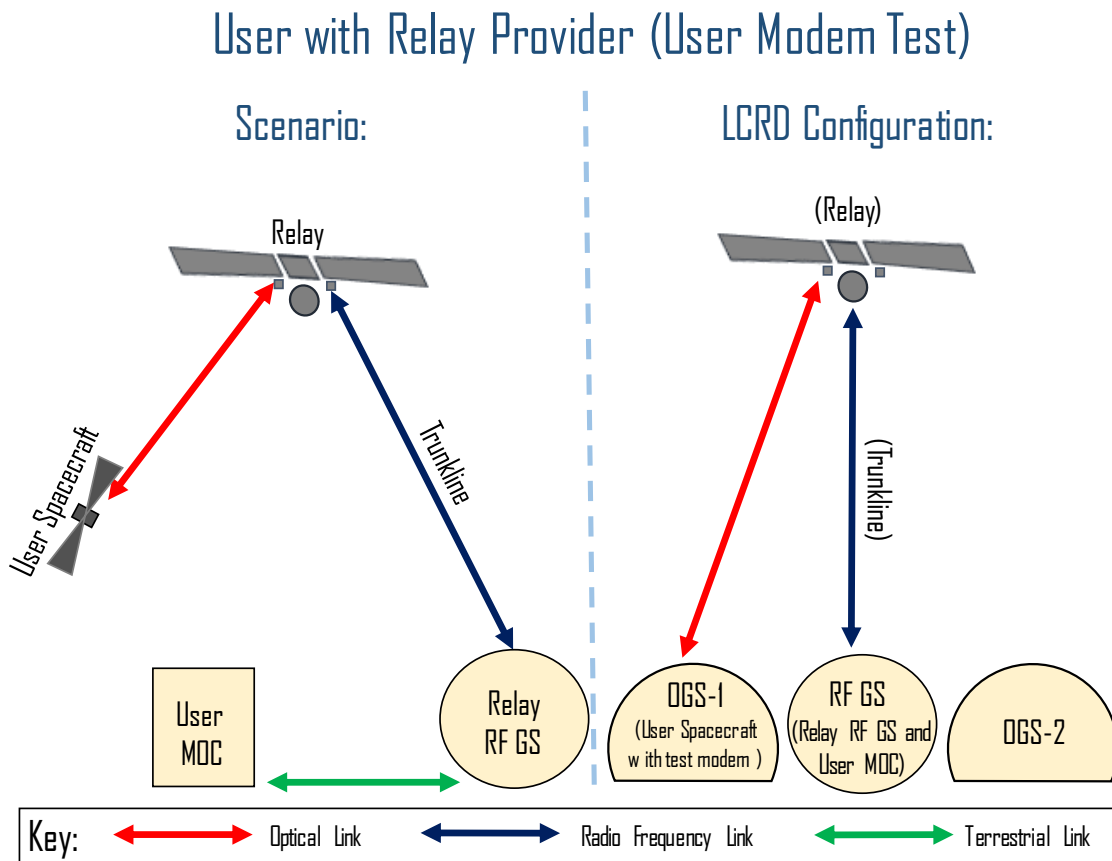## User with Relay Provider (User Modem Test)

Figure 15. Example LCRD experiment configuration (depicted on the right) to simulate a scenario involving a single user spacecraft communicating with a relay provider (depicted on the left). This experiment configuration enables testing and characterization of a candidate user spacecraft modem, which is installed at OGS-1.

THE PROPOSAL PROCESS

WHO CAN SUBMIT A PROPOSAL

The LCRD Project may accept experiment proposals from various sources, including academia, the commercial sector, and international parties. NASA may also establish partnerships with other domestic agencies for the purpose of conducting LCRD experiments. NASA is also capable of supporting LCRD experiments involving proprietary data, as needed. Experiments that require support beyond basic LCRD experiment coordination and operations will require external funding.

HOW TO SUBMIT A PROPOSAL

The LCRD Project will periodically solicit experiment proposals. Potential experimenters can find additional details about LCRD proposal requirements and the proposal process via the LCRD website (https://lcrd.gsfc.nasa.gov/). The LCRD team will be available to discuss LCRD interfaces and capabilities and help experimenters translate their goals into a potential experiment.

ONCE A PROPOSAL IS ACCEPTED

Once NASA accepts an LCRD proposal, a designated LCRD Experiment Coordinator will work with the experimenter to refine the proposal and ensure all required information is specified. The Experiment Coordinator will then establish a schedule for the activities required to successfully run the experiment, including any preparation or equipment installation activities. Experimenters can also arrange to observe the experiment execution from the LMOC-E at GSFC or from another location, as appropriate. Once the experiment has concluded, NASA will provide the experimenter with data related to the experiment, as specified in the proposal.

REFERENCES AND ADDITIONAL SOURCES OF INFORMATION

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ABBREVIATIONS AND ACRONYMS

Acronym	Definition
ACM	Atmospheric Channel Monitoring
BIT	Built-in Test
CODEC	Coder/Decoder
CWER	Code word error rate
DPSK	Differential Phase Shift Key
DTE	Direct to Earth
FEC	Forward Error Correction
GEO	Geosynchronous Earth orbit
GS	Ground Station
GSFC	Goddard Space Flight Center
HBRF	High-bandwidth Radio Frequency
JPL	Jet Propulsion Laboratory
LCRD	Laser Communications Relay Demonstration
LEO	Low Earth Orbit
LMOC	LCRD Mission Operations Center
LMOC-E	LCRD Mission Operations Center Extension
Mbps	Megabits per second
MITLL	Massachusetts Institute of Technology Lincoln Laboratory
MOC	Mission Operations Center
NASA	National Aeronautics and Space Administration
OCTL	Optical Communications Telescope Laboratory
OGS	Optical Ground Station
OST	Optical Space Terminal
PI	Principal Investigator
PPM	Pulse Position Modulation
RF	Radio Frequency
r_0	Atmospheric coherence length
SSU	Space Switching Unit

Acronym	Definition
STMD	Space Technology Mission Directorate
STPSat-6	Space Test Program Satellite-6
UMS	User MOC Simulator
UPS	User Platform Simulator
USG	User Services Gateway
WSC	White Sands Complex