

A Geosynchronous Orbit Optical Communications Relay Architecture

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Abstract— NASA is planning to fly a Next Generation Tracking and Data Relay Satellite (TDRS) next decade. While the requirements and architecture for that satellite are unknown at this time, 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. The Laser Communications Relay Demonstration (LCRD) project, scheduled for launch in December 2017 as a hosted payload on a commercial communications satellite, is a critical pathfinder towards NASA providing optical communications services on the Next Generation TDRS. While it is obvious that a small to medium sized optical communications terminal could be flown on a GEO satellite to provide support to Near Earth missions, it is also possible to deploy a large terminal on the satellite to support Deep Space missions. Onboard data processing and Delay Tolerant Networking (DTN) are two additional technologies that could be used to optimize optical communications link services and enable additional mission and network operations. This paper provides a possible architecture for the optical communications augmentation of a Next Generation TDRS and touches on the critical technology work currently being done at NASA. It will also describe the impact of clouds on such an architecture and possible mitigation techniques.

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 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 spacecraft communications in the Near Earth vicinity. 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.

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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, and Earth stations that otherwise would not be able to communicate at all or would

2. RELAY ARCHITECTURE

A minimal relay satellite would have 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. Both the inter-satellite link and the space-to-ground link could be RF or optical. A future complex relay could 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. There is no single right answer as it really depends on the requirements to be met, the state of the art and the cost of the technology at the time the decision is made to build a relay, the availability of RF spectrum, etc. 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. As exhibited by the current Space Network, using RF, only one ground station would be required to support the Earth relay with very high availability. 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 Gb/s 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 and onboard storage, or employ a number of optical communication ground stations to support the relay. For example, a future Earth relay could have onboard memory and an RF space to ground link at 1 or 2 Gbps, coupled with an optical space to ground link at 10 Gbps. Thus, some data could be transmitted to Earth via RF, even if all of the optical ground stations were covered by clouds. The RF space to ground link could be eliminated by increasing the amount of onboard storage or the number of available optical ground stations.

A previous study done by the German Aerospace Agency DLR concluded that 11 optical communication ground terminals scattered generally throughout Europe to support a GEO satellite would provide 99.67% availability [1]. That same study showed that 10 ground terminals placed only in the south of Europe would provide 99.89% availability. Further analysis in that study also showed that 8 carefully placed ground terminals in Europe and Africa would provide 99.971% availability. Likewise, a study by NASA showed that five ground terminals carefully located over Maui, California, Chile, Israel, and Europe (Uzbekistan) would result in about 91% availability. The large number of ground stations quoted above assumes that the relay satellite is simply a traditional real-time high-availability link (bent pipe) like most RF communication relay satellites in orbit today. In other words, the optical signal arrives at the relay satellite and then has to be transmitted to the ground instantly. That architecture is one of many possible architectures; it is simple and based on RF heritage, but it may not be the ideal architecture for the future. A future

architecture could use storage and networking protocols to provide sufficient availability, while reducing the number of required ground stations.

A future Earth relay satellite with both RF and optical space to ground links could provide high availability to user spacecraft in LEO. Suppose a downlink data rate of 5 Gb/s was required on the space to ground link from the relay. The Earth relay could have an RF space to ground link with a maximum data rate of 2 Gb/s and an optical space to ground link with a maximum data rate of 5 Gb/s. Assuming there is only one ground terminal on Earth to support the optical space to ground link, the RF link would be a slow-speed backup when the optical link is not available (due to cloud coverage, for example). Of course, there would have to be enough buffer onboard the Earth relay to make this approach work, or the capacity (number of users supported) would have to be limited. If more optical ground terminals were added to support the optical space to ground link, the capacity of the overall Earth relay would increase. A systems engineering trade would have to be conducted to determine the optimal solution from both a technical and cost perspective; since technology and its related costs are constantly changing, such a study would have to be performed when a space agency was ready to deploy an operational system.

The current RF bent-pipe system provides a space relay that takes received RF spectrum from one antenna and frequency and transmits it via a different antenna at a different frequency. This greatly simplifies the relay payload, since no demodulators, modulators, decoders, encoders, or other link processing is required. The bent-pipe system also enhances relay longevity by allowing the evolution to newer communications methods with changes required only to user platform systems and ground systems. The bent-pipe system, however, makes some critical assumptions: all user signals received by the relay are intended for one and only one destination, the destination is in contact with the relay simultaneously as the source, and the trunkline or Space-to-Ground Link is essentially 100% available and reliable.

A relay payload with minimal capabilities to demodulate and modulate signals, which is required for any relay with optical links, allows 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 addition of storage onboard the relay would provide additional benefits. Minimal storage could at least allow for rate buffering and data retransmissions between the relay and destination. This would be especially beneficial for

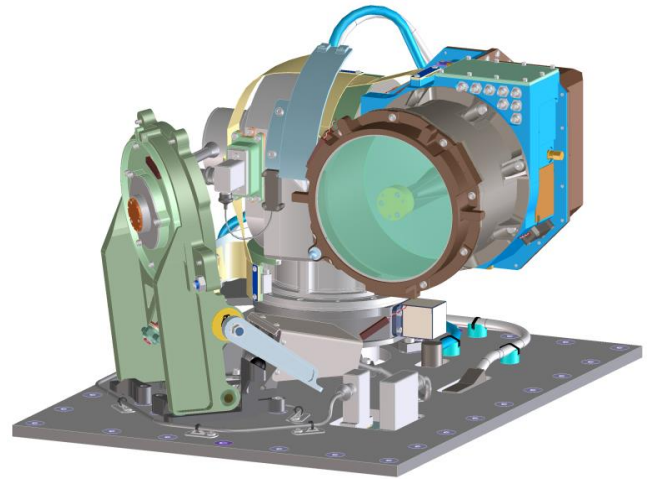
optical links which may have momentary drop outs due to atmospheric effects. An increase in the amount of storage onboard the relay could allow for advanced operations concepts, such as the support of relay links when only one link is available, pre-positioning of user data on the relay for later retrieval, and maximizing bandwidth utilization by multiplexing lower priority stored data with realtime 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 [X].

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.

3. 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 2017. 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) [1] which launched to the Moon in September 2013 as a secondary payload on the Lunar Atmosphere and Dust Environment Explorer (LADEE). LLCD has been a great success and proves the feasibility of 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 to support mission critical communications; 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.

Figure 1- Inertially Stabilized 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 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.

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 Geostationary 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 [1] 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.

4. DEEP SPACE SUPPORT

A satellite in Earth orbit, such as the previously defined GEO relay, could also be augmented with a larger optical system to support optical communications to and from deep space. Such a deep space capability would provide excellent viewing geometry for planetary missions depending on the exact orbit of the relay (See Table 1).

<u>Earth Orbit Type</u>	<u>Average Visibility to Mars (better for outer planets)</u>
LEO	84%
HEO	94%
GEO inclined at 28°	91%
GEO inclined at 65°	95%
2 GEOs separated >20% GEO arc	100%

Table 1. Average Visibility to Mars from Different Earth Orbit Types

Such a system could be used instead of large deep space ground terminals at Earth; the apertures required at Earth would be smaller in space than on the ground since the space platform will be above Earth's atmosphere and its negative impact on optical transmissions; a large deep space ground terminal would have scattered sunlight in the atmosphere and suffer from turbulence which requires a large blur circle (i.e. many spatial modes of background light). A previous NASA study showed that a 2.6 meter aperture in space could provide the same capability from Mars as an 8.1 meter aperture on the ground. Data rates coming back from the planets will most likely be very low, compared to near Earth optical communications transmissions, and thus could be relayed to the ground from the Earth orbiting satellite via either optical or RF. For example, a data rate in the order of 100's of Mbits/second from Mars would already be considered very high speed and beyond the current state of the art for RF communications from Mars. If the deep space transmissions were transmitted from Mars via optical and then relayed from a satellite in Earth orbit using RF, then there would not be weather related outages or the need for handovers due only to weather.

Assuming the use of RF from the relay satellite, the key attributes above imply essentially no unscheduled handovers and fewer scheduled handovers between deep space flight terminals and the Earth relay satellites. This greatly simplifies overall operations and control strategies; this is especially significant for deep space links wherein 2-way light times vary from ten's of minutes (40 min @ Mars at max distance) to several hours (11 hrs @ Pluto). Nominally, all handovers are predictable and can be scheduled well in advance for the Earth relay network concept.

As in the case of a ground terminal on Earth, a deep space terminal on an Earth orbiting relay may also need to transmit a beacon signal and a command link to deep space. Due to atmospheric turbulence effects, ground-based laser powers of 100's watts will be required from the ground. Providing sufficient beacon power from terrestrial lasers is problematic because it raises serious safety and avoidance concerns that will require on-going regulatory coordination -- resulting in increased operational constraints and complexities. For example, previous NASA studies have shown that to provide a beacon signal to Mars that could be used to mitigate spacecraft platform jitter requires only 10 W from a space-based laser vs. 300 W or more for a ground-based laser. The utility of a space-based beacon may be so great that even if

the ultimate receive network consists of only terrestrial telescopes, the associated uplink beacon may very well still be space-based.

With the RF Tracking and Data Relay Satellite System (TDRSS) concept in mind, NASA has been interested in the use of orbiting platforms to support deep space communications since the late 1970's. In the past, very large space apertures were required that stressed technology and cost budgets. In particular, the Deep Space Relay Satellite System (DSRSS) study in the early 1990's concluded that a 15 m Telescope was required based on the near-term optical communications technology capabilities that could be projected at the time.

However, based on the recent technology breakthroughs in laser communications (wherein only fractions of a photon per bit are required) space telescope apertures of 2-3 m diameter appear sufficient to support Mbits/second data rates from Mars. Moreover, there have been significant efforts over the last several years in developing lightweight space telescopes and optics, spurred on by such needs as the James Webb Space Telescope (JWST) and the Single Aperture Far-Infrared (SAFIR) Observatory. Even though, the communications telescope of concern here is a 'Photon Bucket' collector rather than a true 'imager', it is still important that the optics be close to diffraction-limited to reduce the detector size/complexity and to enhance performance. One key difference that makes the deep space optical telescope design more difficult here is that it needs to point to within a few degrees of the sun --- unlike most science observatories that operate at much greater sun angles. This also reinforces the need for good optics to reduce the stray light effects. Thermal effects on the support structures and across the aperture also require careful design attention.

Based on the preceding considerations, NASA has conducted a feasibility assessment of an "integrated" GEO Relay concept that supports mission locations from LEO through Lunar and beyond. In other words, the system "integrates" the RF TDRSS functions with that of an optical terminal(s) for both near Earth and deep space applications. The spacecraft design concept consists of the current TDRS-like spacecraft augmented with: (1) a 2 m telescope aperture for Deep Space optical communications and (2) a smaller 10 to 30 cm telescope for high rate LEO optical communications and support out to the Sun-Earth Libration points L1 and L2 (~ 1 million miles from earth). Figure 3 illustrates the concept. The telescope concept used here to provide the 2 m aperture actually consists of four 1-m telescopes. However, there are many aperture concepts that would have to be considered in an actual design.

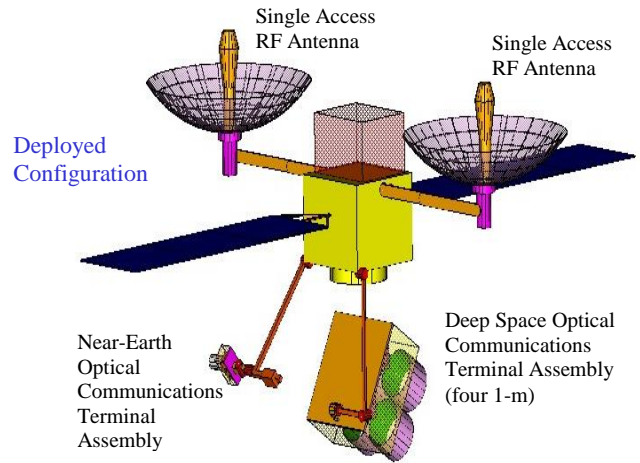


Figure 3. Example of an integrated GEO spacecraft design to support both near Earth and deep space optical communications

Concerns have been raised in the past about the feasibility of a space platform that must simultaneously support a narrow beam (e.g., ~ 3 urad for a typical system at Mars) optical communications link and multiple large articulating RF antennas. Space-based optical communications requires that the host spacecraft bus be relatively "quiet" from a vibrational/stability perspective. A typical spacecraft host for an optical communications system is expected to have an attitude uncertainty of ≤ 1 mrad (3σ). Noteworthy is that the latest generation of TDRSS spacecraft have uncertainties of that order (i.e., ~ 3 mrad (3σ)) even during antenna slew events. Residual attitude control errors affect initial link acquisition, while platform jitter affects the spatial tracking design that may consist of closed loop tracking using fast steering mirrors augmented with passive isolators to mitigate high frequency disturbances.

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.

A future relay satellite could provide both RF and optical communication services for in space inter-satellite links. Such a relay could have either a RF or optical space-to-ground link or both for the feeder link between the relay and Earth. A particularly attractive architecture for the relay satellite architecture from cost and availability perspectives has a RF space to ground link for low latency requirements and a high rate optical space to ground link. The RF link allows such a future relay to be supported with a minimum number of optical ground stations while still providing high availability. The addition of onboard capabilities to include link level processing, as well as networking and

storage functionality could further expand and enhance the performance and services available.

NASA's Laser Communications Relay Demonstration, will be the necessary pathfinder for future GEO relay services when in launches in late 2017. LCRD will provide two years of continuous high data rate optical communications via a hosted payload on a commercial communications satellite.

As shown in previous NASA studies, it is even possible to support deep space optical communications from an orbiting Earth relay satellite. This would help enable NASA's use of optical communications throughout the solar system to achieve higher data rates than RF systems, enabling bandwidth-hungry instruments, such as hyperspectral imagers on planetary missions. If the Earth relay satellite used a lower speed RF link than an optical link to ground to relay the deep space transmissions, then Earth's weather would not impact the deep space communications.

Such a deep space terminal must be designed to minimize weight, volume, and power. However, there are no atmospheric channel effects so the required collection area is lower than a system sitting on the Earth for a given data rate. Depending upon the orbit selected, two terminals in Earth orbit should provide high availability throughout the solar system.

In the not so distant future, optical communications will enable new science and exploration missions for both near Earth and deep space applications.

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REFERENCES

- [1] Bischl H. et al., Feasibility Assessment of Optical Technologies & Techniques for Reliable High Capacity

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Feeder Links (Executive Summary) (ESA Study Contract Report, 21991/08/NL/US, 2011).

- [2] B. S. Robinson, D. M. Boroson, D. A. Burianek, D. V. Murphy, "The Lunar Laser Communications Demonstration", International Conference on Space Optical Systems and Applications, May 2011
- [3] Caplan, D.O.; Rao, H.; Wang, J.P.; Boroson, D.M.; Carney, J. J.; Fletcher, A.S.; Hamilton, S.A.; Kochhar, R.; Magliocco, R.J.; Murphy, R.; Norvig, M.; Robinson, B.S.; Schulein, R.T.; Spellmeyer, N.W.; , "Ultra-wide-range multi-rate DPSK laser communications," Lasers and Electro-Optics (CLEO) and Quantum Electronics and Laser Science Conference (QELS), 2010 Conference on , vol., no., pp.1-2, 16-21 May 2010
- [4] Edwards, B., et. al., "Overview of the Mars Laser Communications Demonstration Project", AIAA Space 203, Long Beach, California, September 2003.
- [5] Hunter, J., "Orbiting Deep Space Relay Satellite System (ODSRSS)," JPL Study 1979.
- [5] Benjamin, T., et al., "Deep Space Relay Satellite System (DSRSS)," 5 Volume Final Report, ITT Industries, June 1992.
- [6]"TDRSS-Continuation Lasercomm Assessment Readout," NASA/GSFC Integrated Mission Design Center (IMDC), 23 July 2003.

[x] MORE REFERENCES WILL BE INCLUDED

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 was a member of the Interagency Operations Advisory Group (IOAG) Optical Link Study Group 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.