4 Development of Optical Ground Station System

4-1 Overview of Optical Ground Station with 1.5 m Diameter

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The OICETS experiment, LEO Satellite-Ground Optical Communication experiment system was installed one of Coude bench in Optical Space Communication Ground Center of NICT, in which a central facility of 1.5 m diameter optical telescope built in 1988. This paper overviews optics, control system, guide camera system for optical tracking including hardware and software. Especially, one of subsystem used to evaluate tracking accuracy including orbit prediction and guiding system, a satellite laser ranging and its performance before the main experiment. We describe the operation result using telescope and sub-system as well.

Keywords
Optical space communication, LEO satellite, Telescope, Tracking, Satellite laser ranging

1 Introduction

The Optical Inter-orbit Communications Engineering Test Satellite “Kirari” developed by the Japan Aerospace Exploration Agency (JAXA) and optical ground stations have conducted experiments in later satellite operations. During the periods March to September 2006, October 2008 to February 2009, and September 2009, optical communication experiments were performed between the airspace above the optical ground station (NICT Optical Ground Station) and the optical ground stations in foreign countries [1]-[3]. The NICT Optical Ground Station, was built in 1988, is a multi-purpose facility consisting of a 1.5 m diameter optical telescope with a multi-focus port, an observation dome, optical communication systems, laser radar systems, cameras, and other observation systems and subsystems [4][5].

Table 1 shows events on the telescope and systems that have been built to date, as well as the main experimental events. Before starting the experiments, ground-to-satellite optical communication experiments using the Engineering Test Satellite-Ⅵ (ETS-Ⅵ, KIKU-6) between 1994 and 1996, and optical tracking and ranging experiments using other satellites were performed successfully. Therefore, the optical tracking and ranging experimental accomplishments using the OICETS (height of about 600 km) or equivalent Low Earth Orbit (LEO) Satellites exceeded those using the ADEOS (800 km) and μ-LabSat (770 km) in Japan, Starlette (800 km) and ICESAT (600 km) in France, and other laser ranging satellites in other countries (ten satellites in total) [6]-[9].

This paper describes the Coude focus and tracking systems of the 1.5 m diameter optical telescope used for the OICETS experiments, and the configuration, features, and performance of the laser ranging system, the subsystem of which contributed to experiment prepa-

Table 1 *Events on telescope system and experiments*

Year	Systems and experiments
1988	The 1.5 m telescope was built.
1990–96	Satellite laser ranging subsystem installed and became operational
1990–94	Astronomical observations using IR cameras, CCD stationary satellite observations
1994	Improvement of pointing and tracking accuracy, recoating of the primary mirror
1994–96	ETS-Ⅵ Optical space communication experiment
1996–97	ADEOS-RIS Satellite laser radar experiments
1997–2000	Fundamental AO experiments
1999	Control system updated.
2000–03	Laser guide star experiments
2002–03	LRE (H2A-first), ADEOS-2 experiments
2004–09	ETS-Ⅷ ranging experiments
2004	μ-LabSat Satellite laser transmission
2006	OICETS-ground experiment 1
2008–09	OICETS experiment 2
2009–	Quasi-zenith satellite laser ranging
2010	Dome control system updated.

rations. Regarding the optical communication experiment system, refer to [1].

2 Telescope system

2.1 Configuration

Figure 1 shows the configuration of the telescope, and Fig. 2 shows a picture of it.

This telescope system was manufactured by Contraves (now L-3 Brashear) in the U.S., and the telescope is classified as a medium diameter astronomical quality telescope (1.5 m) with laser transmit and receive capability under international standards.

The primary mirror has an f-number of 1.5 and its tube length is short. One of the large direct drive DC motors is configured to rotate in azimuth and two in elevation. These can be used to track a Low Earth Orbit (LEO) satellite with an angular velocity around each axis of 10 degrees per second or less. It has 4 focuses and about 10 ports branching from them which can be switched by replacing the secondary mirror and using the rotation system of the port selection mirror. Installing the laser transmitting and receiving equipment and various cameras on these ports allows multi-purpose experiments to be conducted. Also, the

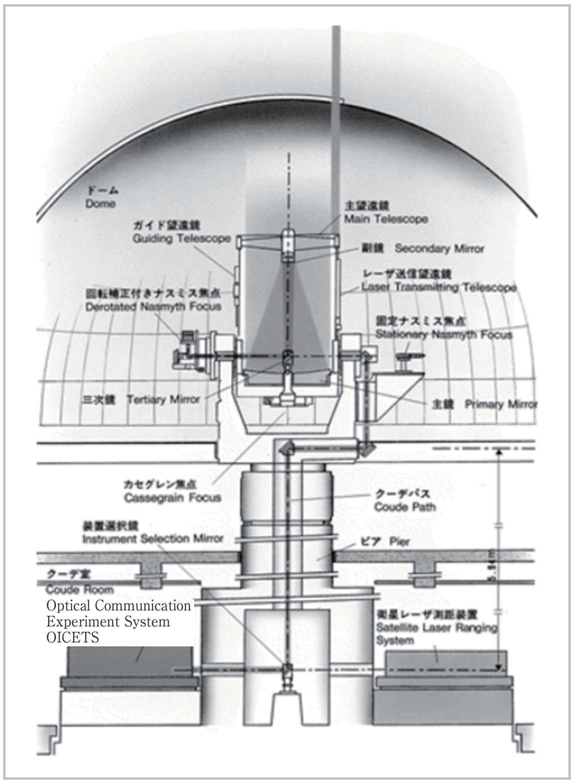


Fig.1 *Configuration of 1.5 m telescope*

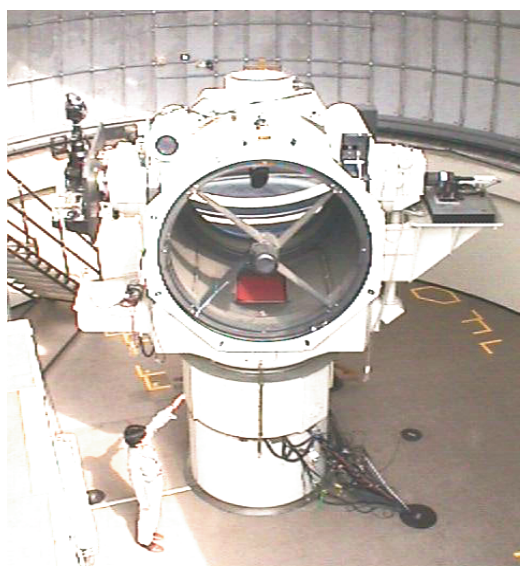


Fig.2 *1.5 m telescope appearance*

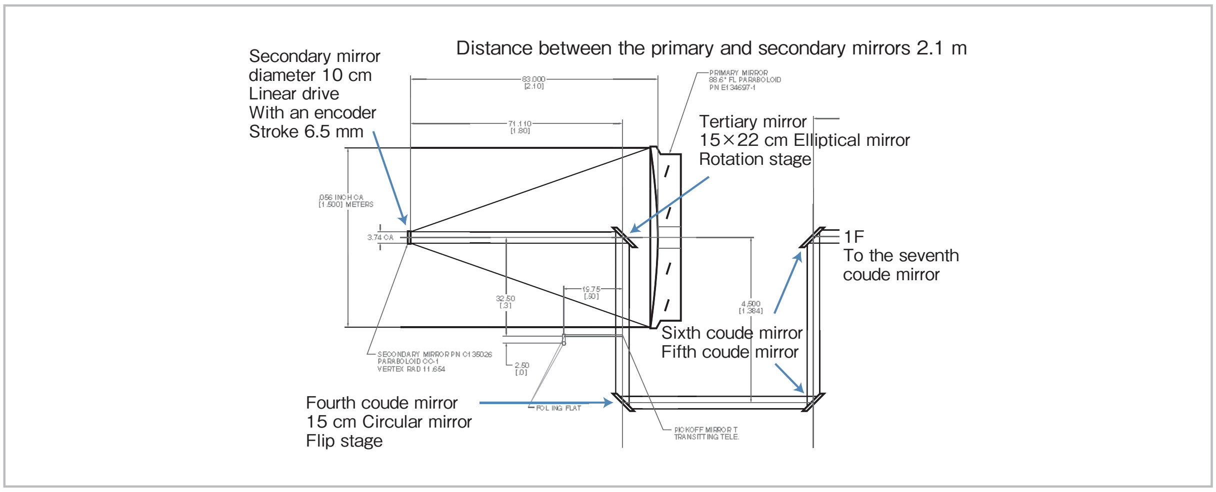


Fig.3 *Configuration of coude optical mirrors*

guide and transmitting telescopes and small cameras are placed in the upper part of the primary mirror. Cameras with different view fields monitor the satellites, laser beams, background stars, weather, and airplanes for supporting the experiments. In the optical communication experiments, the transmitting system was used with the Coude focus. The receiving system was used with the focus of the transmitting telescope from March to September 2006, and it was used with the Coude focus from October 2008 to February 2009. The 808 nm beacon source, which is placed on the service bench of the azimuth table in the telescope, sends the signal to the collimator on the bent Cassegrain bench in the bottom part of the body tube via optical fiber.

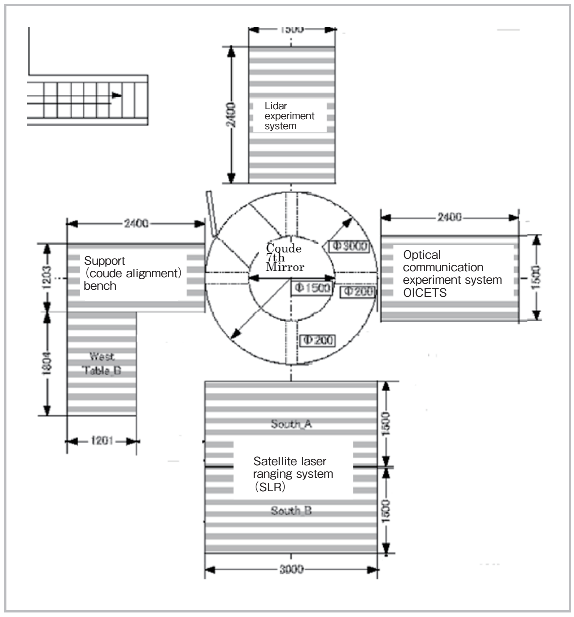


Fig.4 *1.5 m telescope coude bench*

2.2 Coude optical system

The coude optical system includes a primary mirror, a secondary mirror, and a tertiary mirrors as the main optical system. The beams are transmitted to four coude bench afocally using the fourth mirror and seventh mirror, and gathered toward the various sensors and cameras on the benches. The distance between the coude secondary mirror parabolic mirror with 108 mm diameter and interface mirror on the coude bench is about 14.3 meters and the view field of the camera optical receiver on the bench is limited to about 1.5 arc minutes.

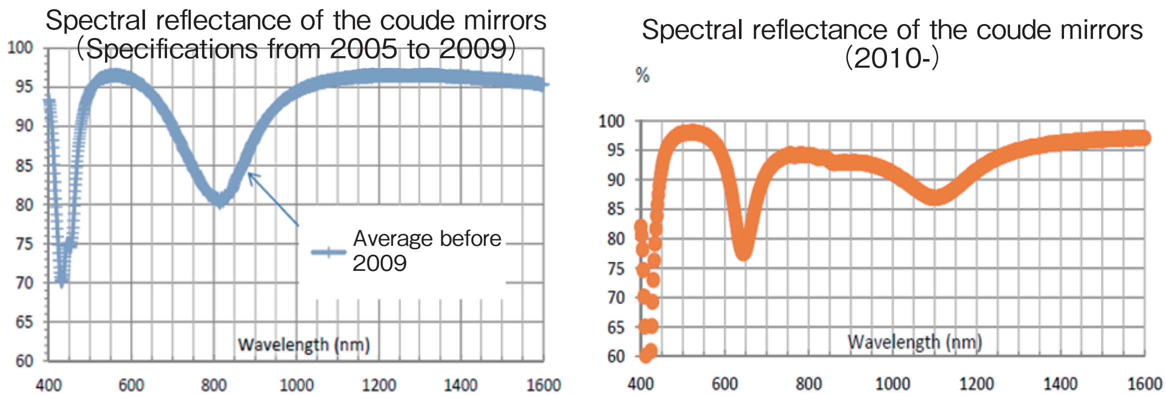
The optical communication system is equipped in a dark clean booth which is one of the coude benches. The laser ranging optical system described later is equipped in one of the other benches. Its system and the optical communication experiment system can be switched easily by rotating the seventh coude mirror (C7) on the indexed rotation stage which is placed within the center pillar.

Between the primary and secondary mirrors comprising the Coude focusing system, focusing can be performed by a few microns by using the linear drive motor and encoder embedded in the support structure (Spider) of the secondary mirror.

2.3 Specifications of coude mirrors

The primary mirror is covered with aluminum and protective hard coating and has not been recoated since 1994. Because of the protective coating, the surface has only been degrading gradually for 14 years. The degradation of the reflectance which might affect our experiments was avoided by regular cleaning. However, the coude mirrors other than the primary one have severely deteriorated. The reasons may include high humidity, coating penetration due to condensation, dust in the air, and chemical action. The mirror in the upward direction has quickly deteriorated. Also, high power laser beam exposure may cause damage partially on the mirror. Because of these complex reasons, degradation happens. Regular recoating is needed and has been performed once every one to three years.

In the construction phase, the coude mirror



(a) The average of the three monitor glasses when coatings were applied under the specifications in 2005 to 2009

(b) The average of the six monitor glasses when coatings were applied after 2010.

Fig.5 *Spectral reflectance of the coude mirrors*

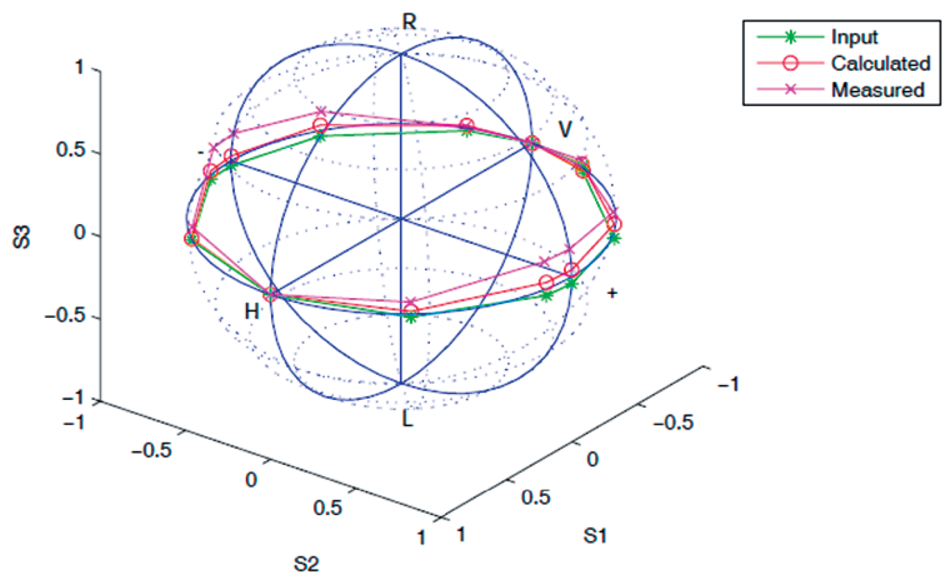


Fig.6 *Measurement examples for the polarization properties of the reflective coating coude mirrors*

was coated with silver which is more reflective, but the surface had degraded within a year. After that, it was covered with an aluminum coat and a protective and reflective coat with a few dielectric layers. This increases durability depending on the location and some mirrors have been used for more than three years.

Figure 5 (a) shows the spectral reflectance of the coude plane mirrors (with an incident angle of 45 degrees) with an aluminum coat for the OICETS experiments of the coude mirror. Figure 5 (b) shows the spectral reflectance of the coude plane mirrors which were covered with an aluminum coat and a protective and reflective coat after that.

The wavelength of the OICETS downlink is 847 nm and the wavelength of the uplink communication transmission is 815 nm. From Fig. 5 (a) and (b), the reflectance in the 800 nm band was not always optimized in the OICETS experiments. However, it had the optical transmission power and light gathering power of the 1.5 m diameter as obtained by our link calculations, so they did not cause any problems.

In the uplink and downlink of the OICETS, the circular polarized laser beams on the left were used. Therefore, we measured the polarization properties (with an incident angle of 45 degrees) of the coude mirror. Figure 6 shows the measured results in Poincare sphere form. The polarization properties of the reflective light were measured when the incident light source polarized in the 800 nm band.

There was a little crosstalk from the polarization on the aluminum reflective coat. The overall polarization properties such as the primary mirror are ground station parameters important to optical communication applications including quantum communication experiments in the future using polarization.

2.4 Guide telescope camera

The optical experiments are performed at night. As described above, the guide telescope needs to be equipped in the same gymbal as the primary mirror because the view field of the coude focusing is usually narrow. Table 2 shows the specifications of the guide telescope mirror.

In the experiments, after starting the tracking according to the commands of each axis which was tracked using programs based on the forecast of 6 orbital elements, we recognized the transmitted light from the OICETS through this guide telescope and led it into the manually focused primary mirror.

For the primary mirror focusing, the received image is checked with two types of cameras equipped in the optical transmitting and receiving sections to gather it to the center. After these rough capture tracking operations, the precise tracking system led the beam to the photo receiver, and the imaging camera for atmospheric turbulence (DIMM) and the optical communication receiver at the same time.

Figure 7 shows the images of the OICETS, which were received with TX cameras, before and after leading by coarse acquisition. The offsets, depending on the experiment data and

Table 2 Specifications of the guide telescope

Parameter	Value	Comment
Type	Schmidt Cassegrain	
Diameter	20 cm Φ	
Focusing distance (effective)	2000 mm	Technical proposal document in 1988
Reflectance	0.6	Aluminum coat (0.9), Estimated value with consideration of aging with two reflections
Camera	With an electronic shutter, current amplification type CCD	WATEC120N +
Sensitivity	Minimum sensitivity 0.00002 lx	Maximum exposure at F1.4 Lowest shutter speed
View field	0.4 degrees (effective) 0.33 (AZ) ×0.25 (EL) degrees	

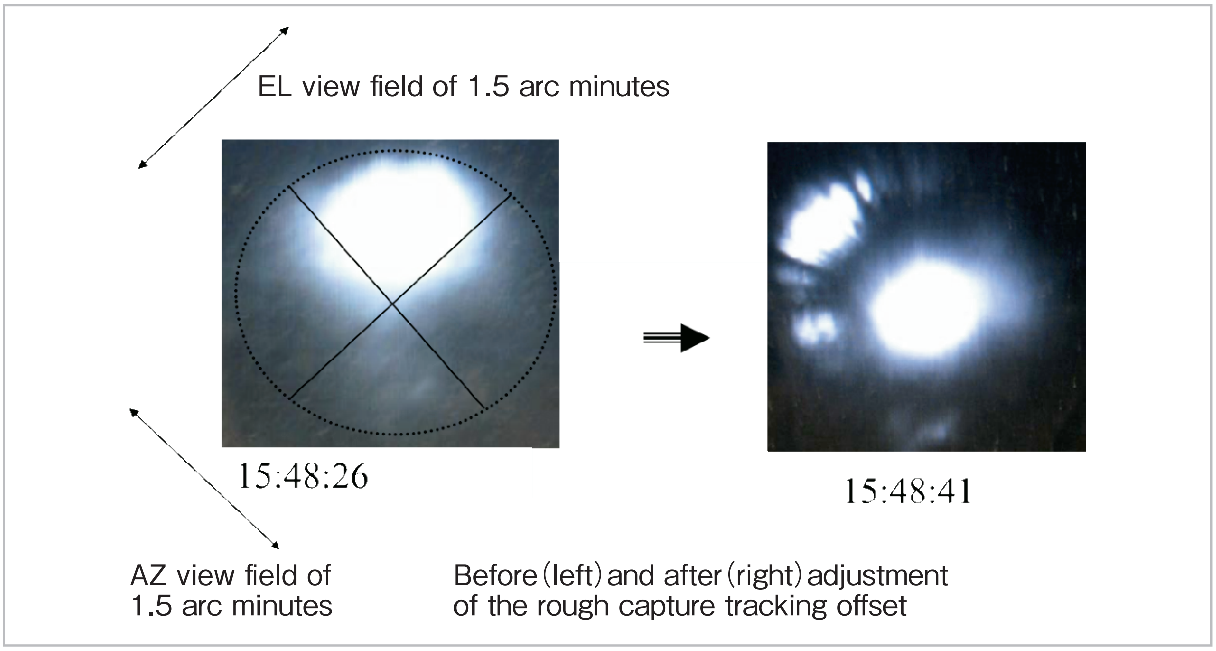


Fig.7 *Example record of the OICETS TX-CCD camera (March 30, 2006)*

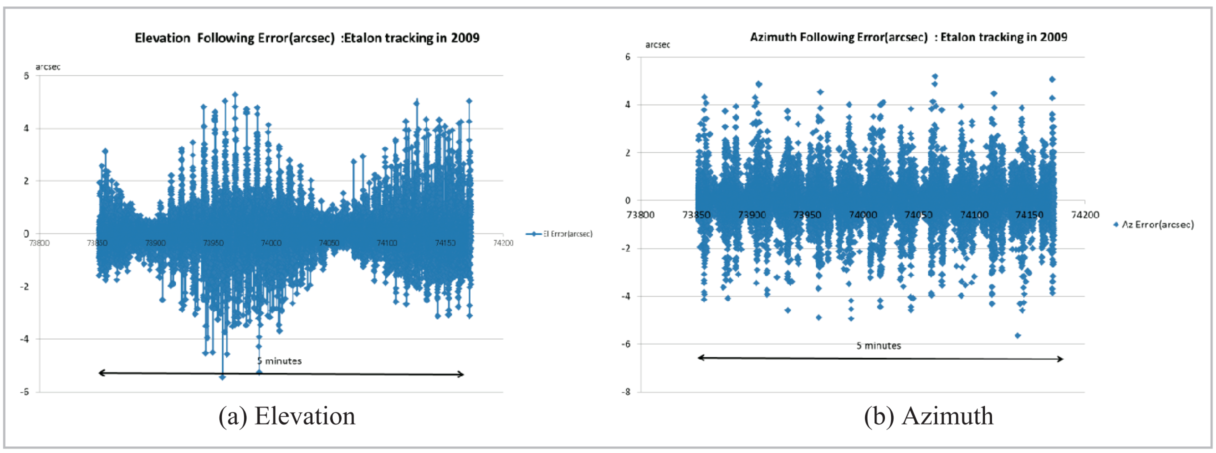


Fig.8 *Examples of errors in satellite tracking*

Etalon (at an altitude of about 2000 km)
Horizontal axis: Time About 5 minutes, Vertical axis: Tracking error Arc seconds

elevation angle, were detected at between 2 to 5 arc minutes from the center of the field of view. The good forecast value was the main reason in this example why coarse acquisition was succesful.

2.5 Control system tracking error

The control system of the 1.5 m telescope was upgraded in 1999, but the motor and encoder have been used since their introduction. Except for the zenith, the tracking errors were almost within a few arc seconds in the OICETS experiments, some of them were the P-P periodic errors of 10 arc seconds as shown in Fig. 8 (a) and (b).

Figure 8 shows an example of the satellite at an altitude of about 2,000 km and then the differences between the angle command values and current degrees. The converted short cycle was about 0.5 degrees.

The source of the error was not known during the experiments. Afterwards, a broken cable was found in the azimuth precise encoder of the telescope in 2010. The precise encoder encodes the small angles under 0.5 degrees by Inductsyn with 720 poles. For this reason, it is estimated that the control system was affected by noises because of bad connections with the encoder cable where twisting fatigue had occurred due to rotating of the telescope azimuth. After that, the failed telescope cables were upgraded, the twisting section was fixed again, and a connection test was performed.

3 Laser ranging subsystem

During OICETS steady flight, the CCR (Corner Cube Reflector) array for laser ranging is placed on the earth oriented surface. It was equipped to identify the satellite location with laser ranging from the ground and obtain a correction value for the orbit.

The ranging system was upgraded between 1990, when the first generation system was introduced, and 2002. In the OICETS experiments, we used the Master Ranging Control System made by an Australian manufacturer. The new ranging control engine KREs supporting the laser repeating frequency of 2 kHz have been developed since 2009 [10]-[14]. This system allows operation by switching to the Japan Standard Time (UTC) signal, which is transmitted in 10 MHz though the optical fiber in-house, as well as with a GPS clock.

Also, the nanosecond laser is equipped for ETS-Ⅷ in the OICETS experiments. Figure 9 shows examples of the OICETS ranging data obtained from this laser ranging.

During the laser ranging experiments, we

Table 3 *Specifications of exiting SLR system*

	Koganei 7308 (1.5 m mirror)* * 7308 is a ground station identification number for ILRS [15].
Telescope	
Open diameter	1.5 m
Focusing	Coude
Mount	Alt-Azimuth
Orientation precision	One arc second
(RMS)	9 degree/s (maximum velocity in operation)
Tracking speed	Azimuth +300 –330 degrees
Driving range	Elevation +110 –5 degrees
Dome	Ash dome shutter remote. Open/closed
Laser	
Wavelength	532 nm
Pulse width	35 ps FWHM
Repetition	20 Hz
Energy	50 mJ/Pulse (Maximum)
Receiving system	
Detector	Single photon APD
Filter	3A insert switching
Time reference	UTC-NICT/GPS switching
Event	MRCS/KRE switching
Timer	MRCS = Master Ranging Control System KRE = Koganei (kHz) Ranging Engine

Table 4 *Participating stations and the number of paths in the OICETS tracking campaign*

Site Name	Station ID	The first Campaign 2006 Mar.–May	The second Campaign 2008 Oct.–2009 April	TOTAL
Yarragadee	7090	35	162	197
Greenbelt	7105	8	61	69
Herstmonceux	7840	13	34	47
Graz	7839	1	25	26
Wettzell	8834	3	20	23
Monument Peak	7110	15	2	17
Zimmerwald	7810	4	11	15
Mount Stromlo	7825	4	10	14
Potsdam	7841	2	12	14
Papeete	7124	2	11	13
Arequipa	7403	0	10	10
Changchun	7237	0	10	10
Hartebeesthoek	7501	5	4	9
Riga	1884	9	0	9
Shanghai	7821	0	8	8
Borowiec	7811	7	0	7
Haleakala	7119	0	5	5
Kiev	1824	0	4	4
Simeiz	1873	3	0	3
Beijing	7249	0	2	2
Katzively	1893	0	2	2
Matera	7941	1	1	2
Simosato	7838	2	0	2
Concepcion	7405	0	1	1
Mcdonald	7080	1	0	1
Total Passes		115	395	510

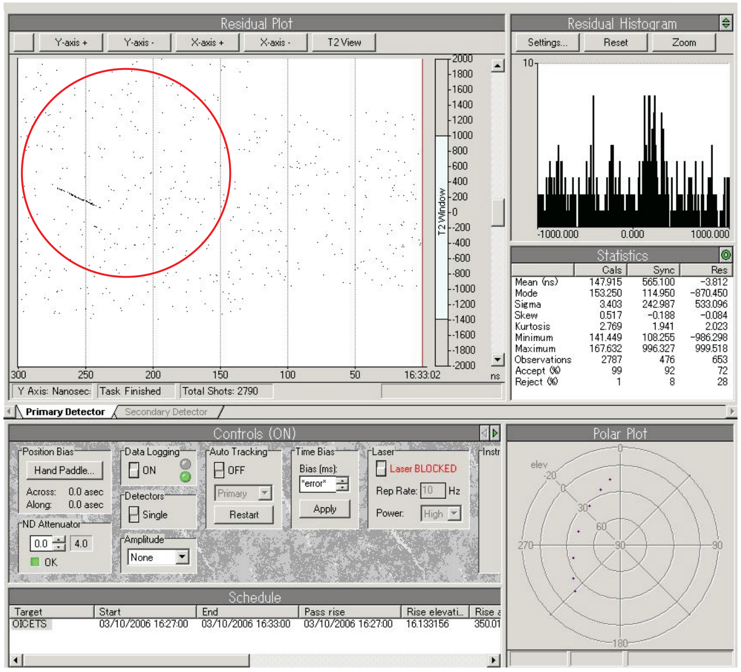


Fig.9 *Examples of OICETS ranging*

Observation software screen snap shot, a circle in red
Horizontal axis: time, Vertical axis: ranging value (nanosecond laser), Acquisition time: about 34 seconds 68 shot, RMS: 60 cm

confirmed the orbit forecast values used and checked out the elevation alignment and the elevation of the telescope.

The ground station took the SLR from the LEO satellite except for under OICETS.

We also performed two tracking campaigns by calling to the ground station network with JAXA in the international laser ranging project (ILRS) [15]. Table 4 lists the participating stations and the number of acquired paths.

The Yaragadee station in Western Australia, the NASA Greenbelt station in North America, and the Herstmonceux station in Britain responded positively.

In this OICETS communication experiment, location of CCR array was on the side opposite to the optical antenna, so verification could not be performed under close time conditions on the same day.

For the 9 mrad optical communication beacon, the satellite orbit had no program, and maintained accuracy comparable to a communication beam of about 200 μrad (about 1 arc minute). Both of them had large enough margins for narrow SLR beams, and SLR was a way to validate the open tracking ground stations if it had been completed just prior.

However, the predictability of normal SLR is not enough to initially acquire the OICETS, so it takes a long time for searching.

It was difficult during the daytime because of solar interference. In the next satellite, it will be useful to create forecast values with the mounted GPS, and validate the tracking using SLR with wide beams depending on the purpose, and to determine the orbits where experiments can be performed during the daytime. It will be possible to support the beacon by placing the CCR of the satellite on the optical antenna surface in the future.

4 Conclusions

This paper describes the equipment and features of the optical ground stations which performed experiments with OICETS, and the evaluations and problems of orbit accuracy in the communication experiments. In the link calculation of the optical communication experiment with the low orbit satellites, the 20 cm diameter telescope is enough over the 1.5 m. In fact, the 20 cm receiving diameter sub telescope and 32 cm-equivalent diameter sub opening were used in the OICETS experiments. However, we could operate a lot of measurement equipment at the same time and could acquire data by light using a 1.5 m telescope with high light gathering power, driving power, and on-board capability with tubes and benches, and could identify problems on the tracking surface by performing an assessment of the orbit accuracy for OICETS and many other LEO satellites before the optical communication experiments. Therefore, the experiments were performed successfully.

This optical experiment equipment with multiple functions will play an important role in space communication.

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