NASA'S CURRENT ACTIVITIES IN FREE SPACE OPTICAL COMMUNICATIONS

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I. INTRODUCTION

NASA and other space agencies around the world are currently developing free space optical communication systems for both space-to-ground links and space-to-space links. This paper provides an overview of NASA's current activities in free space optical communications with a focus on Near Earth applications. Activities to be discussed include the Lunar Laser Communication Demonstration, the Laser Communications Relay Demonstration, and the commercialization of the underlying technology. The paper will also briefly discuss on-going efforts and studies for Deep Space optical communications. Finally the paper will discuss the development of international optical communication standards within the Consultative Committee for Space Data Systems.

II. LUNAR LASER COMMUNICATION DEMONSTRATION

NASA launched the Lunar Atmosphere and Dust Environment Explorer (LADEE) spacecraft in September 2013. On board the spacecraft was a technology demonstration of optical communications, referred to as the Lunar Laser Communication Demonstration (LLCD) [1]. The demonstration consisted of an optical communications terminal in lunar orbit, a primary optical ground station, and two additional backup optical ground stations. The demonstration was a joint effort between NASA Goddard Space Flight Center, MIT Lincoln Laboratory, NASA Jet Propulsion Laboratory, and the European Space Agency (ESA). The primary ground station, referred to as the Lunar Lasercom Ground Terminal, was specifically designed for LLCD to meet all of the requirements, and it was located at White Sands, New Mexico, and operated by MIT Lincoln Laboratory. The two backup optical ground stations existed before LLCD and they were modified to support the demonstration, but could not operate at the highest data rates. The Optical Communications Telescope Laboratory at Table Mountain, California was a backup optical ground station operated by NASA Jet Propulsion Laboratory; the other backup optical ground station was the European Space Agency's Optical Ground Station at Tenerife, Spain. LLCD proved the feasibility of optical communications from beyond Earth orbit by routinely transmitting at rates up to 622 Mbps from the Moon. The demonstration was a huge success and opened the door for future project managers and systems engineers to consider the technology for their missions.

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 Disruption Tolerant Networking (DTN) over optical links

III. LASER COMMUNICATIONS RELAY DEMONSTRATION

NASA's next step in high rate optical communications is the Laser Communications Relay Demonstration (LCRD) [2]. 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.

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. 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. MIT Lincoln Laboratory and NASA Goddard Space Flight Center will make modifications to the LLCD Lunar Lasercom Ground Terminal (LLGT) so that it can be used as Ground Station 2 for LCRD. The primary enhancement for both ground stations is the addition of an adaptive optics system to couple received light into a single mode fiber to support the DPSK signal.

The LCRD architecture will allow the mission to:

- 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
- Demonstrate 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
- Support performance testing and demonstrations of coding and link layer protocols over optical links via an orbiting testbed

IV. NEAR-EARTH OPTICAL COMMUNICATIONS COMMERCIALIZATION EFFORTS

In order to make optical communications more easily available to future NASA science and exploration missions and to reduce costs, NASA would like at least one commercial provider for an entire optical communications terminal. NASA's current vision is to use an LLCD / LCRD type optical module in as many scenarios as possible. Studies show that the 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.

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.

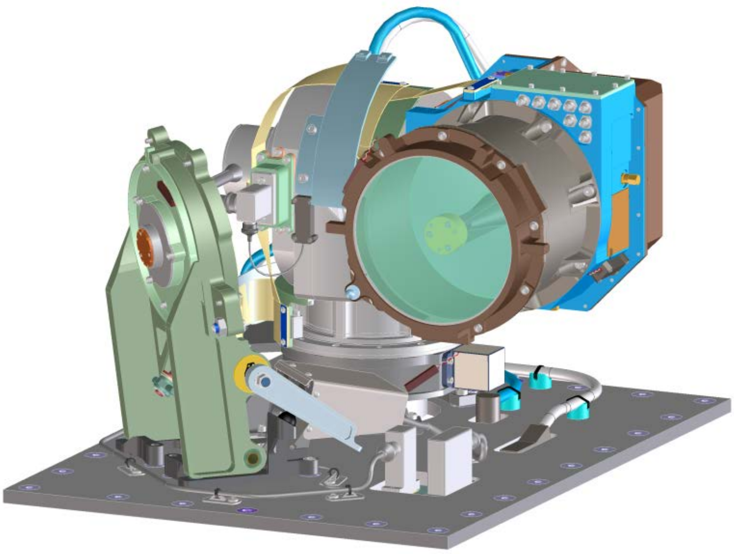

Figure 1 - Inertially Stablized LLCD / LCRD Type Optical Module

A. Optical Module Commercialization

Commercialization of a LLCD / LCRD type optical module has already started, and the 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.

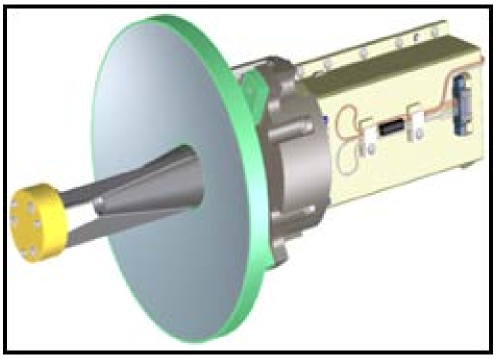

Figure 2 - Optical Assembly

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.

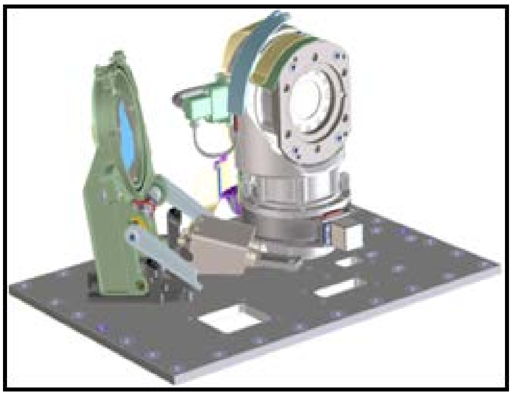

Figure 3 - Gimbal and Latch Assembly

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.

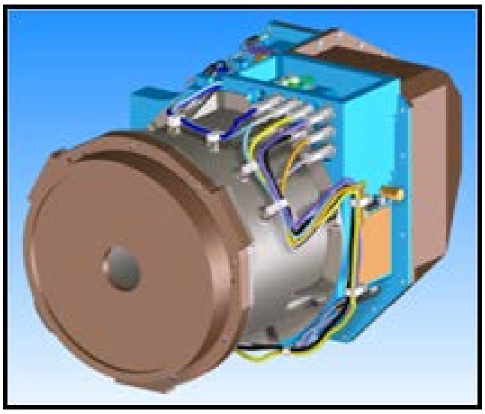

Figure 4 - Inertially Stable Platform

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

B. 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 CE is being fabricated and tested by Moog Broad Reach of Golden, Colorado.

C. 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 [3, 4] 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. 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.

LCRD’s DPSK modem will also support pulse position modulation (PPM). 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 [5].

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.

D. 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.

V. ON-GOING DEEP SPACE EFFORTS

In the area of Deep Space optical communications, NASA Jet Propulsion Laboratory is developing a Deep Space terminal for long haul communications, and performing a separate study of putting an optical terminal on the Mars 2020 rover to support proximity communications around Mars and to perform a very limited direct-to-Earth demo

The long haul Deep Space terminal design was started under a project called Deep Space Optical Terminal (DOT). That was simply a concept development and technology maturation project. DOT was being designed to support at least 100 Mbps from a distance of 0.42 AU to a 5 meter optical ground station at Earth and at least 250 Mbps to a 12 meter optical ground station. [6] The goal of the concept development was is to develop a preliminary design of an optical communications terminal that could demonstrate 10 times the current RF performance using the same mass and power. [7] The system would use photon counting Pulse Position Modulation for both the uplinks and downlinks. Today, however, NASA HQ has asked that JPL move the work into an actual space flight hardware development project with the goal of building and flying a terminal as soon as possible. With that in mind, in the July 2014draft Discovery Announcement of Opportunity released by NASA’s Science Mission Directorate, there is mention of the next Discovery mission carrying a Deep Space Optical Communications (DSOC) technology demonstration. Since it is tied to an Announcement of Opportunity, which is basically a competition for the best mission idea for NASA to execute, all details of DSOC are currently embargoed but hopefully will be released soon to potential proposers.

The other area that the Jet Propulsion Laboratory is working on is for a small optical terminal to possibly be mounted on the Mars 2020 rover. Such a terminal would primarily provide proximity communications with an overhead relay satellite; of course a satellite carrying an optical communications terminal would have to be launched before that could happen. A secondary function would be to do a very limited demonstration from the surface of Mars to the surface of Earth at very low data rates.

VI. INTERNATIONAL STANDARDIZATION EFFORTS

At the beginning of the Space Age each international space agency began developing their own space communication capabilities to communicate with their spacecraft. Most of them did use the same radio frequency band, known as S-band, for spacecraft communication, but that was typically the only commonality among the networks. The result was that in order to provide global coverage for their spacecraft, each agency had to build their own ground stations around the Earth. They could not share each other’s ground stations since they did not have a common set of communication protocols; they only had a common frequency band.

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). Today, the CCSDS is a huge success and it is a multi-national forum for the development of communications and data systems standards for spaceflight. The organization is 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.

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. As of the writing of this paper, 609 space missions have adopted and used various CCSDS standards.

With all of the optical communication demonstrations being performed around the world, and with the building of experimental ground stations, the Inter-Agency Operations Advisory Group commissioned a study in 2010 on the business case for establishing cross support standards for optical communications. The study group was named the Optical Link Study Group (OLSG) and it was co-chaired by NASA and ESA.

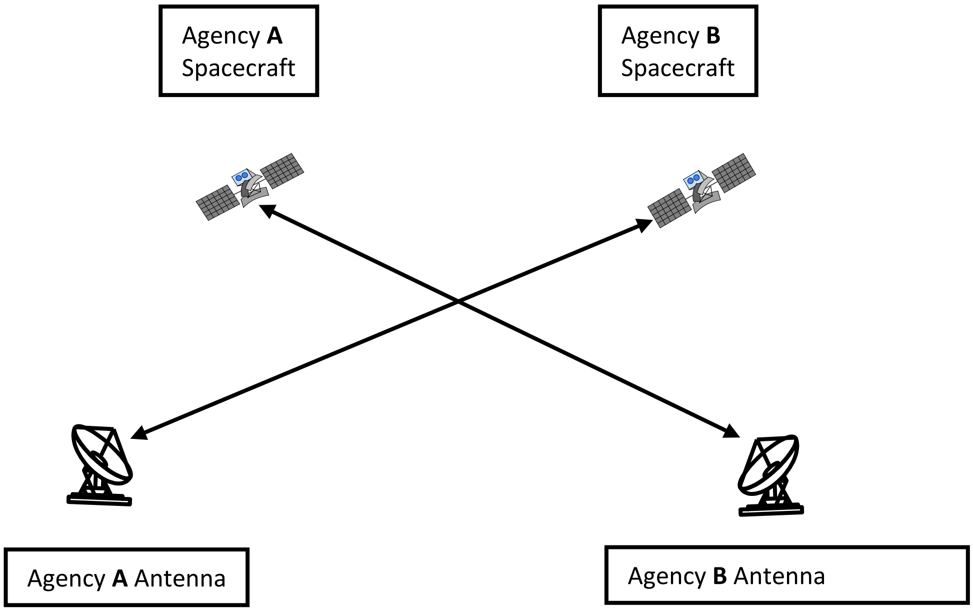

Figure 6: Cross Support

The OLSG had six member agencies and assessed the business 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. Some of the scenarios that the OLSG looked at were Earth relay satellites, Low Earth Orbit (LEO) direct-to-ground, lunar direct-to-Earth, and deep space optical direct to Earth communications. In all of the scenarios examined, 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" [9]. Thus it found there is a business case for cross support of optical communications for space links. The OLSG completed its Final Report in 2012, with an official addendum with more details added in 2013, stating that a business case had been found for optical communication cross support. [10] Having a worldwide standard for optical communications would enable cross support by other space agencies, thereby increasing the number of communication paths available to a given mission. The OLSG recommended that the IOAG ask CCSDS to form an Optical Communications Working Group to develop an international standard for optical communications to facilitate the worldwide deployment of this technology. As in the case of radio frequency standards, having an international standard for optical communications would allow one space agency to use the optical ground stations of another.

The CCSDS Optical Communications Working Group is co-chaired by NASA and ESA 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.

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 [11]. 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.

VII. CONCLUSION

In recent years there have been significant advancements in the development of laser based communication systems for space applications. These optical communication systems hold the promise of better than an order of magnitude higher data rates over RF space communications while using less power, having lower mass, and occupying less volume than comparable RF communication systems. A few international space agencies have already begun to demonstrate the technology in space and build experimental ground stations.

NASA has completed an in space demonstration of a high rate optical communications systems. The Lunar Laser Communication Demonstration was a complete success and demonstrated 622 Mbps from lunar orbit to the Earth's surface. NASA is following that demonstration with the Laser Communications Relay Demonstration, which will put two optical communications terminals on a commercial communications satellite. As part of that demonstration, NASA is also embarking on the commercialization of the underlying technology so that future missions will have a commercial source for their optical terminals. In addition to the work going on for Near Earth applications, NASA is also continuing to develop Deep Space optical communications concepts and technologies and is embarking on a flight project for an upcoming Deep Space mission. Finally, NASA is working with the international community to develop an international standard for optical communications; such a standard will allow space missions of one agency to use the optical communications infrastructure of another. It is an exciting time for the development of this advance form of communications.

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