

Next-Generation NASA Earth-Orbiting Relay Satellites: Fusing Optical and Microwave Communications

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Abstract — NASA is currently considering architectures and concepts for the generation of relay satellites that will replace the Tracking and Data Relay Satellite (TDRS) constellation, which has been flying since 1983. TDRS-M, the last of the second TDRS generation, launched in August 2017, extending the life of the TDRS constellation beyond 2030. However, opportunities exist to re-engineer the concepts of geosynchronous Earth relay satellites. The needs of the relay satellite customers have changed dramatically over the last 34 years since the first TDRS launch. There is a demand for greater bandwidth as the availability of the traditional RF spectrum for space communications diminishes and the demand for ground station access grows. The next generation of NASA relay satellites will provide for operations that have factored in these new constraints. In this paper, we describe a heterogeneous constellation of geosynchronous relay satellites employing optical and RF communications. The new constellation will enable new optical communications services formed by user-to-space relay, space relay-to-space relay and space relay-to-ground links. It will build upon the experience from the Lunar Laser Communications Demonstration from 2013 and the Laser Communications Relay Demonstration to be launched in 2019. Simultaneous to establishment of the optical communications space segment, spacecraft in the TDRS constellation will be replaced with RF relay satellites with targeted subsets of the TDRS capabilities. This disaggregation of the TDRS service model will allow for flexibility in replenishing the needs of legacy users as well as adding new capabilities for future users. It will also permit the U.S. government access to launch capabilities such as rideshare and to hosted payloads that were not previously available.

This paper also explores how the next generation of Earth relay satellites provides a significant boost in the opportunities for commercial providers to the communications space segment. For optical communications, the backbone of this effort is the adoption of commercial technologies from the terrestrial high-bandwidth telecommunications industry into optical payloads. For RF communications, the explosion of software-defined radio, high-speed digital signal processing technologies and networking from areas such as 5G multicarrier will be important.

Future commercial providers will not be limited to a small set of large aerospace companies. Ultimately, entirely government-owned and -operated satellite communications will phase out to make way for commercial business models that satisfy NASA's satellite communications requirements. The competition provided by new entrants in the space communications industry may result in a future in which all NASA communications needs can be satisfied commercially.

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1. INTRODUCTION

August 2017 marked the launch of NASA's final Tracking and Data Relay Satellite (TDRS) of the third generation. For decades, TDRS have employed radio frequency (RF) links to provide reliable space communications services to a variety of users.

Now, NASA is determining its plan to maintain RF capabilities for space communications and also expand its scope to include evolving optical communications technology. Optical communications links enable users to bring down exponentially greater volumes of data without being restricted by availability of spectra. On the other hand, weather and atmospheric conditions could impede the optical links, whereas RF links are nearly impervious to weather.

NASA is considering a disaggregated approach for the heterogeneous future of space communications. In this strategy, future RF and optical systems would launch and operate on separate spacecraft, making it easier and more cost-effective to maintain individual systems. Moreover, scheduled services provided by one system would not be burdened by the schedules of other communications relays; disaggregation would enable users to continue receiving communications support from providers, even while certain space-based relays are not in service or not available. [1]

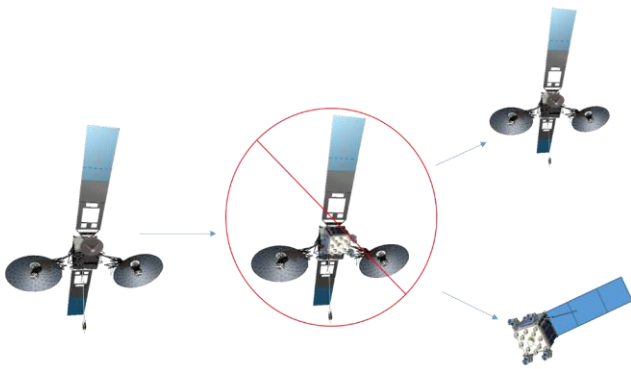


Figure 1. The disaggregated approach involves individual systems with different communications capabilities.

2. RADIO FREQUENCY SYSTEMS

As the fleet of TDRS relays ages, NASA will need to evaluate service requirements and ensure that RF capabilities are in place and performing well to meet user needs. The TDRS constellation will be maintained to meet those RF requirements, but new relays will eventually be necessary.

RF service provision is not limited to NASA; NASA could launch new generations of RF systems, or the same service could be provided by the commercial segment.

3. DEVELOPMENT OF THE FIRST OPTICAL COMMUNICATIONS NODE

NASA has taken a number of inputs into consideration to determine what the first optical node communications node should look like. These inputs include:

- (1) Past and current mission plans for optical communications in space
- (2) Assessment of future communications requirements and lessons learned from the introduction of Ka-band into the NASA mission space
- (3) State of technology available to support future optical communications

Past and Current Mission Plans for Optical Communications in Space

The U.S. has successfully completed two major optical communications missions. The first was the Massachusetts Institute of Technology Lincoln Laboratory (MIT LL)-led GeoLITE (Geosynchronous Lightweight Technology Experiment), which resulted in the first successful demonstration of high-rate space laser communications. This 2001 mission used direct detection, intensity modulation-based communications at 1550 nanometers. [2] The success of this mission led to a collaboration for the second successful optical communications mission, LLCDC (Lunar Laser

Communications Demonstration). That mission, led by MIT LL and NASA’s Goddard Space Flight Center (GSFC), consisted of a laser communications payload carried aboard the NASA Ames Research Center’s LADEE (Lunar Atmospheric Dust and Environment Explorer). LLCDC successfully demonstrated 622 Mbps communications from lunar orbit to a ground station at the NASA/GSFC White Sands Complex (WSC) called the Lunar Laser Ground Terminal. LLCDC was more advanced than GeoLITE and represented a substantial improvement in the state of the art. LLCDC had a 10-centimeter telescope in the optical module, a 0.5-watt laser at 1550 nanometers, and demonstrated 622 Mbps downlink at 400,000-kilometer distance using 16-ary pulse position modulation (PPM), and 20 Mbps uplink using 4-ary PPM. [3]

These successes led to LCRD (Laser Communications Relay Demonstration). LCRD is planned for a 2019 launch into geostationary orbit as a hosted payload aboard STPSat-6. LCRD’s features are summarized in Table 1. LCRD and the future missions described below are all based on an evolutionary path arising from MIT LL optical communications technology and NASA operations staff, facilities and expertise.

Subsystem	Description
Two optical modules	10.8-cm telescope, 2-axis gimbal
Laser	1550 nm at 0.5W
RF downlink	Host spacecraft provided
Module-to-module switching	Gbps-class high-speed space switching unit
Data rates	Up to 1.244 Gbps forward and return links
Optical ground stations	Haleakala, HI Table Mountain, CA
Mission operations center	GSFC Space Network at WSC, NM

Table 1. Key features of LCRD

ILLUMA-T

NASA is also developing a terminal called ILLUMA-T (Integrated LCRD LEO [Low Earth Orbit] User Modem and Amplifier Terminal) for an LCRD user.

ILLUMA-T will fly aboard the International Space Station (ISS) attached to the Japanese Experiment Module (JEM). From the JEM location, it will communicate with LCRD at 1.2 Gbps return link and 51 Mbps forward link. ILLUMA-T will be the first LEO user of the LCRD system to demonstrate pointing and tracking to/from a moving spacecraft, and end-to-end operational relay of optical communications. ILLUMA-T is not designed for direct-to-Earth communications.

Additional Optical Communications Demonstration: The Orion EM-2 Optical Communications (O2O) Project

The NASA Optical to Orion (O2O) project will fly on the Orion Exploration Mission (EM) -2. It will demonstrate cis-lunar, direct-to-Earth optical communications at a maximum range of 500,000 kilometers at 80 Mbps downlink and 20 Mbps uplink. O2O exists as an Orion development test objective for the EM-2 mission.

State of Technology Available to Support Future Optical Communications

The NASA Space Communications and Navigation program office at headquarters has chosen an ambitious path to implement commercial, off-the-shelf technology (COTS), with a goal for the maximum implementation of commercial practices at all levels of acquisition, design and implementation. There are practical reasons for this approach.

- (1) The terrestrial telecommunications market has invested billions of dollars in high-speed, high-volume communications components. NASA cannot design or duplicate space-based versions of these systems at any cost. The decision has been made to target commercial products such as “top-of-the-rack” datacenter switches and long-haul fiber communications transceivers to be adapted for spaceflight usage. These products are qualified to Telcordia standards for high reliability in the terrestrial environment.
- (2) There exists a large commercial base that acquires and builds communications satellites without NASA requirements. These profit-driven businesses operate hundreds of spacecraft on-orbit, providing billions of dollars’ worth of services without NASA requirements.

4. HIGH-LEVEL DESCRIPTION OF THE NEXT-GENERATION EARTH RELAY COMMUNICATIONS NODE AND THE CONCEPT OF OPERATIONS

Based upon the preceding two points, NASA has directed an approach to achieve specific performance goals using COTS where possible. Depicted in Figure 3 is the concept of operations for relay-to-relay, relay-to-ground and user-to-relay operations. The image envisions relays that are capable of storing, multiplexing and forwarding three optical user data 10 Gbps channels over a 100 Gbps optical trunk line. In the proposed plan, there will be a minimum of four ground stations for geographical diversity at:

- (1) Haleakala, Hawaii
- (2) WSC, New Mexico
- (3) Table Mountain, California
- (4) Lawrence Livermore, California

Figure 4 depicts the concept of operations for a network of three relays. The NASA plan envisions all RF and optical operations to occur on secure U.S. territory. The concept of operations involves three phases:

- Phase 1. Relay Node 1 operated from WSC to support optical communications customers
- Phase 2. Relay Node 2 operated from WSC to support optical communications customers and allow Relay 1-to-Relay 2 crosslink (73,395 kilometers)
- Phase 3. Relay Node 3 in the Indian Ocean operating region at approximately 270 degrees W; operated from Guam to support optical communications customers and allow Relay 3-to-Relay 2 crosslink (64,599 kilometers)

Driving Requirements for the Relay Payload

Each optical payload will carry four independent optical space terminals. The nomenclature for the relay payload is shown in Figure 2.

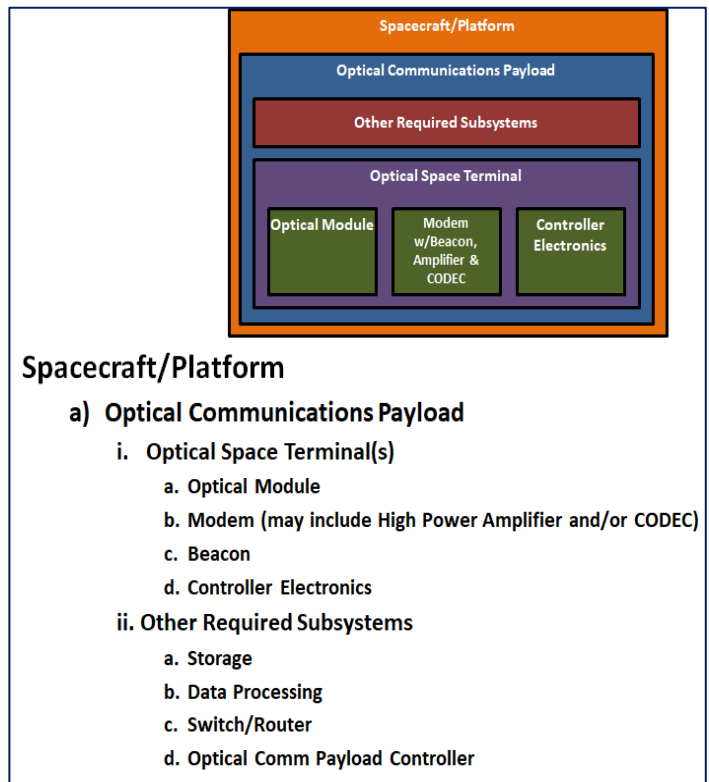


Figure 2. Relay Payload Nomenclature

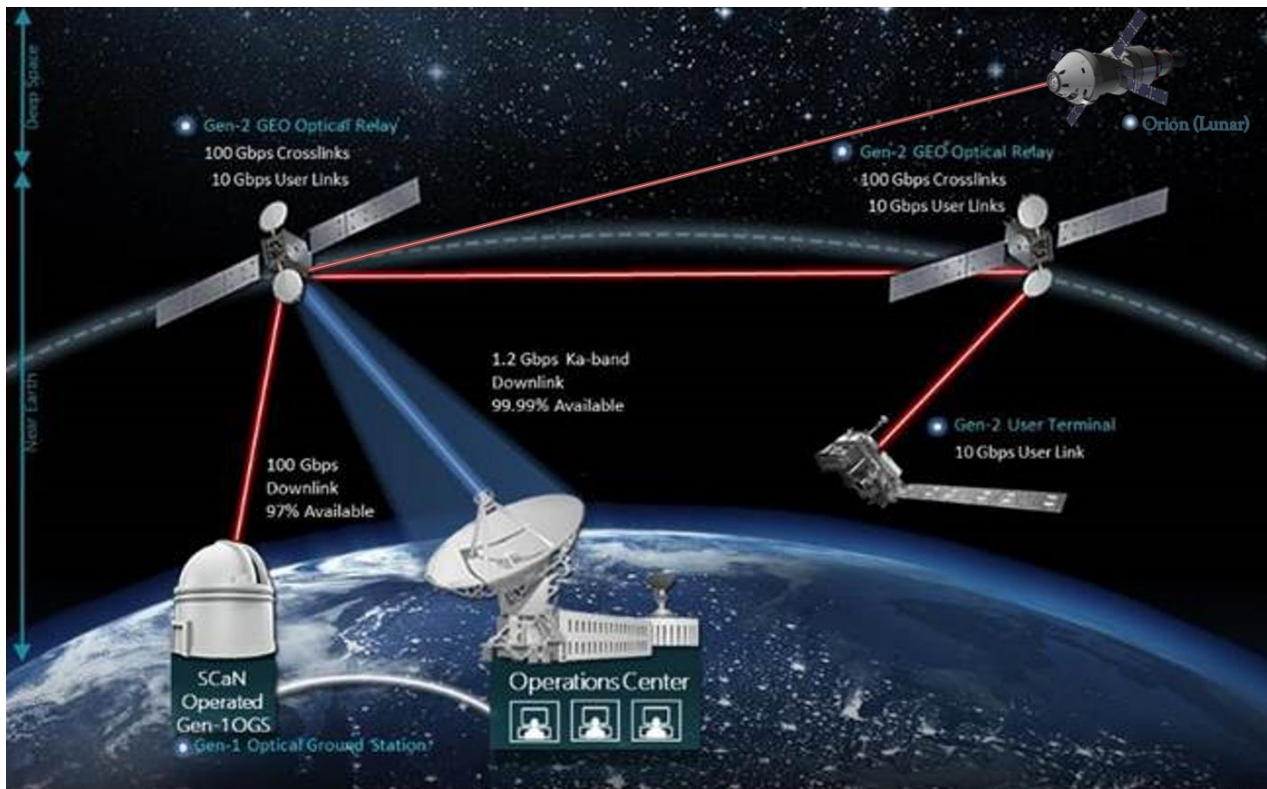
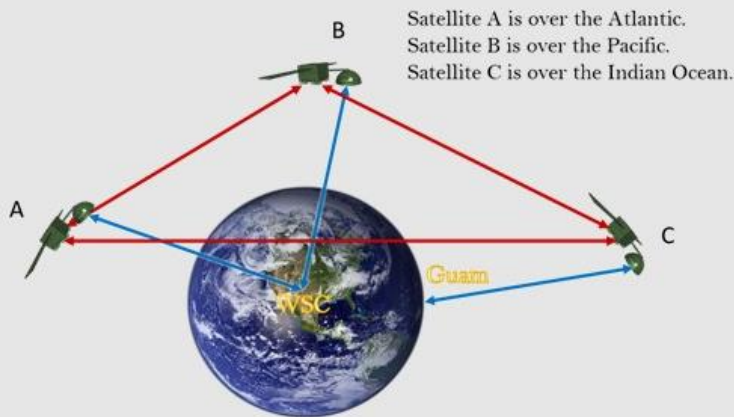


Figure 3. Next-Generation Earth Relay Concept of Operations

All optical data relayed through WSC.



GEO-GEO crosslinks are up to 100 Gbps using 100 Gbps modems between relay terminals.

User links are up to 10 Gbps using 10 Gbps modems between user terminals and relay terminals.

GEO-GEO crosslinks go C -> B -> A then ->WSC via the optical space-to-ground link.

Together, they provide global coverage.

An example assuming all user links are running at 10 Gbps:

Operationally, Satellite C can track all three users (10 Gbps each at 80 Gbps) and has a GEO-GEO crosslink to Satellite B (over which it transfers the 80 Gbps).

Satellite B has two user links (collecting a total of 20 Gbps) and GEO-GEO crosslinks to Satellite A and Satellite B. Satellite B has the 80 Gbps of user data from Satellite C plus its own collected 20 Gbps, totaling 50 Gbps, which it transfers to Satellite A via a GEO-GEO crosslink.

Satellite A collects 20 Gbps of data from its users plus it gets 50 Gbps from Satellite C. So it is downlinking 70 Gbps to WSC through its optical space-to-ground link.

Figure 4. Notional option for GEO-GEO relay spacecraft concept of operations with store-and-forward capability relay node to relay node to White Sands Complex. Blue links are RF; red links are optical.

The relay payload requires:

- (1) Support for multi-rate user links up to 10 Gbps from the ground or air, or from LEO to GEO. This includes a mode to facilitate backward compatibility with the LCRD 2.88 Gbps data rate and format.
- (2) Incorporation of a high-power (greater than 3-watt) beacon for acquisition and tracking by users in LEO.
- (3) Support for aggregated 100 Gbps space-to-ground links (SGLs) and crosslinks.
- (4) Development of the 20-centimeter next-generation terminal optical module to close 100 Gbps SGLs and crosslinks.
- (5) Support for time-of-flight measurements and time transfer concurrent with communications to support relay navigation requirements.
- (6) Reprogrammable spacecraft command and data-handling (C&DH) interface (MIL-STD-1553 vs. SpaceWire vs. RS422), exclusive of the 10 GigE data interface.
- (7) The use of commercial space practices and upscaled, Telcordia-certified COTS components where possible.
- (8) A design life of at least eight (to be resolved) years.

NASA Rationale Behind the Requirements

NASA is attempting to write forward-looking requirements with the goal of mitigating some of the obsolescence issues that will occur. The reprogrammable C&DH interface will allow the payload to be seamlessly integrated with a variety of spacecraft bus interfaces. NASA is currently funding development of an improved 10-centimeter aperture optical module, which can be upsized by industry to create a commercially available 20-centimeter version.

NASA's goal is to launch the first operational optical system no later than 2025 and eventually achieve total global coverage with three relay satellites. The communications payload and spacecraft buses are to be commercially procured separately to NASA requirements; integration at a NASA center is a possibility.

Risks to the NASA Approach

- (1) Cost risks: It may be determined that the cost of adapting COTS telecommunications components for the radiation environment exceeds predictions. It may be determined that the mechanical, thermal and electromagnetic compatibility adaptations required to fly these COTS components are substantial and greatly increase the size, weight and power. Also, NASA usually procures in small quantities, making amortizing non-recurring costs difficult. Mitigations include changes in acquisition strategy to increase buys, reduction of spacecraft requirements and mission life, and acceptance of higher mission risk.
- (2) Obsolescence risk: The life cycles of COTS telecommunications products are a fraction of the NASA project lifecycle. An eight-year spacecraft life exceeds these COTS product lifetimes. Commercial companies undergo continuous refurbishment and upgrades to stay ahead of obsolescence. NASA operates on discrete project boundaries for funding, which may include substantial gaps between acquisition of spacecraft and payloads.

Risk-Reducing Technology Development

NASA recognizes that some technology development may be required as upgrades are made to LCRD or as new capabilities are desired for the Next-Generation Earth Relay.

Alternative Acquisition Strategies to Buy Down NASA Risks

It may be possible for NASA to either:

- (1) Buy optical communications relay services commercially from one of the emerging startups in the optical communications industry; or
- (2) Form a partnership with one or more commercial entities to allow NASA to obtain the specific services summarized above.

It remains to be determined if there is a profitable business case for a company to invest in space-based optical communications in a fee-for-service business model with NASA. NASA is investigating the possibilities.

5. OPTICAL GROUND SEGMENT

The optical ground segment under development has to account for both direct-to-Earth optical communications from projects such as O2O as well as optical relay traffic from the Next-Generation Earth Relay. For space microwave traffic, NASA has segregated ground segment activities across three networks: the Deep Space Network (DSN), the Space Network (SN) and the Near Earth Network (NEN). Each network is populated with equipment specific for its mission. DSN traffic is very different from SN traffic, which is very different from NEN traffic. The three networks have been successful by implementing the appropriate hardware, software and concepts of operation for optimal performance for their specific missions.

The optical ground segment for the Next-Generation Earth Relay will be a subset of the overall optical ground segments of all space users. Locations with larger apertures (e.g. the 1-meter telescope in Table Mountain, California) can service deep-space and near-Earth customers if equipped with the necessary high-photon efficiency detectors, high-power laser uplinks and enhanced adaptive optics. Other locations may be limited to near-Earth support within 2 million kilometers of Earth. The opportunity to use very low-cost, amateur-grade telescopes also exists to service university class missions. A series of spatially diverse sites is planned utilizing existing sites at:

- 1) Haleakala, Hawaii
- 2) White Sands Complex, New Mexico
- 3) Table Mountain, California
- 4) Livermore, California

The four sites will provide 97 percent availability as shown in Figure 5 for the continental U.S. locations.

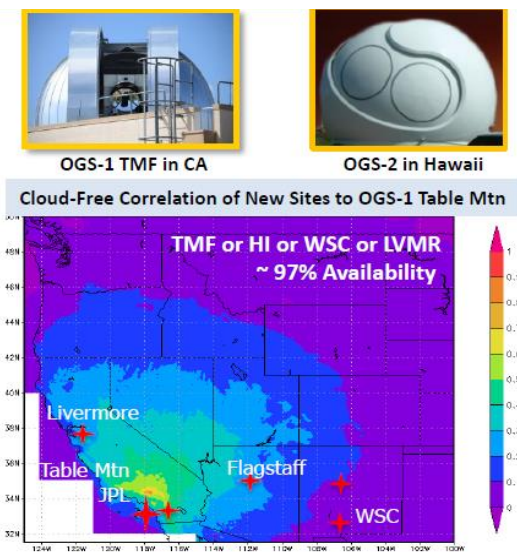


Figure 5. Cloud-free availability for four sites

Optical Ground Segment Services

A service is defined as the set of all parameters necessary to define an operational link between the ground and an orbiting space vehicle. The larger the number of services, the higher the cost of initial development and of operations and maintenance. The wavelength plan for uplinks and downlinks, the variety of data rates, coding and modulation schemes, uplink power, downlink signal-to-noise ratio and other factors will drive the number and complexity of the variety of transmit and receive chains coupled to each aperture in the ground segment. There are also benefits to arraying the ground apertures for higher performance, which carries additional costs.

A commercial optical communications business segment is expected to emerge from the large number of startups in this field, which will service some segment of the NASA market, and NASA will not duplicate their offerings. It is expected that NASA will take an evolutionary approach by instituting services for known customers and incrementally increasing the service options for state-of-the-art research and for customers with no viable commercial options.

NASA is currently assessing all of the possible ground segment services to support the Next-Generation Earth Relay and will develop a set of requirements to cover the set of services to be offered within the ground segment. The current span of data rates being considered is between 1 Mbps to 200 Gbps with on-off keying, differential phase shift keying, pulse position modulation and dual polarization quadrature phase shift keying modulation types. Near-Shannon limit coding schemes and interleaving to combat atmospheric fading effects will be in the trade space. Consultative Committee for Space Data Systems recommendations will be pursued, as well as interoperability between the optical communications systems of the European Space Agency and Japan Aerospace Exploration Agency.

6. CONCLUSION

Multiple studies are underway within NASA to explore optical communications capabilities and the disaggregated approach.

NASA's LCRD project will use a space-based relay and several ground stations to test how optical links would operate in real life. The LCRD study team will conduct experiments to test atmospheric effects, and will simulate scenarios involving single or multiple relays and providers, and both RF and optical links. [4]

NASA is also investigating applying optical communications links to operational settings. For example, O2O will bring optical communications to Orion Exploration Mission-2, a manned spacecraft.

Additionally, NASA is conducting studies to determine the feasibility of and requirements for the first optical relay node, targeted for the year 2025. This node would be one of the primary steps in the disaggregation method of the future. [5]

Aside from the convenience and cost efficiency afforded by disaggregation, the approach also brings about opportunities for commercialization. Commercial providers could individually launch RF and optical systems, creating a competition-based space communications model and expanding the options for spacecraft users.

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Biography



David J. Israel is the architect for the NASA Goddard Space Flight Center's Exploration and Space Communications Projects Division, and the principal investigator for the Laser Communications Relay Demonstration (LCRD) at Goddard. He has been working on various aspects of space communications systems since joining NASA in 1989. He received a bachelor's degree in electrical engineering from Johns Hopkins University in 1989 and a master's degree in electrical engineering 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 served as the principal investigator for multiple communications technology activities concerning advanced space communications concepts and networking protocols, including the LPT CANDOS experiment on STS-107 and disruption-tolerant networking demonstrations on the Lunar Laser Communications Demonstration.



Harry Shaw is a staff engineer for NASA Goddard Space Flight Center's Space Network (SN) project. The SN operates a fleet of geosynchronous, space-based Tracking and Data Relay Satellites (TDRS) that provide global space communications for a variety of users. He is also involved with the development of CubeSats and CubeSat technologies compatible with the NASA networks. Harry has more than 30 years of experience in technology development, computer networking, information theory, microelectronics and space communications, mission planning and proposal development. Harry has a doctorate in electrical engineering from George Washington University.