3-3 Optical Compatibility Test between Engineering Model of Laser Utilizing Communication Equipment on the Ground and the ARTEMIS Satellite in a Geostationary Earth Orbit

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A ground-to-space laser communications experiment was conducted to verify the optical interface between a laser communications terminal in an optical ground station and an optical payload onboard a geostationary satellite 38,000 km away, before the launch of the satellite. The end-to-end optical characteristics such as intensity, sensitivity, wavelength, polarization, and the modulation scheme of optical signals as well as acquisition sequences of the terminals were tested under fairly good atmospheric conditions. The downlink's bit error rate was on the order of 10^{-10}, in spite of atmospheric turbulence. Signal fading induced by atmospheric turbulence increased the uplink bit error rate, because the turbulent layer near the Earth's surface affects the uplink signal more than the downlink signal. The best error rate achieved was 2.5×10^{-5}. Far-field optical antenna patterns were measured through the ground-to-satellite laser links. From these results, a more accurate dynamic link design of the optical communications link can be performed, which would be useful for system designers, especially of optical commercial systems.

Keywords
Atmospheric turbulence, Optical ground station, Random pointing jitter, Long-term statistics, Free-space laser communications

1 Introduction

The Optical Inter-orbit Communications Engineering Test Satellite (OICETS) was developed by the Japan Aerospace Exploration Agency (JAXA). This project was implemented with the cooperation of the European Space Agency (ESA). OICETS carries an optical communication terminal called Laser Utilizing Communications Equipment (LUCE), which has optical acquisition, tracking and communication capabilities when in orbit. The proto-flight test of the OICETS flight model was completed in January 2002[1]. To mitigate risks facing the OICETS program, an optical acquisition, tracking, and communications test was performed to confirm the optical interface between the two satellites from September 8th to 16th, 2003[2][3]. For this test, a LUCE engineering model (EM) was set up at the ESA's Optical Ground Station (OGS) in Tenerife, Spain, where it established communications with the Semiconductor-laser Intersatellite Link EXperiment (SILEX) optical payload, called the Optical PAyload Laser Experiment (OPALE), onboard the Advanced Relay TEchnology MIssion Satellite (ARTEMIS) in Geostationary Earth Orbit (GEO) at 21.5°E. The objectives of the optical compatibility tests were to verify end-to-end optical characteristics such as intensity, sensitivity, wavelength, and polarization, as well as the modulation scheme of the optical signals and the acquisition sequences between the terminals.

2 Experimental configuration of the optical compatibility tests

Figure 1 shows a schematic of the setup of the optical compatibility tests, and a photograph of the setup is shown in Fig. 2. The ESA Earth station in Redu, Belgium, received the telemetry from ARTEMIS, and the feeder return and forward links were used during the communications tests. The Canary Islands are an excellent test site to perform this kind of experiment because they have very high mountains with excellent seeing conditions. The observatory's altitude is 2,393 m, which is above the thermal inversion layer under nominal conditions[4][5]. The structure parameter at the OGS altitude corresponds to C_n^2 (2,393 m) = 0.698 × 10^{-14} $m^{-2/3}$. The direction of ARTEMIS in GEO from OGS was at an azimuth angle of 123° (north is zero) and at an elevation angle of about 37°. The atmospheric coherence length and the seeing size respectively correspond to 23 cm and 0.76″ at an angle of elevation of 37° toward ARTEMIS. The beam parameters for the OPALE and the LUCE EM terminals are shown in Table 1[6][7].

3 Test results and discussion

3.1 Link statistics

Figure 3 shows the statistics of the link establishment during the test campaign. There were 32 sessions of 20 min duration each. The link establishment was succeeded at 78% and it was failed at 22% due to the clouds and the other reasons. The signal fading due to atmospheric turbulence was significant because the LUCE terminal transmitted only a single beam, which is included in 47% of LUCE bidirectional link established. The OGS system transmitted four laser beams in order to reduce the scintillation effect, as shown in Fig. 4[8]. The optical links with the LUCE terminal were also established with the aid of OGS system in 22% of LUCE acquisition failure of LUCE. An example of the downlink probabili-

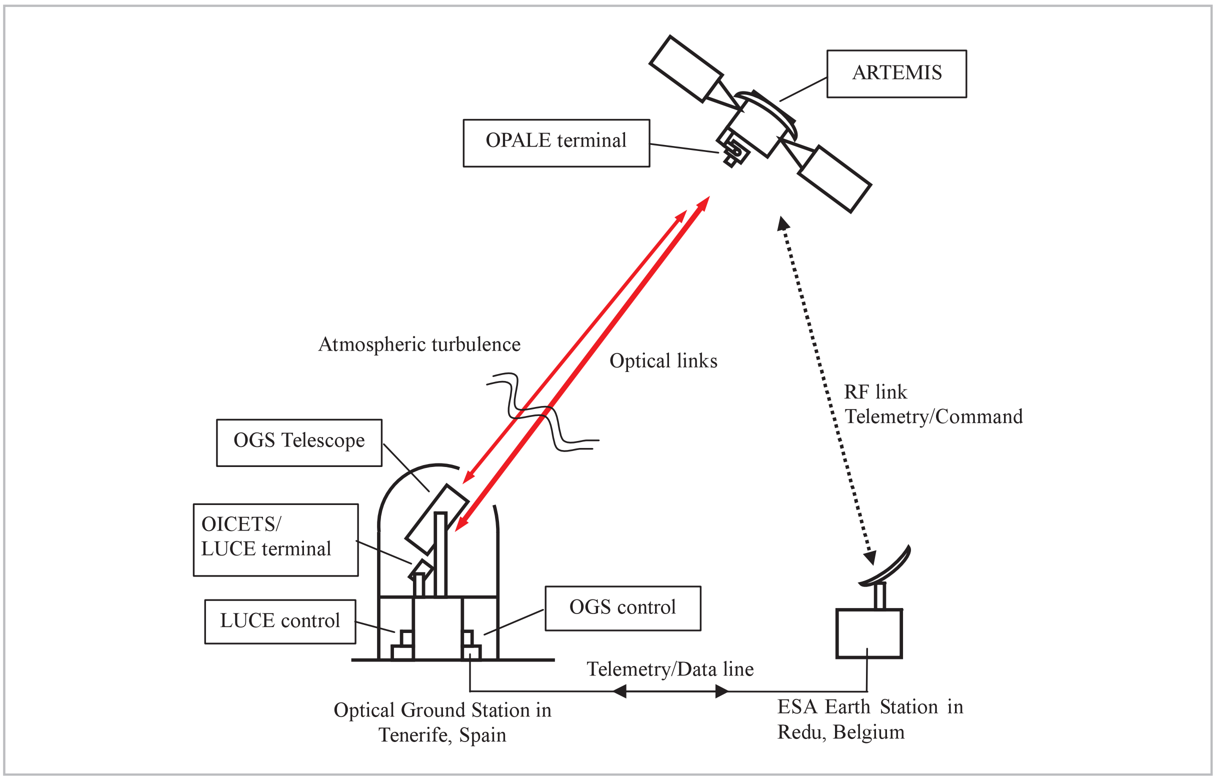

Fig.1 Setup of the optical compatibility test in Tenerife

Fig.2 *Photograph of the optical compatibility test in Tenerife*

ty density function is shown in Fig. 5. The role of OGS was to assist in the initial acquisition and to maintain the optical link between the LUCE terminal and the OPALE terminal during the experimental sessions. The initial acquisition used the LUCE terminal only, and succeeded autonomously without OGS support when the LUCE terminal transmitted the CW laser beam. In all the communication sessions, once the ground-to-satellite optical link was established, it could be maintained with only the single beam transmitted from the LUCE terminal.

3.2 Downlink results

The OPALE terminal transmits a modulated communications beam with a data rate of 2.048 Mbps. In spite of the variation in the optical downlink signal, the bit error count measured by the LUCE terminal was zero during about 866 seconds of the session period, or er-

Table 1 *Specifications of the optical beams*

Terminal	OPALE beam(s)	LUCE EM beam
Wavelength	Communication: 819 nm (Beacon: 801 nm)	Communication: 847 nm
Beam diameter ($1/e^2$)	125 mm (at telescope aperture)	120 mm (at telescope aperture)
Transmitted power	10 mW (at telescope aperture)	40 mW (at telescope aperture)
Signal format	2 PPM	NRZ
Data rate	2.048 Mbps	49.3724 Mbps
Polarization type	LHCP	LHCP

LHCP: Left Handed Circular Polarization, 2 PPM: 2-Pulse Position Modulation, NRZ: Non Return to Zero.

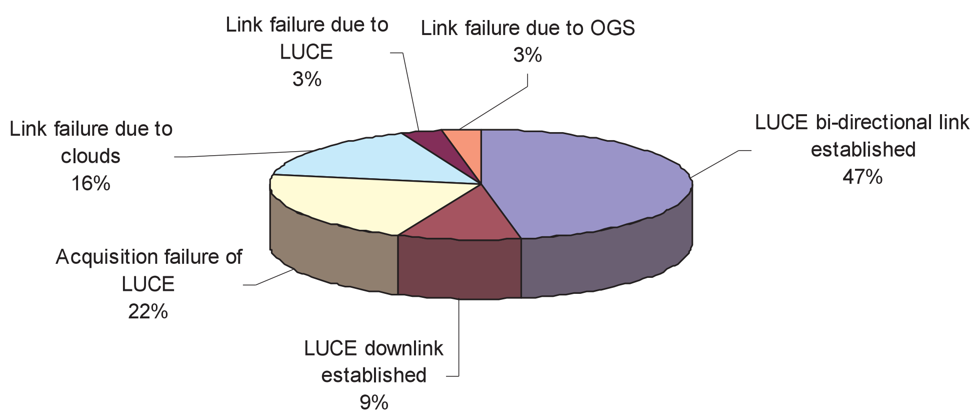

Fig.3 *Statistics of link establishment during the test campaign*

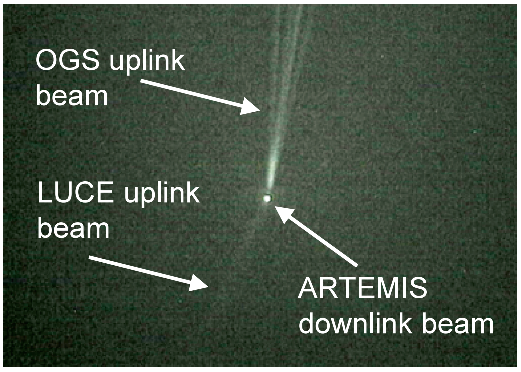

Fig.4 *Photograph of the uplink and downlink laser beams*

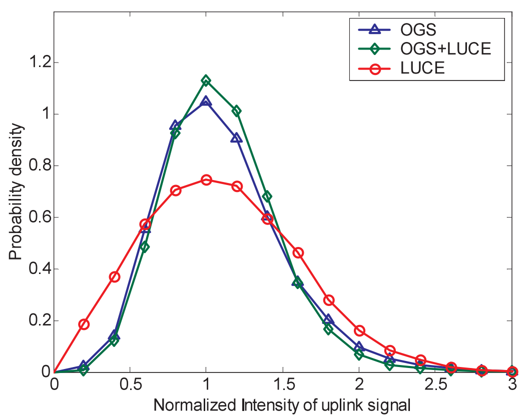

Fig.5 *Uplink probability density functions of LUCE with and without OGS assistance*

ror free, corresponding to a downlink bit error rate (BER) of better than 5.6×10^{-10}. The results show the communications performance of the forward link was perfect, with the static link margin of 7 dB. The communications function of the OPALE optical transmitter and the LUCE optical receiver was thus verified. The dominant power spectra of atmospheric turbulence reside below 10 Hz.

3.3 Uplink results

The LUCE terminal transmits a communications signal modulated with PN code and a data rate of 49.3724 Mbps. The uplink error bits were counted every second by the OPALE terminal and the best uplink BER during 1 s

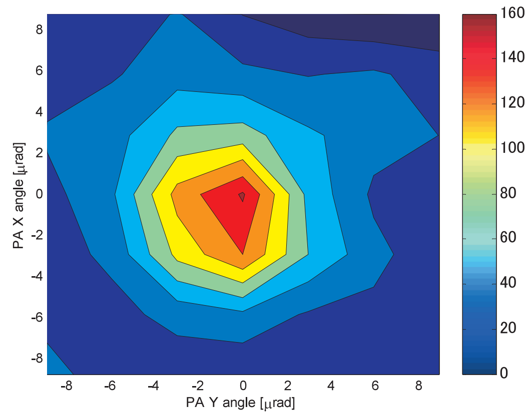

Fig.6 *Far-field pattern of the LUCE transmitted laser beam with a CW mode in the units of nW/m^2*

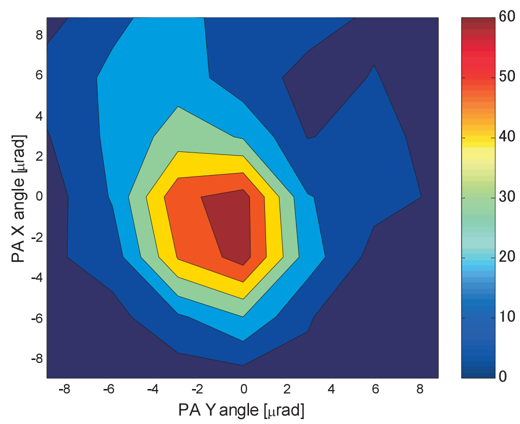

Fig.7 *Far-field pattern of the LUCE transmitted laser beam with a PN mode in the units of nW/m^2*

was 2.5×10^{-5}. The average degradation in BER at around 10^{-4}~10^{-3} is consistent with the static link margin of –1.47 dB[3]. For the on-orbit experiments, the communications performance of the return link was 6.45 dB better than the link budget analysis because there was no atmospheric turbulence and no atmospheric transmission loss in orbit. The uplink frequency components of atmospheric turbulence, mainly due to beam wander, reside below 30 Hz.

The far-field patterns of the transmitted laser beams from the LUCE terminal were measured through the ground-to-satellite optical links during the tests. The LUCE terminal makes a raster scan by deflecting the point-ahead angles with 7 × 7 grids. The step angle is about 3 μrad. Figures 6 and 7 show the far-field patterns of the LUCE laser beams with the CW and the pseudo-noise modulation modes, which are mapped in the point-ahead angles of PA X and PA Y directions, respectively. The tip-tilt tracking performance was perfect within 0.81 μrad (3σ) during this experiment. In order to evaluate the far-field pattern under the atmospheric turbulence, the short-term beam width at the satellite was calculated as 8.5 μrad (FWHM) based on the Hufnagel-Valley model. One can compare the calculated beam width and the measured far-field patterns as shown in Figs. 6 and 7, the theoretical values are in agreement with the measured data[9][10].

4 Conclusion

The optical compatibility test between the laser communications terminal onboard the OICETS satellite and the counter terminal carried on the ARTEMIS satellite was conducted. The downlink's bit error rate was on the order of 10^{-10}, in spite of atmospheric turbulence. Signal fading induced by atmospheric turbulence increased the uplink bit error rate, because the turbulent layer near the Earth's surface affects the uplink signal more than the downlink signal. The uplink bit error rate achieved was 2.5×10^{-5} at best. This fact showed that the end-to-end optical characteristics such as intensity, sensitivity, wavelength, polarization, and the modulation scheme of optical signals were confirmed. And the compatibility of acquisition, tracking, pointing, and acquisition sequences of the terminals were also confirmed. From these results, a more accurate dynamic link design of the optical communications link can be performed, which would be useful for system designs for space laser communications.

At the tail of this paper, as the test results verified the in-orbit design and operation of the optical terminals and the optical compatibility for the optical communication link between JAXA's laser communications terminal and ESA's counter terminal was confirmed before the launch of the OICETS satellite, this test contributed to the re-activation of the launch of the OICETS satellite.

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