NASAô s Next Generation ≥100 Gbps Optical Communications Relay

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Abstract- NASAô s Space Communications and Navigation (SCaN) program is creating an operational optical communications network to complement its current radio frequency (RF) networks. NASA is currently planning for a new optical communications relay node in geostationary (GEO) orbit to be commissioned in 2025, developed by NASAô s Goddard Space Flight Center (GSFC), as evolved from Goddardô s Laser Communications Relay Demonstration (LCRD) GEO relay payload that will launch in 2019. The Next Generation optical relay node will serve as an initial element in a larger optical networking constellation that will consist of Government and commercial, and international relays. NASAô s nodes will aggregate traffic at data rates of up to 10 Gigabits per second (Gbps) from users on the Earthô s surface and up through suborbital, LEO, MEO, GEO, cislunar and even out to Earth-Sun Lagrange (1.25 Mkm) distances. Users that require low-latency will be serviced with an onboard complementary Ka-band downlink service. The next generation network will deploy ≥ 100 Gbps space-to-ground links and also optical crosslinks between nodes to allow for user traffic backhaul to minimize ground station location constraints.

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INTRODUCTION

NASA is currently developing and testing optical communications systems to advance space communications capabilities. Throughout the last 50 years, NASA has primarily used standardized radio frequency (RF) systems to bring critical science data down from space. Using optical communications technologies will enable NASA to support enormous volumes of data at higher rates with quicker response times more securely. By developing a multi-satellite optical communications relay system for near-Earth and Lunar regions, NASA will significantly enhance low-latency communications capabilities for future missions.

Goddard Space Flight Center (GSFC) is developing the relay payloads and the initial relay node (relay) for NASAô s SCaN next-generation network in conjunction with our partners at MIT Lincoln Laboratory under the Laser Optical Communications Near-Earth Satellite System (LOCNESS) Project. LOCNESS will be one of the operational relay satellites within the multi-satellite relay system, enabling relay support to user links and cross-links and at rates of tens to hundreds of gigabits per second. This paper will discuss the development of LOCNESS and the communication advancements provided by switching to a global optical relay system.

NASAôs OPTICAL COMMUNICATIONS PROGRAM: PAST AND CURRENT MISSIONS

Optical Communications:

While RF technologies have been a reliable method of space communications throughout the last 50 years, recent advancements have shown that there are significant advantages to using an optical communications system. By utilizing optical capabilities, NASA can achieve a lighter, more efficient and secure process of beaming data down to users on Earth.

Optical technologies enable data rates that are 10 to 100 times higher than standard RF systems. Additionally, optical communications systems require less size, weight, and power (SWaP), and thus can be more easily accommodated on both user and relay spacecraft. Furthermore, in the era of data security, narrow beams of light, make it harder for outsiders to infiltrate the data stream.

LLCD

In 2013, NASA demonstrated the use of bidirectional optical communications through the Lunar Laser Communications Demonstration (LLCD) on the Lunar Atmosphere and Dust Environment Explorer spacecraft (LADEE). LLCD successfully transmitted data from the Moon to Earth, 400,000 kilometers (km) at download rates of 622 Megabits per second (Mbps) [1]. Additionally, LLCD successfully demonstrated an optical data upload to the LADEE spacecraft at data rates of 20 Mbps. LLCD demonstrated instantaneous acquisition and operated error-free under all conditions, including to within 3 degrees of the Sun during the day as shown in Figure 1.

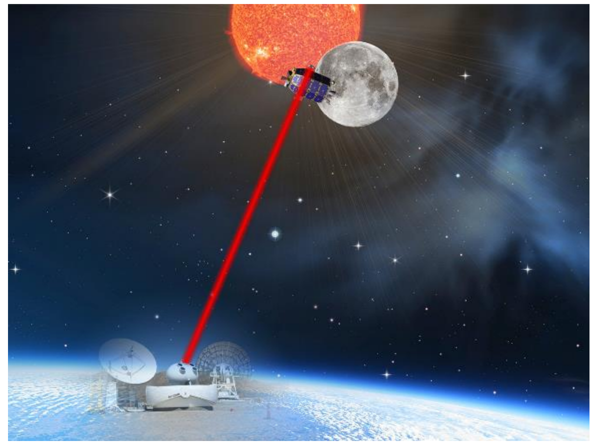

Figure 1: LLCD delivered 622 Mbps from the Moon, including to within 3 degrees of the Sun.

LCRD

The next optical communications mission will be NASAôs Laser Communicat Demonstration (LCRD). LCRD will showcase the operational reliability of an optical communications relay satellite and system. LCRD will be able to communicate bi-directionally with user rates of 1.244 Gbps to and from ground stations located at Haleakala, Hawaii and Table Mountain in California [2].

LCRD, depicted in Figure 2, is scheduled to launch in late 2019 and will provide at least two years of global high-data-rate optical communications coverage from a geostationary orbit (GEO). It will demonstrate optical communications capabilities for missions in low-Earth orbit (LEO).

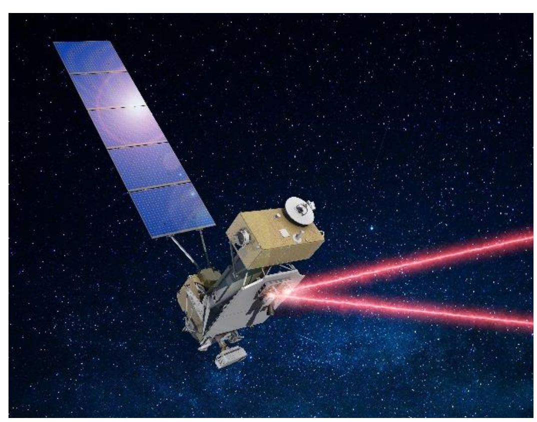

Figure 2: Artistic Rendition of LCRD

User Terminals for the ISS and Orion

Currently, NASA is developing the Integrated Low-Earth Orbit Laser Communications Relay Demonstration User Modem and Amplifier Terminal (ILLUMA-T), which will use LCRD to relay science data from the International Space Station (ISS) to users on Earth at the LCRD user rate of 1.244 Gbps, with a forward link to the ISS of 51 Mbps. ILLUMA-T is the first of several new user terminals that will be deployed to provide operational services to users in LEO [3].

Laser communications capabilities will also be onboard NASA's human spaceflight mission to the Moon, the Orion Exploration Mission (EM)-2. EM-2 is scheduled to launch in 2023 and will be the first spacecraft in over 50 years to take astronauts back to the Moon. The Optical to Orion (O2O) terminal will be able to support HD video links both to (20 Mbps) and from (80 Mbps) to the Moon [3], essential to allowing the American public to come along for the ride.

ILLUMA-T and O2O are the first space mission terminals developed through NASA GSFC's Laser-Enhanced Mission Communications Navigation and Operational Services (LEMNOS) project office, which will become the pipeline for future space mission terminals developed by GSFC to interact with the next generation optical communications network.

Next Generation Optical Communications Network

As NASA advances further with optical communications capabilities, a system of optical communication relay nodes becomes more feasible. This system will complement the capabilities of NASA's Tracking and Data Relay Satellite System (TDRSS). Currently, NASA has 10 active TDRS satellites orbiting the Earth at 22,000 miles in GEO. Using RF technologies, TDRSS provides continuous global communications coverage for over a hundred missions in space. The LOCNESS relay will be the first node in this next generation architecture with a second node to be commercially-provided through a Public-Private Partnership managed by NASA's Glenn Research Center (GRC).

CONCEPT OF OPERATIONS

Nodes in the Network

LOCNESS will be one of at least three nodes in the next-generation relay network. A next generation architecture is being developed to provide the concept of operations for evolving NASA's space communications capabilities, as shown in Figure 3.

The system differs from the TDRSS in that each node in the next generation system will be able to communicate with other nodes. In the TDRSS, the satellites can only receive and communicate data down to Earth, rather than pass the data to another TDRS in GEO. Connectivity between the nodes is vitally important to data communication in the next generation relay system. Optical communications are vastly more advantageous for data rates, security, and mission costs, however, optical communications downlinks cannot be performed if the receiving ground station in under cloud coverage. By enabling the nodes to communicate with each other, the data sent to one node can either be downlinked directly to the ground or, if that ground station cannot be reached, the data can be further transmitted to another node, which can then send it to a clear ground station. This interoperability will allow the communication of vital science data to the ground despite weather conditions at one ground station.

LOCNESS will primarily use optical communications to downlink data; however, if all ground stations within view are optically unavailable, the communications system can revert to utilizing RF technologies. LOCNESS will host a high data rate Ka-band RF terminal to communicate with Ka-capable ground stations as a backup during weather incidents. In addition, LOCNESS will provide a weather-independent low or no-latency downlink to meet user requirements.

LOCNESS will have a user range from Earth's surface to GEO, with limited performance at cislunar and Lagrange Point 1 (L1) and Lagrange Point 2 (L2) distances.

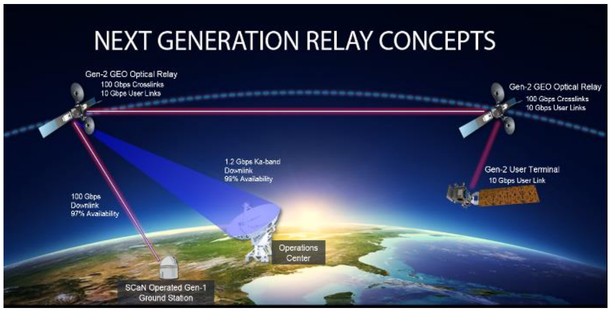

Figure 3: Next Generation Relay Concept with 10G user services, 100G crosslinks and space-to-ground links, and 1 Gbps Ka-band RF services for lower-rate but low-latency requirements.

Interoperability

LOCNESS, which is planned to operate for a minimum of five years, will be a dedicated NASA asset. However, SCaN's goal is to have an interoperable system of optical communications relays comprised of NASA, commercial, and other government agencies. Parts of the next generation system can be created through public-private partnerships to assist in obtaining constant, global coverage for missions in space.

To ensure interoperability between the initial nodes the payloads provided by GSFC will have the same design. The initial space mission terminals also use the same design architecture as the node payloads. The node payloads are required to maintain backward compatibility with LCRD users for continuity of service. Use of the Consultative Committee for Space Data Systems (CCSDS) standards, currently under development, throughout the network will enable continued interoperability nationally and internationally as the optical communications industry grows.

OPTICAL COMMUNICATIONS PAYLOAD AND SPACE MISSION TERMINALS

Relay Payloads

In the next generation network, each relay will have one optical payload. The government relay payload is planned to have four identical, independent, and interchangeable optical terminals. The nomenclature for the relay payload is shown in Figure 4.

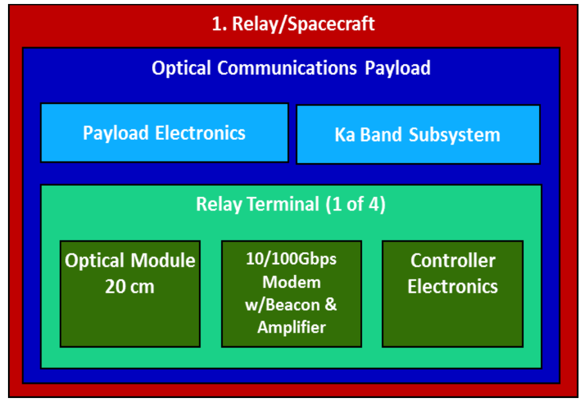

Figure 4: Optical Communications Payload

The gimbaled telescope for each optical terminal will have a 22 cm diameter aperture. The unobstructed Field of Regard (FOR) for the next generation payload's four optical modules is anticipated to be +/- 120 degrees in elevation and +/- 175 degrees in azimuth. This will enable the maximum opportunity for the terminals to view users in all of the required orbits, regardless of the platform on which they reside. The controller electronics command all of the functions of the optical terminal, including the pointing, acquisition, and tracking.

Two modems are associated with each terminal. One will receive up to 10 Gbps data from mission users, and the other will have approximately 100 Gbps capability for the downlink and crosslink functions. The 100 Gbps modem leverages highly-integrated commercial off-the-shelf technology from the fiber telecommunications industry based on a silicon photonic integrated circuit and a coherent Digital Signal Processor Application Specific Integrated Circuit that has been space-qualified and will be demonstrated in LEO in 2019 [5, 6].

The payload electronics manage the functions of the payload external to the optical terminal. These include the payload controller and data handler, local data storage, a controller for disruption tolerant networking (DTN), and a switch/router. The latter moves data from the receiving terminal to the optical downlink, the cross-link, or to the Ka-band RF system for downlink. The switch may also move designated data to the DTN system to be stored and forwarded later. The Ka-band system is integral to the payload and is for the payloadôs use.

Space Mission Terminals

The space mission terminals, located on user missions, will provide the link from a user mission to an optical communications relay or direct to Earth to an optical ground station. The nomenclature, shown in Figure 5, is similar to a payload optical terminal. The telescope aperture will vary in size based on the link budget requirements of the mission. The modem data rate may also vary between the 1.244 Gbps ILLUMA-T modems and the relay ~10 Gbps user modem.

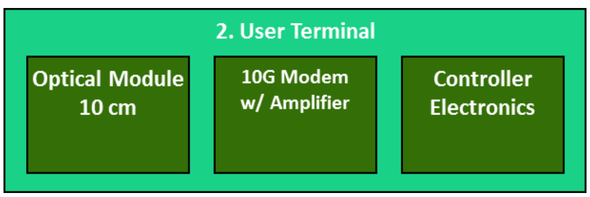

Figure 5: Optical User Terminal

REQUIREMENTS

CCSDS

To achieve an international interoperable system, the Optical Communications Working Group (OCWG), within the international Consultative Committee for Space Data Systems (CCSDS) organization, is developing a set of standards for optical communications technologies. A commercial entity or other government agency intending to build optical communications satellites should consider following the CCSD guidelines, ensuring interoperability with the next generation relay system.

Disruption Tolerant Networking

The next generation network will have DTN capabilities onboard the relays. DTN uses interoperable protocols to provide routing and data security. DTN technology ensures reliable data delivery despite intermittent link availability [7]. The most significant aspect of DTN is the Bundle Protocol (BP) capability. BP, using a store-and-forward approach, allows the data, in the form of DTN bundles, to be routed and if, necessary, stored at relay nodes within the next generation system. A user can deliver data reliably to the relay. The relays then can either route the data immediately if the link is available or store the bundle until a link is restored. The user can send its data without concern for whether or not there are any disruptions along the path. Before DTN onboard the relay, if communications beyond the relay were disrupted mid-transfer, the spacecraft would have to ensure that the data was retransmitted, causing additional communications costs. [8]

An additional advantage to the DTN technology is the network-layer functionality. DTN enables the data being downlinked to ground stations to automatically send the data to the end user based only on the received data headers instead of a priori configuring data paths. Furthermore, DTN includes automatic rate buffering to accommodate rate mismatches between space links and terrestrial data lines. [7]

By incorporating DTN into LOCNESS and the entire next generation relay system, transmitting data becomes more automated and reliable. Users that are latency tolerant may choose to route their data through the DTN system while latency intolerant data can be routed directly to ground. DTN capabilities can be seen in Figure 6. [9]

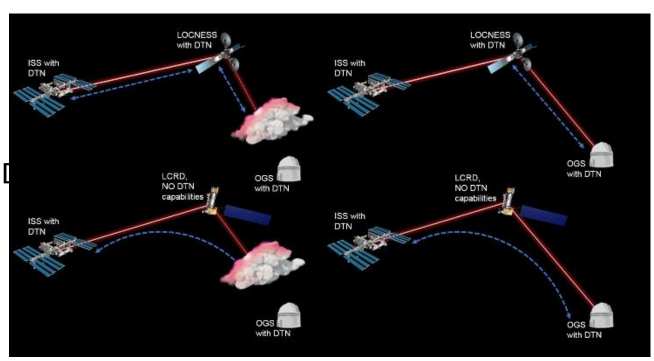

Figure 6: LOCNESS versus LCRD DTN Capabilities

Data Security

In the era of hacking, data security will need to be built into the system design of the next generation network. Using optical communications is inherently more secure, as the data is encoded into beams of light rather than transmitted through radio frequency, which could potentially be accessed. Even with the security advantages of optical communications systems, security should be implemented into the network at each layer through encryption methods.

DTN provides an added layer of security as well. A security protocol will secure data within each bundle. This protocol will add protection for the bundles being transmitted as well as protect links to relays. [9]

DEVELOPMENT STRATEGY

The development plan for the next generation network is currently underway. The GSFC team developing the LOCNESS mission is performing multiple spacecraft bus studies including multiple industry approaches. The goal is a reduced-cost bus with the potential to launch on a ride-share opportunity. Toward the end of 2018, NASA will decide on the approach for the spacecraft bus.

As NASAôs Center of Excellence for optical communication, GSFC is also solely in charge of developing the flight payloads for the next generation system. Building on the partnership with MIT Lincoln Laboratory and recent design advancements, GSFC plans to build a prototype payload from enhanced LEMNOS designs with industry providers. After testing the prototype, the GSFC team will start developing two flight payloads, one for LOCNESS and one for the GRC node. These flight payloads will be built in parallel to enable a robust, two-node start to the optical communications network.

Commercialization Plan

The next generation relay system will evolve beyond the initial three relays. With this evolution, demand for optical communications technology is expected to increase. NASA plans to push the optical communications technology out to industry while developing the initial network. With an increase in industry providers, a systematic supply chain will be created for interoperable optical terminals for future optical communications missions. The technology transfer from NASA to industry is crucial to meet future user demand and for an interoperable next generation relay system.

CONCLUSION

NASAôs next generation re
provide constant, global, high-data-rate communications services for hundreds of future missions. This multi-satellite optical communications relay system will complement
the current capabilities
system, TDRSS.

Currently, GSFC is developing the flight payloads for two of the relay nodes within the system. As NASA intends this network to be fully interoperable, optical communications standards are being developed within the Optical Communications Working Group (OCWG) within the CCSDS, enabling commercial companies and other government agencies to develop additional optical relay nodes and space mission terminals for the network.

Utilizing optical communications systems will
significantly increase NAS
The optical terminals within this system will provide up to 10 Gbps relay services to users and $\geq$ 100 Gbps relay crosslinks and space-to-ground services. Additionally, the use of optical communications technologies provides a more secure method of data transfer, and lower spacecraft costs for missions in LEO, GEO, cislunar and Earth-Sun L1/L2 distances.

GSFC, with SCaN and GRC, is in the process of developing this operational optical communications relay node system and plans to launch the first node, LOCNESS, by 2025.

[6] Robinson, B. S., D. M. Boroson, C. M. Schieler, F. I. Khatri, O. Guldner, S. Constantine, T. Shih, D. Cornwell, "TeraByte InfraRed Delivery (TBIRD): a demonstration of large-volume direct-to-Earth data transfer from low-Earth orbit." In Free-Space Laser Communication and Atmospheric Propagation XXX, vol. 10524, p. 105240V. International Society for Optics and Photonics, 2018.

[7] ³5DWLRQDOH 6FHQDULRV DQG 5HTXLUHPHQWV IRU '71 LQ 6SDFH ´ 5H
CCSDS 734.0 G-1. Green Book. Washington, D.C. CSDS, August 2010.

[8] Israel, David J., Donald Cornwell, Gregory Menke, and W. John Guineau. "Demonstration of Disruption Tolerant Networking across Lunar Optical Communications Links." In 32nd AIAA International Communications Satellite Systems Conference, p. 4481. 2014.

[9] 'DYLG - ,VUDHO &KULVWRSKHU - 5REHUWV 5REHUW 0 0RUJHQVWHUQ
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beyond Low Earth Orbit. November 2018.