National Aeronautics and
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Insights and Observations From Operating A Laser Communication Terminal On The International Space Station (ISS)

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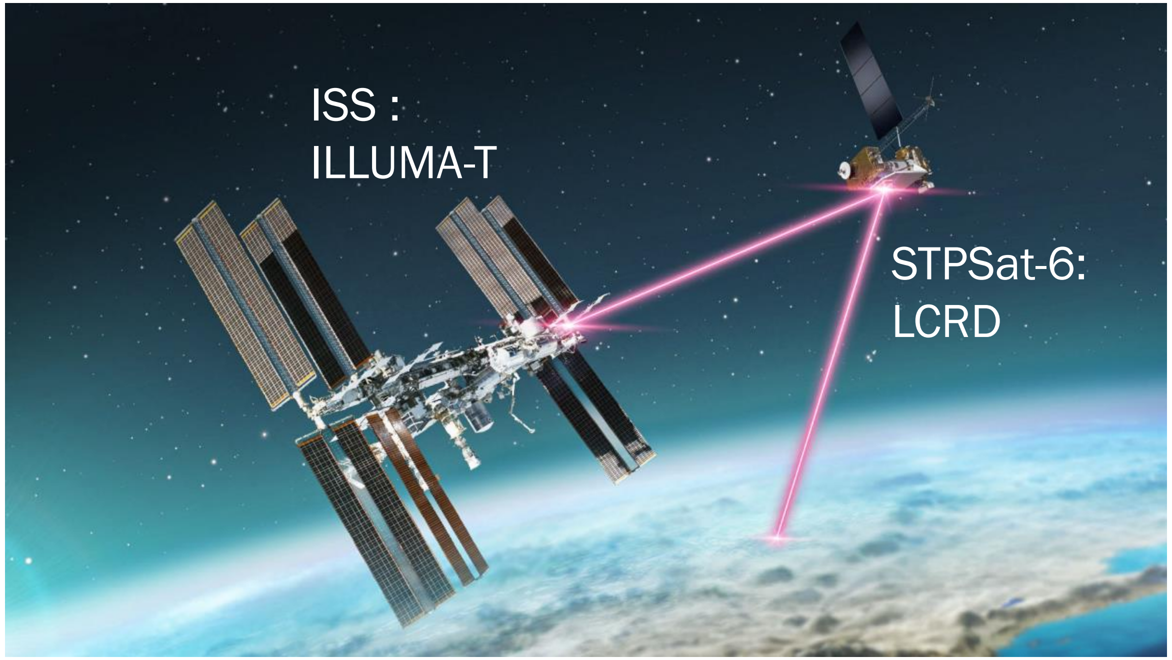
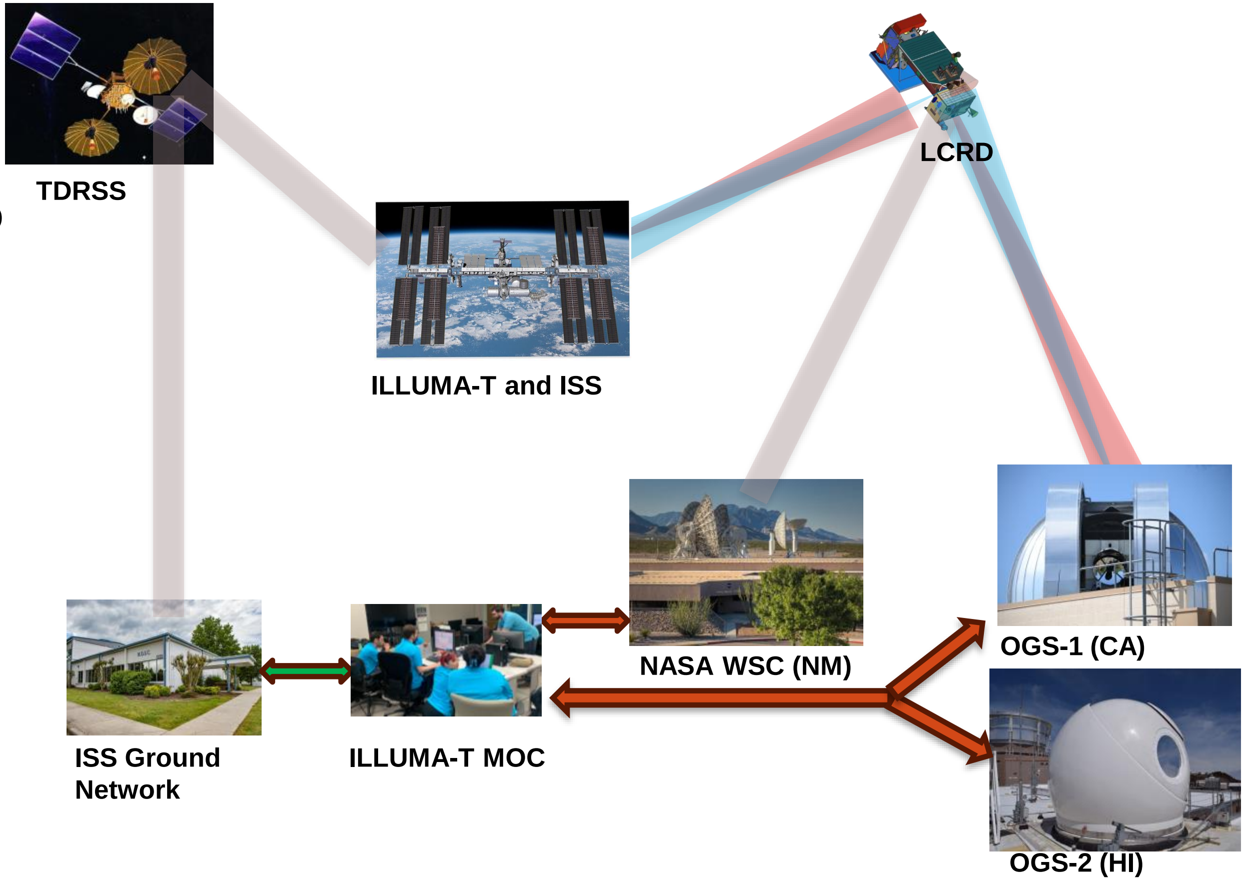
ILLUMA-T and LCRD Background

- 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 in Haleakalā, Hawai'i, and an RF ground station in New Mexico
- The Integrated LCRD LEO User Modem and Terminal (ILLUMA-T) was NASA's first LEO user platform communicating via laser link with LCRD
  - ILLUMA-T was hosted as an external payload on the Japanese module of the International Space Station (ISS)
- ILLUMA-T was a technology demonstration mission with one optical space terminal.
  - Used the ISS RF network for command and telemetry
  - Sent user data over the laser link to LCRD
- ILLUMA-T sent and received user data up to 1.2 Gbps over a bi-directional laser link to LCRD
  - Conducted experiments exploring laser link performance, Doppler characterization, and delay tolerant networking



ILLUMA-T with LCRD Day-In-The-Life Sequence

- Generate daily acquisition products and visibility reports
- ILLUMA-T ops team daily meeting
  - Review experiment configuration and operation actions
  - Review ISS communication restrictions that impact ILLUMA-T's command and telemetry windows
- ILLUMA-T with LCRD ops team daily meeting
  - Confirm experiment configuration of ILLUMA-T and LCRD
- Prepare ILLUMA-T terminal for contacts
  - Configure and upload the terminal's contacts for that day
  - Obtain and review contact ephemerides from LCRD
- Contact activities
  - Once LCRD is in ILLUMA-T's line-of-sight, the ILLUMA terminal initiates a spiral acquisition, that leads to coarse and fine-track
  - Once fine track is achieved, then flight modem clock lock occurs, and the system is ready for data transmit and receive
  - Operator adjusts system per experiment protocol
- Post-contact
  - ILLUMA-T terminal is commanded to stow for back orbit
  - Post-pass analysis
- Configure terminal for no operations overnight



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Approach on Lessons Learned

- These lessons learned were provided by the ILLUMA-T operations team and operations support teams
- Lessons on Best Practices
  - Includes best practices during pre-launch and through the six months of mission operations
- Pointing, Acquisition, and Tracking Lessons
  - Explores some of the difficulties and lessons observed while preparing for, establishing, and maintaining laser communication links
- Telemetry and Command Element Lessons
  - Describes some of the command and telemetry difficulties and solutions

ILLUMA-T Launch 11/9/2023 on SpaceX Falcon 9

Best Practices

- Transitioning Integration and Test (I&T) Personnel to Operations Personnel
  - Motivation: short operational timeline – two years of I&T followed by six months of operations
  - Test operators were crossed trained during I&T, allowing the team to fulfill multiple roles during operations
  - Saved time training a new ops team, and the experienced team was knowledgeable about system behavior
- Interns (Academic Trainees) Developing Supporting I&T and Mission Operations Documentation
  - Motivation: Small team of experts and short timeline required creative delegation of tasking
  - Interns developed and updated project documentation under guidance of team of experts
- Intern-Developed Payload Software Simulator
  - Motivation: Launches, especially ISS launches, are highly prone to change due to crew member needs
  - ILLUMA-T needed to be able to handle a 12-month storage scenario
  - A challenging project for a skilled college software engineer, lower cost than full-time engineer
- Extended Commissioning Timeline
  - Motivation: Limited end-to-end compatibility testing during I&T
  - Five-week timeline allowed for system calibration, correction for hardware misalignments due to launch, and operational process improvement

ILLUMA-T operations team after install in November 2023.

Best Practices, Cont'd

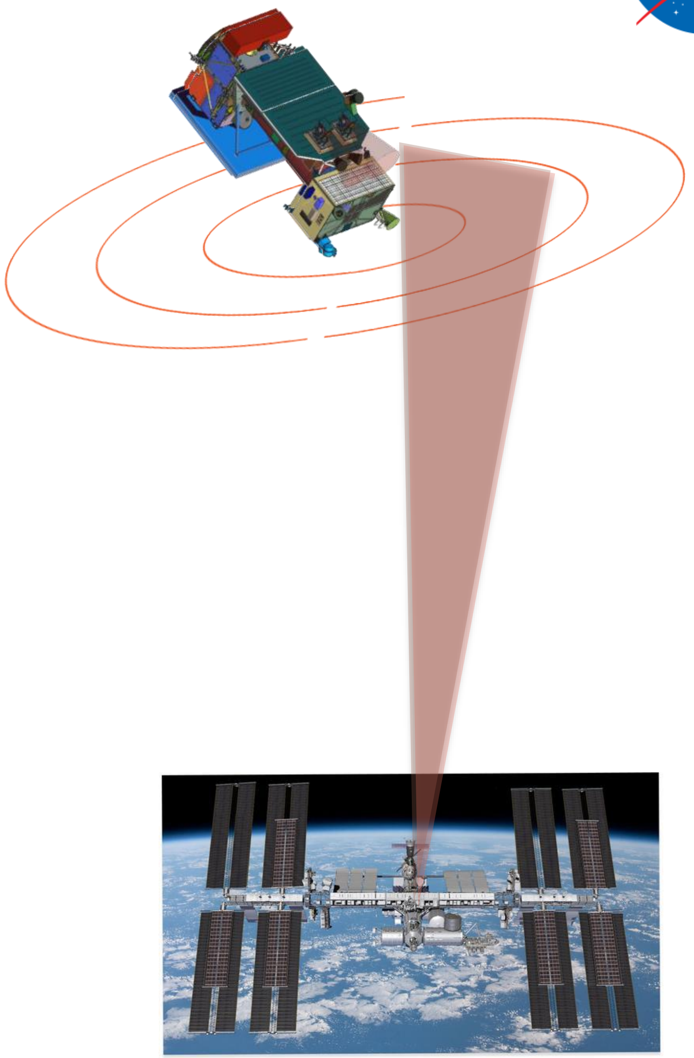
- Flexible Operations Procedure Configuration Management
  - Motivation: Short operations period required quick and thorough communication of operational changes as the systems were used for the first time on orbit
  - One additional operations personnel on shift allowed for accurate and thorough execution of tasks by performing support tasks such as documentation updates
- Inclusion of Personnel with Prior ISS and Laser Communication Operations Experience
  - Motivation: Multi-partner communication networks
  - Allowed for streamlined troubleshooting during commissioning phase and enabled the six-month experiment campaign to start on time with refined operational processes in place
- Routine Reporting and Planning
  - Motivation: Daily changes in orbit geometry due to the LEO orbit, ISS maneuvers, and LCRD host vehicle maneuvers; daily changes due to space weather and ground station weather
  - Allowed for immediate communication of changes to ephemerides

Pointing, Acquisition, and Tracking Lessons

- Ephemerides
  - Motivation: The ISS performs orbit determinations (OD) three times a week, but the ephemerides provided were not sufficiently accurate for consistent laser link acquisitions between ILLUMA-T and LCRD
  - ILLUMA-T mission instead used CelesTrak's daily two-line element (TLE) sets to generate contact windows, acquisition products, and derived ephemeris files to account for drift between ODs, and for any propulsive or attitude maneuvers
  - Future missions: Assess contributors to ephemeris uncertainty to balance orbit determination cadence against pointing budget
- Acquisitions and Visibility
  - Motivation: The dynamic nature of the ISS attitude and structure altered visibility to LCRD and required routine mask updates to calculate contact windows
  - The initial mask was too conservative; most contact windows could be extended by five minutes
  - The visibility report was initially generated 3x/week but after the first two months, daily visibility reports were preferred
  - Future missions: Automating the regeneration of visibility reports due to attitude-only maneuvers would save considerable time
- Open Loop Pointing Lessons
  - Motivation: Onboard open loop target information file was defined in five-minute intervals, but target was often lost under five minutes
  - Interval was changed to one-minute intervals improving laser link acquisition success
  - Future missions: Consider refining the optimal interval cadence as compared to time spent for larger uploads

Pointing, Acquisition, and Tracking Lessons

- Fine Tuning Acquisition Scan Profiles
  - Motivation: Uncertainties in pointing information led to late laser signal acquisition (or no acquisition at all)
  - ILLUMA-T used three configurable scan parameters: radius, speed, and pitch (distance between scan rings)
  - Scan profile parameters needed to be slow enough for LCRD to acquire with a large enough radius to cover a realistic uncertainty and a small enough pitch to adjust for adequate received power
  - Future Missions: Incorporating a feedback loop providing signal status information directly between laser systems while scanning could help refine and accelerate the acquisition process
- Star Trackers, Terminal Placement, and Rotation Matrices
  - Motivation: The ISS star tracker was not co-located with the terminal and accurate attitude knowledge was influenced by flexure of the ISS structure
  - Several updates to the rotation matrix were necessary since thermal gradient variability affected ISS structure flexure
  - Future Missions: Schedule routine updates or develop automated processes that generate new matrices when using star trackers that are not co-located with the onboard terminal



ILLUMA-T performing an acquisition scan

Telemetry and Command Element Lessons

- Command Window Outages
  - Motivation: Higher frequency of command window outages than estimated during mission planning leading to configuration challenges
  - Developed an onboard automated script and a partner configuration file to configure the telescope before, during, and after contacts. Configuration file was uploaded daily
    - Despite command and telemetry outages, ILLUMA-T was able to configure for LCRD contacts
  - Future missions: Develop automated configuration scripts before entering operations
- User Performance Data Messages
  - Motivation: The ILLUMA-T mission needed supplemental real-time analysis of end-to-end laser link performance
  - Allowed for assessment of the laser link status when ILLUMA-T was in a command and telemetry outage
  - Enabled real-time troubleshooting of laser link during contacts
  - Provided real-time laser link assessment to support experiments
  - Future missions: Recommend providing an expanded set of user performance data for both users and ground stations to ensure successful laser link performance

Positioning ILLUMA-T for decommissioning

Conclusions

- ILLUMA-T mission successfully operated a LEO-to-GEO-to-ground station laser link relay for 6 months leading to numerous operational lessons learned
- Laser communication systems require higher precision flight dynamics products and a higher cadence of activities vs. RF communications systems
- ILLUMA-T and LCRD mission operations have presented key differences in the operational processes needed for laser communication systems vs. RF communication systems
- ILLUMA-T operations showed the benefits of configurable scan profiles and precise determination of terminal placement on user platforms
- Recommendations for future space laser communication systems include incorporating real-time feedback loops during acquisition scans and making laser terminal telemetry available to both users and ground stations

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