National Aeronautics and Space Administration

Insights and Observations From Operating a Geostationary Laser Communication Relay Mission: Operational Lessons from NASA's Laser Communications Relay Demonstration and Associated Optical Ground Stations

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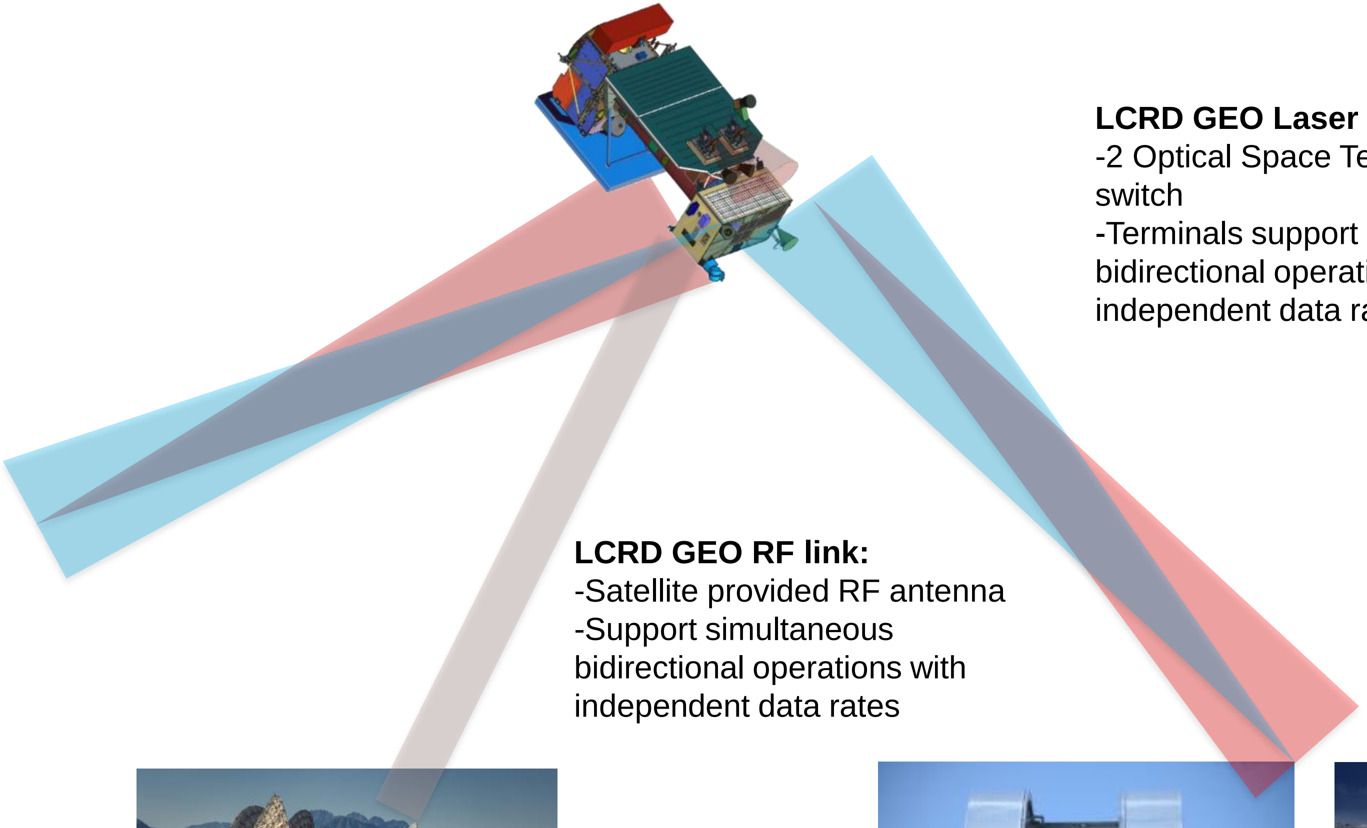
LCRD Mission Background

- LCRD is a technology demonstration mission and is NASA's first end-to-end laser communication relay
- The LCRD payload is hosted on a GEO spacecraft and includes two Optical Space Terminals and a data interconnect switch; the spacecraft provides an RF link
- LCRD mission is supported by two Optical Ground Stations, located on Table Mountain, California and Haleakalā, Hawai'i and a RF ground station in New Mexico

LCRD Laser and RF Network



LCRD GEO Laser links:
-2 Optical Space Terminals and data switch
-Terminals support simultaneous bidirectional operations with independent data rates

LCRD GEO RF link:
-Satellite provided RF antenna
-Support simultaneous bidirectional operations with independent data rates

ILLUMA-T and ISS

- ILLUMA-T installed on the ISS (Nov 2023-June 2024)
- Downlink information rate up to DPSK up to 1.24 Gbps, Uplink rate up to 155 Mbps

NASA-WSC

- RF Ground Station located at NASA's White Sand's Complex (NM)
- Ka-band Downlink information rate up to 622 Mbps

OGS-1

- OGS-1 located at NASA/JPL's Table Mountain Facility (CA)
- Uplink/Downlink information rate DPSK up to 1.24 Gbps; PPM up to 311 Mbps
- Operated by JPL

OGS-2

- OGS-2 located at Haleakalā, Maui (HI)
- Uplink/Downlink information rate up to 1.24 Gbps DPSK

Approach on Lessons Learned

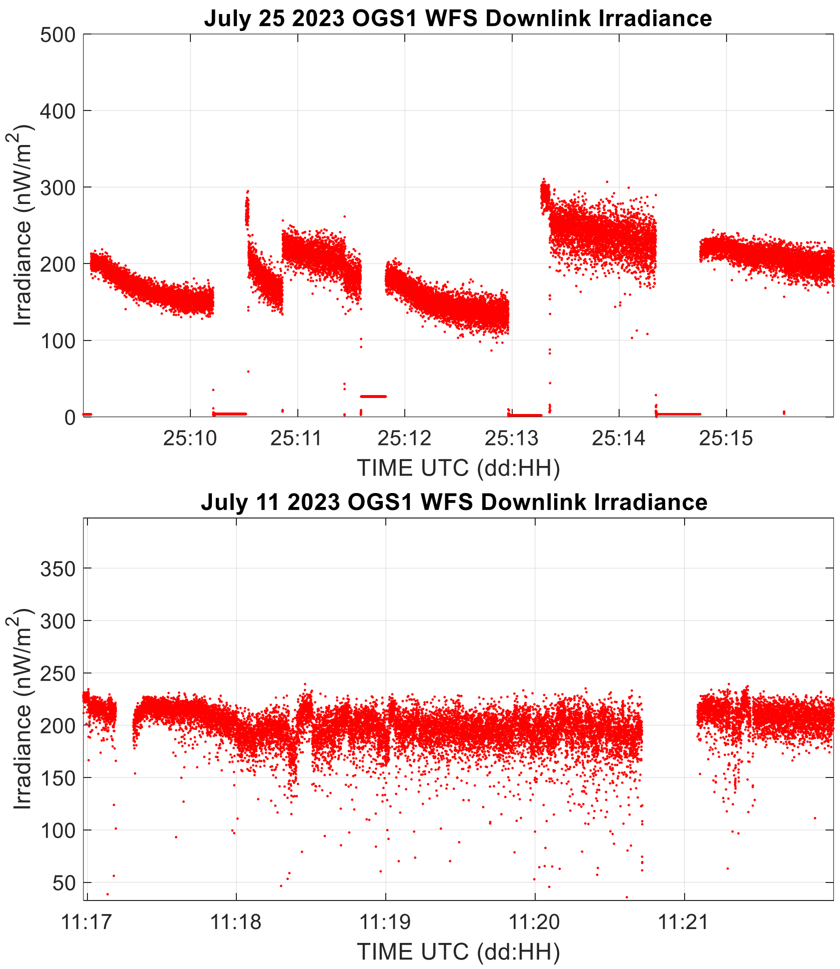
- Operational lessons come from the experiences of the LCRD operations teams during day-to-day operations
  - These lessons may help drive Mission Operational Concepts and processes for projects considering using laser communication
  - We note differences in operations between laser and RF communication systems where appropriate
- Lessons cover
  - Operational Activities
    - Differences in operational processes and adjustable parameters between laser and RF communication systems
  - Payload System Troubleshooting Activities
    - A series of common troubleshooting steps used for Laser Communication
  - LCRD Ground System Lessons and Operational Considerations
    - Space-to-ground links and ground station operational availability

LCRD Operational Activities –Ephemeris Generation

- LCRD ephemeris generation cadence
  - Ephemeris data needs to be up to date, and terminal clocks need to be well-synchronized
    - Narrow laser beamwidth requires more accurate ephemeris than is needed with an RF system
  - LCRD orbit determination (OD) is performed daily
    - This cadence is much more rapid than usually required for RF systems.
    - Link acquisition performance drops the older the ephemeris gets
  - Post-maneuver ODs can take greater than 12 hours for GEO satellites
    - During the time between maneuver and OD, LCRD is drifting away from the pre-maneuver orbit, which can cause missed contacts.
    - Some ephemeris products contain the predicted maneuver information, and it is recommended to use these products
- Loading target ephemeris (for both flight and ground terminals)
  - LCRD pointing files are updated daily

LCRD Operational Activities –Thermal Control

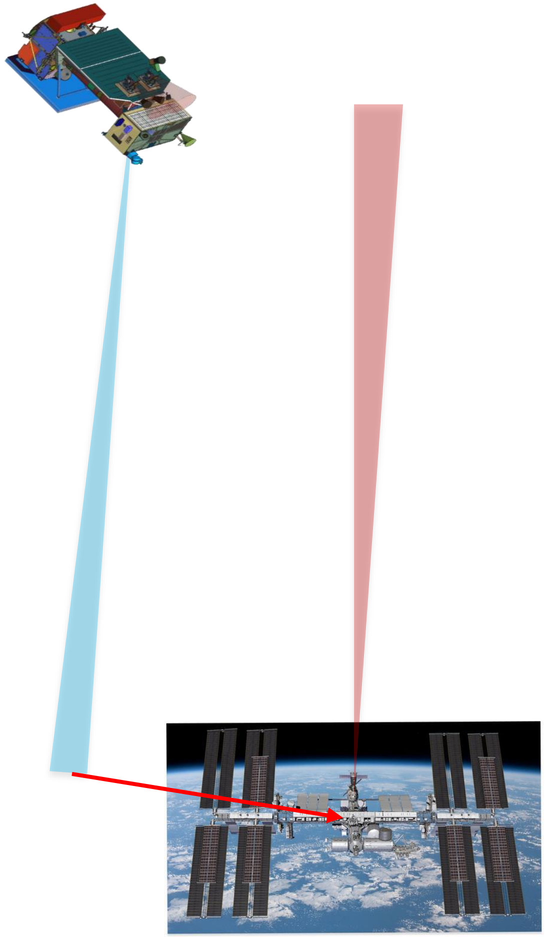
- LCRD payload performance is greatly impacted by temperature variations
  - Maintaining a narrow operational range on the satellite baseplate heaters minimizes bus thermal impacts on the Optical Module
  - Excursions of only a few degrees outside of calibrated range can affect:
    - Wavelength drift, which impacts signal quality
    - Optical head alignment (impacting downlink pointing) and target irradiance
  - Thermal profiles change through the year due to orientation of the host vehicle with respect to the Sun
    - Certain periods of the year (e.g. around the summer solstice) may have a greater thermal impact on pointing vs others



Received Irradiance at OGS-1 WFS with and without pointing loss due to thermal effects

Payload System Troubleshooting Activities

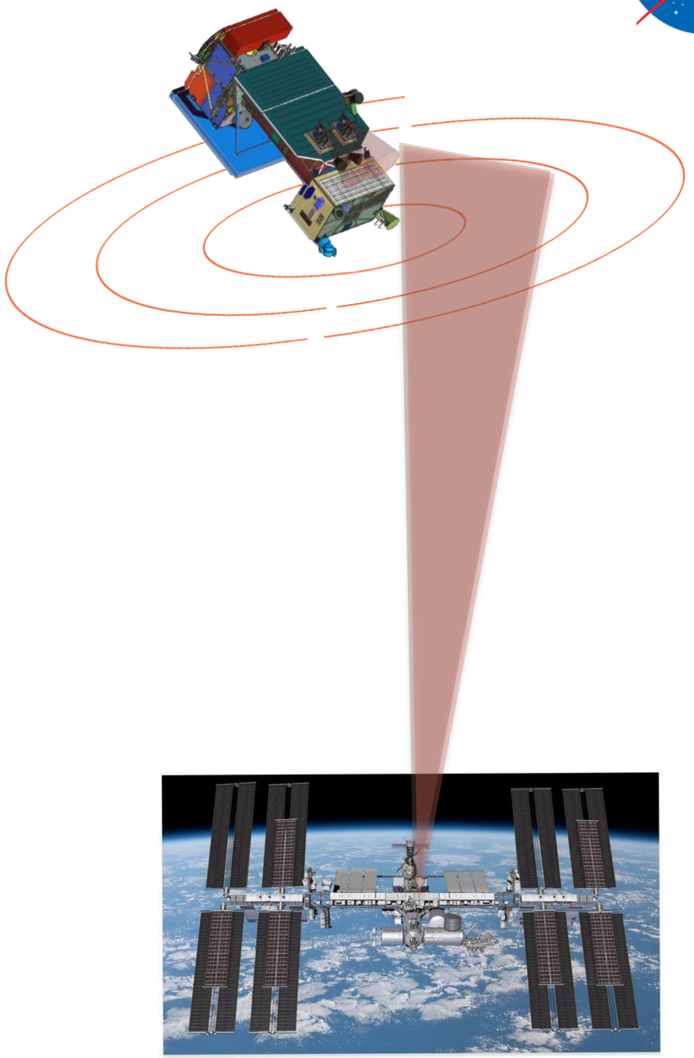
- Negative acquisition troubleshooting
  - Troubleshooting steps for "can't acquire" or "loss of comm" are very similar to gimballed Ka-antennas
  - Narrow tolerances require finer precision on pointing and tracking for both ends of the link
    - This is especially apparent after launch when trying to perform first set of pointing calibrations to account for launch shift
- Timing epochs (and errors)
  - Due to high pointing precision, an incorrect conversion from one epoch to another can easily cause a miss of target
    - Leap seconds are easy to get incorrect
    - ISS travels nearly 300 km in 37 seconds (current delta between UTC and International Atomic Time (TAI))
    - Ephemeris errors affect links with orbiting platforms more than ground stations
  - LCRD has not encountered this issue on-orbit, but did during initial testing during ground integration



The ISS moves nearly 300 km in 37 seconds.
An incorrect epoch causes mis-pointing and negative acquisition.

Payload System Troubleshooting Activities

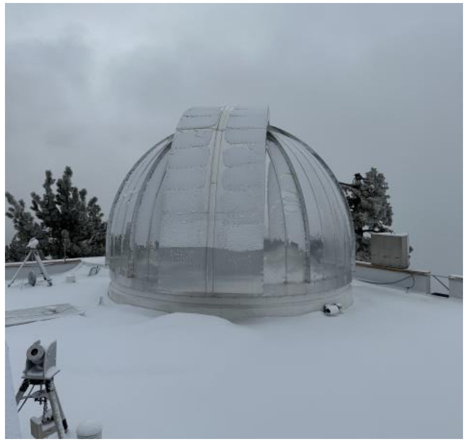
- Products for troubleshooting
  - Pointing accuracies were the most challenging issue encountered during payload and ground station commissioning
    - Missions should have flexible, pre-canned scanning profiles available for both ground and flight
    - Scanning profiles should include both open- and closed-loop acquisition scans
  - Real-time telemetry
    - Diagnostic telemetry modes that sample and report at rates exceeding the Nyquist frequency of relevant dynamics (atmospheric fading, pointing jitter, feedback loops, etc.) are extremely valuable for troubleshooting and optimization
      - Under sampling can mask performance issues
    - System state metrics are useful, as are high speed telemetry dwells but have associated overhead to process or store these data



ILLUMA-T performing an acquisition scan

LCRD Ground System Lessons

- Storm fronts and other atmospheric conditions such as smoke from wildfires or snowstorms can bring multiple-day outages
  - Ground Stations located lower than the cloud line will have this impact more often, or if the stations are located on the windward/prevailing side of a mountain range
- The strongest optical turbulence occurs at ground station local noon
  - Strong optical turbulence affects the quality of the downlink signal and the adaptive optics corrections
- Ground station microclimates may not be captured in regional forecasts
  - A frequent, quickly disappearing morning fog at one of the LCRD ground stations is an example
- Changing weather patterns will affect station availability
  - OGS-1 had record drought and record snowfalls in the same year

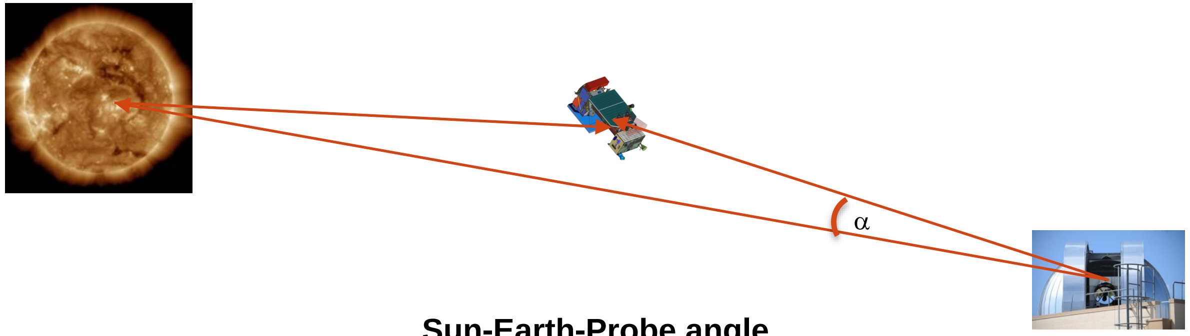


OGS-1 dome winter 2024 (Credit: NASA/JPL)

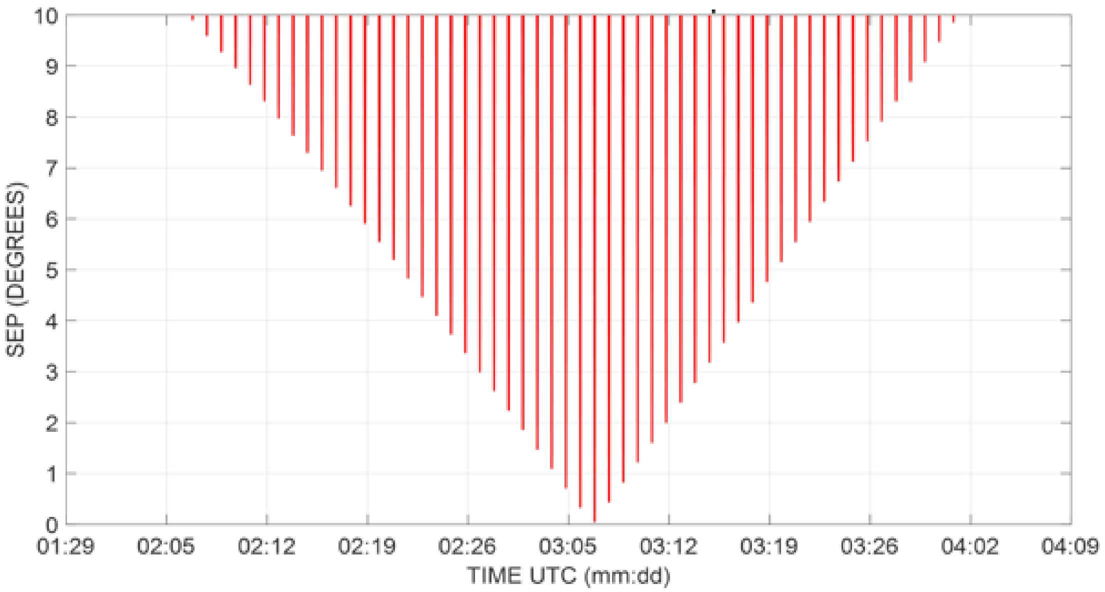
OGS-1 summer 2024 during wildfire event (Credit: NASA/JPL)

LCRD Ground System Operational Considerations

- Ground Station operational restrictions
  - Optical turbulence effects on laser links and beam propagation are stronger at lower elevation angles
    - Optical ground stations have a higher minimum elevation angle than traditional RF stations
    - This limits contact duration for low Earth orbiters, deep space and cislunar missions
  - Heavenly Body Orientation
    - Sun-Earth-Probe (SEP) impacts are seasonal
    - Low SEP angle can cause degradation of the Signal-to-Noise Ratio (SNR) at the receiver
    - Thermal and optical keep-out zones are required to prevent damage from pointing to close to the Sun
      - Keep-out zones vary depending on ground station configuration and location
      - Think of this as a "moving antenna mask in the sky"
    - Diagram to the right shows the SEP angle at OGS-1 in spring 2023
      - OGS-1 had daily outages for close to 2 months
      - OGS-1 Keep out zones are SEP <10 degrees
      - These outage periods occur twice a year



Sun-Earth-Probe angle



SEP angle at OGS-1 Feb-Apr 2023

Conclusions

- Two years of successful LCRD mission operations have yielded numerous operational lessons
- LCRD mission operations have demonstrated key differences in the operational processes needed for laser communication systems vs. RF communication systems
- Laser communication systems require higher precision flight dynamics products and a higher cadence of activities vs. RF communication systems
- Laser communications architectures will need to be configurable to accommodate future growth of laser communication networks

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