National Aeronautics and
Space Administration

Early Results from the LCRD Experiment Program

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Goddard SPACE FLIGHT CENTER
JPL

Agenda

- LCRD Background and Description
- Experiment and Availability Statistics
- Day-in-the-Life Performance
- Experiments to Date
- Upcoming Experiments
- Summary

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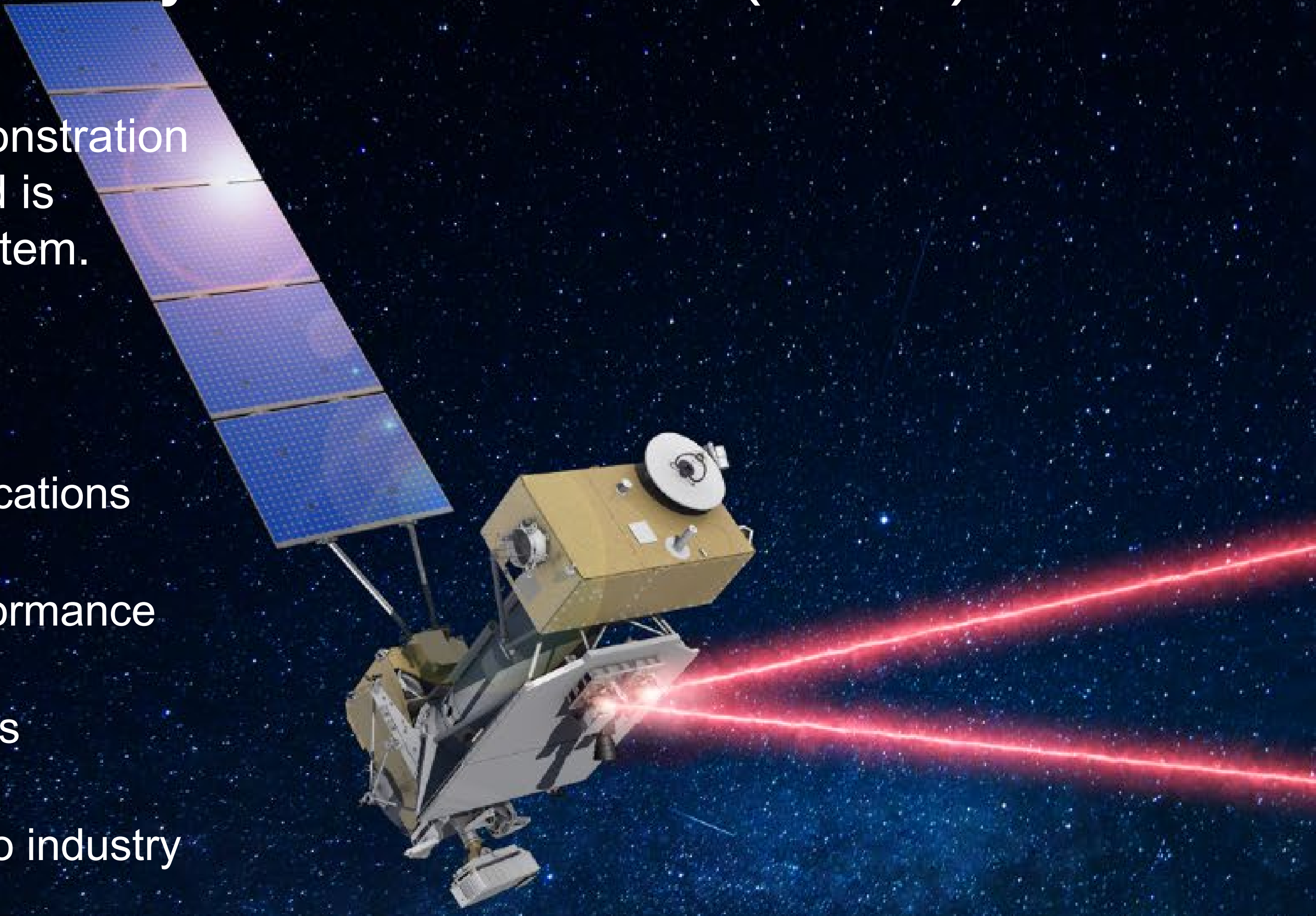
The Laser Communications Relay Demonstration (LCRD)

NASA's Laser Communications Relay Demonstration (LCRD) launched on December 7, 2021 and is NASA's first laser communications relay system.

LCRD Objectives:

- Demonstrate bidirectional optical communications between GEO spacecraft 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
- Provide an on-orbit capability for test and demonstration of standards for optical relay communications



LCRD on STPSat-6

The U.S. Space Force Space Test Program Satellite 6 (STPSat-6) is hosting LCRD, 22,000 miles from Earth in geosynchronous orbit.

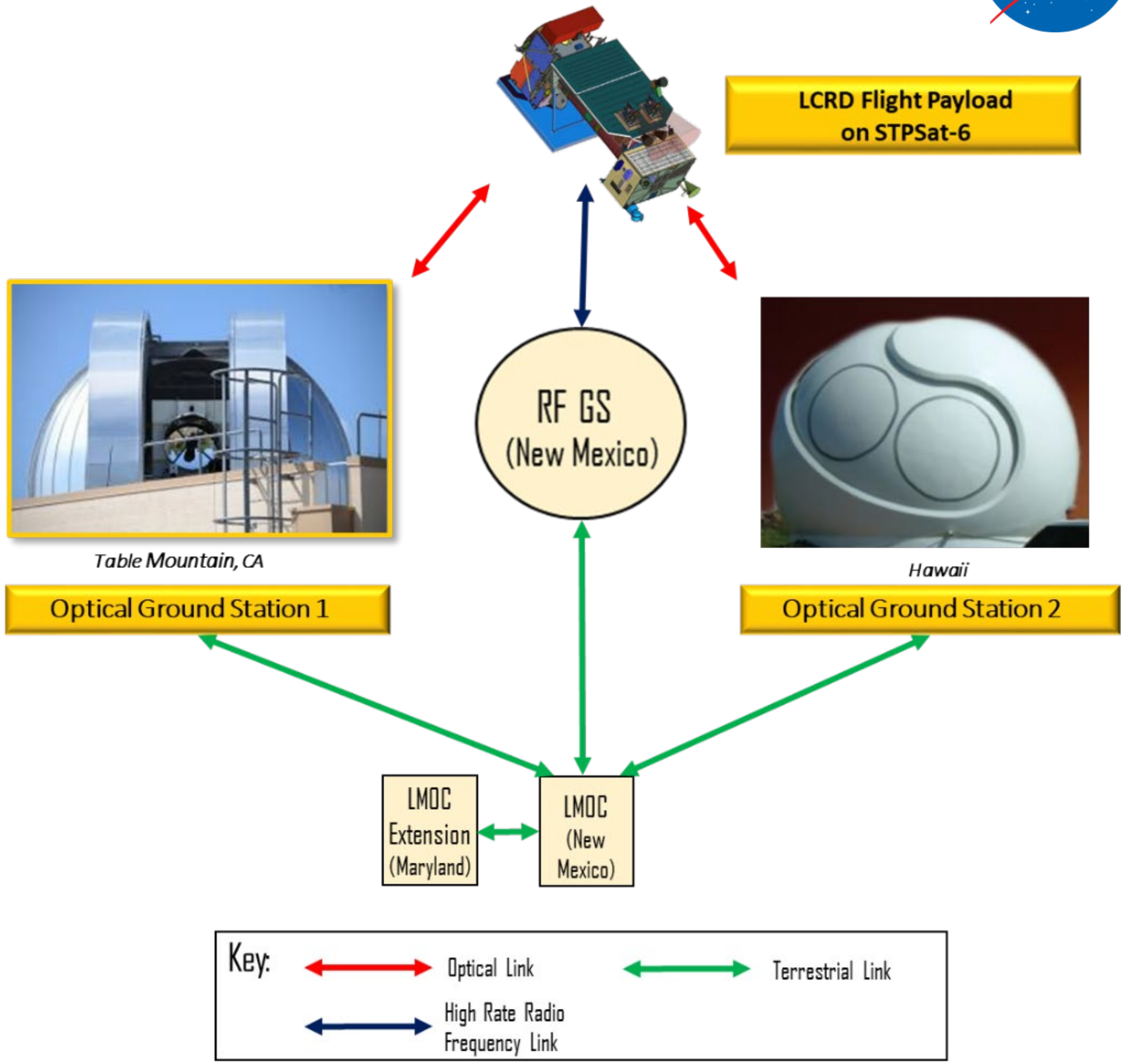
The payload will support missions in the near-Earth region, including the International Space Station.

LCRD, like many NASA missions, was created and planned by numerous partners, including:

- Massachusetts Institute of Technology – Lincoln Laboratory
- Northrop Grumman
- U.S. Space Force
- United Launch Alliance
- NASA's Jet Propulsion Laboratory

LCRD Mission Architecture

- LCRD Flight Payload onboard the Space Test Program Satellite-6 (STPSat-6)
  - Two optical space terminals, OST1 and OST2, capable of simultaneous operation.
  - A high bandwidth RF system
  - Onboard data switching
- LCRD Ground Segment
  - Two optical ground stations (Optical Ground Station 1, or OGS-1, and Optical Ground Station 2, or OGS-2)
  - Radio Frequency Ground Station (RF GS)
  - LCRD Mission Operations Center (LMOC)
  - LMOC Extension (LMOC-E)



LCRD Experiments Overview

- The LCRD Experiment Program began on June 10, 2022
  - The high priority experiments will demonstrate technology readiness for operational optical communications systems
    - Laser Communications Link and Atmospheric Characterization
    - Relay operations
    - Optical-based Networking Services
  - Other Experiment Include
    - Development of operations efficiency (handover strategies, more autonomous ops, etc)
    - Planetary/Near-Earth Relay scenarios (additional delays, reduced data rates, non-continuous trunkline visibility
    - Low Earth Orbit (LEO) - real or simulated
    - User-to-User Relay
    - Direct Uplink/Downlink
    - Commercial applications
- LCRD Introduction for Experimenters document describes experiment types as an introduction for the Guest Experimenter Program

- **Total of 56 experiments have been proposed and 45 are under consideration and development so far.**

LCRD Experiments

NASA & Co-I

Operational Pathfinder

- Data services using optical comm
- Disruption/Delay Tolerant networking
- Navigation: Using the optical comm beam to aid orbit determination
- Planetary delay and low optical power simulation
- Relay comm with LEO terminals
- Comm with alternate ground terminals

Qty: 10

Characterization

- Optical Comm in the atmosphere
- Optical Comm in the presence of clouds
- Pointing, Acquisition and Tracking (PAT)
- Link Budget Verification and Validation
- Off-nominal network Configurations
- Variable Beacon
- Forward Error Correction (FEC) and Interleaver Parameter study

Qty: 21

Partnerships

Commercial

- Networking
- Uplink Fade Modelling
- Adaptive Link Rates
- Atmospherics at Optical Ground Station (OGS-2)
- Novel multi-mode receiver test

OGA/ University

- Machine Learning for Bit Decoding
- Deep Learning for Data rate reduction
- Large File Transfer
- Balloon terminal
- Laser Guidestar

Qty: 14

Total Experiment Quantity: 45

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LCRD System Availability

	Online Availability Percentage (Overall)	Online Availability Percentage (Planned)	Offline Availability Percentage (Overall)	Offline Availability Percentage (Planned)	24 Hr Availability Percentage (Overall)	24 Hr Availability Percentage (Planned)
Total Payload Availability	98.21	99.71	99.62	100.00	99.19	99.91
Total GS availability	77.70	92.22	90.04	94.42	86.05	94.05
Total OGS Availability	67.29	88.59	86.00	92.48	79.93	91.72

- System Availability statistics collected to capture the availability of the major LCRD subsytems
  - Statistics gathered from daily availability logs
- Total Payload Availability
  - Availability of LCRD payload
- Total GS Availability
  - Availability of OGS1, OGS2 and the RFGS
- Total OGS Availability
  - Availability of OGS1 and OGS2

- Overall/Planned
  - Overall: Anytime that LCRD could not support a contact
  - Planned: When LCRD is planned to operations, but could not support a contact
- Online/Offline/24 Hr Availability
  - Online: LCRD is staffed and can operate
  - Offline: LCRD is unstaffed, but could have been operated
  - 24 Hr: Both online and offline availabilities

LCRD Experiment Statistics

LCRD Experiment Operations Statistics Master Report Table											
	Data					LCRD Experiments					
Time Frame	First Date	Last Date	First DOY	Last DOY	Calendar Days Included	Cancelled	ANS Weather	ANS Technical	Contingency	Executed	Scheduled
Total	6/10/22	01/01/23	161	366	206	103	48	26	32	352	561

- Experiment statistics collected to capture the disposition of scheduled experiments
  - Provide some indication as to reason experiments were not run
- Statistics gathered from daily activity logs
  - Generated by operations team during experiment operations activities
- LCRD Experiment Categories
  - Cancelled: Experiment was not attempted
  - ANS Weather: Attempted Not Successful (ANS) due to weather
- Categories (con't):
  - ANS Technical: ANS due to a technical issue somewhere in the system
  - Contingency: Experiments scheduled when part of the system is unavailable
    - i.e. during a relay contact when one OGS is occluded due to weather
  - Executed: Experiment completed and data collected for more than 10 minutes
  - Scheduled: Total number of the experiments planned

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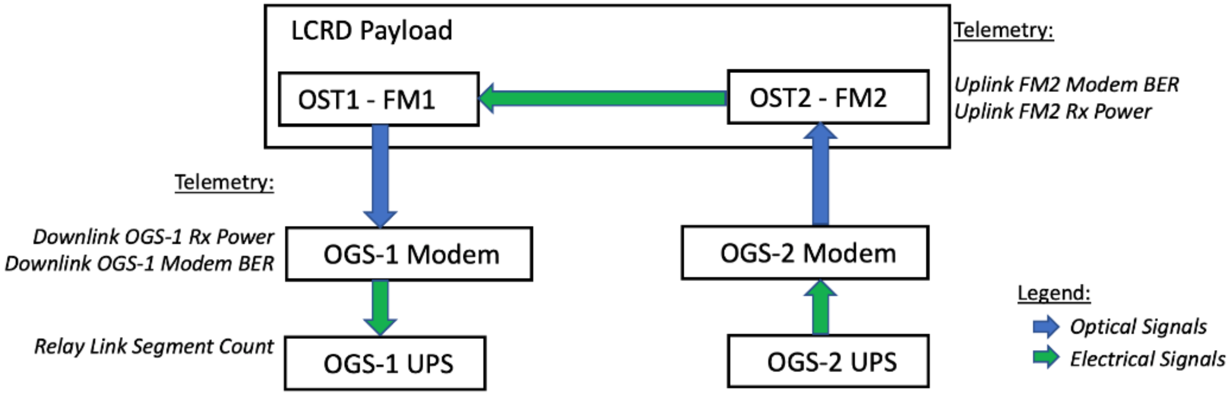
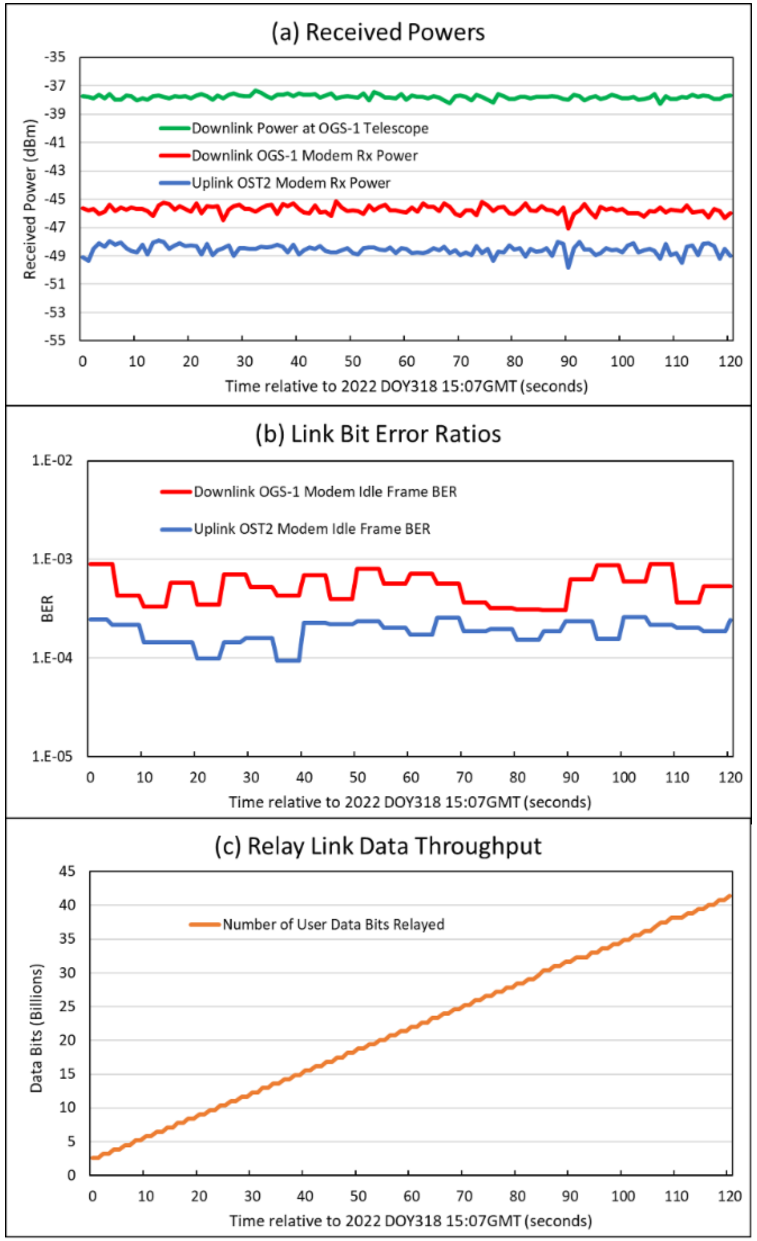
LCRD Day in the Life Performance (1 of 2)



- Day in the life performance of LCRD system
  - Relay experiment run on day of year (DOY) 318 in 2022
- Link Start
  - OGS-2 User Platform Simulator (UPS)
- Payload Path
  - Uplink received at OST2-FM2
  - Demodulated & header refreshed digital data passes across SSU high-speed switch
  - Downlink sent from OST-FM1
- Link Termination
  - OGS-1 UPS

LCRD Day in the Life Performance (2 of 2)



- Communications performance of LCRD on a typical day when the weather is favorable (DOY 318 in 2022)
- Received Powers (a) Plot
  - Received powers at the OST2 Flight Modem #2 (FM2), the OGS-1 telescope and the OGS-1 modem
  - Received powers at the payload and OGS-1 are sufficient for the modems to achieve frame lock and demodulate the signals
  - The power difference measured at the OGS-1 telescope and the OGS-1 Modem indicate the total losses in the OGS-1 ground station
- Link Bit Error Ratios (b) Plot
  - Uplink channel bit error ratio (BER) at OST2-FM2 and the downlink channel BER at OGS-1
  - The channel BERs on both relay links are sufficient for the Interleaver & FEC to decode the data at the receiving (OGS-1) ground station
- Relay Link Data Throughput (c) Plot
  - Number of data bits transmitted across the relay
  - Data volume: 40 Gigabits
  - Duration: 2 Minutes

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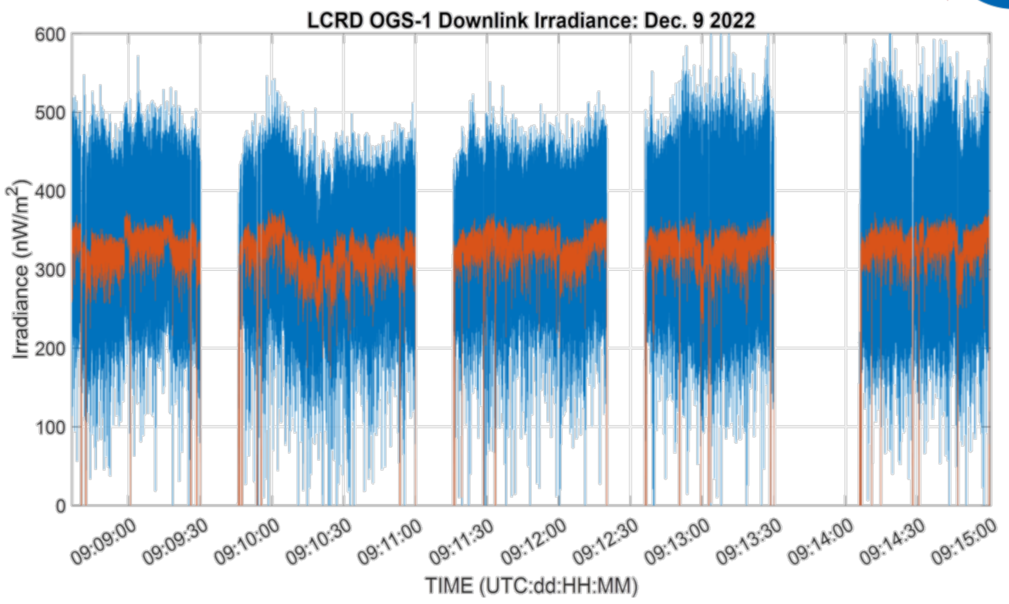
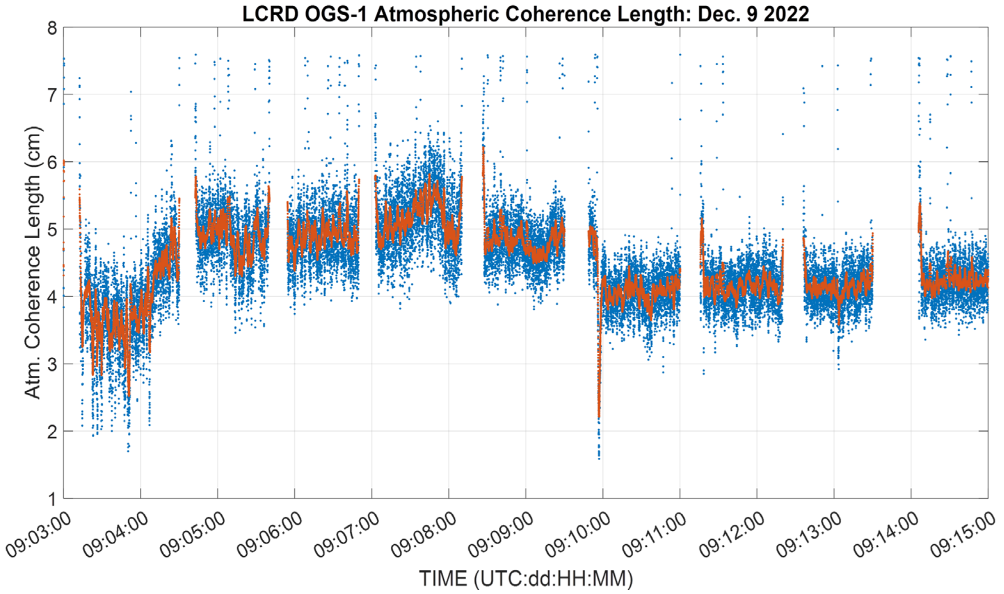
LCRD Exp: Optical Turbulence Characterization

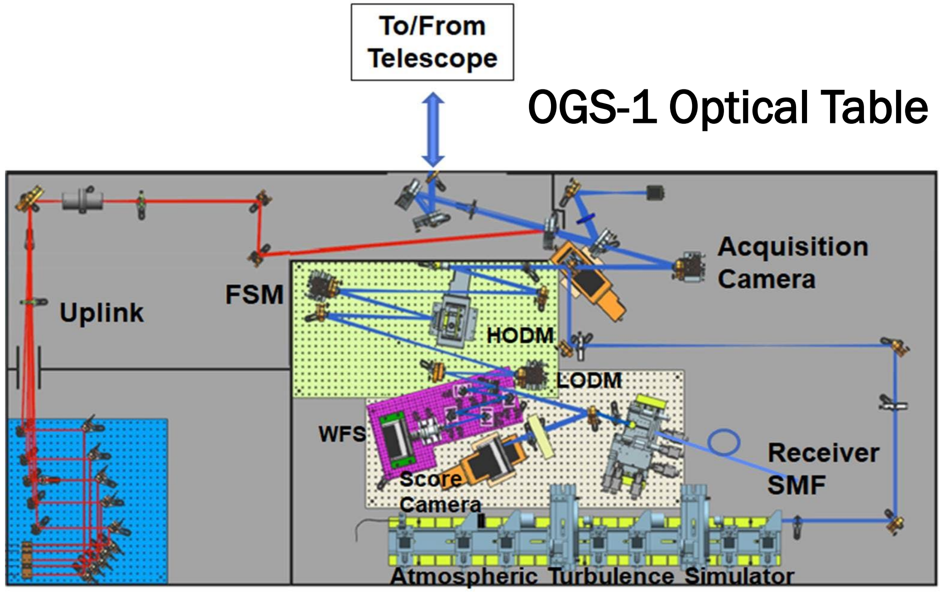
- Atmosphere Optical Turbulence strength affects the quality of the downlink and uplink optical beam
  - Downlink: fading, aberration
  - Uplink: fading, atmospheric Strehl loss
- Experiment to characterize the effects of optical turbulence at OGS-1 and OGS-2 are ongoing
- Optical Turbulence strength is measured at OGS: **atmospheric coherence length**, **high rate downlink irradiance**, uplink/downlink signal strength
  - Data are reported and archived
  - Considered all the link configurations: optical relay link, loopback link, direct to earth
- Effects on the quality of the link are observed anc correlated with link parameters including BER, CWER, optical signal strength, and fading

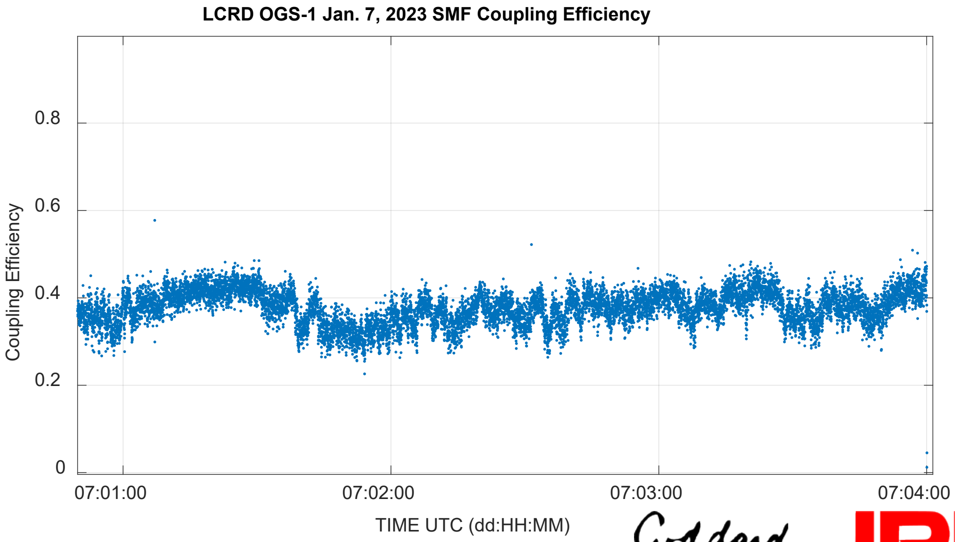




LCRD Exp: Adaptive Optics Optimization

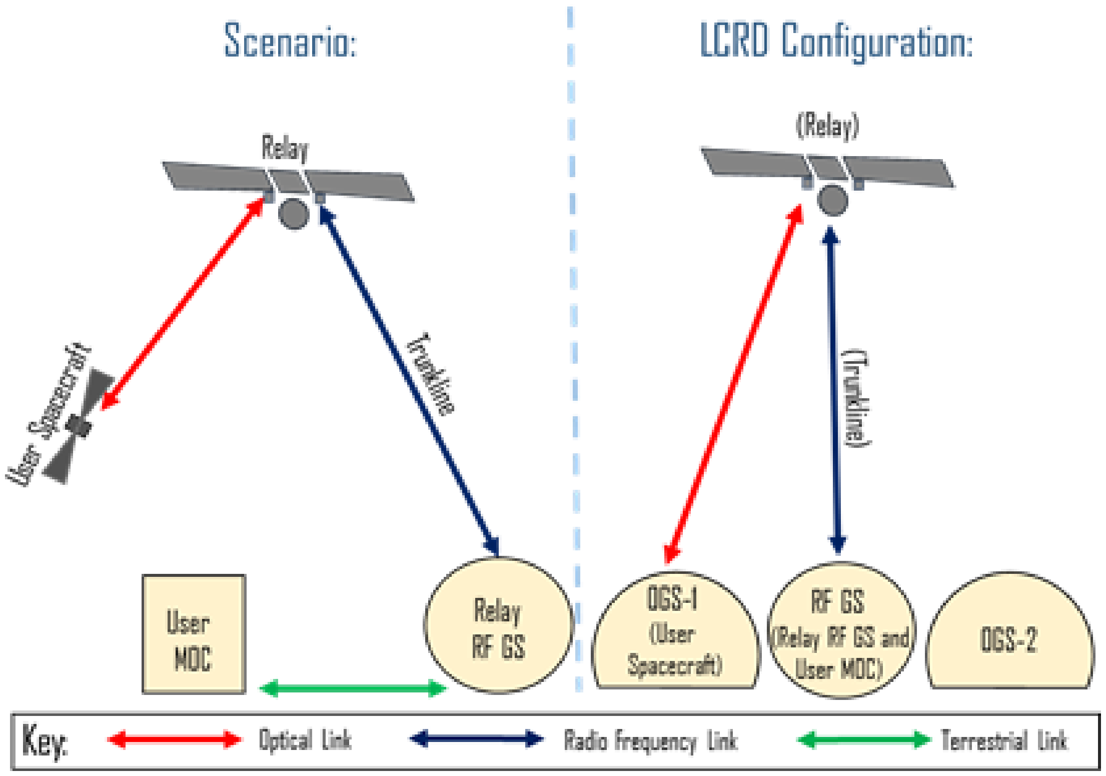
- OGS-1 and OGS-2 include adaptive optics (**AO**) systems
  - Compensate for atmospheric aberration originating from optical turbulence
  - Couple downlink signal into receiver Single Mode Fiber (**SMF**)
- Figure of merit of AO is the efficiency of the coupling of the downlink signal into the receiver SMF
  - Coupling efficiency is the ratio between the optical signal after and before the coupling into the SMF
- Experiments are run under different 1) optical turbulence strengths 2) different times of the day and season 3) different optical link configurations
  - Relay Link, Loopback link, Direct to Earth link
- AO is tuned to optimize coupling efficiency by varying
  - Wave front sensor (**WFS**) frame rate
  - Fast steering mirror (**FSM**) gain
  - High Order and Low Order Deformable mirrors (**HODM** and **LODM**) gains





LCRD Exp: Data Services using Optical Links

- LCRD flight payload and ground systems emulate operational relay scenarios
  - One OGS performs the role of one or more LCRD users, receiving and transmitting an optical forward and return link respectively from the LCRD flight payload
  - The trunkline to the relay is either over RF to the RF Ground Station or over an optical trunkline to the other OGS.
  - Each ground location includes a User Platform Simulator (UPS) and a User Mission Operations Center (MOC) Simulator (UMS), each capable of providing the functionality of the data endpoints
  - Metrics collected include data completeness and proficiency (service received/service scheduled).
- Following the initial demonstrations, these experiments will be scheduled and executed in a manner more closely aligned to true operational supports.
  - LCRD systems and operations team will experience multiple “Days in the Life” of an operational optical relay provider.
- LCRD has run 229 successful data service test cases focusing on RF-to-optical relay, OGS loopback, and Direct-to-Earth configurations.
  - Optical-to-optical relay data service test cases are planned for the near future.



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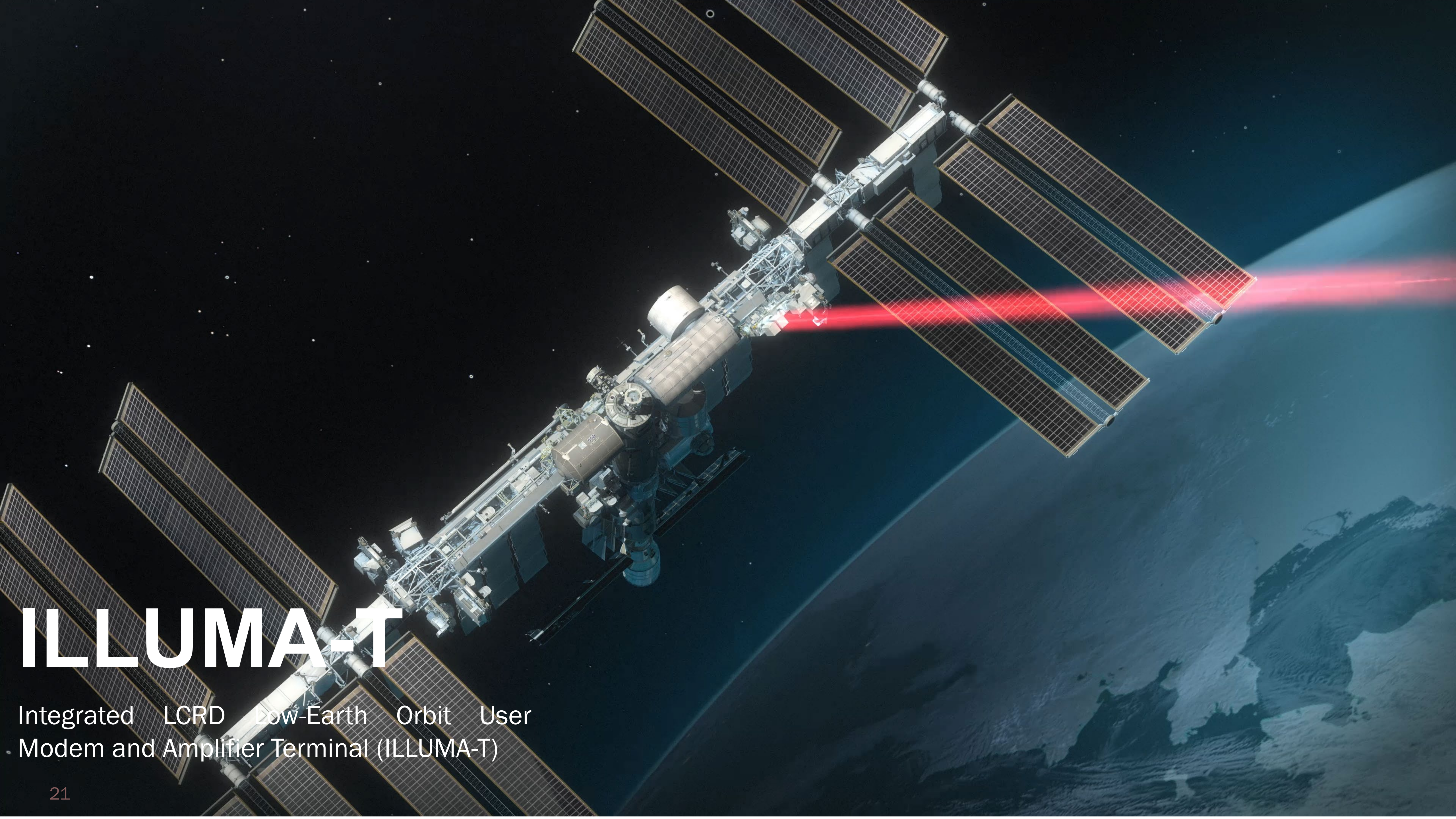
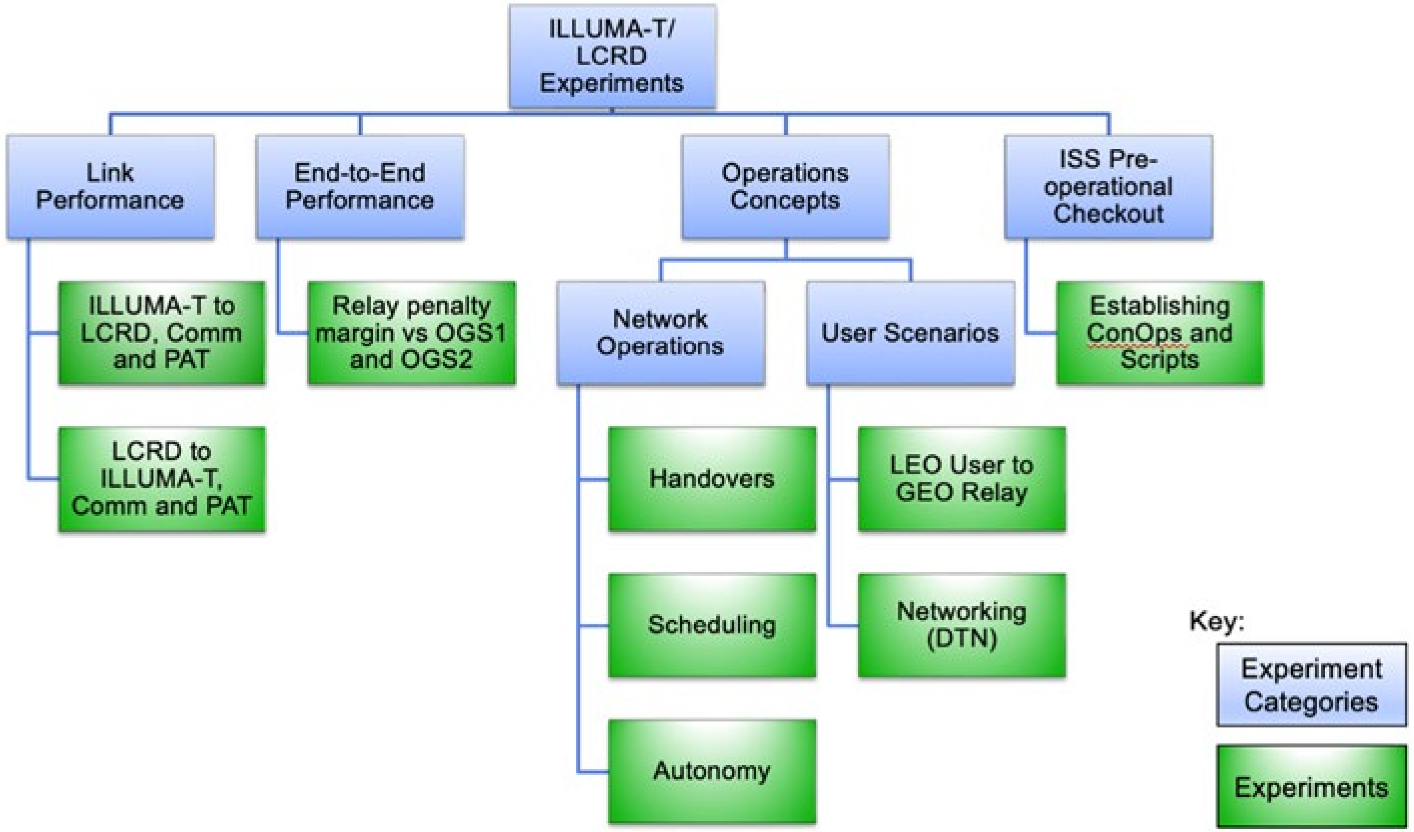


ILLUMA-T

Integrated LCRD Low-Earth Orbit User Modem and Amplifier Terminal (ILLUMA-T)

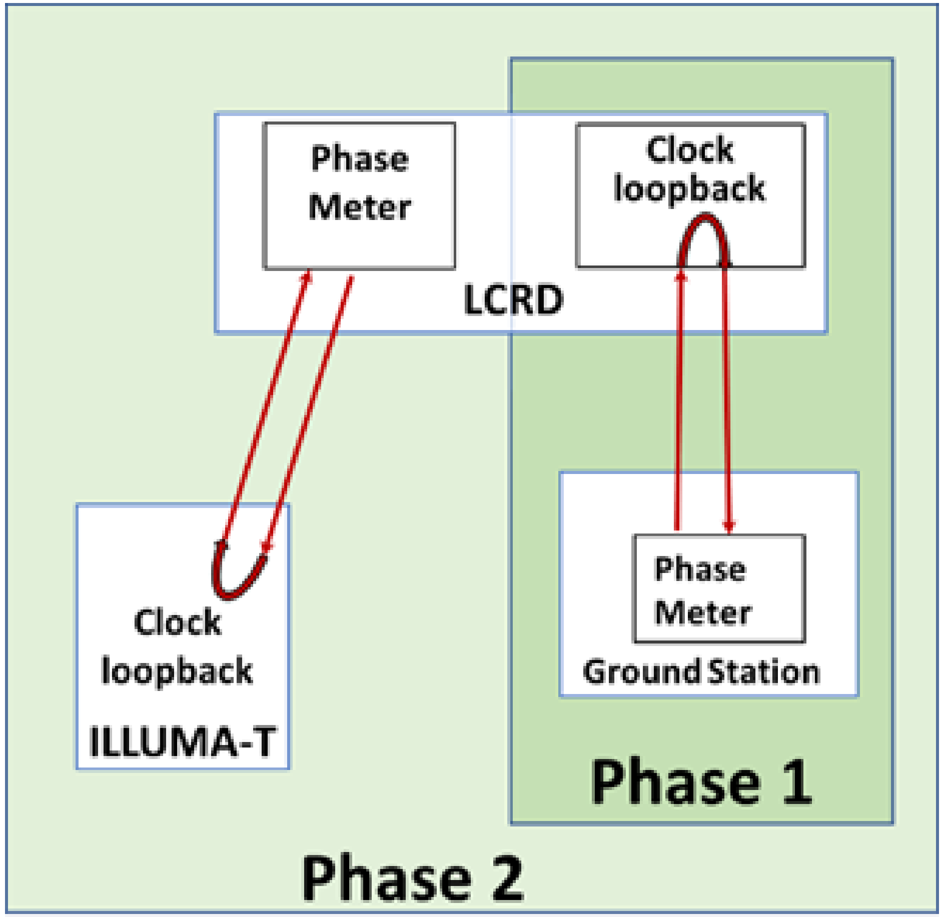
LCRD Exp: ILLUMA-T

- ILLUMA-T is scheduled to launch in 2023 for six months on the ISS
- LCRD support of ILLUMA-T will demonstrate the capabilities of an optical terminal for communications and navigation for a user in low earth orbit.
  - Return rates up to 1.244 Gbps
  - Forward rates of at least 51 Mbps
- ILLUMA-T experiments are grouped into several categories
  - *Link Performance* and *End-to-End Performance*: focus on the pointing, acquisition, and tracking between an orbiting user and a GEO relay and the performance of the links
  - *Operations Concepts*: extension of the data services experiments to include an actual orbiting user
  - *ISS Pre-operational Checkout*: Series of tests and training activities will occur to enable ILLUMA-T optical communications for operational use, if desired



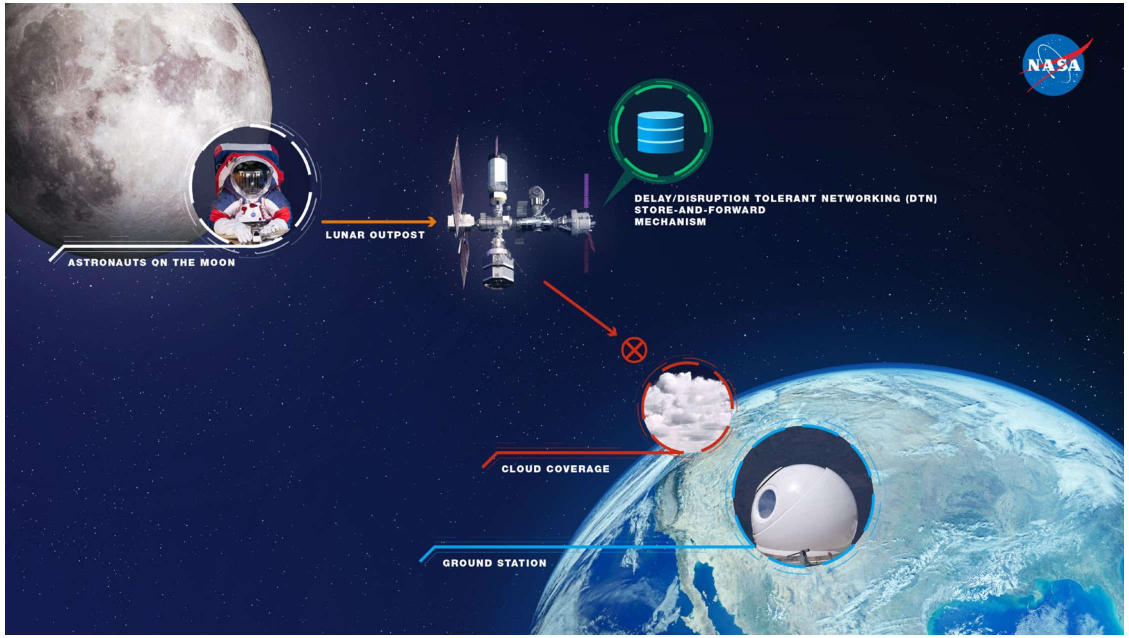
LCRD Exp: Optimetrics

- Optical links may be capable of providing tracking data (range and range rate) that is orders of magnitude more accurate than tracking data provided by RF links
- LCRD optimetrics experiments will be performed in two phases
  - LCRD flight modem will perform a coherent clock loopback on a bidirectional link with OGS-1
  - The ILLUMA-T modem will also provide a coherent clock loopback, enabling the first optimetric measurements through an optical relay to an orbiting user



LCRD Exp: Delay Tolerant Networking (DTN)

- Delay/Disruption Tolerant Networking (DTN) is a network architecture approach for networks with links subject to long and variable propagation delays and networks lacking continuous connectivity of nodes.
- LCRD provides an opportunity to explore approaches and infrastructure for enabling DTN in future operational lasercom networks
- DTN Experiment goals include measuring speed/reliability, implementing DTN Network Management (NM) capabilities, and preparing for operational DTN services
- This LCRD experiment is divided into several phases
  - Transfer of bundles between two DTN nodes over the LCRD links, and capture information about the quality of the data transfer using Bundle Protocol version 6 (BPv6)
  - Testing with multiple implementations of Bundle Protocol, including Bundle Protocol version 7 (BPv7)
  - Inclusion of more DTN protocols, such as convergence layers, security, and network management
  - Experiments will connect the LCRD links to NASA-controlled cloud-based DTN node
  - Subsequent experiments will pursue connection to broader DTN test networks
    - Existing nodes at other NASA centers
    - Nodes external to NASA
    - Once ILLUMA-T is on-orbit, the DTN experiments will include nodes onboard the ISS



Example future scenario illustrating DTN usage with an optical link

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Summary

- The two-year LCRD Experiment Program began in early June 2022
- As NASA's first mission to specify, build, launch, and operate an optical communications relay, the full experiment really started with the initial proposal.
  - Many lessons learned and experiences before launch
  - On-orbit experiments are yielding both experiment data and operational experience
- As the data continues to be collected, and as planned experiments occur, individual papers dedicated to specific experiments and results shall be published
- This collection of results concerning all aspects of optical relay performance and operations will be of great value as NASA and others plan to incorporate optical communications links into their future systems