CONFERENCE REPORT

Trends in Laser Communications in Space

Report on International Workshop "GOLCE2010"

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Abstract

In space, radio frequencies (RFs) are usually used for long-distance linkage. However, recent progress in optics and laser technologies, especially in fiber optics, is ushering in an era of inter-orbit communications using laser beams. Both RFs and optical waves are electromagnetic waves, but optical waves offer many advantages in space, including reduced mass, power, and volume of equipment, higher data rates, no tariffs and no regulatory restrictions such as with RF bands. The benefits are due to optical waves' high frequency. In Europe, the European Space Agency (ESA) in its Semiconductor Laser Intersatellite Link Experiment (SILEX) has routinely used a 50Mbps optical communication link twice a day between a low earth orbit (LEO) and geostationary earth orbit (GEO) satellite since 2003. In Japan, the Optical Inter-orbit Communications Engineering Test Satellite (OICETS) developed by the Japan Aerospace Exploration Agency (JAXA) was launched in August 2005 and a laser communication link with the SILEX terminal was successfully established. After these experiments, ground-to-OICETS laser communications experiments including four optical ground stations (OGSs) were conducted and laser beam propagation data were acquired. The National Institute of Information and Communications Technology (NICT) organized an international workshop called Ground-to-OICETS Laser Communications Experiments 2010 (GOLCE2010) in Tenerife, Spain, through which recent trends in the research and development of laser communications in space were reported.

Keywords Laser communication, Optical communication, Free-space, Space communication, GOLCE2010

1. Introduction

Free space laser communications have been received increasing attention as a promising future means of communication due to features like reduced mass and size, higher data rates, larger communication capacities, and freedom from regulations and tariffs[1]. Specifically, development of LEO-to-ground optical high-rate data transmission systems should be the initial step in terms of the continually increasing need for establishment of a next-generation major communications system to transmit vast amounts of data from an earth observation satellite (EOS) and the like[2]. This type of data transmission system with a high-speed direct link requires stability of uplink transmission under atmospheric turbulence, which makes technical demonstration essential.

The Optical Inter-orbit Communications Engineering Test Satellite (OICETS), developed by the Japan Aerospace Exploration Agency (JAXA), was launched in August 2005, which led to the world's first successful bidirectional inter-satellite laser communications experiment, between the OICETS and the Advanced Relay Technology Mission Satellite (ARTEMIS), a geostationary earth orbit (GEO) satellite of the European Space Agency (ESA)[3]. The next year, the world's first LEO-to-ground laser communications were achieved between the OICETS and the NICT optical ground station (OGS) in Tokyo's Koganei City[4]. In 2008-2009, with three other international agencies – the NASA Jet Propulsion Laboratory (JPL), ESA and German Aerospace Center (DLR) – collaborative ground-to-OICETS laser communications experiments were conducted using four respective OGSs. The experiments successfully resulted in acquiring laser propagation characteristics through data obtained at different locations on Earth[5].

The International Workshop on Ground-to-OICETS Laser Communications Experiments 2010 (GOLCE2010) held in Tenerife, Spain on May 13-15, 2010 served as a roundup for exchanging and discussing the fruitful results of these experiments[6]. A total of 66 people from 6 countries such as Switzerland, Germany, Netherlands, USA, Spain, Japan have participated in GOLCE 2010. Movements also exist that are centered mainly on NICT to lead the results toward standards development such as formulating propagation models and optimum coding. Related discussions have begun in the Consultative Committee for Space Data Systems (CCSDS). This paper presents current trends in free space laser communications, mainly based on the reports from GOLCE2010.

2. Trends in the United States

2.1. NASA

NASA, with regard to space laser communications, emphasizes deep space exploration missions. Compared with radio frequency (RF) systems, laser systems can save about 50% in weight, 65% in consumption power and achieve about a twenty-fold increase in data rates. NASA currently has a scheme for the combined use of laser and RF systems as future communications architecture, which is divided into three major categories of development: a near-Earth flight terminal, deep space flight terminal and optical ground infrastructure. For the near-Earth flight terminal, the agency will soon conduct a Lunar Laser Communications Demonstration (LLCD) on the Lunar Atmosphere Dust Environment Explorer (LADEE); literally, laser communications experiments from a lunar orbiter to Earth. In the demo, it will employ a ground terminal consisting of a base receiver designed on photon-counting technology, an array of 40 cm telescopes for the receiver, and an array of 15 cm telescopes for the beacon. Its optical flight terminal equipped with a 10 cm telescope can transmit data at 600Mbps for the downlink and 16Mbps for the uplink, and is capable of centimeter-level ranging. For development of the deep space flight terminal, aiming at the launch of the Deep Space Optical Terminal (DOT) in 2018, NASA is now conducting studies for identifying key technology, and is scheduled to complete Phase-A study in summer 2010. Its key technological developments include leading-edge items such as high-efficiency photon-counting detectors, jitter-damping systems, lightweight optics and low-mass modem technology. Meanwhile, it considers international interoperability of optical ground stations to be a major issue for optical communications since it is essential to mitigate cloud influence. In this context, it notes that key parameters such as wavelength, modulations and coding should be promptly standardized by the CCSDS initiatives.

2.2. JPL

NASA JPL envisions the use of laser communications in deep space exploration. It has thus far developed certain element technology for planetary laser communications, such as 4x4 Nb TiN nanowire superconducting detector arrays, a low-frequency vibration isolation platform, a flight laser transmitter incorporating a 1550 nm 2W Er/Yb co-doped optical amplifier; high-order PPM electronic circuits capable of achieving a 1Gbps data rate, OOK/PPM methods in which modulation/codes approach a fraction of 1 dB of the channel capacity of the Shannon limit, low-cost large-diameter telescopes, and an atmospheric visibility monitoring system. In the Mars laser communications project, it is planning an 0.4 AU-distant trunk line from the Mars orbiter to Earth at a data rate of 0.25Gbps for downlink and 0.2Mbps for uplink, with mass and power consumption less of than 30 kg and 110W, respectively. In this scheme, a 12 m ground telescope is assumed as a receiver.

Lunar surface laser communications and a Mars-Moon access link are under study for the conceptual base. JPL has also recently succeeded in an aircraft test of laser communications with data transfer over the 20-30 km range. For LEO, it is studying a compact optical terminal with a 5 cm aperture diameter. This flight transceiver will be capable of a 10Gbps downlink data rate and have a fine tracking mechanism with a 20 μrad pointing jitter. A 0.6 m ground telescope is assumed as a receiver. Another project of JPL is development of laser ranging to planets, and study is underway for measuring between Earth-to-Mars at a range to 1 mm. In this area, it has conducted ground-to-aircraft laser ranging tests comparing optical and differential GPS range measurements. The results over 5 km range show systematic error within 1 m and post-systematic error correction shows residual error within 10 cm. JPL is also studying a 10Gbps fiber-optic bus for a spacecraft with features for reducing cabling complexity, mass and power consumption, elimination of current electromagnetic interference and increased onboard data-flow throughput from 100Mbps to 10Gbps. It will conduct evaluation of the bus under simulated realistic environmental conditions.

2.3. Aerospace Corporation

Aerospace Corporation has been operating the NFIRE satellite equipped with a laser communication terminal (LCT) developed by Germany's Tesat-Spacecom. This collaborative project between the US and Germany started in 2005 and led to a launch in 2007. Since then, inter-satellite communications experiments between NFIRE and Germany's TerraSAR-X have been implemented, resulting in the world's fastest data rate of 5.6Gbps, employing a coherent homodyne BPSK method at a wavelength of 1.064 μm. As described in greater detail in 3.4. Tesat-Spacecom GmbH, Germany has provided its developed LCT for the US' NFIRE as well as its own country's TerraSAR-X. Over 300 demonstrations have taken place between the two LEOs within tracking accuracy of around 6.8 μrad. LEO-to-ground demonstrations were also conducted with ESA and Hawaii OGSs. The company has achieved successful data transmission of 8.1 TBytes equivalent to 1800 DVDs. It is planning further LEO-to-ground laser communication demonstrations in 2011.

3. Trends in Europe

3.1. ESA

Starting with the Semi-Conductor Inter Satellite Link Experiment (SILEX), in which an optical data-relay link between the LEO satellite of SPOT4 (Satellite Pour l'Observation de la Terre) and the GEO satellite of ARTEMIS was successfully demonstrated, ESA has been conducting laser communications experiments such as those between OICETS and ARTEMIS; ARTEMIS and an aircraft, which is an airborne laser optical link named the Liaison Optique Laser Aéroportée (LOLA); and ARTEMIS and OGS in Tenerife, Spain. These experiments were performed with a 0.8-μm wavelength beacon and at a data rate of 50Mbps. Since 2003, the laser link with SPOT4 has come into regular use for the twice-weekly transmission of Earth observation data. The most recent case of its laser communication experiments is between TerraSAR-X and an LCT engineering model developed by Germany with a wavelength of 1.06 μm.

ESA has the prospect of integrating LCT into its future satellite planning. One of the initial projects is a 1.2Gbps data relay between LCTs onboard the GEO satellite of AlphaSat and the LEO satellite of Tandem-X, respectively. In the meantime, the EU has been undertaking a space policy of geo-environmental measurement under the Global Monitoring of Environment and Security (GMES) program in order to provide useful information on environmental control and security of human life, and the Sentinel series EOSs are employed for this mission. In this connection, ESA proposes the concept named the European Data Relay Satellite System (EDRS) to relay data provided by these EOSs. This plan includes the use of LCT to meet the needs of data downlink at over 6 TBytes/day; capacity essential for timely provision of Synthetic Aperture Rader (SAR) and multispectral optical observation data in times of natural disasters such as earthquakes and fire. In the EDRS, GEO satellites equipped with laser communications devices are designed to be used for data relay in teaming with EDRS piggyback payloads.

ESA has also been planning the DOLCE project in which science satellites will be launched into the Lagrange points for optical data relay. In the project, for example, the James Webb Space Telescope (JWST) will be able to demonstrate laser communications at 10Mbps using LCT with a 10 cm aperture diameter. Another proposal is the Moon-Earth optical data relay at 1W and 170Mbps, which is feasible if using 1 m OGS, and also a Mars-Earth optical downlink, which requires 300MB of data transmission per day based on the estimation results of the ROSA project and is feasible at 320kbps if using a 10 m-class OGS at a distance of 2.6 AU. ESA also plans a demonstration of quantum key distribution from the International Space Station (ISS), which is called the Space-QUEST (Quantum Entanglement in Space experimenTs) project. It is now developing quantum light sources, etc. and aims at a 2015 launch.

To date, ESA OGS has made substantial contributions such as: conducting laser communications with satellites; providing an inter-island link of 142 km for laser communications; providing a test facility for laser-based techniques such as light detection and ranging (LIDAR); monitoring and cataloging the space debris population; enabling backup observations of science missions such as Deep Impact (comet 9P/Temple-1), Corot and Rosetta; assisting in the accurate orbit determination of spacecraft such as the XMM Newton and Herschel/Planck; and enabling astronomical observations by ESA. This year it is introducing the adaptive optics (AO) system for optical communications, for which installation is underway. It also plans a major upgrade of telescope systems by replacement of a dome to enable LEO tracking which, however, costs 170 k€ per year for maintenance. Though ESA is capable of executing various experiments on OGSs despite its limited budgets thus far, the current budget is only guaranteed until 2010. It is considering adoption of a charging system for the use of OGS facilities as a financial countermeasure taking advantage of favorable situations such that: prospective users of ESA's respective future missions are realistically anticipated; ESA OGSs have the benefits of excellent vision in good weather conditions, as well as easy accessibility; and ESA has been building good relationships with other organizations.

3.2. DLR Institute of Communications and Navigation, Optical Free-space Communications Group

DLR Optical Free-space Communications Group emphasizes direct LEO-to-ground laser communications through laser communications demonstrations employing a balloon and OICETS. As laser communications are interrupted by clouds, it has studied the probability distributions of cloud blockage aiming at mitigation of cloud influences with globally diversified locations of OGSs. Adopting four OGSs in Chile, Spain, Australia and Greece as data transmission terminals achieves 99% accessibility. It owns an OGS with a 40 cm aperture diameter located on the roof of one of its facilities in Munich, and is currently developing another OGS that is transportable and with a 60 cm aperture diameter for possible operation in 2011. By 2012 it will also prepare another new ground terminal with a coudé room. DLR is also developing a laser terminal on board a compact satellite, named OSIRIS, to measure atmospheric influences.

Another of its future development prospects is full-fledged application of AO to laser communications. It is considering employment of phase-shifting interferometry using a reference beam, instead of a wavefront sensor, to measure the distortions in a wavefront. This system has characteristics such as the fact that only an image sensor like a charge-coupled device (CCD) is needed for its receiving sensor via requiring an interferometer. By 2010 it plans to conduct closed-loop tests with a Xenics infrared camera at 1550 nm as well as long-distance demonstrations over 1 km using an AO system.

3.3. DLR Headquarters

A major plan of DLR is to load the LCTs developed by the German company Tesat-Spacecom on wide-range satellite systems of European organizations. Initially, ESA AlphaBus will be equipped with the LCT and a Ka-band downlink payload (300-600 Mbps) in Technology Demonstration Programme 1 (TDP-1), and then laser communications will be demonstrated with the AlphaSat satellite in GEO position at 25° East at the rate of 1.8Gbps after the 2012 launch. In the GMES Sentinel project, the Sentinel 1A radar satellite and Sentinel 2A optical satellite are scheduled to be launched in 2012 and 2013, respectively, and 50% of the entire Sentinel data transmission will be performed over laser links. To ESA EDRS, a system for relaying data collected by the above-mentioned observation satellites, €230 million has been invested by the EU as well as €114 million by Germany. Laser communications at 1.8Gbps will be executed in this project, with the first launch scheduled for 2012. The LCT will be also loaded as a main payload on a small GEO platform developed by Germany's OHB for a 2014 launch. This will also be included as a data relay satellite in EDRS. EDRS will be controlled by a commercial operator that will be selected in the third or fourth quarter of 2010.

3.4. Tesat-Spacecom GmbH & Co. KG

Tesat-Spacecom is a German developer of LCTs, and these have been selected for usage in various European satellite missions. One of the cases is that both satellites of TerraSAR-X of Germany and NFIRE of the US have carried its LCTs, and been conducting laser communications cooperatively at 5.6Gbps since 2007. The company has realized 78 communication tests (as of May 6, 2010) including 650 sec uninterrupted communication, for a total data transmission time of 17,800 sec, equivalent to 2,770 DVDs. Thus far, it has achieved pointing error with a mean of 141 μrad. Therefore the time needed for spatial acquisition was reduced from 18.7 sec to 2 sec, and optical frequency acquisition time on coherent laser communications from 30 sec to 8 sec. Operations of LCT-loaded satellites have now been transferred to a satellite operation center.

Tesat-Spacecom has also been conducting satellite-to-ground laser communications tests with OGS equipped with its LCT in Maui, Hawaii, with the first demonstration achieving 43 sec communication. Another demonstration with the LCT on OGS in Tenerife, Spain achieved 87 sec communication in the first performance with a measured bit error rate (BER) of 10^{-5} for uplink and 10^{-12} for downlink. The recent results from OGS in Tenerife show a coherent constant tracking duration of a maximum 65 sec and the longest coherent tracking duration at 130 sec.

Tesat LCT has already been adopted for future missions such as a GEO terminal for AlphaSat, LEO terminals for Sentinel 1A and 2A, and a GEO terminal for EDRS for which it will be employed as the data backbone. Based on all of the above-mentioned demonstrations, its technology has reached Technology Readiness Level (TRL) 9.

3.5. RUAG Space Ltd.

RUAG Space Ltd. (formerly Oerlikon, which was formerly Contraves) in 2008 and 2009 acquired Saab Space, Austrian Aerospace and Oerlikon Space. The company is located in eight cities in Switzerland, Sweden and Austria, and headquartered in Zurich. It has engaged in numerous missions concerning optical communications and an integrated RF-optical network for ESA's deep-space projects. Study is now underway on an optical link from Lagrange points L1/L2 and from a Mars orbiter for projects such as O-DSL, DOLCE, ROSA and IPComm. Studies for DOLCE include a 1.5 mio km optical link from a space terminal with a 135 mm antenna to 1 m OGS at 10Mbps using an MOPA laser, and for ROSA a 400 mio km optical link from the space terminal similar to DOLCE's to 4 m OGS at 160kbps. Both projects employ PPM algorithms with specifics of: 2048 slots at a pulse reflection frequency (PRF) of 6 kHz; 128 slots at PRF 30 kHz; and 32 slots at PRF 10 MHz. For those system demonstrations, the company has implemented scaled PPM communications field tests through a 142 km path between Tenerife and La Palma in Spain, achieving a

10Mbps scaled optical link with a Lagrange L2 point with receiver sensitivity of -68.9 dBm, and a 161kbps scaled link with Mars with sensitivity of -84.2 dBm. With 2-3 dB of scintillations being detected, these were a technical success. For further application, study is being conducted on a Mars sample return in which a 390 mio km optical link between Mars and 17 m OGS around 1Mbps is proposed. Prospects for the near future are the interplanetary communications project and the 2011 inter-island test campaign using further improved communications devices.

4. Trends in Japan

4.1. JAXA

Since 2005, JAXA has executed over 100 experiments on inter-orbit laser communications in the OICETS program. Over 90% probability of acquisition and tracking was established, and less than 10^{-6} BER without error correction code was successfully achieved in the demonstrations.

After the OICETS program, JAXA is now studying LCT-mounting in the Advanced Land Observation Satellite 3 (ALOS-3). On an Earth observation mission, ALOS-3 equipped with an optical imager will generate more than 130GBps of data for one high-resolution image, thus high-rate data transmission systems are essential. Also, in this program data-relay satellites are planned to be used for direct data transmission to ground. Corresponding optical terminals now developed are one with a 10 cm antenna diameter for LEO satellites and the other with a 20 cm diameter for GEO satellites. The data relay between them will be conducted at 1.0-2.5Gbps in the homodyne BPSK modulation method at a 1.064 μm wavelength. R&D on the corresponding laser source is now advanced and, thus far, 2.3W operation was achieved in CW operation and receiver operation was checked by phase-locking up to 7Gbps. The agency has a roadmap in which development of the both LEO and GEO LCTs will be completed by 2014 and operative service will commence after 2015.

4.2. NICT

In 1994, NICT achieved the world's first GEO-to-ground laser communication demonstrations with the Engineering Test Satellite VI (ETS-VI), and in 2006 the world's first LEO-to-ground laser communication demonstrations with OICETS. Subsequently, in April-September 2007, NICT rebuilt ground functions for satellite operation for further OICETS-OGS experiments. In 2008, demonstrations with OICETS were restarted, which led to the successful international campaign involving four OGSs in different locations on Earth. In this campaign, NICT succeeded in establishing an optical link 15 times in 27 planned experiments, NASA JPL achieved 4 out of 7, DLR 5 out of 10, and ESA 8 out of 9.

Using the same optical receiver in space is a huge advantage for comparing the respective uplink data obtained by the four OGSs. According to the preliminary report on the uplink data analysis, scintillation indices of the four OGSs data are distributed at 0.05-0.35, and hundreds of hertz were recognized in the frequency fluctuation. Most covariance data also indicate that correlation time length is 2-5 ms. This time length limits coding length or block length of the uplink signal.

Regarding the downlink data, the comparison makes sense because of the same laser source in space. The scintillation indices JPL measured indicate 0.1-0.3, and the figure of BER is nearly consistent with theory. DLR's indices are 0.05-0.4 and the frequency fluctuation is around 500-700 Hz. For the measurement of atmospheric turbulence, DLR measured the wavefront error with a Shack-Hartmann sensor, and then analyzed the data. ESA's indices are 0.05-0.5 and the frequency fluctuation is about 200 Hz. NICT obtained data with two different telescopes, with 5 cm and 32 cm apertures, then compared the data through frequency analysis and analyzed aperture averaging data. NICT has also developed a Matlab program that contains analysis program modules such as the scintillation index, power spectral density, probability density function and covariance. NICT plans to provide the program as a common tool for analyzing factors such as frequency and probability distribution of propagation data so that the data obtained at each site can be compared with the same measure, which will substantially contribute to the establishment of the future free-space propagation model.

NICT has launched a new project called the Space Optical Communications Research Advanced Technology Satellite (SOCRATES), studying laser communications with a 50 kg-class small satellite[7]. It has begun development of a small optical terminal weighing around 5 kg to be loaded on a small satellite, aiming to achieve laser communication demonstrations around 10Mbps between a small satellite and networked OGSs[8]. A small satellite is planned to be launched piggybacked with a main rocket, and a well-timed space experiment is expected. An engineering model is currently being developed for a 2012 launch.

5. Conclusion

Recent trends in research and development on space laser communications were introduced based on the reports of the international workshop on Ground-to-OICETS Laser Communications Experiments 2010 (GOLCE2010) in Tenerife, Spain in May 2010.

After the international collaborative campaign for common laser experiments using OICETS, space-to-ground laser propagation data acquired in each country were collected, and are expected to actively contribute toward building a free-space propagation model. These activities will also encourage standardization of the free-space optical link in stages such as CCSDS and ITU. In R&D trends, the US is mainly advancing projects for laser communications in deep space exploration. In Europe, there is active promotion of laser communications in data relay systems and a German LCT is scheduled to be mounted. Overall, full-fledged adoption of AO systems is becoming the trend and some organizations have begun system demonstration. Moreover, there are moves to employ laser communication systems for small satellites given the successful conducting of several laser communication demonstrations with LEO satellites in space. From here forward world trends in space laser communications R&D are sure to attract increasing attention.

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