A Space Based Optical Communications Relay Architecture to Support Future NASA Science and Exploration Missions

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Abstract – Space optical communications, onboard data processing, and Delay Tolerant Networking (DTN) are key communication technologies in development at the National Aeronautics and Space Administration (NASA) for possible deployment on future space based relays. The Laser Communications Relay Demonstration (LCRD) project, scheduled for launch in March 2018 as a hosted payload on a commercial communications satellite, is a critical pathfinder towards NASA providing optical communications services on the Next Generation Tracking and Data Relay Satellite. The project builds upon the success of the recent Lunar Laser Communication Demonstration (LLCD) and leverages the technologies developed for it. This paper provides an update on both projects and on other Near-Earth space optical communication developments at NASA, and describes a possible optical communications architecture for future Geosynchronous Earth Orbit (GEO) relays to support multiple science and exploration missions. This paper will also touch on the necessary commercialization of optical communications and the development of inter-operability standards.

I. Introduction

The National Aeronautics and Space Administration (NASA) has extensive experience with flying communications relay satellites in Earth orbit. NASA's Earth relay satellites are satellites placed in geostationary orbit (GEO) to relay information to and from non-GEO satellites, aircraft, and Earth stations that otherwise would not be able to communicate at all or would not be able to communicate for long periods of time. A network of Earth relay satellites would increase the amount of time that a spacecraft in Earth orbit, especially in low Earth orbit (LEO), could be in communications with a mission operations center, and thus would increase the amount of data that could be transferred.

NASA's current series of Earth relay satellites is referred to as the Space Network and it consists of Tracking and Data Relay Satellites (TDRS) in GEO with the associated ground stations and operation centers. The network supports very low latency and high availability spacecraft communications in the Near Earth vicinity. There are currently three different generations of TDRS spacecraft in orbit and NASA is studying the requirements for a future generation to be launched around the 2025 timeframe.

While the exact requirements for the future generation of relay satellites are currently unknown, NASA is investing in new communications technologies that could be deployed on the satellite to provide new services to users. One of those new technologies is space based optical communications.

In order to make space based optical communications a reality for NASA missions in the future, there needs to be a suitable demonstration of the technology, optical communications terminals developed for various mission profiles, the development of ground stations and network infrastructure, and the adoption of international standards to support future cross support requirements.

II. Relay Satellite Architecture

A future relay satellite will have at least one space-to-space inter-satellite link and one space-to-ground link. That would allow the relaying of communications to and from a single user spacecraft or aircraft. Both the inter-satellite link and the space-to-ground link could be RF or optical. A future relay could even provide both RF and optical inter-satellite links. Likewise a future complex relay could have a RF space-to-ground link, an optical space-to-ground link, or both. Optical space to ground links can be severely impacted by atmospheric effects, especially clouds; the result is that a single relay with a space-to-ground optical link might have to be supported by several optical ground stations to overcome weather related link outages.

NASA has compared the advantages and disadvantages of an RF versus optical space to ground link in previous relay studies. Using RF on the space to ground link provides the overall relay with high availability due to RF's ability to penetrate most clouds that would block an optical space to ground link. However, an RF space to ground link can be a limiting factor in the design of an Earth relay if a higher data rate is required than can be reasonably handled via RF technology or spectrum availability.

An optical space to ground link is particularly attractive as the downlink data rate from the relay increases. It is easy to envision Earth relays in the not-so-distant future with tens of Gbps of downlink. However, the availability of an optical space to ground link would be impacted by clouds. To provide high availability, the Earth relay would have to use a combination of RF and optical space to ground links supplemented with onboard storage, or employ a number of optical communication ground stations to support the relay.

A future relay payload with minimal capabilities to demodulate and modulate signals will allow for the possibility of user data to be distributed to multiple relay paths in a combination of multi-cast (same data to multiple destinations) and multiplex modes (different data to different destinations). This could allow operations such as high rate science data delivery directly to science operations centers, science alert broadcasts, or transmitting the data over a single or combination of frequency bands, including optical. This is switching at the physical data frame only. The payload does not require the ability to decode the data or inspect any of the data contents within the physical data frame to perform these functions.

The availability of data storage onboard a future Earth relay satellite is an important consideration. Minimal storage could at least allow for rate buffering and data retransmissions between the relay and destination. This would be especially beneficial for optical links which may have momentary drop outs due to atmospheric effects. An increase in the amount of storage onboard the relay could allow for advanced operations concepts, such as the support of relay links when only one link is available, pre-positioning of user data on the relay for later retrieval, and maximizing bandwidth utilization by multiplexing lower priority stored data with real-time high priority data. The Delay Tolerant Network (DTN) protocol suite, including the DTN Bundle Protocol (BP) and Licklider Transmission Protocol (LTP), could provide the reliable data transmissions and network layer functionality for the store and forward operations [1]. DTN can be considered to be a network of smaller networks; it is an overlay and supports interoperability of other networks by accommodating long disruptions and delays between and within networks. DTN technology was originally developed for interplanetary use, where the distances are huge and thus delays are long [2]. However, DTN is a great technology to be used with Near Earth optical communications applications to help overcome the impacts of clouds and turbulence.

The relay network ground segment will include augmentations, corresponding with the new relay architecture beyond the addition of telescopes and optical communications modems, lasers, codecs, etc. The terrestrial data handling at the ground station will increase in complexity. Link protocols will be closed directly between the ground station and relay payload. Relay user data streams will be muxed and de-muxed on optical and RF links. These terrestrial data paths will have to be managed by schedules and also, perhaps, autonomously as link conditions and user traffic vary. The occurrence of handovers between ground station locations due to weather conditions will require smooth handovers of not just the optical space to ground link, but the terrestrial data paths too. Long range scheduling will have to take the potential for weather-based handovers into account.

The first step in making any of this a reality is a successful NASA demonstration of optical communications in space.

III. NASA's Lunar Laser Communication Demonstration – An Initial Stepping Stone

The Lunar Laser Communication Demonstration (LLCD), which flew on the Lunar Atmosphere and Dust Environment Explorer (LADEE) in September 2013 [3], was NASA's necessary first step towards the robust use of optical communications. LLCD was a joint project between NASA Goddard Space Flight Center, MIT Lincoln Laboratory, NASA Jet Propulsion Laboratory, and the European Space Agency (ESA). The demonstration was a huge success and opens the door for future project managers and systems engineers to consider the technology for their missions. The demonstration consisted of a primary optical ground station located at White Sands, New Mexico and two backup optical ground stations: The Optical Communications Telescope Laboratory at Table Mountain, California, and the ESA Optical Ground Station at Tenerife, Spain.

Some highlights of the LLCD demonstration include:

- Consistent all optical acquisition and tracking, usually occurring within seconds

- Error free downlink at 40, 80, 155, and 311 Mbps
- 622 Mbps downlink with a code word error rate < 1x10-5
- Error free uplink at 10 and 20 Mbps
- Error free operation at low Moon elevation angles (<4 degrees at White Sands)
- Operations to within 3 degrees of the Sun at up to 622 Mbps with no degradation in performance
- The use of Photon Counting and Pulse Position Modulation
- Inertial stabilization in the Flight Payload
- The use of a scalable array ground receiver
- Demonstration of DTN over optical links

LLCD proved the feasibility of optical communications, especially from beyond Earth orbit, but due to the very limited operating time available, it did not provide the necessary operational knowledge to allow optical communications to support mission critical communications on future missions. To make optical communications useful to future projects, long mission life space terminals must be developed and proven. Operational concepts for reliable, high-rate data delivery in the face of terrestrial weather variations and real NASA mission constraints needs to be developed and demonstrated. To increase the availability of an optical communications link and to mitigate cloud cover impacts at a ground terminal, there needs to be a demonstration of handovers among multiple ground sites.

IV. NASA's Laser Communications Relay Demonstration – The Next Step

NASA's next step in high rate optical communications is the Laser Communications Relay Demonstration (LCRD) [4]. LCRD is a joint project between NASA Goddard Space Flight Center, NASA Jet Propulsion Laboratory, and MIT Lincoln Laboratory. The demonstration will provide at least two years of high rate space optical communications from geostationary orbit to two optical ground stations located in the United States.

LCRD's flight payload will be hosted on a commercial communications satellite and consists of two optical communications terminals in space with a switch between them. A single optical communications terminal on LCRD consists of an Optical Module (a telescope or head), a modem, and an optical module controller. The Optical Module (OM) is basically a modified version of the OM used in LLCD at the Moon; LCRD's controller is also similar to what was flown at the Moon for LLCD with a few modifications to interface with the host spacecraft; the modem, however, is completely different.

Each of the two optical communications terminals to be flown on the GEO spacecraft will transmit and receive optical signals. When transmitting, the primary functions of an optical communications terminal is to efficiently generate optical power that can have data modulated onto it; encode, format, and interleave incoming electronic data; modulate the optical beam with this data; amplify and transmit this optical power through efficient optics; and aim the very narrow beam at the ground station on earth, despite platform vibrations, motions, and distortions. When receiving, an optical communications terminal must provide a collector large enough to capture adequate power to support the data rate; couple this light onto low noise, efficient detectors while minimizing the coupled background light; and perform synchronization, demodulation, deinterleaving, and decoding of the received waveform.

LCRD will support differential phase shift keying (DPSK) which can be used at extremely high data rates and has sufficient background noise tolerance to support communications when the sun is in the field of view. LCRD leverages a DPSK modem previously designed by MIT Lincoln Laboratory [5, 6] as a cost effective approach to providing a DPSK signal. It can both transmit and receive, supporting data rates from 2 Mbps to 1.24 Gbps. Reduced data rates are achieved efficiently via a "burst mode" format, with data bursts interspersed with "dead times" where no signal is transmitted. In future relay scenarios, the modem could be replaced by a higher rate DPSK modem that would support data rates beyond 10 Gbps. In addition to DPSK, LCRD will also support pulse position modulation (PPM). The transmitter modulate the signal with a sequence of 16-ary PPM symbols (a signal pulse is placed in exactly one of each 16 temporal slots). The maximum PPM data rate is 311 Mbps.

NASA is also investigating the possibility of flying an optical communications terminal on a Low Earth Orbit (LEO) spacecraft, such as the International Space Station, to demonstrate with LCRD. Thus the LCRD flight payload on the GEO spacecraft has a requirement to be able to support high rate bi-directional communications between LEO and GEO as well as between Earth and GEO.

The LCRD Ground Segment is comprised of the LCRD Mission Operations Center (LMOC) and two optical ground stations: Ground Station 1 and Ground Station 2. Each optical ground station must provide three functions when communicating with one of the two space optical communications terminals on the GEO spacecraft: receive the communications signal from the GEO space terminal, transmit a signal to the GEO space terminal, and transmit an uplink beacon beam so that the GEO space terminal points to the correct location on the Earth.

The uplink beacon, transmitted from each Earth ground station, must provide a pointing reference to establish the GEO space terminal beam pointing direction. Turbulence effects dominate the laser power required for a ground-based beacon. Turbulence spreads the beam, reducing mean irradiance at the terminal in space, and causes fluctuations in the instantaneous received power.

The LMOC will perform all scheduling, command, and control of the LCRD payload and the ground stations. The LMOC is connected with all other segments, and communicates with the two optical ground stations using high capacity terrestrial connections. Connection to the space segment will be provided either through one of the ground stations, or through a lower capacity connection to the host spacecraft's Mission Operations Center (HMOC) and then to the LCRD flight payload by the spacecraft's RF link.

NASA Jet Propulsion Laboratory will enhance its Optical Communications Telescope Laboratory (OCTL) so that it can be used as Ground Station 1 of the demonstration. The OCTL is located in the San Gabriel mountains of southern California and houses a 1-m f#75.8 coudé focus telescope. [7] The large aperture readily supports the high data rate DPSK and PPM downlinks from the LCRD space terminal with adequate link margin. Required to operate 24/7, in the presence of winds, and as close as 5 degrees solar angles, the OCTL telescope shown in Figure 2 will be enclosed in a temperature controlled dome with a transparent window to allow laser beam and radar transmission. The Laser Safety System at the OCTL (LASSO) will ensure safe laser beam transmission through navigable airspace and near-Earth space. [8]

Figure 1 - OCTL telescope will be modified with an optical flat to support links in the presence of more windy conditions.

MIT Lincoln Laboratory and NASA Goddard Space Flight Center will make modifications to the LLCD Lunar Lasercom Ground Terminal (LLGT) [9] so that it can be used as Ground Station 2 for LCRD. The LLGT, shown in Figure 5, was deployed to White Sands, New Mexico for LLCD but it is a relatively transportable ground station. It is an array of four 40-cm receive reflective telescopes and four 15-cm transmit refractive telescopes. The primary enhancements for LCRD will be an adaptive optics system to couple received light into single mode fiber to support the DPSK signal).

Figure 2 - Lunar Lasercom Ground Terminal will be enhanced with Adaptive Optics and the ability to receive and demodulate a DPSK signal

The LCRD architecture will allow the mission to demonstrate:

- Demonstrate high rate 24/7 optical communications operations over a 2 year period from GEO to Earth
- Demonstrate real-time optical relay from one Ground Station through the GEO flight payload to the second Ground Station
- Use both a Near Earth (DPSK) and a Deep Space (PPM) compatible modulation and coding
- Demonstrate 1.244 Gbps (2.880 Gbps uncoded) uplink and downlink using Differential Phase Shift Keying (DPSK)
- Demonstrate 311 Mbps uplink and downlink using Pulse Position Modulation (PPM)
- Demonstrate the Next Generation TDRS compatible optical terminal capable of supporting both Direct to Earth and GEO to LEO (ISS Terminal) communications
- Demonstrate operational concepts for reliable, high-rate data delivery in face of terrestrial weather variations typically encountered by real NASA missions
- Demonstrate control of handover among ground sites
- Performance testing and demonstrations of coding and link layer protocols over optical links with an orbiting testbed

To be an optical relay demonstration, LCRD will create a relay connection between two optical ground stations. A significant objective of LCRD is to demonstrate advance relay operations on the GEO spacecraft. LCRD will enable a wide variety of relay operations through the Space Switching Unit that connect the two optical terminals. A known challenge with optical communication through the atmosphere is the susceptibility to cloud cover; link operations will be configurable to allow support for a variety of scenarios.

V. An LLCD / LCRD Type Flight Optical Communications Module

NASA's current vision is to use an LLCD / LCRD type optical module in as many scenarios as possible. Studies show that the MIT Lincoln Laboratory designed terminal can be used from Low Earth Orbit out to the Sun-Earth L1 and L2 Lagrange Points with only a few modifications depending on the mission profile.

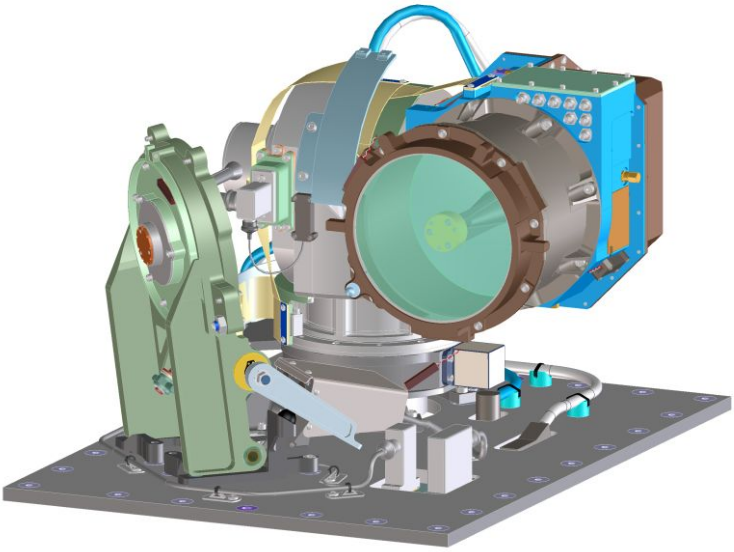

Figure 3 - Inertially Stablized LLCD / LCRD Type Optical Module

Each optical module, shown in Figure 1, is a 4-inch reflective telescope that produces a ~15 microradian downlink beam. It also houses a spatial acquisition detector which is a simple quadrant detector, with a field of view of approximately 2 milliradians. It is used both for detection of a scanned uplink signal, and as a tracking sensor for initial pull-in of the signal. The telescope is mounted to a two-axis gimbal and stabilized via a magnetohydrodynamic inertial reference unit (MIRU). Angle-rate sensors in the MIRU detect angular disturbances which are then rejected using voice-coil actuators for inertial stabilization of the telescope. Optical fibers couple the optical module to the modems where transmitted optical waveforms are processed. Control for each optical module and its corresponding modem is provided by a controller. Each optical module is held and protected during launch with a cover and one-time launch latch.

VI. Optical Module Commercialization

In order to make optical communications more easily available to future NASA science and exploration missions and to reduce costs, NASA would like a commercial provider for an entire optical communications terminal. Commercialization of a LLCD / LCRD type optical module has already started; the optical module has been divided into four subassemblies that are commercially available:

- Optical Assembly
- Gimbal and Latch Assembly
- Inertially Stable Platform
- Solar Window Assembly

The Optical Assembly (OA) consists of a beryllium Cassegrain telescope and small optics bench. The small optics bench accommodates three separate wavelengths, each boresight aligned to the telescope. The LCRD OAs will be fabricated and tested by Exelis Geospatial Systems of Rochester, NY.

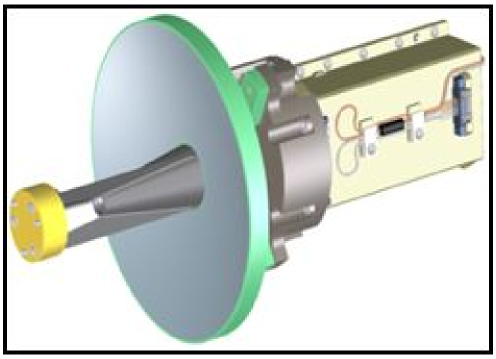

Figure 4 - Optical Assembly

The Gimbal and Latch Assembly (GLA) contains four distinct subassemblies: the two-axis Gimbal Assembly, the Latch Assembly, the Instrument Panel Assembly, and the Bridge Mass Assembly. The Instrument Panel Assembly is used to mount the Gimbal Assembly and Latch Assembly, and serves as the base for the full Optical Module (OM). The Bridge Mass Assembly is a stand-in to represent the mass and inertia of the other OM subassemblies. The LCRD GLAs are being fabricated and tested by the Sierra Nevada Corporation facility in Louisville, CO.

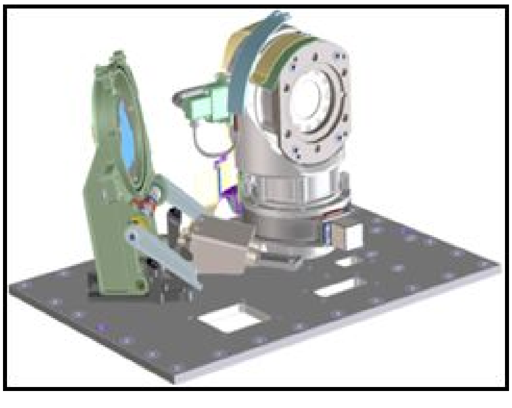

Figure 5 - Gimbal and Latch Assembly

The core of the Inertially Stable Platform (ISP) is the Magneto-hydrodynamic Inertial Reference Unit (MIRU), which provides the inertial stabilization system for the OA, once the OM has been assembled. The ISP also contains environmental covers and mass stand-ins for the OA and SWA. The LCRD ISPs are being fabricated and tested by Applied Technology Associates of Albuquerque, NM.

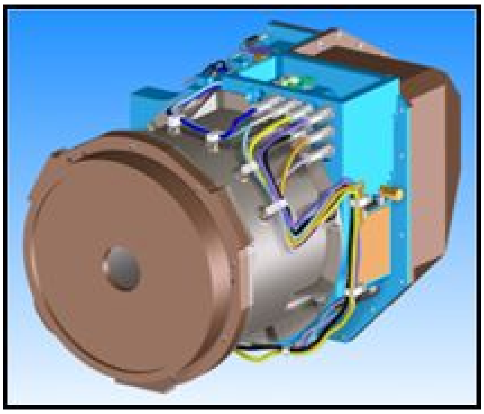

Figure 6 - Inertially Stable Platform

The Solar Window Assembly (SWA) provides environmental protection for the OA once the OM has been assembled. The main component of the SWA, the solar window, was designed to minimize the amount of solar energy that reaches the OA. The window attenuates optical energy of all wavelengths, except for the band in which the OA operates. The LCRD SWAs are being fabricated and tested by L-3 Integrated Optical Systems of Wilmington, MA.

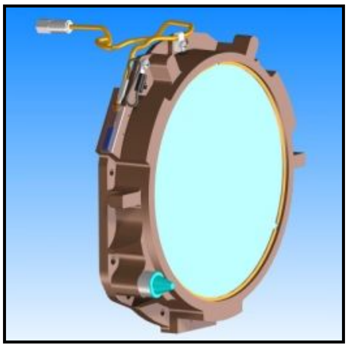

Figure 7- Solar Window Assembly

VII. Controller Electronics Commercialization

The Controller Electronics (CE) used in LLCD and LCRD is basically a commercial off-the-shelf space qualified computer with just a few modifications; the software is the critical component and it was modified in going from LLCD operations at the Moon to LCRD operations in GEO. The CE interprets commands to configure the Optical Module (OM) in order to provide proper pointing for optical communications operations. The CE contains the processor for the Pointing, Acquisition and Tracking (PAT) algorithm and all the analog interfaces for the OM. The closed loop system operates at 5 kHz. The CE receives commands from the Space Switching Unit (SSU) which acts as the LCRD payload C&DH. The LCRD communication to the host spacecraft is a MIL-STD-1553B interface, which is a card within the CE box. The 1553 communications passes through the CE to SSU via a SpaceWire interface where the command is processed and directed. The CE is being fabricated and tested by Moog Broad Reach of Golden, Colorado.

VIII. Modem Commercialization

LCRD will support Differential Phase Shift Keying (DPSK) which has better sensitivity and fading tolerance than simple on-off-keying, although less sensitivity than Pulse Position Modulation (PPM). DPSK can be used at extremely high data rates using commercial components, and because of the use of a single-mode receiver (received light is coupled into a single-mode optical fiber which serves as a spatial filter) and optical bandpass filtering, supports communications when the Sun is in the field of view. LCRD leverages a MIT Lincoln Laboratory previously designed DPSK modem [5, 6] as a cost effective approach to providing a DPSK signal. It can both transmit and receive data at an (uncoded) rate from 72 Mbps to 2.88 Gbps. In future relay scenarios, it could be replaced by a higher rate DPSK modem that would support data rates beyond 10 Gbps.

The DPSK modem employs identical signaling for both the uplink and downlink directions. The DPSK transmitter generates a sequence of fixed duration pulses at a 2.88 GHz clock rate. A bit is encoded in the phase difference between consecutive pulses. As demodulation is accomplished with a single Mach-Zehnder optical interferometer regardless of data rate, the clock rate remains fixed. The DPSK transmitter utilizes a Master Oscillator Power Amplifier (MOPA) architecture similar to the PPM transmitter used in LLCD [10]. The Erbium Doped Fiber Amplifier (EDFA) amplifies the optical signal to a 0.5-W average power level. Data rates below the maximum are accomplished via “burst-mode” operation, where the transmitter sends pulses only a fraction of the time, sending no optical power the remainder of the time. Since the EDFA is average power limited, the peak power during the bursts is increased; thus the rate reduction is accomplished in a power efficient manner.

The DPSK receiver has an optical pre-amplifier stage and an optical filter, at which point the light is split between a clock recovery unit and the communications receiver. The receiver uses a delay-line interferometer followed by balanced photo-detectors to compare the phases of consecutive pulses, making a hard decision on each channel bit. While coding and interleaving will be applied in the ground terminal to mitigate noise and atmospheric fading, the DPSK flight receiver does not decode nor de-interleave. The modems instead support a relay architecture where up- and down-link errors are corrected together in a decoder located at the destination ground station [6].

LCRD will also support pulse position modulation (PPM) utilizing the same modem that supports DPSK. The transmitter utilizes the same 2.88 GHz clock rate, and modulates the signal with a sequence of 16-ary PPM symbols (signal is placed in exactly one of each 16 temporal slots). When operating in PPM mode, the receive modem utilizes the same optical pre-amplification and optical filter as is used in DPSK. The optical signal is converted to an electrical signal by means of a photo-detector. The electrical signal in each slot is compared to a threshold (which can be varied to account for atmospheric turbulence) in a simple, yet sensitive PPM receiver implementation. This method leverages previous work performed by MIT Lincoln Laboratory [11].

This particular modem design has not been commercialized yet, but NASA and MIT Lincoln Laboratory have been studying several approaches to do just that. Having a commercial supplier for the modem will make all of the components needed for a space optical communications terminal be readily available for future Near Earth science and exploration missions.

IX. Space Switching Unit Commercialization

The Space Switching Unit (SSU) is basically the “glue” on the LCRD flight payload that interconnects the two optical communications terminals. The unit is the central Command and Data Handling unit for the flight payload. The SSU provides the following core functions:

- Passes high speed data frames between multiple optical space terminals based on frame addressing
- Loads firmware and software into each Integrated Modem at start-up
- Receives commands from host spacecraft and optical ground stations (originating from LMOC)
- Sends health and status telemetry to LMOC via host spacecraft and optical ground stations
- Distributes time packets via SpaceWire interfaces

The SSU hardware is being produced by SEAKR Engineering of Denver, Colorado and the software is designed by MIT Lincoln Laboratory, making the entire unit basically commercially available for future missions.

X. LEO Terminal Concept

NASA and MIT Lincoln Laboratory are currently studying the concept of putting an optical communications terminal on a Low Earth Orbit (LEO) spacecraft. The terminal would be based on the LLCD / LCRD Type Optical Module, the Controller Electronics, and the LCRD DPSK modem. However, some important modifications would have to be made in order for the terminal to provide high rate communications from the LEO to the GEO relay. That is due to the larger distance involved in LEO to GEO communications relative to GEO to Earth and due to the LEO spacecraft's higher velocity. Specifically, the output laser power needs to be increased from 0.5 Watts to approximately 3 Watts, a beacon needs to be added to the terminal, the gimbal range of motion needs to be increased, and a larger point-ahead angle needs to be supported.

Of these changes, the higher laser power to cover the increased range is the easiest to accommodate. Testing has been done on various components in the OM to confirm that a higher laser power will not cause any degradation in performance. In fact, high power tests in excess of 10 Watts will be performed to understand the limits of the OM design to accommodate either higher data rates in the future or increased range.

The hardest change to accommodate is the addition of a beacon. The LCRD GEO terminal expects to see a beacon to aide acquisition from one of the ground stations. That beacon will have to be provided by the LEO terminal. In the future, it is expected that the beacon wavelength will be provided by the terminal flying on the future GEO relay; another option would be to use a beaconless approach to pointing and acquisition, which has been studied by NASA in the past. A promising option for an upcoming LEO demonstration is to mount an external beacon that is co-aligned on the side of the OM.

XI. Standardization

To ensure compatibility in the future between user spacecraft and the relay spacecraft, or between a spacecraft and an optical ground station, an optical communications standard will have to be created and maintained.

NASA would like to see a worldwide standard created for optical communications. This would enable cross support by other space agencies, possibly increasing the number of communication paths available to a given mission. Cross support is where one space agency uses its communications infrastructure to support the mission of another country.

To that end, NASA participated in the Interagency Operations Advisory Group (IOAG) Optical Link Study Group (OLSG). The IOAG is an organization made up of international space agencies that provides a forum for identifying common needs, coordinating space communications policy, high-level procedures, technical interfaces, and other matters related to interoperability and space communications.

The OLSG was established by IOAG to assess if there is a "business case" for cross support in the space communication domain for optical space communication. The OLSG assessed the case by defining mission scenarios, developing a credible operational concept for each scenario, and examining the corresponding space communication system designs, estimated costs, and their expected performance. The OLSG found that "cross support will allow sharing of the cost and usage of the global optical terminal infrastructure needed to serve future missions, and will boost missions' scientific return." [12]

Earth relay satellites are expensive to develop, build, and operate. Sharing of an Earth relay satellite will reduce the cost of providing worldwide coverage for optical inter-satellite communication links. Sharing of Earth relay satellites should also provide higher availability by making more resources available to a specific spacecraft.

While optical ground stations are much less expensive to develop and build, sharing those resources will also help to make optical communications more reliable and affordable. Optical communications through the Earth atmosphere is nearly impossible in the presence of most types of clouds. Therefore, the optical communication system solution for a particular mission has to utilize optical ground stations that are geographically diverse, such that there is a high probability of a cloud-free line of site (CFLOS) to a ground station from a spacecraft at any given point in time (e.g. at the same longitude, or at a sufficient number of stations at different longitudes to allow the stored onboard data to be transmitted within the allocated time). Sharing ground stations around the world help to increase the probability of getting the data to the ground within the time period required.

The OLSG Final Report [14] recommended that the Consultative Committee for Space Data Systems

(CCSDS) form an Optical Communications Working Group to develop world-wide standards for space optical communications. The CCSDS is a multi-national forum for the development of communications and data systems standards for spaceflight comprised of the world's major space agencies. The goal of the CCSDS is to enhance governmental and commercial interoperability and cross-support, while also reducing risk, development time and project costs..

The CCSDS did indeed form an Optical Communications Working Group which had its kick-off meeting in January 2014. The working group plans to develop:

- New standards in wavelength, modulation, coding, interleaving, synchronization and acquisition which are likely different from existing RF standards
- New standards for definition, exchange and archiving of weather data for predicting and operating optical links among optical ground stations and their network operations centers

Standards specifically for space optical communications are required for the modulation, coding, interleaving, synchronization, and acquisition of signals and will have to take into account the severe impact of the Earth's atmosphere on space-to-ground links. The atmospheric impacts on the link are typically more severe than the corresponding impacts on RF links. Several space agencies are developing optical communications terminals that can support both space-to-ground and space-to-space links and the objective is to develop maximum synergy, as far as practical, between the various scenarios.

In addition to the typical standards that have to be developed for any communications system, such as modulation and coding, space optical communications also requires a standard for the definition, exchange and archiving of weather and atmospheric data. That is because optical space communications through Earth's atmosphere is nearly impossible in the presence of most types of clouds. Therefore, the optical communication system solution for a particular mission has to utilize optical ground stations that are geographically diverse, such that there is a high probability of a cloud-free line of site (CFLOS) to at least one ground station from the spacecraft at any given point in time. The exchange of weather and atmospheric data among optical ground stations and network operations center is critical to maximizing the data return from a mission while efficiently utilizing the various optical ground stations involved. The new working group will define the physical parameters that should be collected and shared between ground stations via existing CCSDS cross support services.

XII. Conclusion

Optical Communications is an important communications technology for future space missions. It has the potential to enable new science and exploration missions throughout the solar system. Optical communications can provide increasingly higher data rates over comparable RF systems. While the capacity of current and near-term RF communications technology is still increasing, it is eventually limited by bandwidth allocation restrictions, power requirements, flight terminal antenna size, and weight limitations. The cost and complexity of expanding the existing Space Communications Networks to enable these higher data rates using RF solutions alone with large aperture antennas is a significant undertaking. A future Space Communications Network should offer both RF and optical communication services. RF can be reserved for those cases where high availability and thus low latency is absolutely required, since optical communications through the atmosphere for space to Earth links will always be impacted by clouds. For space to Earth links, optical communications can be reserved for scenarios in which a potential delay in reception is not a problem; in space to space links, optical communications can provide both high data rates and high availability. In both space to space and space to Earth links, optical communications can potentially provide high data rates with smaller systems on user spacecraft and on the ground.

NASA's recent success with the Lunar Laser Communication Demonstration, proving the feasibility of optical communications from the Moon, was a critical first step for NASA. NASA's next step in high rate optical communications is the upcoming Laser Communications Relay Demonstration (LCRD) which will launch in 2018. LCRD will provide two years of continuous high data rate optical communications in an operational environment, demonstrating how optical communications can meet NASA's growing need for higher data rates or how it enables lower power, lower mass communications systems on user spacecraft. LCRD is a critical stepping stone to providing optical communication services on NASA's Next Generation Tracking and Data Relay Satellite to be flown sometime next decade.

The authors strongly believe that the next generation relay satellite will supply both RF and optical services. To facilitate that, a commercial supplier of compatible space optical terminals needs to exit. Finally, a standard for space optical communications needs to be developed to enable inoperability. Ideally, an international standard will be created in the future to allow optical communications terminals built by one country to use the infrastructure of another. It is definitely an exciting time to be working in this critical technology area.

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