SAFETY & DEFENSE
Scientific and Technical Journal ISSN 2450-551X

NASA Space Laser Communications System: Towards Safety of Aerospace Operations

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DOI: https://doi.org/10.37105/sd.85

Abstract

Bidirectional space communication is a fundamental prerequisite for maintaining contact with objects performing missions in space, whether manned and unmanned. Until recently, it relied solely on the propagation of electromagnetic waves (the radio) using frequency bands dedicated for objects outside the Earth's atmosphere. However, modern space technologies are subject to ongoing development as they are being fitted with advanced communication systems. Given the constant enhancement of our technological capabilities, the traditional radio-based communication shows a glaring inadequacy and contributes to the widening of a gap between this and the high technology of on-board devices installed on modern spacecrafts. The technology that complies with the up-to-date requirements of space communication is optical space communication. It is expected to provide for high-speed data transfer and increase the bandwidth several times, while ensuring immunity to common cyber threats, including jamming, spoofing and meaconing. The deployment of laser-based optical communication will not only contribute to increasing the air and space operation safety levels, but also enable deep space exploration. To this end, NASA's Laser Communications Relay Demonstration Project (LCRD) is currently undergoing development and testing. This chapter undertakes to characterize the emerging technology with respect to its operating principles, the future scope of applications and involvement in currently conducted experiments. The results from the analysis are presented in the form of scenarios outlining possible applications of laser communication.

Keywords: Laser Communication Relay Demonstration, optical space communication, outer space, security, space security

1. Introduction

Since the dawn of civilizations, space has been in the keen interest of philosophers, scientists, mathematicians and astronomers alike. In ancient times, celestial bodies such as stars and planets were the objects of observations and discourses attempting to understand how they influence the lives of people. Space was the source of continuing fascination, and yet it had for long remained in the realm of the fantastic and the unattainable for further investigation, not to mention its use. This changed no sooner than in the 20th century, following the rise of two powers – the United States and the Union of Soviet Socialist Republics, which were the first to have embarked on the space race – the race to dominate the extra-terrestrial. Initially, the space exploration aimed to investigate the conditions that were highly dissimilar to the ones found on the Earth and to launch artificial satellites. The space race became an important issue and a cultural reference in these countries; it had a marked influence on the national morale, paved the way for new ideological trends, but, predominantly, it became a major indicator of the military capabilities of the states and a marker of their technological advancement. Two events are regarded as the milestones of space exploration. The first event was the launch of the first artificial Earth satellite, Sputnik 1, and its placement in the orbit in 1957 (Polkowska, 2018). The second most important step was the landing of the manned mission on the moon, which took place in 1969. Over time, the competition between these and new contenders has evolved into cooperation – since outer space is the province of all mankind and cannot be regarded as belonging to any particular state or be subject to their control. Today, the near-Earth orbits accommodate artificial telecommunications satellites, space stations and various components of the present and developing global satellite navigation systems infrastructure. The systems provide the technological capabilities for locating objects on earth, water or in the air. On the other hand, the systems handle the communication with unmanned space flights, which are reaching increasingly remote regions of space, and in the future, this may include manned missions. Regardless of the type of object performing space flight, it is essential to maintain constant bidirectional communication to enable the transfer of data to Earth-bound centers. Given the long distances involved, it is critical that space communication should be highly reliable, continuous and resistant to electromagnetic, electronic or radio-frequency interference, whether as an intentional act or the result of natural space weather phenomena.

2. Modern space communication in the face of cyber threats

Outer space exploration has always been associated with launching objects that would deliver data from their research to centers on Earth. The communication systems of modern and future spacecrafts must, therefore, exhibit high reliability and resistance to interference, while ensuring uninterrupted data transmission over extended distances (Brandt-Pearce and Noshad, 2016). Accordingly, the bidirectional space communication networks are classified into three broad categories below (Figure 1).

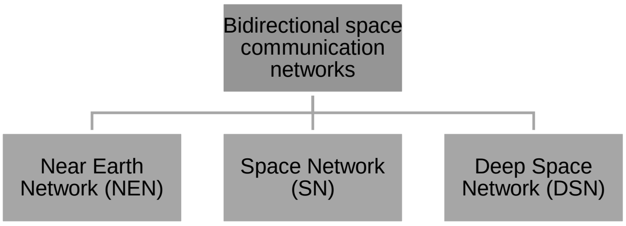

Figure 1. Classification of bidirectional space communication networks

The first scope of communications is managed by the Near Earth Network (NEN). The NEN infrastructure has two major components: the space and the earth segments. The space segment is composed of 14 satellite stations strewn across the Low Earth Orbit (LEO), the Geosynchronous Orbit (GEO), the highly elliptical orbit and the selenocentric orbit. The stations constituting the Near Earth Network include NASA-operated objects and commercial satellites. The other component of the NEN system is the ground segment comprising 25 antennas. The antennas' locations have been selected so as to provide the optimal coverage of the Earth: the stations are on several continents and at a considerable spacing. This configuration ensures constant and uninterrupted communication with the satellites, which, *nota bene*, constantly change their positions. The connection is established provided that the station is at a specified height directly above the receiving antennas (Dale, 2019). The Near Earth Network operates on a relatively small range, estimated at one thousand nautical miles, and it primarily handles the transmission of satellite data that provide telemetry and communication services to spacecrafts, command, ground tracking to a range of recipients, including national and international entities, governments and trade organizations, notwithstanding NASA. The unit in charge of NEN management is the Robert H. Goddard Space Flight Center, located in Greenbelt, USA.

The second system of communications in question is the Space Network – SN. It comprises an extensive technical infrastructure composed of several elements: the Tracking Data Relay Satellite (TDRS) – a constellation of geosynchronous satellites orbiting the Earth, satellites operating at an altitude of 73 kilometers in the Low Earth Orbit, the ground systems that form a relay system between the satellites, other ground objects and a high-speed broadband network connecting all the elements in a continuous cooperation. The range of uses of the Space Network is not limited to one task – its secondary tasks include: supporting telecommunication transmissions, testing, tracking, providing service and assuring required safety levels during unmanned space flights. In the future, SN is set to participate in the operation of manned flights to Mars. Currently, it delivers communication with astronauts performing space resupply flights, monitors their vital functions and space telemetry. The Space Network has substantially contributed to the exploration of orbital regions. The range of service of the SN has never been precisely defined due to the fact that its primary function consists in providing communication with objects in continuous motion; however, it may be described as operating on the orbital distance. As in the case with the NEN, it is the Robert H. Goddard Space Flight Center, located in Greenbelt, USA that is responsible for the supervision and management of SN operations.

The system for establishing and maintaining communication with objects and devices exploring the most remote sectors of outer space is the Deep Space Network (DSN). It is a system of 3 large terrestrial antennas (34-70 m in diameter) whose location facilitates communication with distant regions of the Solar System. According to calculations, the optimal spacing angle between the antennas in question, i.e. ensuring full signal coverage, is 120°. The antennas are situated in Madrid, Canberra and Goldstone, California, and thus, every satellite in space can at all times communicate with at least one station. The ground stations connect with satellites to initiate course corrections, provide software updates and introduce changes in the procedures of scientific observations carried out by these objects. Although the DSN range is not specified, it has been designed to support only interplanetary missions, that is to deliver communication with rovers and probes exploring the Moon and Mars, as well as with objects sent to perform missions in the vicinity of the giant planets located in the most distant areas of the Solar System. The secondary role of the Deep Space Network is to support the other two networks: the Near Earth Network and the Space Network. The safety of DSN space operations is supervised by the Jet Propulsion Laboratory of the National Aeronautics and Space Administration (JPL NASA), located in Pasadena (California) in the United States.

To ensure that space communication is performed as intended, it was necessary to establish the uplink/downlink frequencies, i.e. the electromagnetic spectrum bands to be used by the systems (Table 1).

Table 1.

The traditional designation of the microwave radio bands for space communication

Band	**Frequency [*f*]**
L	1.5÷2.7 GHz
S	2.7÷3.5 GHz
C (downlink)	3.7÷4.2 GHz
C (uplink)	5.9÷6.4 GHz
X (downlink)	7.2÷7.7 GHz
X (uplink)	7.9÷8.3 GHz
K_u (downlink)	10.7÷12.75 GHz
K_u (uplink)	12.75÷14.5 GHz 17.3÷18.1 GHz
K_a (downlink)	18.1÷21.2 GHz
K_a (uplink)	27÷31 GHz
Q–V	36÷51 GHz

The classification of electromagnetic microwaves for space communication with satellite systems, given in Table 1, presents the traditional division of the spectrum and band designations. In modern and emerging space communication satellite systems, the frequency bands below 3 GHz are disregarded, which is a consequence of their excessive use and insufficient capacity, as well as of natural factors, such as the high impact of space radiation and the nature of the ionosphere, which is known to reflect and absorb electromagnetic waves. Currently, frequencies below 3 GHz provide for the mobile satellite networks, satellite telecommunication users and deep space research. The terms *downlink* and *uplink* designate the direction of communication, *i.e.* respectively, from the satellite to the Earth station receiver and from the Earth to the satellite system in space.

3. Space Laser Communications System

In the past, the limitations in communication between objects performing space flight and terrestrial observatories would frequently subject the scientific mission plans to revision. The conventional space communication systems employ the transmission of electromagnetic (radio) waves (Radio Frequency – RF) in specified frequency ranges. The problems in question primarily stem from the non-parallel progress of the communication technology and the rapid technological evolution of equipment and instrumentation fitted in modern space vehicles. Radio waves travel in space at a near-lightspeed velocity (in vacuum it is 299.792.458 m/s). Given the distances covered, there is an inherent substantial delay involved in space communication (e.g. an approximate time offset for a Moon rover is one second); the time delay increases with distance. This effect is exemplified by the Martian rover: in the most disadvantageous scenario of the planets' mutual position, the maximum delay time may reach up to approximately thirty minutes. The optical communication technology is expected to overcome the technological limitations of the existing electromagnetic-wave-based space communication. The new solution is expected to ensure considerably higher quality, thus effectively supporting future space flight missions. One of the key distinct advantages of optical communication consists in that it ensures data transmission speeds of the order of a hundred times faster than the traditional RF systems at the same weight and power requirements of the equipment. Moreover, the new communication solution eliminates such underlying problems as microwave spectrum overload and allocation, limited bandwidth while providing higher security against cyber threats, which are rather common in radio communication. The new type of space communication network is set to be activated once the objects performing space flights are fitted with high-bandwidth instruments, such as hyperspectral cameras and instrumentation operating in high-resolution spectral, spatial and temporal modes. In the future, optical communication is envisaged to provide the technological capability for the establishment of a "virtual presence" on a remote planet or another celestial body within our solar system, enabling fast and reliable space communication.

In essence, optical communication is the transfer of data by means of an optical waveguide. Fiber optics uses the spectrum of the light, not the radio waves, to transfer information in a specific medium, which is in this case, between the space communications center on Earth and a space probe). Concerning its applications in telecommunication, it should be taken into consideration that data transmission in optical fibers occurs as a result of lightwave modulation that is caused by a semiconductor laser (LD) or a light-emitting diode (LED). A characteristic feature of fiber optic technology is that it is highly resistant to electromagnetic interference, as it does not emit an external electromagnetic field that would cover a certain extensive area (Furch et al., 2002). In such a special kind of telecommunications (Drzewiecki, 2015) as bidirectional space communication, it is necessary to clearly distinguish between the classic use of optical fiber in terrestrial and space applications. The technology in question employs photon propagation from the transmitter (Wu et al., 2019) to the receiver that is carried out through a waveguide; the latter could be a properly adapted optical fiber structure constituting a closed-loop glass-fiber system for data transmission. In the case of space communication, however, which makes use of a laser beam directed at a specified receiver target, it is the Earth's atmosphere that becomes the medium. Therefore, the created network is apparently an open-loop system based solely on the emission of light waves. This allows the use of unlimited bandwidth and reduces the risk of radio interference.

The results from the preliminary analyses of the capabilities of optical techniques in bidirectional space communication, originally developed for the United States Department of Defense (DoD) and NASA itself, have encouraged the space agency to put it to further testing, under the working title – Laser Communication Relay Demonstration (LCRD). During the demonstration, the laser communication relay has been employing the existing technical infrastructure to set up a bidirectional space communication network. The procedure that is being followed is expected to allow the researchers to gain operational experience while maintaining an optimal cost variant. The tests are scheduled to extend over the period of at least two years (to be completed no sooner than in 2021), over which time high-speed optical communication will be provided in the operational environment. The LCRD tests are intended to show whether the optical communication possesses the potential to meet the growing demand of NASA and other agencies for high data transmission rates and, secondly, whether it is suitable for low-power and low-mass spacecraft systems. The LCRD architecture is further assumed to serve as a platform for testing advanced communication tools, including adaptive optics (Wang et al., 2019), symbol coding, data link layer protocols and network layer protocols. The double optical link to be incorporated in the LCRD system will handle optical communication, enable the presentation of the new generation space relay system capabilities and provide early operational support for low-altitude orbit (LEO) terminals. An important step in the testing plan is to verify the effect that the Earth's atmosphere has on the laser space communication system and to create new atmospheric models. LCRD is likely to provide the spur for the development of optical communication technology for space and near-Earth systems while boosting the efficiency of the industrial sector to produce cost-effective communication systems and components for terrestrial and space applications.

With respect to the design of the Laser Communications Relay Demonstration, it is composed of two major segments: the flight segment and the ground segment. The former segment houses the flight payload and the high-bandwidth Radio Frequency transceiver, both fitted on the spacecraft. For tests, the LCRD payload will be flown in the geosynchronous orbit on the Space Test Program Satellite-6 (STPSat-6). The payload will be composed of the Space Switching Unit (SSU) and Optical Space Terminals (OST). The SSU is the central controller of the LCRD payload, whose core functions are to receive and relay the incoming data according to physical layer frame, process commands, collect and transmit flight payload telemetry data. In addition, the LCRD system is equipped with an optical module for collecting and transmitting laser signals, a Pulse Position Modulation (PPM) transmitter and Differential Phase Shift Keying (DPSK) for uplink and downlink directions. The modem handles the operation of high-speed electronics with the Pointing, Acquisition and Tracking (PAT) algorithm and thermal control in space. It is also equipped with rudimentary calibration (Chen et al., 2019) and testing tools, such as the built-in test (BIT) for internal modem or flight payload loopback checks. With respect to the high-frequency radio terminals that constitute the second component of the LCRD flight segment, they communicate in the Ka wave band. In the uplink direction, the HBRF terminal supports one or two users with a maximum data transmission rate of 32 Mb/s each. On the downlink, the terminal accommodates the transfer from one user with an effective data transfer rate of up to 622 Mb/s; alternatively, the bandwidth may be split, in which case, the transfer rate of the order of 311 Mb/s is allocated to each user. The HBRF terminal forwards combined data packs in either direction: to (return link) or from (forward link) both optical space terminals. Finally, given that the HBRF terminal remains permanently connected to the SSU, it is possible to switch between the transmissions through optical and RF links (NASA 2017, pp. 4, 6–8) with no interruption in communication.

The ground segment of LCRD is composed of two core components – two networked ground stations, i.e. Optical Ground Station 1 – OGS-1 and Optical Ground Station 2 – OGS-2 located in California and Hawaii. The optical ground stations are systems composed of an Optical Telescope Assembly, a Ground Modem, a Coder-Decoder (CODEC), a User Services Gateway (USG), an Atmospheric Channel Monitoring System (ACM) and User Element Simulators (UMS) that comprise a User Mission Operations Center Simulator (User MOC) and a User Platform Simulator (UPS). The differences between OGS-1 and OGS-2 are revealed when their technical architectures are compared in detail. OGS-1 is a 1-meter optical telescope with an adjacent room for transmitting and receiving optics, whereas OGS-2 is installed in an approx. 5.5-metre dome equipped with a 60-cm receive aperture and a 15-cm transmit aperture. The receiving systems of each telescope rely on adaptive optics to collect efficient light at the wavelength of the forward link to a single-mode waveguide, which is subsequently directed to the terrestrial modem and CODEC. Both OGS-1 and OGS-2 utilize the uplink channel (Du et al., 2018) to send a reference beam for the optical space terminal to adjust the pointing direction. The ground modem of the stations modulates the signal on the uplink direction and demodulates it on the downlink, however, while in OGS-1 both Pulse Position Modulation (PPM) and Differential Phase Shift Key (DPSK) modulation is enabled, OGS-2 only enables the latter. Furthermore, as for the coder/decoder function, before modulation, the signal is subjected to Forward Error Correction (FEC) on the uplink and the flight payload data can be integrated (interleaving) with user service data, if necessary. Upon encoding and interleaving, the data is labelled with a correct logical path identifier (the “unique word”) and a physical layer frame. Thus, the prepared uplink data is multiplexed into a single stream and directed to the ground modem. The received return data and payload telemetry data are subsequently decoded by the CODEC on the downlink. Multiple terrestrial users of space infrastructures exchange data with flight payload over a laser link within the user services gateway. User Element Simulators connect to service gates thus enabling data transmission and reception for all services desired by a particular user. The reverse link transmissions are forwarded to particular CODEC channels and distributed on the downlink to User Mission Operations Centers or LMOC. The user services gateways also process protocols for space or terrestrial transport within the provided user service. For presentation and testing purposes, LCRD uses two types of simulators: the User MOC Simulator (UMS) and the User Platform Simulator (UPS). By connecting to the LCRD via USG, the UMS enables the transmission and reception of data via the optical link. It is also an important element from the perspective of planning future services and receiving relevant data, giving a range of prospective possibilities for multiple user applications. The last component of the system is the Atmospheric Channel Monitoring, which collects current weather forecast data for analysis at a specific place and time. Weather observation is a vital element of the infrastructure due to the dangers and other impacts of weather conditions on optical links during experiments. The acquired data will remain available to researchers only for the duration of the system testing period, it can be thus assumed that this component will be withdrawn afterwards. The system will provide data regarding:

- Weather – temperature, humidity, atmospheric pressure, wind velocity and direction;
- Atmospheric transmittance;
- Daytime sky radiance;
- Strength of optical turbulence at the ground layer;
- Atmospheric coherence length during daytime;
- Cloud coverage;
- Atmospheric coherence length along the downlink path (during experiments);
- Downlink signal irradiance.

The radio communication system is the second cardinal component of the terrestrial segment of the laser space communications transmissions. It is composed of the RF Ground Station (RF GS) (Dreischer et al., 2009), a New-Mexico-based operations control center that is a part of the LCRD Mission Operations Center (LMOC) and a Maryland-based LMOC Extension – LMOC-E, i.e. an additional facility for monitoring LCRD operations and experiments. The capabilities and the function of the RF ground station are the same as of CODEC, i.e. it provides the user gateway and simulator (UMS and UPS) in optical space communication laser relay systems, and, therefore, it provides radio communication in support of the same user services and experiments. Numerous auxiliary elements are included in the LCRD RF ground station: antennas, amplifiers, transmitters, receivers and other processing equipment required to combine the LCRD high-frequency data stream with CODEC. A system playing an essential function in coordinating all activities related to safe operation is the LCRD Mission Operations Center (LMOC). Connected via ground networks to all radio and optical stations supporting LCRD missions, LMOC enables integrated mission scheduling, telemetry data acquisition, storage and analysis, centralized monitoring of operations, service management, remote monitoring of ground stations and experimental operations. The LMOC extension will support the LCRD testing process, ensuring at least a suitable level of space communication and security. Its capabilities provide invaluable insight into planning and monitoring of experiment operations, which in turn enables the assessment of the LCRD link performance during testing and analysis of weather factors and their effect on the system's uninterrupted functioning (NASA, 2017). The diagram below (Figure 2) illustrates the general principle of the system operation and its key elements.

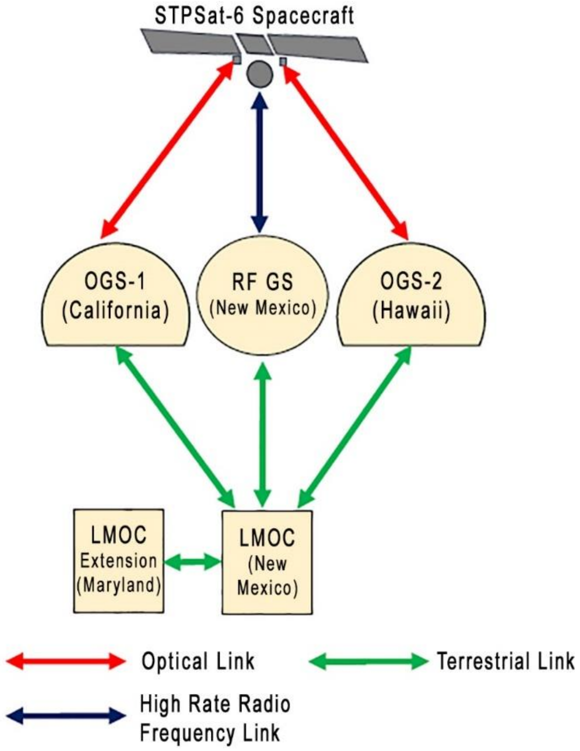

Figure 2. The main architecture of the Laser Communication Relay Demonstration (NASA 2017, p. 6).

Given the presented technical structure of the entire LCRD system, the forecasted purpose of laser communication, the opportunities it creates with respect to improving the current radio-based space communication, the primary objectives of LCRD testing are as follows (NASA 2017, p. 5):

- demonstrating the potential of bidirectional optical communication between the flight segment relay on the GEO orbit and the Earth-bound facilities;
- performance testing of the novelty communication system in various atmospheric or space weather conditions;
- developing operational procedures and evaluating its potential for future space missions;
- laser space communication technology transfer to the space industry (Strauch, 2015);
- ensuring GEO's capability for testing and demonstrating suitable relay standards for optical communication.

The National Aeronautics and Space Administration has planned the first phase of LCRD tests, which are set to last two years (tests to end in 2021). While the tests are expected to verify the points above, the agency has not excluded additional experiments should the need arise. The supplementary tests can be requested by parties involved in the laser communications relay demonstration project or external to it, this includes individuals or institutions from NASA, other government agencies, academia or the space industry. This open approach to testing is dictated by the desire to adapt the functional characteristics of the LCRD program to the needs of various optical communication users.

The laser communication relay demonstration is not the first attempt to replace radio waves with the optical technology in space communication, as the first successfully tested technology was the Lunar Laser Communications Demonstration (LLCD), by the European Space Agency – ESA. The tests confirmed the capability of the solution in question, which provided record data transmission speed over the optical link between the Earth and the LLCD (Lunar Lasercom Space Terminal – LLST) located on the satellite of NASA's Lunar Atmosphere Environment Explorer (LADEE) placed on the lunar orbit. The downlink transmission was shown to handle data at a speed of 622 Mb/s and, in the uplink direction, at a 20 Mb/s rate. The operational capabilities of the LLCD architecture support a range of conditions and multiple ground terminals of various designs and capabilities, limited contact times, energy, as well as thermal and viewing conditions (Khatri et al., 2015).

4. Results from experiments and potential LCRD application case stories

While the use of solutions based on optical techniques in various sectors of telecommunication has been relatively common for years, in space communications, it is an absolute novelty. The provision of space optical communication services to users presents numerous technical challenges related to the development and placement of dedicated infrastructure in the GEO orbit. In addition, it is vital to account for the atmospheric and space weather conditions, which could have a negative effect on the technical devices. Nevertheless, unlike in the case with the conventional radio communication, these conditions will not affect the transmission, reception and storage of data, nor the bandwidth or performance of the optical link. Therefore, prior to becoming fully operative, the laser space communication system will be subjected to various test and experiment scenarios developed with the participation of its future stakeholders. The implemented testing procedure ensures that the system's operational capabilities can be developed along with testing so as to respond to the needs of its various users. At the current stage of development, the optical links are expected to be predominantly utilized by research centers and private businesses involved in the space industry. In this respect, the following part of this section moves on to describe two experiments that could be performed as part of the LCRD testing. The reader should note that the capabilities of the laser space communication relay are by no means limited to scientific and commercial purposes. The laser relay technology will be subjected to a variety of tests aimed to establish a range of its potential applications in space. In the initial stages, the testing objectives are likely to focus on determining the performance rates, thus providing an estimate of the system capabilities and the scope of service that it can provide at the present time. Additional tests will, in turn, serve to set the direction for the future development of the technology with a view to optimizing the optical communication systems and improving the level of service provided. Relay providers will be presented with an opportunity to determine the effectiveness of their pre-developed operational procedures and establish the necessary improvements to be introduced in the future with a view to future full automation of laser space communication system.

The first scenario (Figure 3) concerns providing the service to multiple users. In the diagram, the communication configuration with a space probe via relay providers is given on the left. On the right-hand side, there is the simulated configuration of the LCRD experiment. In this test, OGS-1 employs its UPS to simulate the function of a user spacecraft, exchanging data with one of the on-board space terminals via an optical link. OGS-2 functions as a second user spacecraft. The LCRD flight segment then tracks several simulated objects – spacecraft – with a single relay, exchanging data via radio transmission between the HBRF terminal and the ground station. Due to the great bandwidth, it is capable of supporting up to approximately 20 users and track their space objects with no interference or time delays.

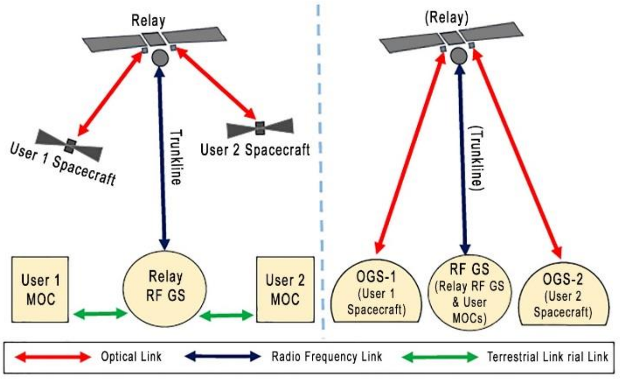

Figure 3. Example LCRD experiment configuration (depicted on the right) to simulate a scenario involving a relay provider supporting multiple user spacecrafts (depicted on the left) (NASA, 2017, p. 18).

The other potential scenario tests the functions important for flight segment relay providers supporting a single user spacecraft

(Figure 4); the simulated activity is the “station handover.” The handover is presented on the left side of the diagram: the line connecting the optical terminal to the ground station is transferred between the ground stations. In the experiment (on the right), the RF ground station functions as a relay spacecraft, while the two remaining optical ground stations are free for the station handover. To simulate a user spacecraft, the ground radio station employs its UPS simulator to mock the data package of the links and their exchange with the flight segment using the HBRF terminal. The optical trunkline is established between the LCRD optical space terminal and the OGS-1 station, which also simulates the functions of User MOC. The handover procedure is initiated with the termination of the initial optical trunkline that becomes replaced by a new optical line between the same optical relay in the flight segment and the OGS-2 station. Having formed a new optical link, the OGS-2 station begins to function as a relay optical ground station and the user operations center simulator (User MOC). The use of electromagnetic links in this simulation (Wan et al., 2010) enables relay providers in the flight segment to determine the characteristics of the handover process. The tests could be modified to include a range of other conditions, e.g. a simultaneous transfer of data with multiple users or in the presence of adverse weather conditions – to test the handover process times. The results from the experiments would deliver reliable data enabling providers to calculate how far in advance station operators would need to prepare for station handover. To determine the effectiveness of handover needs prediction, the provider could establish a communication link and subsequently test the capacity for prediction when the connection will be severed by weather conditions (NASA 2017).

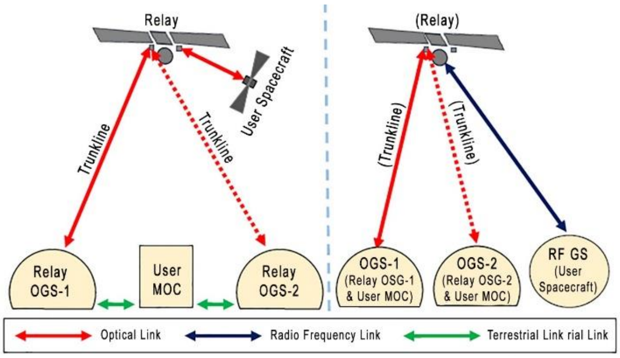

Figure 4. Example LCRD experiment configuration (depicted on the right) to simulate a scenario involving a relay provider executing station handovers (depicted on the left) (NASA, 2017, p. 19).

5. Conclusions

In the text, the Harvard referencing citation style should be used (Smith, 2017) or (Smith, and Bradley, 2017). In the case of more than three authors, write the surname of the first of them and add the abbreviation et al. (Bradley et al., 2017).

Several general conclusions emerge from the presented analysis of existing literature on the subject and the results from the author’s own study:

- contemporary technologies providing communication with in-space objects employ the propagation of electromagnetic waves in various frequency bands. Space communication accomplished by radio is divided between three bidirectional networks that are used according to the distance between a given object and the Earth. In its current form and technical capabilities, the conventional communication is largely insufficient with respect to providing effective bidirectional communication with spacecrafts, which is a consequence of a widening gap between advanced space and communication technologies installed on spacecraft or satellites that are incompatible with radio communications;
- in view of the status quo, there emerges a need to replace the bidirectional radio space communications networks,

which appear to be headed for obsolescence, with a new type of communication that exhibits a higher future potential. Optical space communication, which uses a laser beam as an information carrier, is widely regarded to be the most likely successor to radio-based technologies. The laser beam in space communication provides higher bidirectional throughput for both uplink and downlink data, undisrupted communication with objects, lack of time delays and resistance to disturbances, which could result from e.g. space weather;

- optical space communication technical infrastructure will combine components of the existing radio-based systems and laser-beam propagation devices, which is expected to reduce the cost-intensity of the project;
- the development of optical space communication is predominantly aimed to provide technological support to future interplanetary space flight missions, organized by research centers and private enterprises involved in the space industry;
- to ensure that laser communications relay technology is compliant with the needs of various users, it is crucial to perform extensive and comprehensive testing of the entire system, which is currently in progress.

Acknowledgements

This work is financed through funds for scientific activity as part of the research task: Unmanned Aerial Apparatus in Provision of Safety and Security (task number: II.1.25.0).

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