Vol. 46 No. 1 *Journal of the Communications Research Laboratory* *March 1999*
Printed in Tokyo, Japan *pp. 103−109*

4.2 TELESCOPE AND ENCLOSING DOME

By
Jun AMAGAI, Hideyuki NOJIRI, Chihiro MIKI,
and Hiroo KUNIMORI

ABSTRACT

The telescope used for the Key Stone Project has a main mirror with an effective aperture of 75 cm, an Az-El drive mount, and Coude-type optics. A corner cube reflector mounted beside the sub-reflector of the telescope is used to calibrate the internal delay.

The telescope is enclosed by a sealed dome with a transparent glass window, preventing it from being damaged adverse weather conditions.

Keywords: Satellite laser ranging, Telescope, Laser

1. Introduction

In satellite laser ranging (SLR), the telescope and optics are the most important elements and their performance directly affects the reliability of the observed data. An SLR system should be adjusted carefully to achieve mm-level accuracy for crustal deformation measurement. High reliability and safety are also required to achieve fully automatic and continuous observation.

The telescope used for the Keystone Project (KSP) is installed on a pedestal in a tower and enclosed in a sealed dome. It is connected with the optics installed in the trailer box through a Coude path.

All facilities of the KSP system were designed to operate automatically, so that no one oversees the system directly at the observation site. If the telescope were enclosed in an ordinary dome with a shutter that is opened during observation, we could not deal with sudden weather changes, and the telescope could be damaged by rain or wind. Therefore, we use a completely sealed dome with a transparent glass window for observation.

In this paper we describe the specifications and features of the telescope and dome.

2. Telescope

2.1 Overview

The telescope was designed specially for the KSP SLR. Although the effective aperture of its main mirror is 75 cm, a 1 m-diameter mirror could be installed. The structure of the telescope is shown in Fig. 1, and its specifications are summarized in Table 1. The telescope is controlled by a computer located in the telescope tower.

2.2 Optics

(1) Main mirror and telescope tube

The main mirror is a parabolic surface mirror, 75 cm in diameter, supported by a mechanically stabilized telescope tube. A temperature-stabilized support system is used for the telescope tube to compensate for any deformation caused by temperature changes. As a result, frequent maintenance is not needed to recover defocusing

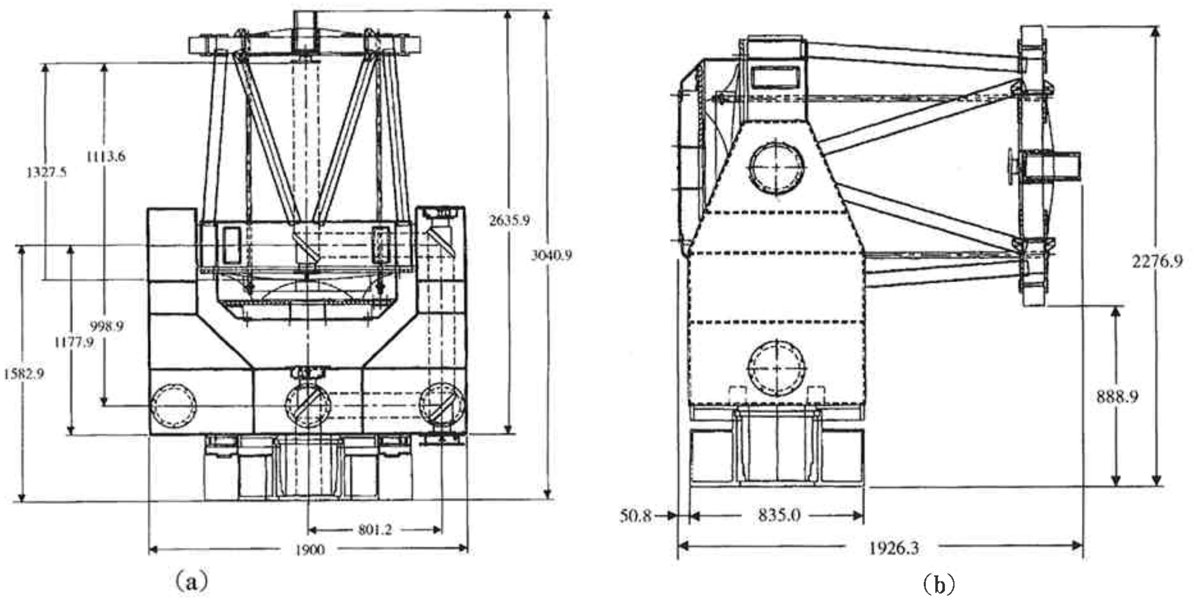


Fig. 1 Telescope structure, with all lengths expressed in mm.

Table 1 Specifications of telescope

Configuration	Az-El type with Coude path
Az drive range	+/- 270 deg.
El drive range	-20 deg. to +90 deg.
Encoder resolution	<0.3 arcseconds for both axes.
Encoder accuracy	<1.1 arcseconds for both axes
Maximum velocity	>12 deg./second for both axes
Minimum velocity	>0.0005 deg./second for both axes
Acceleration	5 deg./second^2 for both axes
Weight	<1500 kg excluding electronics and base
Rotational Inertia	Az <800 kg m^2
	El <400 kg m^2

caused by temperature changes. Regular annual maintenance is sufficient to maintain performance.

(2) Focal point

Coude focusing is used for the satellite laser ranging. The field of view is about 1 arc minute depending on the Coude path length. The path length at the Koganei station is longer than that of other stations because the tower at Koganei station is higher than that at other stations to avoid any obstruction by the trees around the station.

(3) Sub-reflector

The sub-reflector is also a parabolic surface mirror; it is mounted on a precise actuator. The position of the sub-reflector is controlled remotely through the computer to optimize telescope performance or to adjust the beam divergence. This control system is also used for observing targets at a finite distance.

(4) Tertiary mirror

The tertiary mirror is located on the invariant point of the telescope. It is mounted using a support system with a temperature-compensation function. This function is achieved mechanically and is highly reliable.

(5) Telescope reference point and calibration target on telescope

The invariant point of the telescope is referred to as the reference point of the SLR station. A calibration target is mounted beside the sub-reflector (Fig. 2). By ranging this target simultaneously with a satellite and subtracting the range of the target from the range of the satellite (correcting for the distance between the target and the telescope reference point), we can get the correct range between the telescope reference point and the satellite. Using this calibration technique compensates for the system delay in real time.

(6) Pentagonal prism for benchmark ranging

By ranging to benchmarks mounted immediately below the telescope with three other ground targets, we can monitor the changes in the telescope reference point and the system delay[1]. It is impossible to sight the benchmarks directly through the telescope because the elevation angle of the telescope is limited to greater than − 20 degree. We thus use a pentagonal prism mounted beside the sub-reflector. It bends the beam through 90 degrees (Fig. 2).

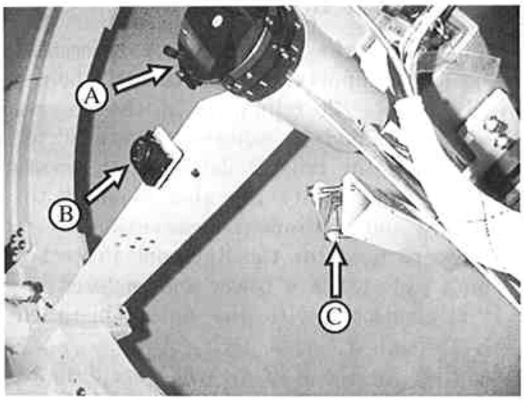


Fig. 2 Picture of calibration target
(A: Subreflector, B: Calibration target, C: Pentagonal prism)

(7) Coude path

The Coude path consists of four mirrors. The beam diameter of the Coude path is 110 mm. The mirror mounted under the pedestal is rotated to select the port through which the beam departs or enters the trailer box. There are two ports for each KSP SLR station. One port is used for regular observation, and the other is used for a redundant trailer box, which backs up the regularly used one. For the Kashima station, there are four ports. We carried out our collocation experiment by using these four ports[2].

(8) Mirror coating

The transmit and receive efficiencies of the telescope vary with the mirror coating material. The reflectivity of the mirror depends on the wavelength. A narrower wavelength window is preferable for laser ranging because the wavelength width of the laser is very narrow, so other wavelength signals can cause noise in the observation. A wider wavelength window in which stars are observed visually is preferable for axis calibration. The wavelength used, the maintenance ability, and the star visibility determine which material should be used for

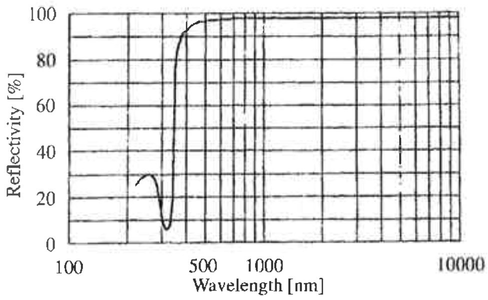


Fig. 3 Reflectivity of silver

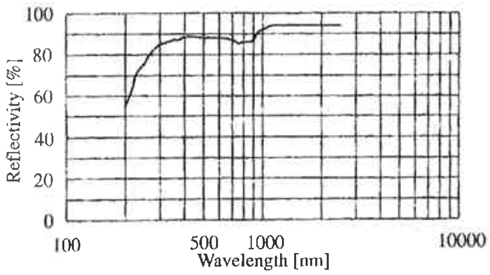


Fig. 4 Reflectivity of aluminum

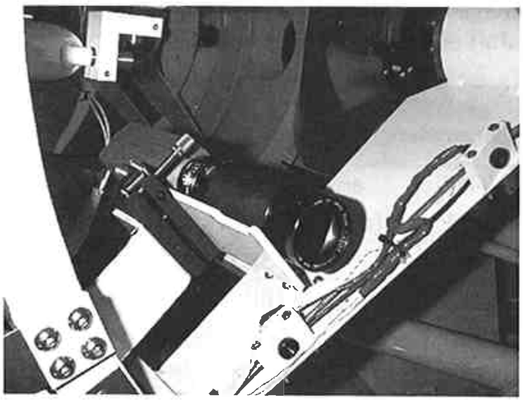


Fig. 5 Wide field of view camera

mirror coating. Accordingly, we use a combination of silver and aluminum for the coating materials. Figs. 3 and 4 show the respective reflectivities of silver and aluminum. Table 2 shows the total reflectivities for combinations of silver and aluminum. In the case where all mirrors, i.e. the three telescope mirrors and four Coude mirrors, are aluminum, the total reflectivity for 532 nm is 44% and for 355 nm is 27%. If we use aluminum for the three telescope mirrors and silver for the four Coude mirrors (it is easier to change the Coude mirrors than the telescope mirrors), the total reflectivity for 532 nm is 75% and for 355 nm is less than 20%. We use all aluminum mirrors for the Kashima station, where we plan to carry out dual-wavelength ranging[3]. The three/four combination is used for the other stations, where only one wavelength (532 nm) is used for laser ranging. The reflectivity of this combination is 50% higher than that with all aluminum mirrors. Although silver can be easily

Table 2 Total reflectivity for combinations of silver and alumimium. The data for only two stations are listed; however, the data for the other stations sre almost the same as that for Koganei station.

Transmit

	Kashima	Koganei
T/R output window	0.934	0.934
Steering mirrors	0.980	0.950
Beam expander	0.985	0.985
Steering mirrors	0.985	0.985
Splitter	0.950	0.950
Translation mirrors	0.980	0.950
Beam expander secondary	0.950	0.950
Beam expander primary	0.880	0.880
Coude mirrors	0.530	0.909
Telescope secondary	0.880	0.880
Telescope primary	0.938	0.935
Dome window	0.865	0.865
Total	0.262	0.420

Receive

	Kashima	Koganei
Ranging window	0.865	0.865
Telescope primary	0.938	0.935
Telescope secondary	0.880	0.880
Coude mirrors	0.530	0.909
Beam expander primary	0.880	0.880
Beam expander secondary	0.950	0.950
Translation mirrors	0.950	0.950
Splitter	0.950	0.950
Steering mirrors	0.950	0.950
Beam expander	0.985	0.985
Steering mirrors	0.950	0.950
T/R output window	0.934	0.934
SHG	0.970	0.970
532-nm dicroic mirror	0.850	0.850
532-nm spectral filter	0.530	0.530
532/355-nm mixing mirror	0.852	0.852
Spatial-filter focusing lens	0.970	0.970
Spatial-filter re-imaging lens	0.970	0.970
SPAD steering mirror	0.850	0.850
1060-nm notch filter	0.960	0.960
SPAD focusing lens	0.972	0.972
SPAD input window	0.940	0.940
SPAD efficiency	0.200	0.200
Total	0.012	0.021

damaged by harsh ambient conditions, clean air in the sealed dome enclosing the telescope alleviates this problem, thereby extending the telescope's life.

(9) Monitor cameras

A camera with a wide field of view is mounted on the telescope to monitor the sky conditions (Fig. 5). On an optical table in the trailer is another camera with a field of view of 1 arcmin (Fig. 6). It has a CCD image sensor with 164 X 192 pixel resolution; images detected by this camera are transmitted to the host computer. This camera is used to calibrate the telescope pointing, as discussed in the next section

2.3 Drive system

The telescope direction, the sub-reflector, the prism shutter, and the main mirror shutter are controlled by the dome-control computer (DCC) installed in the telescope tower. Information on the telescope pointing position, the sub-reflector position, the sun sensor reading, the shutter status, the drive-limit switch status, the prism-shutter status, and the temperature sensor reading are transmitted from the telescope to the DCC. The DCC is primarily controlled by the site control computer (SCC) located in the trailer box. It can also be controlled by other computers connected via the LAN. This is done to evaluate telescope performance.

Fig. 7 shows the tracking error of the telescope as observed using the Lageos satellite when it passed near its zenith, so its velocity was at a maximum and its sign of acceleration changed across zero. We can see from the figure that the RMS of the tracking error was around 2 arcsec.

The pointing error, i.e., the difference between the actual direction of the optical beam and the desired pointing direction, is compensated for by software. The axis-

Fig. 6 Coude camera

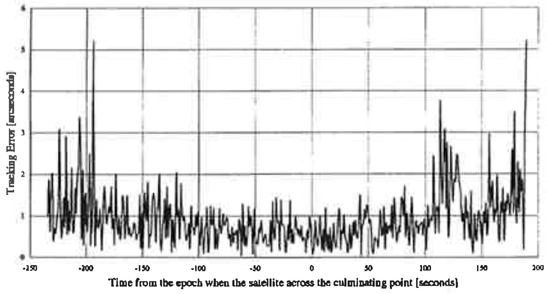
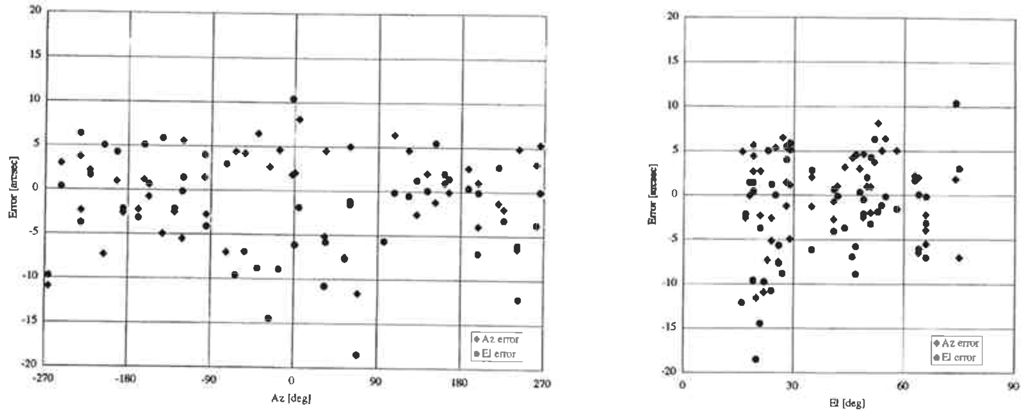


Fig. 7 Tracking error of telescope observed when the Lageos satellite was crossing culmination point on July 28, 1998 at Miura station

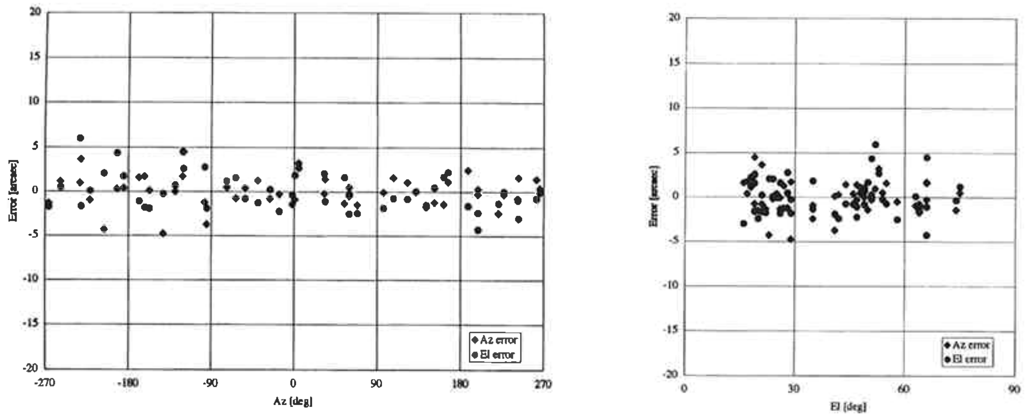
Table 3 Example axis-offset parameters.

	Value [arcsec]	error [arcsec]
Azimuth Encoder Offset	1125.32	6.13
Elevation Encoder Offset	-1444.21	315.38
X Axis Tilt	-42.23	1.00
Y Axis Tilt	-19.65	1.02
Transverse Misalignment	357.89	7.83
Az-El Non-orthogonality	33.82	5.30
Sin(azimuth) in Azimuth	18.78	0.99
Cos(azimuth) in Azimuth	7.78	1.02
Sin(elevation) in Elevation	384.39	180.68
Cos(elevation) in Elevation	-477.58	256.04
Flexure - Tan(Zenith Distance)	-17.72	8.96
Azimuth Encoder Scale	-1.43	0.89
Elevation Encoder Scale	-4059.09	2018.46
Sin(2*azimuth) in Azimuth	2.26	0.57
Cos(2*azimuth) in Azimuth	-0.90	0.57
Sin(azimuth) in Elevation	3.24	1.68
Cos(azimuth) in Elevation	28.21	1.76
El Sin(az) in Elevation	-10.77	1.80
El Cos(az) in Elevation	-15.68	1.96



(a) (b)

Fig. 8 Pointing error before axis-offset calibration



(a) (b)

Fig. 9 Pointing error after axis-offset calibration

offset calibration parameters required for compensation are determined by observing stars. Once every quarter year, stars are observed to obtain the pointing error data. With this data, we determine the axis-offset calibration parameters by using the least squares method. Example axis-offset calibration parameters are listed in Table 3. The pointing errors before axis-offset calibration are shown in Fig. 8, and those after calibration are shown in Fig. 9.

3. Enclosing Dome

3.1 Telescope tower

The telescope tower is a building in which the telescope is installed. The station position as determined by SLR observation is the invariant point of the telescope (intersection of the telescope axes). Therefore, to precisely measure the crustal deformation, the invariant point should be fixed relative to the point representing the crustal movement of the station. Additionally, a highly stable telescope pedestal is needed to maintain stable tracking performance because the beam width of the telescope is as narrow as a few arcsec when the telescope is under SLR operation.

To meet these requirements, the foundation piles for the telescope pedestal were struck into bedrock, and the telescope tower has a doubled structure to negate the effect of outside meteorological conditions. As shown in Fig. 10, the foundation of the telescope pedestal and that of the outer wall are completely isolated, and the temperature and relative humidity inside the telescope tower are maintained at 23 $\pm$ 2 degrees Celsius and under 40%, respectively. By stabilizing the temperature conditions inside the telescope tower, position changes in the telescope invariant point are kept within 1 mm. The outer wall blocks the sun light preventing inclination of the telescope due to expansion of the sunlit side of the pedestal.

The KSP system must generate observation data continuously to monitor the daily crustal deformation. If the system suffers a malfunction, routine observation should be restored immediately. Therefore every instrument, except the telescope, is located in a trailer box that can be transported by truck or a big transport plane. If a problem occurs in the equipment installed in the trailer box, a redundant trailer box (usually used for mobile system) is dispatched immediately to restore the SLR observation. The foundation mounting the trailer box has also piles struck into bedrock to prevent any relative position change between the telescope and box. The foundation of

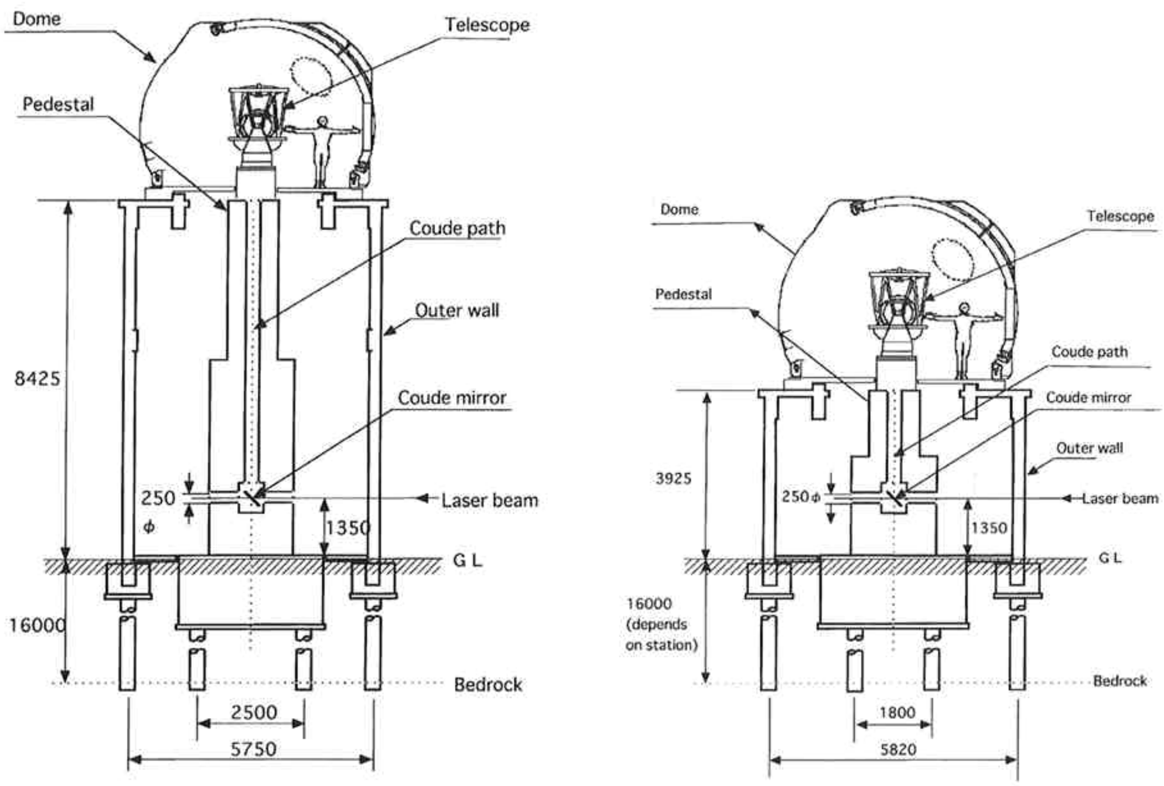


Fig. 10 Telescope tower: (a) Koganei station, (b) other stations with all lengths in mm

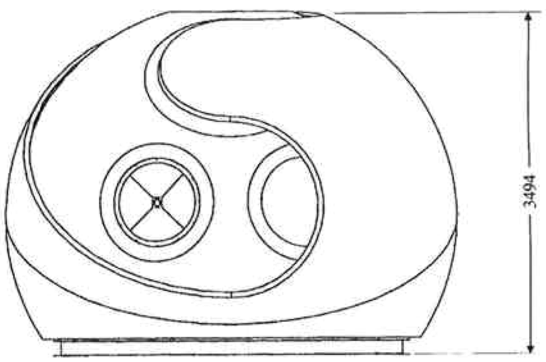


Fig. 11 Telescope dome with all lengths in mm

the telescope and that of the trailer box are joined by a concrete beam 1.5 m under ground. Four foundations support the trailer box at the Kashima station, while two support the boxes at other stations. The four foundations at the Kashima station were used for the collocation experiments(2). Only one trailer box is dispatched to the other stations, and the other foundation is reserved for the redundant box.

3.2 Sealing

We use a sealed dome to enclose the telescope. An ordinary dome opens a slit door to permit observation, while the sealed dome rotates so that its sealed glass window, which has a diameter matching the telescope's effective aperture, aligns with the telescope to permit observation. (Fig. 11) This dome prevents the telescope from being damaged by dust or humid air. Because the dome is made of FRP (Fiber Reinforced Plastic), it is the light weight, resists rust, and is durable. The sealed glass window hides behind the dome structure when the telescope is not in operation. By making the air in the telescope tower also circulates in the dome, the temperature and relative humidity in the dome are also kept within 23 ± 2 degrees Celsius and 40%, respectively.

The window has a transmission spectral range of 0.34 μm to 2.0 μm, and efficiency is more than 75%. A water jet is located outside the dome just above the window. It is controlled by the DCC and used to clean the window.

A skyline wall is built around the dome to block laser beams from areas below the elevation angle of 15 degrees and from objects in the area of the elevation angle higher than 15 degrees.

4. Conclusion

The KSP SLR system is designed to measure crustal deformation to within a few mm. To achieve this, the telescope building was built to have sufficient stability to make such a highly accurate measurement. The telescope tower has a doubled structure, and the environmental conditions are controlled to maintain a highly stable structure.

References

(1) F. Katsuo, et al., "4.8 A concept of monitoring the telescope reference point by using multiple ground targets," J. Comm. Res. Lab., **46**, 1, pp.135-140, March 1999.

(2) H. Kunimori, et al., "8.4 Collocation experiment on four E/O packages for the KSP-SLR system," J. Comm. Res. Lab., **46**, 1, pp.207-211, March 1999.

(3) J. B. Abshire, "Pulsed Multi-wavelength Laser Ranging System for Measuring Atmospheric Delay," Appl. Opt., 19, 3436, 1980.

Jun AMAGAI
Keystone Project Team
Hardware development for radio interferometer and satellite laser ranging
E-mail: amagai@crl.go.jp

Chihiro MIKI
Frequency and Time Standards Section
Standards and Measurement Division
Precise measurement of frequency and time standards
E-mail: c-miki@crl.go.jp

Hideyuki NOJIRI
Technology Policy Division, Communications Policy Bureau, Ministry of Posts and Telecommunications
Software development for satellite laser ranging
E-mail: h-nojiri@mpt.go.jp

Hiroo KUNIMORI
Keystone Project Team
Satellite laser ranging
E-mail: kuni@crl.go.jp