Free-Space Laser Communications: The Japanese Experience

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Abstract *Free-space laser communication demonstrations are introduced in Japan with results obtained through previous demonstration experiments and current developments. A comparison among different optical systems was made relating to the data rate and the receiver sensitivity.*

Introduction

The future of laser satellite communications at optical frequencies depends primarily on their distinct advantages as compared to microwave solutions. The major advantages of a lightwave system over a conventional radio frequency (RF) system include: (1) small antenna (telescope); (2) less mass, power and volume; (3) intrinsic narrow-beam and high-gain nature of lasers; and (4) no regulatory restrictions for frequency use and bandwidths [1]. Most of these advantages are consequences of the short wavelengths associated with optical waves. Laser satellite communication systems have ~60 dB more gain (which can be used to increase the data rate); the system's narrow beams are basically immune to jamming and interception/detection by adverse parties.

However, because of very short wavelengths, the reliability of an optical communication link can be seriously degraded over that of an RF system by considerably greater irradiance (intensity) fluctuations, or scintillations, caused by atmospheric turbulence that affects the propagation of optical waves. A sophisticated optical system is required to maintain the very high acquisition, tracking and pointing accuracy. Therefore, for designing any laser communication system it is important to understand the pointing-jitter effects and the optical signal fade characteristics that result from atmospherically induced scintillations [2,3].

Japanese free-space laser communication projects are introduced in the next section. Then, the current developments for space laser communications in Japan are described and different optical communications systems are compared.

ETS-VI/LCE program

Overview

The NICT (formerly, CRL) began research and development activities on space laser transmission technology in the early 1970s [4,5] and embarked on a space system demonstration for laser communication by using a satellite in the mid-1980s. In 1986, the NICT started developing an experimental system that consisted of a ground optical station and the Laser Communication Equipment (LCE) onboard the Japanese Engineering Test Satellite VI (ETS-VI) satellite [6–8]. This satellite, designed for a geostationary earth orbit (GEO), was launched on 28 August 1994, by the Japan Aerospace Exploration Agency (JAXA, formerly NASDA). Further, experiments for demonstration and assessment of optical inter-satellite link technologies were performed during December 1994 and July 1996 [9–11]. Although the satellite was not injected into the planned GEO, almost all the scheduled experiments were carried out by developing new operational methods and hardware in a ground station. The satellite's non-geostationary orbit resulted in the possibility of transmitting laser to the satellite from many places in the world and joint experiments were carried out at the Jet Propulsion Laboratory (JPL) of National Aeronautics and Space Administration (NASA) from November 1995 to May 1996 [12–14].

Objectives

The major objectives of the ETS-VI/LCE laser communication experiments are to evaluate the basic technologies for an optical inter-satellite communications system and to collect technical data through scientific and engineering experiments using an onboard optical system. The following experiments and measurements were planned: (1) trans-atmospheric laser beam transmission; (2) optical beam acquisition, tracking and pointing; (3) bi-directional optical communications; (4) three-axis satellite attitude measurement; (5) narrow laser beam pattern measurement; (6) optical measurements using optical sensors; and (7) optical device performance monitoring in space.

System description

The LCE has, despite its very light weight (about 22 kg), all the fundamental functions required for optical inter-satellite communications and for other scientific and engineering experiments. It has a two-axis gimbaled flat mirror, a 7.5-cm telescope, an acquisition sensor (CCD: charge coupled device), a fine-pointing mechanism (FPM) with a tracking sensor (QD: quadrant detector), a communications element that includes laser diodes (LDs), an avalanche photo-diode (APD), a point-ahead mechanism (PAM) and a QD for PAM control. An LD emitting at a wavelength of 0.83 μm was used for the downlink transmission, and an argon ion laser with a wavelength of 0.5145 μm was used for the uplink transmission. The optical ground station at the NICT site in downtown Tokyo has a very precise satellite tracking system including a 1.5-m receiving telescope, a 20-cm transmitting telescope, a 10-W argon ion laser, communication electronics and a control terminal for the LCE operation.

Results from the experiments

The received light level varied with time at a high frequency of more than 100 Hz. The fine-tracking error of the LCE was large when compared to a full divergence angle of the downlink beam, 30 μrad, and the downlink was received intermittently along with the atmospheric scintillation effects. The maximum duration for receiving the downlink at the ground was 300 ms. Once an optical link was established, although intermittently, it was possible to detect the received light signal and to perform measurements. The far-field pattern of an onboard laser transmitter was measured using a trans-atmospheric optical link that covered a distance of over 35,000 km; that is, the distance between a satellite and an optical ground station with the pointing probability function. The peak directive gain of the downlink laser beam was 104.3 dB, and the beam width (FWHM: full-width at half maximum) was 28.5 × 17.5 μrad. These results were consistent with the results obtained in a laboratory test [15].

OICETS/LUCE program

Overview

In June 1993, the European Space Agency (ESA) and JAXA signed the "Protocol of Agreement to Collaborate on the Preparation for an Experimental Optical Link between the JAXA Satellite OICETS and the ESA Satellite ARTEMIS". JAXA started the preliminary design of the Optical Inter-orbit Communications Engineering Test Satellite (OICETS) in November 1993, completed the preliminary design review of the OICETS system and started the detailed design in October 1994 [16–18]. The critical design review was completed in July 2000, and the proto-flight tests of the flight model of the OICETS system were carried out in January 2002. The endurance of the satellite against the launch and in-orbit environments such as acoustic, vibrational, shock and thermal conditions was confirmed [19]. Before the launch of OICETS, an optical acquisition and tracking test between the ARTEMIS and the engineering model of the OICETS optical terminal on the ground at Tenerife, Canary Islands, in the Atlantic Ocean, west of Africa, was conducted so as to confirm the compatibility of their optical interfaces in Summer 2003 [20].

The OICETS was launched onboard a Dnepr Launch Vehicle from the Baikonur Cosmodrome in the Republic of Kazakhstan, and placed into an LEO at an altitude of 610.0 km and an inclination of 97.8°. The functions of the satellite systems had been checked for the first three months, and stars and planets were successfully located and tracked. In December 2005, the first bi-directional laser communications demonstration between the OICETS and the ARTEMIS was successfully conducted with a return link of 50 Mbps and a forward link of 2 Mbps [21]. Following the inter-satellite laser communication experiments, the Kirari Optical Communication Demonstration Experiments with the NICT optical ground station (KODEN) were conducted in cooperation with JAXA from 2006 to 2009. Optical LEO downlinks from the OICETS to the optical ground station built by the German Aerospace Center (DLR) near Munich were successfully performed in 2006 [22].

Objectives

The objective of the OICETS is to perform on-orbit demonstrations of pointing, acquisition and tracking technology, and other key technology elements for optical inter-orbit communications with ESA's geostationary satellite ARTEMIS. Major experimental items under consideration are as follows: (1) experiments for evaluating onboard equipment capabilities in space environment, (2) experiments for evaluating the acquisition and tracking mechanisms using stellar acquisition and tracking, (3) inter-orbit optical communications experiments, (4) experiments for evaluating optical characteristics such as tracking under various atmospheric conditions, (5) measurement of micro-vibration of satellite and (6) optical link and precise laser ranging experiments between the OICETS and the NICT optical ground station. Other important items for investigation are a highly precise satellite attitude control system and a ground test equipment to evaluate the optical inter-orbit communication equipment performance.

System description

The satellite is controlled via S-band inter-orbit link with ARTEMIS and DRTS or S-band direct links with Tracking and Communication Stations (TACSs) using conventional radio frequency signals to transmit and receive telemetry, command and mission data. The OICETS satellite carries an optical communication terminal called the Laser Utilizing Communications Equipment (LUCE), which has the optical acquisition, tracking and communication functions in orbit. The mass of the LUCE terminal is 146 kg and its power consumption is 226 W during communication. It consists of two units: LUCE-O and LUCE-E. LUCE-O is the mobile part, residing on the anti-Earth side of the satellite to ensure a sufficiently wide visibility of the partner satellite in GEO. The LUCE-O comprises the following equipments: an optical antenna, internal optics and a two-axis gimbals mechanism called a coarse-pointing mechanism. The internal optics mainly consists of a laser transmitter, a laser communication receiver, a fine-pointing mechanism and sensor, a point-ahead mechanism and sensor, a coarse-pointing sensor and some relay optics. The optical antenna is a centre-feed Cassegrain mirror-type telescope. The diameter of the primary mirror is 26 cm. LUCE-E is an electronics module, including the control and communication electronics, which resides inside the structure of the satellite. The temperature of the optical bench is carefully controlled by a thermal control system to maintain highly accurate alignment and to ensure high performance of the optical devices.

Performance of LUCE

The data rates for forward and return links correspond to 2 and 50 Mbps at 0.8 μm wavelength, respectively. The far-field pattern of the LUCE laser transmitter measured in the thermal vacuum test and the divergence angle of the transmitting laser beam corresponds to about 6 μrad (FWHM). The wavefront phase distribution of the transmitted laser beam at the telescope aperture was measured and the wavefront error was less than $\lambda/10$ rms. The tracking error of ±0.7 μrad (3σ) and the pointing error of ±1.9 μrad (3σ) that includes the point-ahead errors produce a total pointing error of less than ±2.6 μrad (3σ).

Inter-orbit laser communications experiments

The experiment campaign consists of three phases as shown below.

- Commissioning phase: This phase establishes inter-orbit laser communication link, verifies the modulation function and the error counting function and confirms the interoperability between JAXA and ESA space network operation systems.
- Experiment phase: This phase evaluates the beam pointing characteristics and the acquisition and tracking characteristics under various special conditions.
- Routine phase: This phase demonstrates and evaluates an operational link under a condition of normal setup of both satellites.

The commissioning phase began on 5 December 2005. JAXA carried out the commissioning phase for 2 weeks, the experiment phase for 2 months and the routine phase for 5 months. All the experiments were completed on 10 August 2005. One hundred experiments succeeded in acquisition and tracking during the experiment campaign. The beam pointing experiment was conducted to improve the bias pointing error of the transmitted laser beam by measuring the far-field pattern. The calibrated angles were 2.5 μrad in X-axis and 1.8 μrad in Y-axis [21].

Ground-to-satellite laser communications experiments

Phases 1, 2 and 3 of bi-directional ground-to-satellite laser communication experiments were successfully performed in March, May and September of 2006, respectively. After the development of some new devices, optical communication experiments between the OICETS satellite and the NICT optical ground station were successfully conducted again as a Phase-4 experiment from October 2008 to February 2009. The effects of atmospheric turbulence were measured simultaneously. Acquisition and tracking were successfully performed under clear sky conditions. Optical links could thus be established even when there was atmospheric turbulence above the ground station. The manufactured fine steering mirror was tested and a fiber coupling test was successfully conducted. The BER performances for uplink and downlink were measured, and a better BER performance for the downlink was obtained. The forward error correction (FEC) tests were performed with the Low Density Parity Check (LDPC) codes, which should further improve the link quality of the ground-to-satellite laser communications [23].

Current on-going projects and developments for space laser communications in Japan

Laser communication experiments between some optical ground stations and the OICETS satellite were performed from April 2009 as international collaborative experiments at optical ground stations of NASA JPL, ESA, DLR and NICT. This campaign is conducted by NICT in collaboration with JAXA and it will last until September 2009. The laser beam propagation data passing through the atmosphere at various sites will be acquired through this campaign and they will contribute to the future study and standardization.

With the advent of coherent binary phase shift keying (BPSK) receivers in orbit by TerraSAR-X [24], it is going to be imperative to establish the interoperability between different optical communications systems. NICT developed a bread board model (BBM) of an optical receiver that can demodulate both intensity modulation and direct detection (IMDD) and coherent optical schemes for free-space laser communications, which can recover the carrier phase after homodyne detection by means of digital signal processing (DSP) [25]. A mobile optical ground station has also been developed for the site-diversity purpose in order to increase the accessibility between space and interoperable terrestrial systems [26]. Optical power amplifier and low noise amplifier are developed for the space qualified component in the future [27].

JAXA is planning to develop a high resolution land observation satellite system, which produces huge mission data and requires high data rate links. The utilization of the data relay satellites with optical links is the promising solution for such requirements. This possibility motivates JAXA to develop the next-generation inter-orbit optical communication system.

The system realizes a huge data rate link up to 2.5 Gbps with small and light (approximately 30 kg) terminals. JAXA started the feasibility study of a BPSK-homodyne modulation/demodulation system and currently is developing the BBM model. The feasibility will be confirmed through the development of the BBM until 2010. JAXA's target is developing the next-generation inter-orbit optical communication system between GEO and LEO satellites, which will be deliverable and operable in mid-2014. The research and development are cooperatively conducted by JAXA and NICT [28].

Comparison among different optical systems

Figure 1 shows trends of the data rate and receiver sensitivity for different optical systems. This figure also compares some roles for different optical systems. For the 800-nm wavelength band, the receiver sensitivity is poor because of the IMDD modulation scheme. The 800-nm technology will play a role in low data rate applications. On the other hand, the technologies for 1064 and 1550 nm wavelength bands are suitable for high data rate communications with the higher sensitivity. This is due to the fact that the coherent modulation scheme is employed. In addition to this, the 1550-nm technology has the ability to increase the data rate to a much higher level by using the wavelength division multiplexing (WDM) technique in the future.

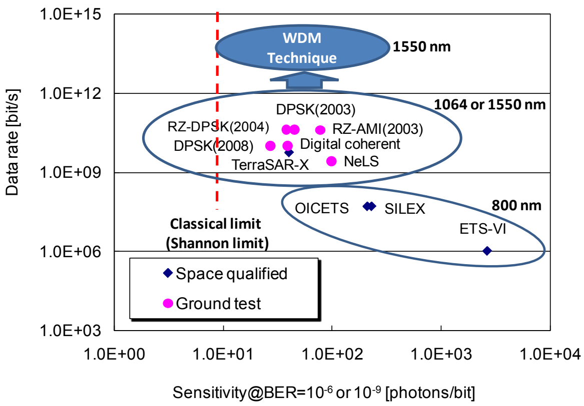

Fig. 1: Trends of the data rate and the receiver sensitivity for different optical communication systems

Conclusions

Previous Japanese laser communication programs and current developments for space laser communications were presented. ETS-VI and OICETS were introduced. NICT developed the interoperable optical receiver for both IMDD and coherent schemes, the mobile optical ground station and optical amplifiers. JAXA developed the BBM of the BPSK-homodyne modulation/demodulation system. The optical communications systems for 1064 and 1550 nm wavelength bands can be used around several tenth Gbps. In addition, the 1550-nm technology can increase the data rate more by employing the WDM technique in the future.

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