

Commercialization and Standardization Progress towards an Optical Communications Earth Relay

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Abstract— NASA is planning to launch the next generation of a space based Earth relay in 2025 to join the current Space Network, consisting of Tracking and Data Relay Satellites in space and the corresponding infrastructure on Earth. While the requirements and architecture for that relay satellite are unknown at this time, NASA is investing in communications technologies that could be deployed to provide new communications services. One of those new technologies is optical communications. The Laser Communications Relay Demonstration (LCRD) project, scheduled for launch in 2018 as a hosted payload on a commercial communications satellite, is a critical pathfinder towards NASA providing optical communications services on the next generation space based relay. This paper will describe NASA efforts in the on-going commercialization of optical communications and the development of inter-operability standards. Both are seen as critical to making optical communications a reality on future NASA science and exploration missions. Commercialization is important because NASA would like to eventually be able to simply purchase an entire optical communications terminal from a commercial provider. Inter-operability standards are needed to ensure that optical communications terminals developed by one vendor are compatible with the terminals of another. International standards in optical communications would also allow the space missions of one nation to use the infrastructure of another.

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1. INTRODUCTION

The communications link between space-based observatories and Earth has long been a critical mission system driver. Sometimes, information from a space-based observing, scientific or exploration mission must be returned to Earth with as low latency as possible. For example, low latency and high availability is extremely

important for human exploration missions. Earth relay satellites are satellites placed in geostationary orbit (GEO) to relay information to and from non-GEO satellites, aircraft, scientific balloons, 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 increases the amount of time that a spacecraft in Earth orbit, especially in low Earth orbit (LEO), can be in communications with a mission operations center. This increase contact time can also dramatically increase the amount of data that can be transmitted to Earth.

NASA's 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. There are currently three different generations of spacecraft in orbit and NASA is studying the requirements for a future generation to be launched around the 2025 timeframe.

NASA is currently performing an architecture study to help the agency make decisions about what services and capabilities will be onboard the next generation satellites. While the exact requirements are currently unknown, NASA is investing in communications technologies that could be deployed on the satellite to provide new communications services. One of those new technologies is optical communications.

Several space agencies are currently working on space based optical communications. The primary motivation stems from the expectation that substantially higher (at least 10 times) data rates than Radio Frequency (RF) based solutions might be feasible with similar user spacecraft onboard terminal burden (mass, volume and power). In addition, optical communications can also be used at comparable RF data rates in order to lower the user communication system's required mass, volume, and power. Finally available RF spectrum is also becoming an issue in high data rate applications.

2. THE LASER COMMUNICATIONS RELAY DEMONSTRATION

In order to gain more knowledge and experience in the area of space based optical communications relay services,

NASA is embarking on the Laser Communications Relay Demonstration (LCRD) to launch on a commercial communications satellite no earlier than December 2018 [1]. 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 optical communications from geostationary orbit to two ground stations located in the United States. NASA is also considering flying an optical communications terminal on a Low Earth Orbit (LEO) spacecraft, such as the International Space Station, to test inter-satellite links with LCRD. LCRD will leverage NASA's investment in the Lunar Laser Communication Demonstration (LLCD) [2] which launched to the Moon in September 2013 as a secondary payload on the Lunar Atmosphere and Dust Environment Explorer (LADEE). LLCD was a great success and proved the feasibility of high rate deep space optical communications, but due to the very limited operating time available during that mission, it did not provide enough operational experience to allow NASA to immediately deploy optical communications on a mission critical platform such as TDRS; LCRD will close that gap when it launches to GEO in a few years.

To make optical communications truly available to NASA future projects, long mission life space terminals must be proven. In addition, optical communications through Earth's atmosphere, such as via a space to ground link, requires a robust operational concept for reliable high-rate data delivery in the face of terrestrial weather variations. To increase the availability of a space to ground optical communications link, which is impacted by clouds, there needs to be a demonstration of handover among multiple ground sites. For Near Earth applications, a demonstration needs to show the relaying of an optical communications signal in space. There also needs to be a demonstration of the modulation and coding suitable for very high rate links.

LCRD's flight payload 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.

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 1 milliradian. It is used both for detection and coarse tracking of an uplink signal. The telescope is mounted to a two-axis gimbal 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 modems are provided by a controller. Each

optical module is held and protected during launch with a cover and one-time launch latch.

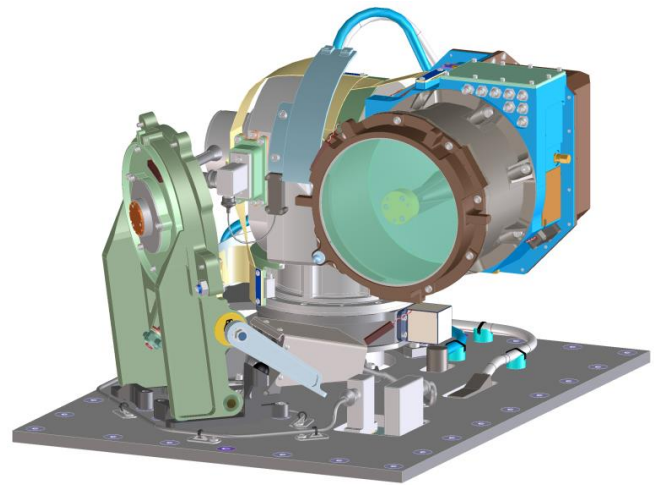


Figure 1 – Inertially Stabilized Optical Module

The LCRD Ground Segment is comprised of the LCRD Mission Operations Center (LMOC) and two ground stations: Ground Station 1 and Ground Station 2. 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 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. This architecture will allow the mission to demonstrate:

- High rate bi-directional communications between Earth and Geosynchronous Earth Orbit (GEO)
- Real-time optical relay from one Ground Station on Earth through the GEO flight payload to the second Ground Station
- Differential Phase Shift Keying Modulations suitable for Near Earth high data rate communications
- Demonstration of various mission scenarios through spacecraft simulations at the Earth ground station
- Performance testing and demonstrations of coding and link layer protocols over optical links over an orbiting testbed.

LCRD will support differential phase shift keying (DPSK) which can be used at extremely high data rates and has

sufficient background tolerance to support communications when the sun is in the field of view. LCRD leverages a DPSK modem previously designed by MIT Lincoln Laboratory [3] 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 will utilize the same 2.88 GHz clock rate, and 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.

3. 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.

3.1 Optical Module Commercialization

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.

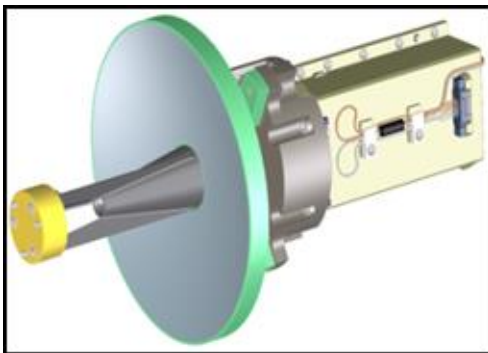


Figure 2 - Optical Assembly

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.

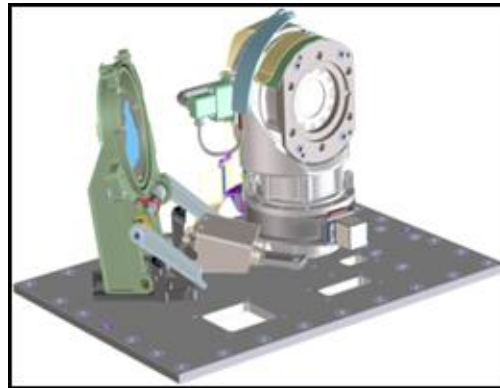


Figure 3 - Gimbal and Latch Assembly

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.

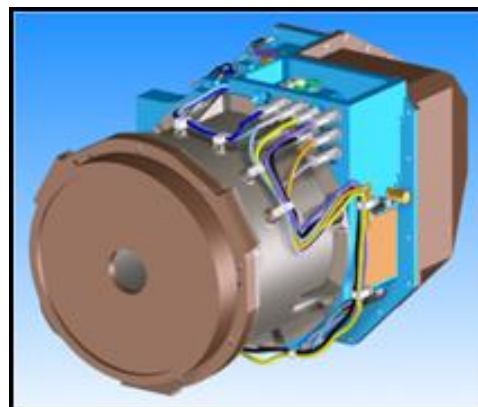


Figure 4 - Inertially Stable Platform

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.

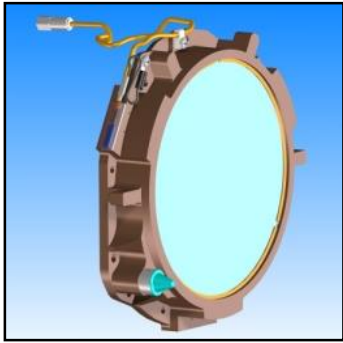


Figure 5- Solar Window Assembly

3.2 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.

3.3 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.

3.4 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 the future missions.

4. INTERNATIONAL STANDARDIZATION

In order to enhance the use of optical communications worldwide and to allow the sharing of communications infrastructure such as optical ground stations and optical relay satellites, the world’s major space agencies are engaged in developing international standards for space optical communication systems as has been done with radio frequency (RF) communications [4].

In 1982, the world’s major space agencies formed an organization to address the issue of providing commonality in space data systems that would allow one member’s spacecraft to be served by other members’ ground antennas. The organization was named the Consultative System for Space Data Systems (CCSDS). The CCSDS is a huge success and today it is a multi-national forum for the development of communications and data systems standards for spaceflight comprised of the world’s major space agencies and observer agencies. Presently, there are 11 member agencies, 29 observer agencies, and 151 commercial associates. The member and observer agencies represent 27 nations plus several European organizations. The stated goal of the CCSDS is to enhance governmental and commercial interoperability and cross-support, while also reducing risk, development time and project costs. Consensus has to be reached by the member agencies before a CCSDS standard can be published.

Since its founding CCSDS has developed standards recommendations, which have become ISO standards, for space link communications and for associated ground data systems. These standards enable interoperability and cross

support among the international space agencies. There are over 130 active CCSDS publications to date.

As the standards have been developed over the past 30 years, the international space agencies have gradually updated their ground space communication antennas and ground data systems to implement the cross support standards. As more and more systems have adapted the CCSDS standards, the agencies have begun to enjoy the benefits of cross support. It has increased options for spacecraft communications and reduced the cost of supporting a single agency’s spacecraft by using communications assets of other agencies to service their spacecraft’s communication needs.

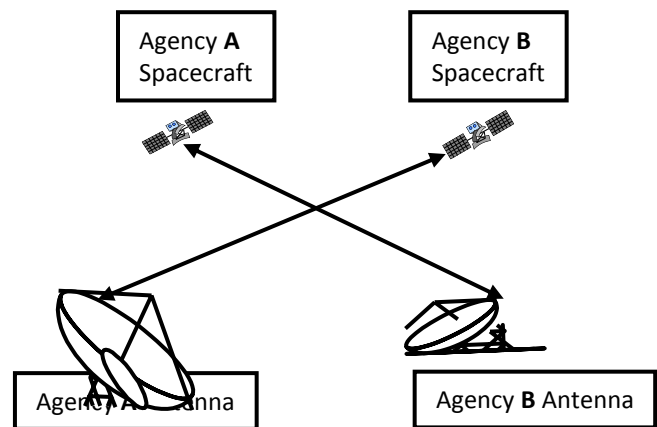


Figure 6: Cross Support

The CCSDS officially formed an Optical Communications Working Group to develop world-wide standards for space optical communications. The Working Group is co-chaired by NASA and the European Space Agency and it 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 communication 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.

The Working Group currently expects to develop standards for two different scenarios: high photon flux links and low photon flux links. High photon flux links are expected to be used for Near Earth applications where extremely high data rates are desired. Low photon flux links are expected to be used for deep space direct-to-Earth links and are basically “photon starved” links; these links could also be used in Near Earth applications where there is limited mass and power to support communications, such as on a CubeSat. Likewise, high photon flux links could be used in deep space, such as from the surface of Mars to Mars orbit. It is expected that the underlying technologies and techniques for modulation, coding, and synchronization will be significantly different between the two signal cases.

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-sight (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 [10]. The new working group will define the physical parameters that should be collected and shared between ground stations via, if possible, existing CCSDS cross support services.

The Working Group currently plans to develop the following CCSDS books:

- 1) Blue Book for Optical Communications Physical Layer
- 2) Blue Book for Optical Communications Coding and Synchronization
- 3) Green Book for Optical Communications Concepts and Terminologies
- 4) Green Book for Real-Time Weather and Atmospheric Characterization Data
- 5) Green Book for Optical Communications Physical Layer and Coding and Synchronization Sublayer
- 6) Blue or Magenta Book(s) for Real-Time Weather and Atmospheric Characterization Data

The Working Group has started working on the first four books with the goal of publishing the books in a couple of years; work on the last two books will start sometime in the

future as resources permit. The first four books are described below.

The Blue Book for Optical Communications Physical Layer shall define the physical layer parameters and techniques required for interoperability of optical communications. It will address low and high photon flux signal scenarios for space-to-Earth and space-to-space links and will standardize one or more techniques for them. This book will focus on modulations for low and high signal photon flux scenarios and with pointing, acquisition, and tracking. The German Aerospace Agency, DLR, has volunteered to be the CCSDS Book Editor for this book.

The Blue Book for Optical Communications Coding and Synchronization shall define the coding, synchronization, interleaving parameters and techniques required for interoperability of optical communications. It will address low and high photon flux signal scenarios for Space-to-Earth and space-to-space links link and standardize one or more techniques for them. NASA has volunteered to be the CCSDS Book Editor for this book.

The Green Book for Optical Communications Concepts and Terminologies will define common terminology and atmospheric models to be used in link and pointing budget calculations, and define a basic concept of operations, including how to conduct handovers from one location to the next. The book will focus on terminology definitions, atmospheric models, and how to perform link and pointing budget calculations. ESA has volunteered to be the CCSDS Book Editor for this book.

The Green Book for Real-Time Weather and Atmospheric Characterization Data will define the physical quantities to be measured at existing and potential optical ground station sites in support of space-to-Earth links CFLOS (Cloud Free Line of Sight) and link budget calculations. The book will include material showing how to produce and use long term weather and atmospheric statistics and how to take real-time measurements. The book will also touch on performing predictive weather in support of optical communications handovers. NICT has volunteered to be the CCSDS Book Editor for this book.

5. SUMMARY

NASA is currently studying different architectures and capabilities for the next generation of Tracking and Data Relay Satellites. With the success of NASA’s recent Lunar Laser Communication Demonstration, there is a lot of interest in providing mission critical communications via optical communication technology on these future satellites.

NASA’s Laser Communications Relay Demonstration will be the necessary pathfinder for future GEO relay services when in launches in late 2018. LCRD will provide two years of continuous high data rate optical communications

via a hosted payload on a commercial communications satellite.

To facilitate the adoption of optical communications by NASA science and exploration missions, a commercial supplier of space terminals compatible with terminals on the next generation Tracking and Data Relay Satellites need to exist. Ideally, more than one commercial source should be developed and terminals from one source should be compatible with the terminals from another source.

A set of standards for space optical communications needs to be developed to enable interoperability between terminals from different commercial sources. Ideally, an international standard will be developed and accepted by the major space agencies worldwide. An international standard will allow optical communications terminals built by one space agency to use the infrastructure of another. Collaboration in optical communications will lower mission cost and risk and likely enable missions which otherwise are unaffordable by one nation on their own. This is the evolutionary next step to today's existing RF cross support.

ACKNOWLEDGEMENTS

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BIOGRAPHIES



Bernard L. Edwards is the Chief Communications Systems Engineer at NASA Goddard Space Flight Center. He received a B.S. in Electrical Engineering in 1989, a M.S. in Electrical Engineering in 1991, and a M.S. in Computer Science in 1993 all from the Johns Hopkins University. He supports the NASA representative to the Interagency Operations Advisory Group (IOAG), and helps represent NASA in the Consultative Committee for Space Data Systems (CCSDS) in the area of optical communications. He has been involved in various NASA optical communication projects and technology developments since coming to NASA in 2000.



David J. Israel is the Principal Investigator for the Laser Communications Relay Demonstration (LCRD) and the Space Communications Manager in the Exploration and Space Communications Projects Division at Goddard Space Flight Center. He has been working on various aspects of space communications systems, since joining NASA in 1989. He received a B.S.E.E from Johns Hopkins University in 1989 and M.S.E.E. from George Washington University in 1996. He has led the development of various Space Network/Tracking and Data Relay Satellite System (TDRSS) operational systems and has been the principal investigator for multiple communications technology activities concerning advanced transceiver concepts and IP protocols, including the LPT CANDOS experiment on STS-107. He was a member of the Interagency Operations Advisory Group (IOAG) Space Internetworking Strategy Group (SISG) and the lead for NASA Space Communications and Navigation Program Space Internetworking Study.