3-2 Optical Inter-orbit Communication Experiment between OICETS and ARTEMIS

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Optical Inter-orbit Communications Engineering Test Satellite (OICETS) is an advanced engineering test satellite developed by Japan Aerospace Exploration Agency (JAXA) with two purposes. One is inter-orbit communication experiment between the OICETS and European Space Agency's geostationary satellite ARTEMIS. Another is optical communication experiment with the NICT optical ground station. Optical inter-orbit communications experiment between OICETS and ARTEMIS were performed from December, 2005 to August, 2006. This paper describes overview of the inter-orbit communication experiment system and summary of experiment results.

Keywords
Optical Inter-orbit communication, Space optical communication

1 Introduction

Unlike radio wave communications, optical communication systems in space can make their antennas compact. Taking advantage of the wide band characteristics of lasers, lightweight compact communication equipment mounted on a satellite can realize high-speed large-capacity communications. Optical communications have therefore attracted attention as next-generation core technologies for space communication networks using satellites. However since the technologies for optical communications, such as high-precision tracking and pointing technology using laser beams, are quite different from those for optical fiber communications on the ground, they have not yet been put into practical use, although their use has been anticipated.

Research activities in Japan have been performed since the 1980s at various research institutes and universities. The National Institute of Information and Communications Technology (NICT), Advanced Telecommunications Research Institute International (ATR), and Japan Aerospace Exploration Agency (JAXA) have conducted trial research [1][2]. In 1994, laser communication equipment (LCE) developed by NICT was mounted on the JAXA engineering test satellite Ⅵ and was successfully used for communications between a satellite and the ground for the first time in the world [3][4].

The Optical Inter-orbit Communications Engineering Test Satellite (OICETS) that will be introduced in this article was developed mostly for two purposes. One was to conduct experiments of optical inter-orbit communications between a low earth orbit and a stationary orbit, using OICETS and stationary satellite ARTEMIS developed by the European Space Agency (ESA). Another was to perform experiments of optical communications between low earth orbit and the ground using OICETS and the NICT optical ground station. OICETS was deployed in August 2005 into a sun synchronous orbit of an altitude of about 610 km and an orbital inclination of 97.8°. The satellite was named “Kirari.”

The experiments of optical inter-orbit communications between OICETS and ARTEMIS were conducted collaboratively by Japan and Europe in the period from December 2005 to August 2006, and experimental results were obtained for various orbits. This article gives an overview of the experiment system, and reports major experimental results obtained in experiments using OICETS and ARTEMIS.

2 Optical inter-orbit communications experiment system

2.1 Optical inter-orbit communications equipment mounted on satellites

Each of JAXA OICETS and ESA ARTEMIS have originally-developed optical inter-orbit communications equipment. To conduct communications experiments in orbit, JAXA and ESA jointly created the Space Segment Interface Document (S-ICD) to share communications interface specifications, and each of them developed optical inter-orbit communications equipment according to these specifications. S-ICD specifies the wave length, modulation method, intensity, pulse characteristics of optical modulating waves, and sequence of tracking and pointing each other's laser beams, etc. The major interface rules of S-ICD are shown in Table 1.

The optical inter-orbit communications equipment mounted on the OICETS is called LUCE (Laser Utilizing Communication Equipment) and that on the ARTEMIS is called OPALE (Optical Payload Laser Experiment). The significant functional difference between LUCE and OPALE is the presence/absence of a beacon light transmission unit. Beacon light is used only at the initial stage of the tracking and pointing sequence. A beacon beam of a spread angle of 750 μrad, wider than the spread angle of 6 μrad of communications laser beams, is radiated to the target satellite. By scanning it in a spiral form, important initial tracking can be secured. For the details of the performance of OPALE, see references [5] and [6]. In what follows I describe LUCE developed by JAXA.

LUCE consists of the LUCE optical unit, which is installed on the outside of the satellite body, and the LUCE electronic circuit unit, which is installed inside the satellite. The appearance of LUCE is shown in Fig. 1 and the internal configuration in Fig. 2. The optical unit consists of an optical antenna with a 26 cm Cassegrain reflecting telescope, a 2-axis gimbal coarse pointing (CP) mechanism unit, and a fine pointing (FP) mechanism unit. The electronic circuit unit consists of a tracking, pointing and directing processor and CP and FP control circuits. The two CP and FP tracking and pointing units take charge of different parts of the function depending on the control drive range, band width, and precision. The CP unit uses an interline, 2-dimensional CCD to track and point the beams that the partner

Table 1 *Major rules of interface for optical inter-orbit communications*

	Forward link (OPALE to LUCE)	Return link (LUCE to OPALE)
Wavelength	819nm (communication beam) 801nm (beacon beam)	847nm (communication beam)
Polarization	LHCP	LHCP
Data rate	2.048M bps	49.3724M bps
Modulation	IM-DD	IM-DD
Signal format	2PPM	NRZ
Extinction Ratio	< 2% Imin/Imax	< 2% Imin/Imax
Intensity	Min. 25.2MW/sr Max. 130MW/sr	Min. 280MW/sr Max. 780MW/sr
Bit error rate	$< 10^{-6}$	$< 10^{-6}$

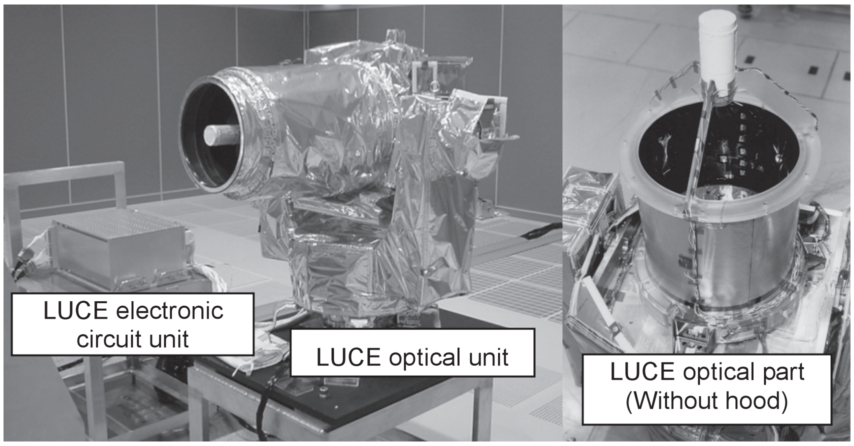

Fig.1 *External view of LUCE*

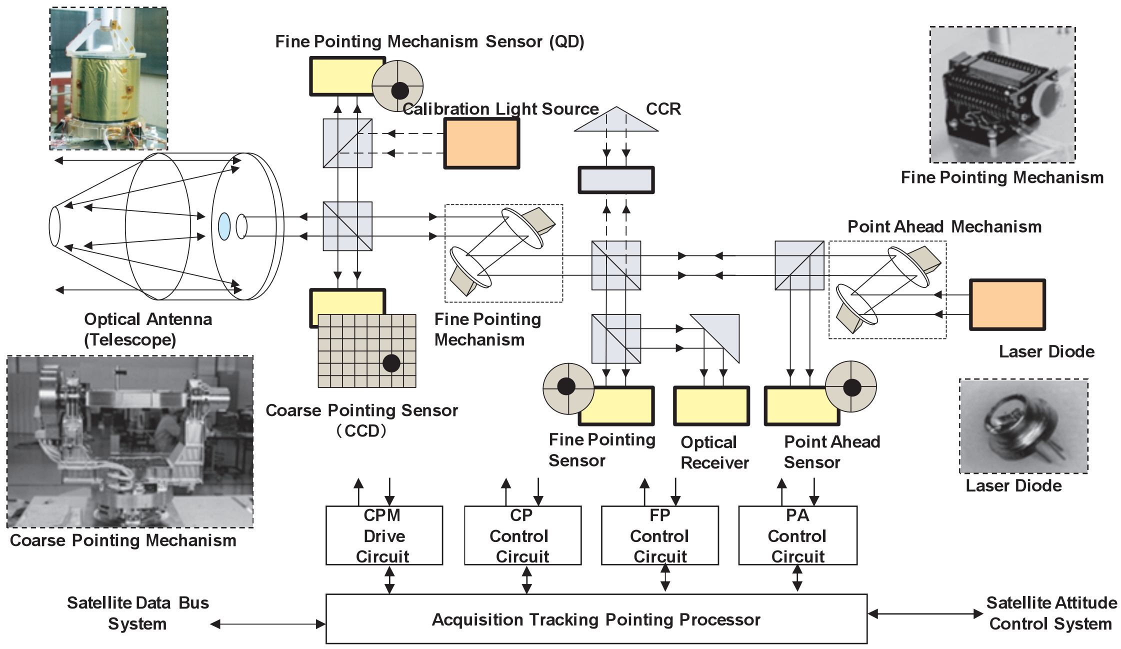

Fig.2 *Internal configuration of LUCE*

satellite emits. It uses a Az-El mount 2-axis gimbal to drive the optical antenna and the entire optical unit so that the received beams can come to the center of the CCD, and to control the partner satellite's laser beams coming in at a visual field of ±0.2° to fit in to a visual field of ±200 μrad for the fine tracking and pointing sensor. The FP unit uses a quadrant photodiode. Controlling two small mirrors with a layered piezoelectric element, the FP mechanism guides the laser beams emitted by the partner satellite to the communication light receiver in the visual field of ±100 μrad. The avalanche photodiode (APD) light receiver converts the light intensity modulating pulse signals to electrical signals. A laser diode AlGaAs with a maximum output 200 mW is used as the laser emission source. The laser emitted from the diode goes along the light receiving axis before the FP mechanism, goes through the mechanism, and is then radiated from the optical antenna to the partner satellite. Since the relative speed of the satellites is about 7 km/sec, this aberration needs to be corrected. LUCE therefore has a point ahead (PA) unit to correct the angle of the emitted laser beams. The PA unit successively calculates the correction angle according to the orbit information of both satellites using the LUCE tracking and pointing processor, and keeps controlling the pointing angle of the emitted laser beams using the layered piezoelectric element. The designed total pointing accuracy of the emitted laser beams, including the CP, FP and AP units, is ±2.6 μrad.

LUCE occupies about 20% of the weight of the satellite and the influence of the LUCE on the attitude of the satellite is inevitable. Therefore, a feed-forward control interface is installed between the LUCE and the satellite attitude control unit. The satellite attitude control unit receives angle information from the LUCE CP unit in real time and maintains the satellite attitude using reaction wheels. On the other hand LUCE receives the satellite attitude angle and its error in real time and uses the data to control the CP unit for tracking and pointing [7].

2.2 Entire experiment system

Figure 3 shows the entire experiment system configuration of optical inter-orbit communications, including the satellite operation and experimental data flows. In this system, necessary commands are sent, before each experiment, from JAXA's tracking station to the OICETS and from the ESA operation control center to ARTEMIS. Among a number of the commands sent to the satellites, the most important one is the information of the orbit of the partner satellite. Since the optical inter-orbit communications use narrower-angle beams rather than radio waves, an error in the orbit data of the partner satellite would disturb initial tracking of the communication link. In the experiments, therefore, the orbit information of the satellites was exchanged between ESA and JAXA every 24 hours and sent to the partner satellites so that each satellite could use the latest orbit data.

For the optical inter-orbit communication data link from LUCE to OPALE (return link), OPALE makes O/E conversions of the optical input signals received from LUCE and the demodulated digital base band signals are sent to

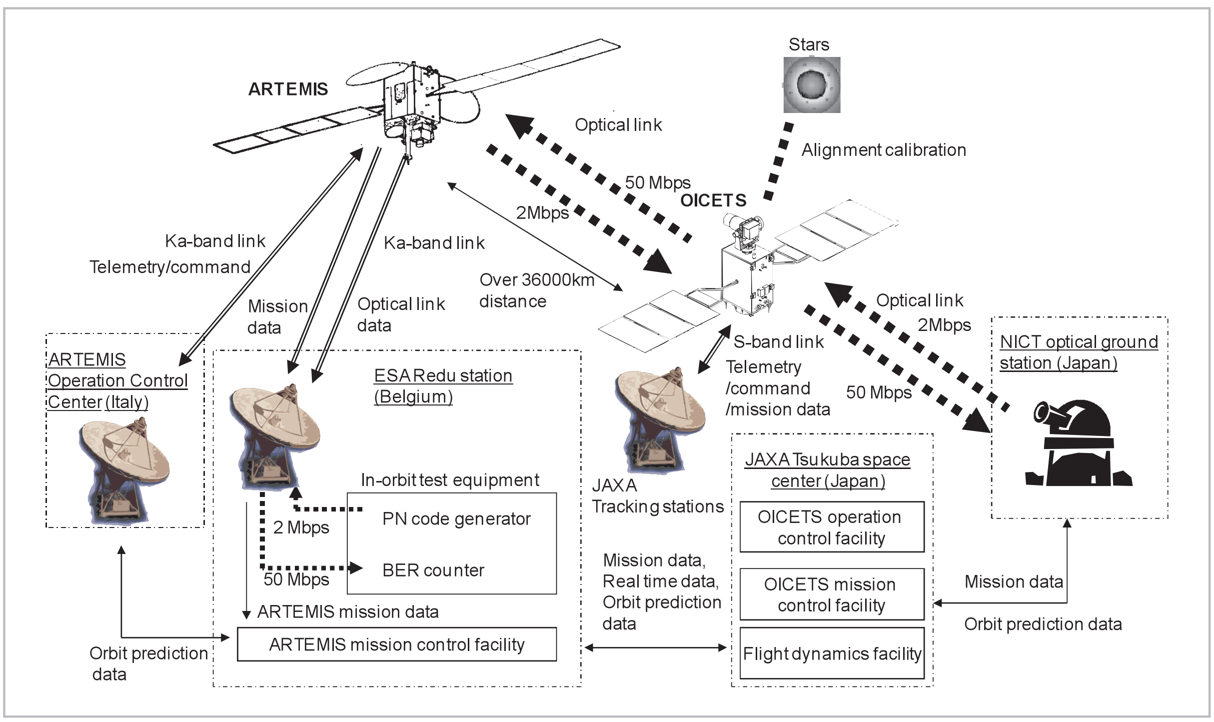

Fig.3 Experiment system configuration

the ESA ground station in Belgium through a Ka-band communication link. For the optical inter-orbit communication link from OPALE to LUCE (forward link), signals are sent from the ESA ground station in Belgium to ARTEMIS through the Ka-band communication link and the OPALE makes E/O conversions of the signals to send to LUCE through the optical communication link. For the communication quality evaluation, LUCE has a pseudo random code (PN code) generator to evaluate the return link and a bit error measurement unit to evaluate the forward link. The ESA ground station in Belgium also has a PN code generator and bit error measurement unit.

Since the stationary position of ARTEMIS is around the African Continent at 21 degrees east longitude, the optical inter-orbit communications experiment was conducted above Europe through the African Continent. Since ARTEMIS is a stationary satellite, its telemetry data can always be monitored. OICETS is a low earth orbit satellite and cannot always be monitored by the JAXA tracking station. For real time monitoring of the status of the optical inter-orbit communications experiments in Japan, a real-time ARTEMIS telemetry monitoring device was installed at the JAXA Tsukuba Space Center.

As necessary for the analysis and evaluation of optical inter-orbit communications experiments, the tracking error data of LUCE was sampled every 125 μsec, stored temporarily in a semiconductor recorder in the satellite, and transmitted after the experiments to the JAXA tracking station through the S-band link. The tracking error data of OPALE was transmitted from ARTEMIS to ESA ground station in Belgium through the Ka-band link and then to the JAXA Tsukuba Space Center through a terrestrial channel. This system allowed the Tsukuba Space Center to evaluate and analyze the experiments in an integrated manner.

3 Results of optical inter-orbit communications experiments

3.1 Course of experiments

The experiments using OICETS and ARTEMIS were planned and conducted in the following three phases.

(1) Commissioning phase

In the optical inter-orbit communication experiments using OICETS and ARTEMIS, this ws the phase of preparation and trial experiments to search for the parameters for the establishment of an inter-orbit communication link and to make various trial runs for the establishment of a bidirectional optical inter-orbit communication link.

(2) Experiment phase

This is a parameter tuning phase where, after the bidirectional optical inter-orbit communications link has been established in the Commissioning phase, the tracking and pointing sequence is validated and the pointing bias error of the laser beams emitted from LUCE is evaluated and corrected, to proceed to the Routine phase.

(3) Routine phase

In this phase, experiments are performed aimed at the practical use of the satellite by acquiring data constantly without changing the settings of both satellites and the optical inter-orbit communication equipment, and by verifying that communications are always stable.

Initial checks of the satellite functions were performed [8] for three months after OICETS was put into orbit, and then we started the Commissioning phase on December 6, 2005. We succeeded in the tracking and pointing of the laser beams from the partner satellite in the first experiment on December 6, and in the demodulation of the optical communication signals in both forward and return links on December 9, which was the world's first successful bidirectional optical inter-orbit communications experiment.

Considering before the experiments that the accurate radiation of a laser beam to the partner satellite was difficult and hence the initial acquisition of the beam would fail, we took the measure of expanding the scanning area of the OPALE beacon beams and scanning of the laser beams emitted from LUCE. Since it would be necessary to make more trial runs in case of a failure of the initial laser-beam acquisition, we expected before the experiment that the Commissioning phase term would be longer. However, as we succeeded in the tracking and pointing operation in the first experiment, the Japanese and European staff all took delight in the success and were greatly relieved to find that it was not necessary to make difficult trial runs.

The Experiment phase began on December 19 for the evaluation and correction of the pointing bias error of the laser beams emitted from LUCE, and finished on February 16, 2006. Then the Routine started to continue the experiments. On August 10, 2006, the on-orbit experiments using OICETS and ARTEMIS were all completed. We conducted a total of 106 experiments with OICETS and ARTEMIS and succeeded in 100 communications experiments. The typical experiment results, including the verification of the tracking and pointing sequence, are shown below.

3.2 Verification of tracking and pointing sequence

The tracking and pointing operation using LUCE and OPALE was conducted in the following sequence.

(1) Beacon beam radiation and scanning by OPALE

(2) Tracking and pointing of the beacon beam and communication laser radiation by LUCE

(3) Tracking and pointing of the communication laser beam by ARTEMIS, which then radiates a communication laser beam and stops the beacon beam

(4) The tracking and pointing of the communication laser beams are maintained between the satellites to start data transmission.

Figures 4 and 5 show the tracking and pointing data of LUCE, which was obtained on February 9, 2006 in the experiments in the Experiment phase. In Figure 4 a beacon beam from the OPALE comes into the LUCE CP sensor FOV, the coarse tracking and pointing mechanism (2-axis gimbal) works by an error signal from the CP sensor to make the error smaller to fit into the fine tracking and pointing sensor FOV, and the FP mechanism works by an error signal from the FP sensor to make the error smaller than 0.5 μrad. Figure 5 shows

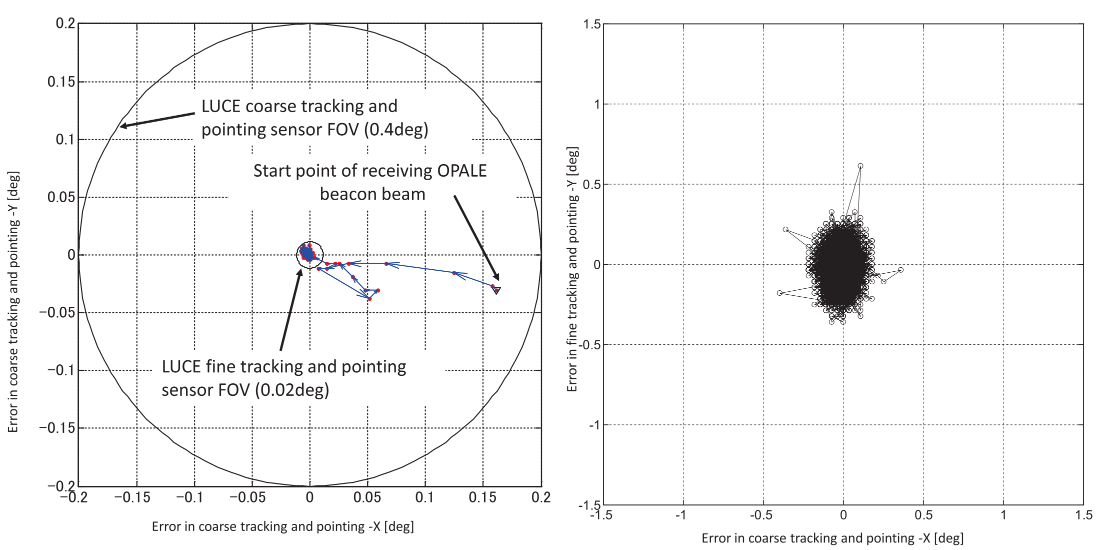

Fig.4 *Error in coarse/fine tracking and pointing in initial acquisition*

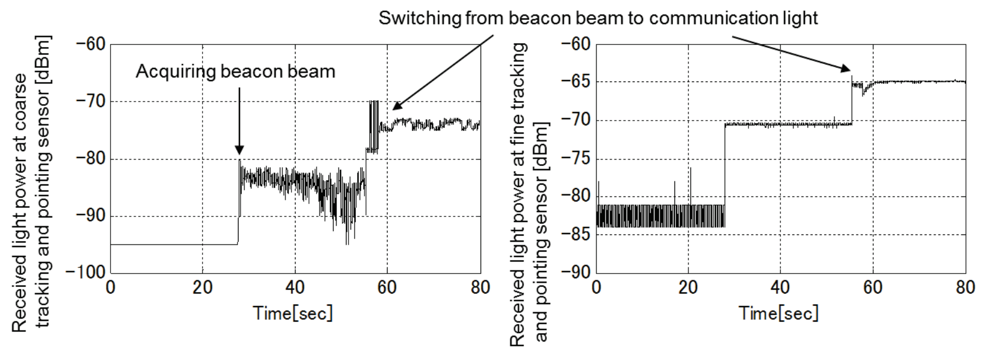

Fig.5 *Received light power at coarse/fine tracking and pointing sensor at initial acquisition*

the following process: Since the pointing error of LUCE is made smaller, OPALE can receive the communication beam from LUCE. The laser beam from OPALE is switched from the beacon beam to communication beam. Then the communication laser beams are mutually maintained. The tracking and pointing sequence thus finishes in about 60 seconds or less from the start of receiving the laser beam.

The beacon beam radiation time of OPALE is restricted to 159 seconds or less due to the heat generated by the beacon laser source. For stable communication links, it is therefore important to finish the tracking and pointing sequence well in advance of the end of this limited time.

3.3 Evaluation and correction experiment of pointing bias error

This experiment aims to measure the intensity of a laser beam received at OPALE by intentionally giving an offset angle in a spiral form to the pointing angle of the laser beams emitted from LUCE. The intensity measurement was conducted to evaluate the intensity distribution of the laser beams from LUCE and estimate and correct the pointing bias error of the emitted laser beams. Figure 6 shows the intensity distribution obtained in the first experiment. From this first measurement, we found that the pointing bias error deviated at the peak of the intensity distribution from the pointing center and that the peak was located outside the measurement range of ±1 μrad. To

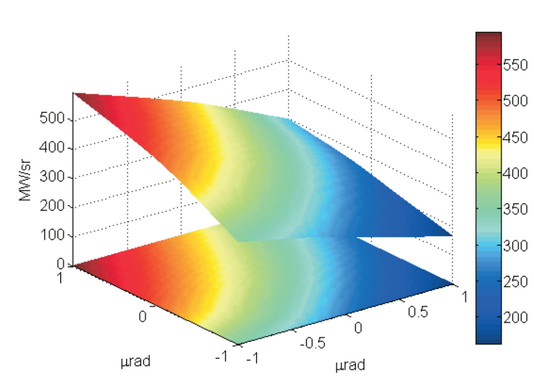

Fig.6 *Intensity distribution of laser beam from LUCE before pointing correction (Measured on December 9, 2005)*

shift the intensity peak to the center, we tried pointing angle correction operations 9 times, and succeeded in shifting the peak of the intensity distribution to the pointing center, as shown in Fig. 7. The pointing correction angle obtained in this experiment, i.e. the pointing bias error, was 2.5 μrad in the –X direction and 1.8 μrad in the +Y direction. The FWHM (full width half maximum) of the transmitted beam, estimated from the intensity distribution data measured after the pointing correction, was about 6 μrad, which correctly reproduced the designed characteristics and the properties obtained in the on-ground experiment. The correction experiment was performed in January 2006. In June 2006, the emission intensity of LUCE was measured. Figure 8 presents the measurement results, where the intensity distribution peak was still in the pointing center even after about 6 months, indicating that the pointing bias error did not change.

Figure 9 shows the laser beam intensity at OPALE, which was emitted from LUCE. It compares the intensity before and after the pointing correction. From the measurement results, we see not only that the beam intensity at OPALE became higher after the pointing correction but also that the fluctuation became smaller.

It was indicated before the experiment that the pointing direction would deviate due to vibrations and impact at the launch of the rocket or upon entering the thermal vacuum environment in orbit. Since we actually had a pointing bias error of about 2 μrad in the experiment, we re-acknowledged that the pointing correction in orbit was essential for the optical inter-orbit communication equipment which required a μrad-order precision laser beam pointing control.

3.4 Bit error rate evaluation experiment

For the evaluation of the characteristics of the optical inter-orbit communications, the bit errors in the return and forward links were measured using 15-step PN codes. Error-cor-

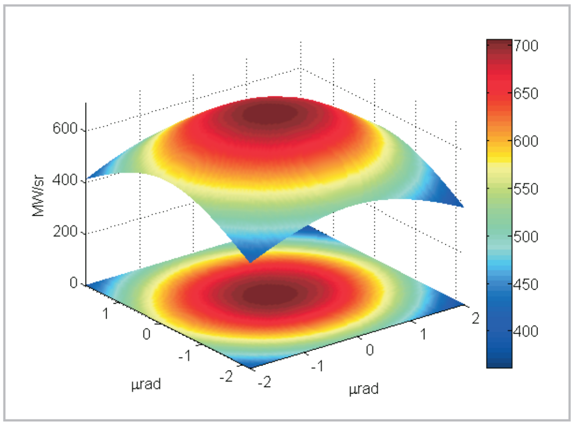

Fig.7 *Intensity distribution of laser beam from LUCE after pointing correction (Measured on January 26, 2006)*

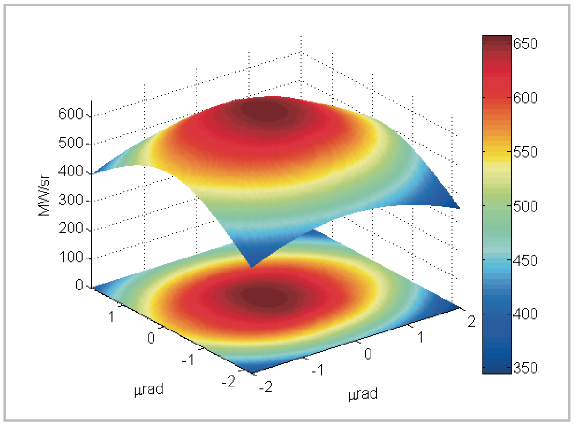

Fig.8 *Intensity distribution of laser beam from LUCE after pointing correction (Measured on June 11, 2006)*

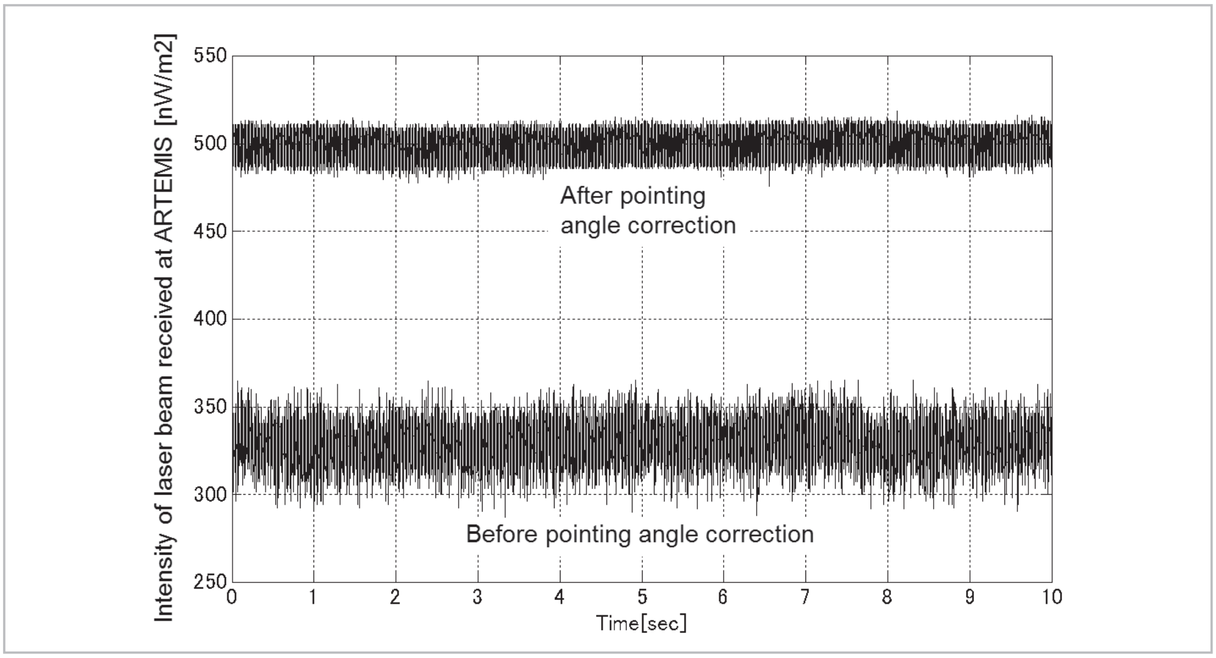

Fig.9 *Intensity of laser beams from LUCE before and after correction*

recting codes were not used for obtaining accurate communication quality data.

Since the laser beam received at OPALE has a low intensity and large fluctuation before the correction as shown above, a bit error in the return link was generated in every 30,000–100,000 bits per second and the bit error rate (BER) was about 10^{-3}, which was much larger than the design target of 10^{-6}. However, the pointing correction drastically improved the intensity and fluctuation, and the BER after the correction was less than 10^{-9}. Figure 10 shows the measurement results of the bit error per second obtained before the correction (December 2005), immediately after the correction (February 2006), and in August 2006. We see from the figure that the bit errors were largely improved with no burst-like bit error after the correction.

In the Routine phase from April to August 2006, BER measurement communication experiments were performed 80 times. Figure 11 shows the BER measured in each experiment in the return and forward links. In every experiment, we obtained BER of less than 10^{-6}, which indicated stable quality of communications. Since BER less than 10^{-6} could be achieved without error-correcting codes, we can conclude that the optical inter-orbit communications would have a communication line of high enough quality to be used even in practical situations if error-correcting codes are applied.

4 Conclusions

We explained the experiment system of optical inter-orbit communications between OICETS and ARTEMIS and showed the typical data obtained in the experiments conducted in orbit.

Optical communications in space have just started and still have many technical problems, although they are a prospective base technology to support future space activities. The experiment results of the optical inter-orbit communications using OICETS in orbit showed a possibility of space communications using laser beams. In particular, the stable line quality indicated that the communication line system was usable in practical situations.

Japan and Europe developed optical inter-

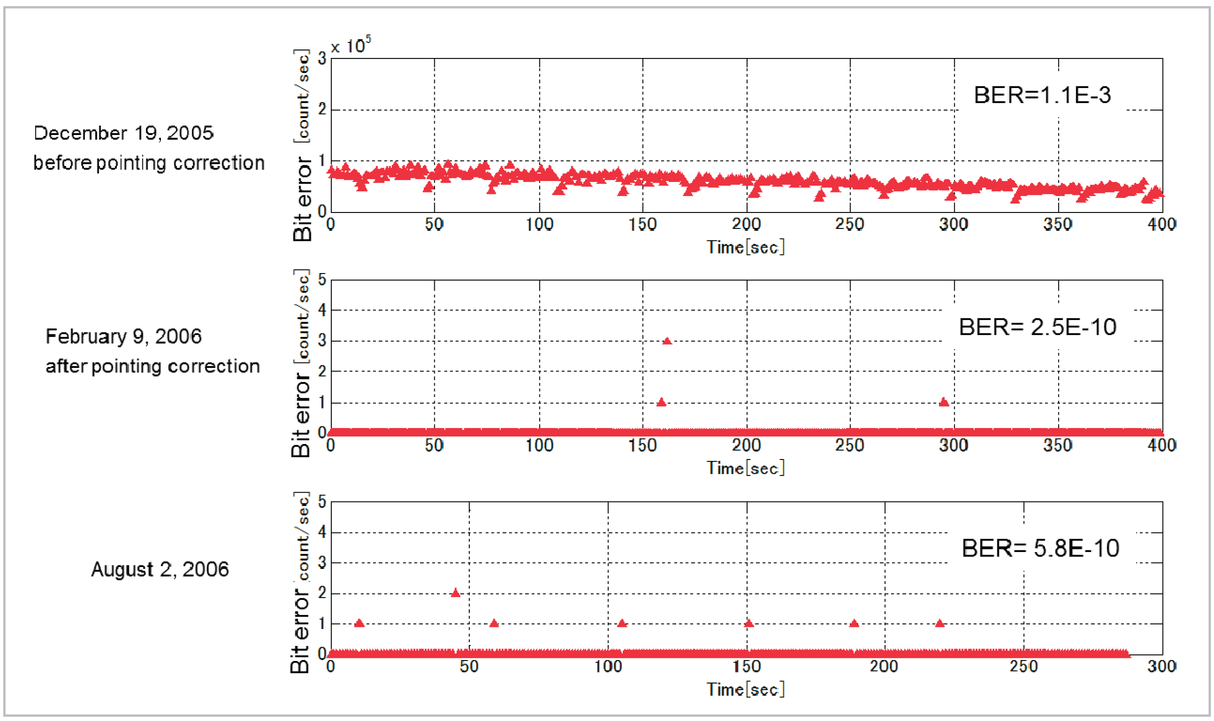

Fig.10 *Results of Measuring bit error in return link*

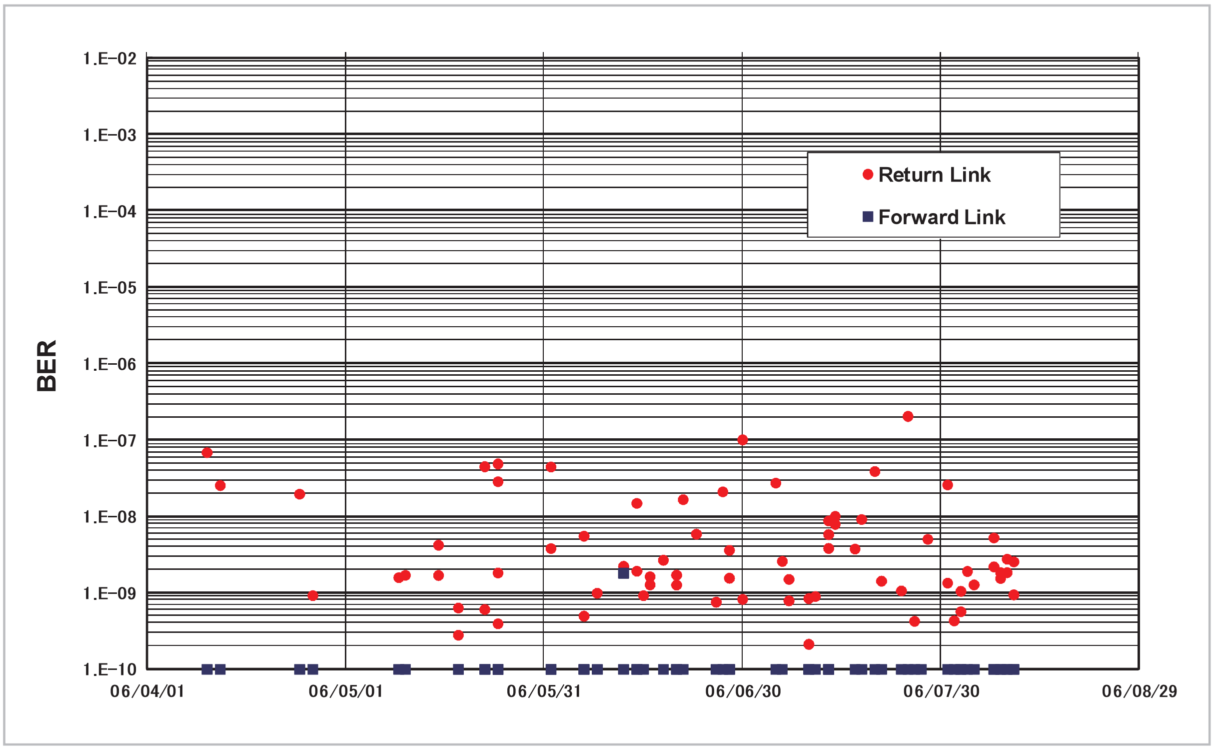

Fig.11 *Results of measurement of bit error in forward and return links in Routine phase*

orbit communication equipment of almost the same specifications based on their own technologies. So the present experiments were somehow special as they clearly demonstrated each group's capability of technological development. Although Japan had sometimes fallen behind Europe and the US in the field of space technology, the success of the experiments using OICETS and ARTEMIS showed the world that Japanese technology was now almost at the same level as European technology.

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