Implementation of 188-element Curvature-based Wavefront Sensor and Calibration Source Unit for the Subaru LGSAO System

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ABSTRACT

The Subaru laser guide star adaptive optics (AO) system was installed at the Nasmyth focus of the Subaru Telescope, and had the first light with natural guide star on October 2006. The AO system has a 188-element curvature based wavefront sensor with photon-counting avalanche photodiode (APD) modules. It measures high-order terms of wavefront using either of a single laser (LGS) or natural guide star (NGS) within a 2' diameter field. The AO system has also a source simulator. It simulates LGS and NGS beams, simultaneously, with and without atmospheric turbulence by two turbulent layer at about 0 and 6 km altitudes, and reproduces the cone effect for the LGS beam. We describe the design, construction, and integration of the curvature wavefront sensor and calibration source unit.

Keywords: adaptive optics, laser guide star, wavefront sensing, curvature sensor, Subaru telescope

1. INTRODUCTION

The Subaru laser guide star adaptive optics (AO) system[1,2] is an upgrade of the existing system with a 36-element curvature sensor at the Cassegrain focus.[3,4] The new system aims to improve the correction performance, especially at the shorter wavelengths such as J band, by increasing the number of correction elements and to increase the sky coverage dramatically by using a laser guide star (LGS). We installed the new system at the IR Nasmyth focus of the Subaru Telescope, and had the first light with natural guide star on October 2006.[5] Also, we succeed in launching the laser beam and obtaining the first image of the LGS.

After the first light, we are making improvements of the system to start the open-use observations in the middle of 2008. As a result, many opto-mechanical components of the 188-element curvature wavefront sensor (high-order wavefront sensor; HOWFS) and the calibration unit were re-designed and rebuilt to improve the accessibility of components, the reliability of adjustment mechanisms of optics mounts, and the light-shielding. In this proceeding, we describe the design, construction, and integration of the hardware of the HOWFS and calibration unit with the new opto-mechanics. The overview of the design of the Nasmyth AO module were presented in Ref. 2, 6, 7 and the current status of the project is presented in Ref. 8.

2. HIGH-ORDER WAVEFRONT SENSOR

The HOWFS is a 188-element curvature based wavefront sensor with photon-counting avalanche photodiode (APD) modules. It measures high-order terms of wavefront using either of a single laser (LGS) or natural guide star (NGS) within a 2' diameter field.[6]

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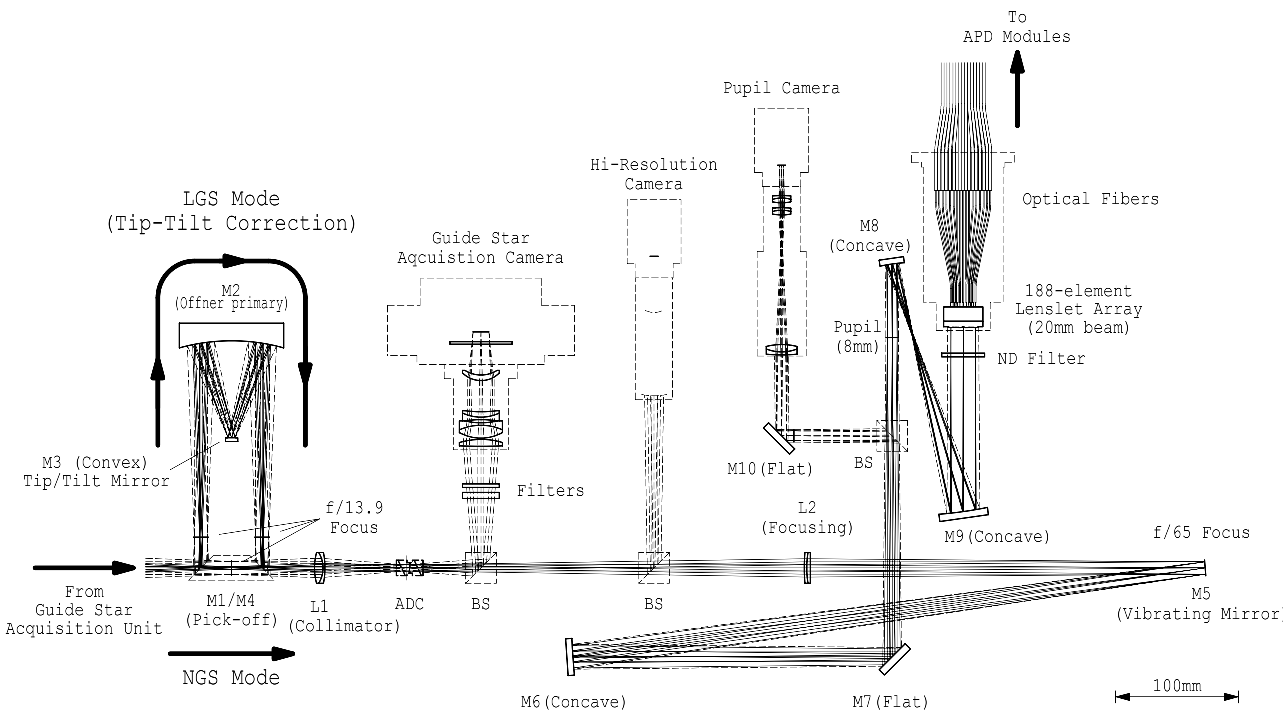

Figure 1. Optical layout of the high-order wavefront sensor.

2.1 Optics

Figure 1 shows the optical layout of HOWFS. For the LGS mode, the pick-off mirror (M1/M4) is inserted and the tip/tilt correction is done by the M3 mirror. The input beam is re-imaged onto the membrane vibrating mirror (M5) by the L1 and L2 lenses, and is collimated by the M6 mirror, and then is expanded by the M8 and M9 mirrors into a 20 mm diameter beam, forming a pupil image at the lenslet array. The pupil image is defocused back and forth when the membrane mirror vibrates. The several beam splitter cubes are insertable for the acquisition camera (20" diameter field of view), high-resolution camera (1.5" $\times$ 1.1" field of view), and pupil camera. The field of view for the wavefront measurement is 4" in diameter.

2.2 Opto-Mechanics

The APD module is very sensitive to light and can be damaged by any excessive light from the environment. Although the optical bench of the AO module is primary light-shielded by the enclosure panels of the bench, to reduce moreover background noises and the chance of damage due to stray light and scattered light in the AO module, we put all the components of the HOWFS except the acquisition unit into the inside of a light-shielding box (HOWFS enclosure; Figure 2 and 3).

The bottom plate of the enclosure is the base plate of the HOWFS optics. It is mounted at three points (pads) on the optical bench of the AO module, to minimize the mechanical stress due to mounting. Also, to avoid the mechanical stress due to the difference of the thermal expansion/construction between the HOWFS (made with aluminium) and the AO module optical bench (made with stainless steel) when the temperature changes, we used linear guides aligned along the direction of the thermal expansion/construction at the two pads (One pad near the $f/13.9$ focus of HOWFS is the fixed point).

In the front of the HOWFS enclosure, the guide star acquisition unit is located (left of Figure 5). This unit consists of two steering fold mirrors mounted on two-axis gimbal mounts.[6] The first mirror can also slide along the optical axis to keep the same travel distance of the beam when the mirrors are tilted for an off-axis field or

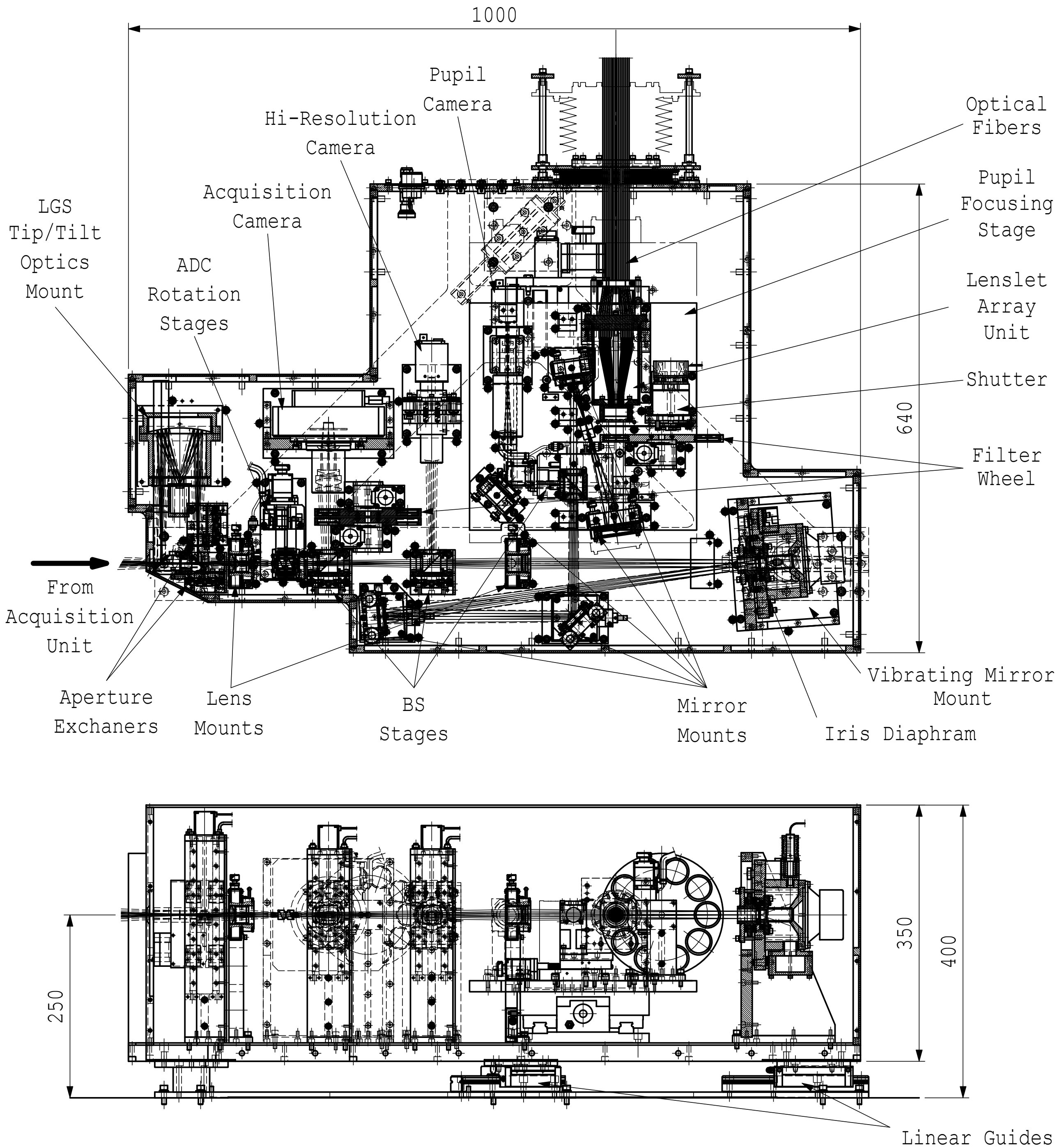

Figure 2. Opto-mechanical layout of the inside of enclosure of the high-order wavefront sensor.

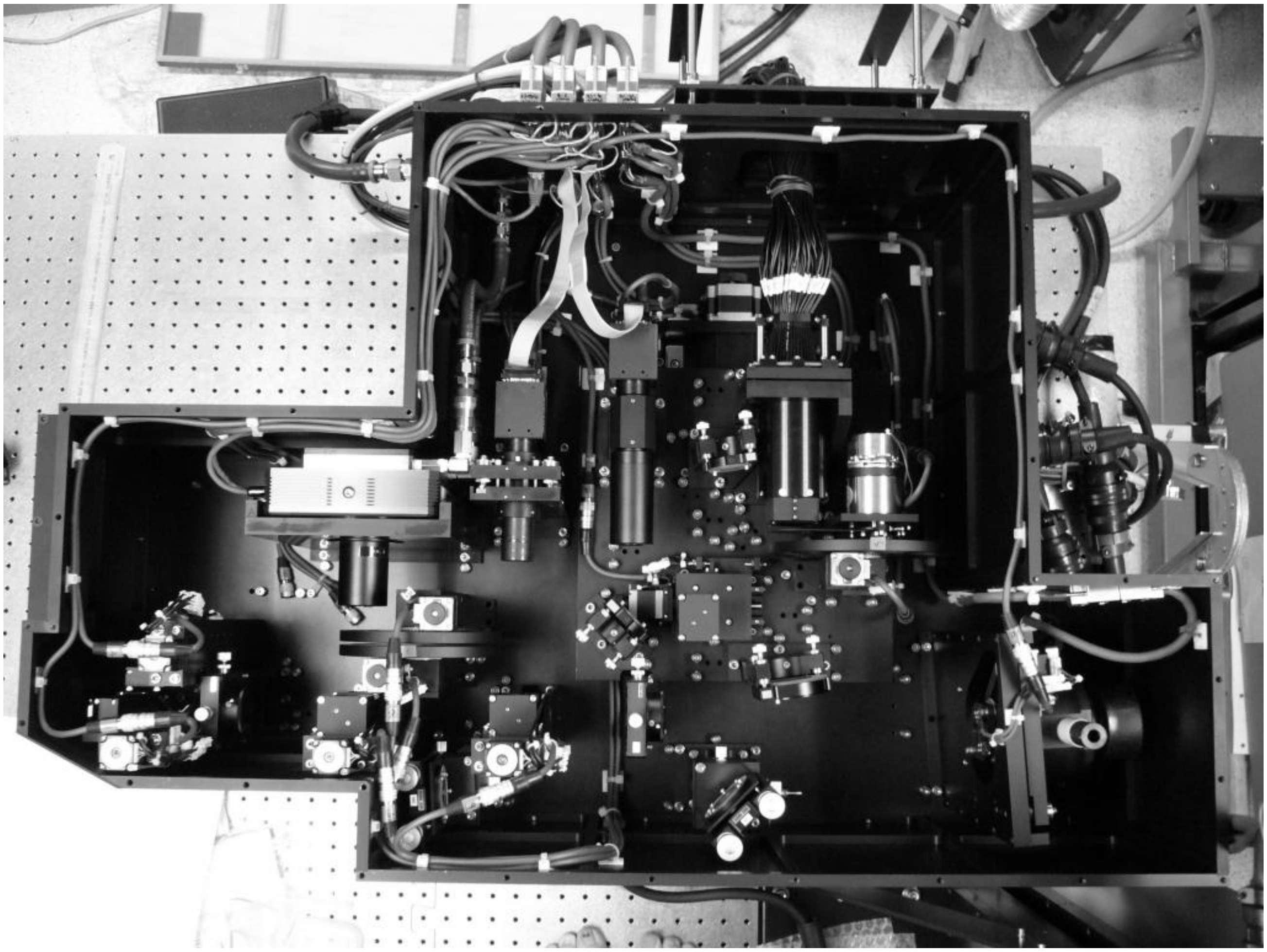

Figure 3. Photograph of inside of enclosure of high-order wavefront sensor. The LGS tip/tilt optics and ADC are not installed.

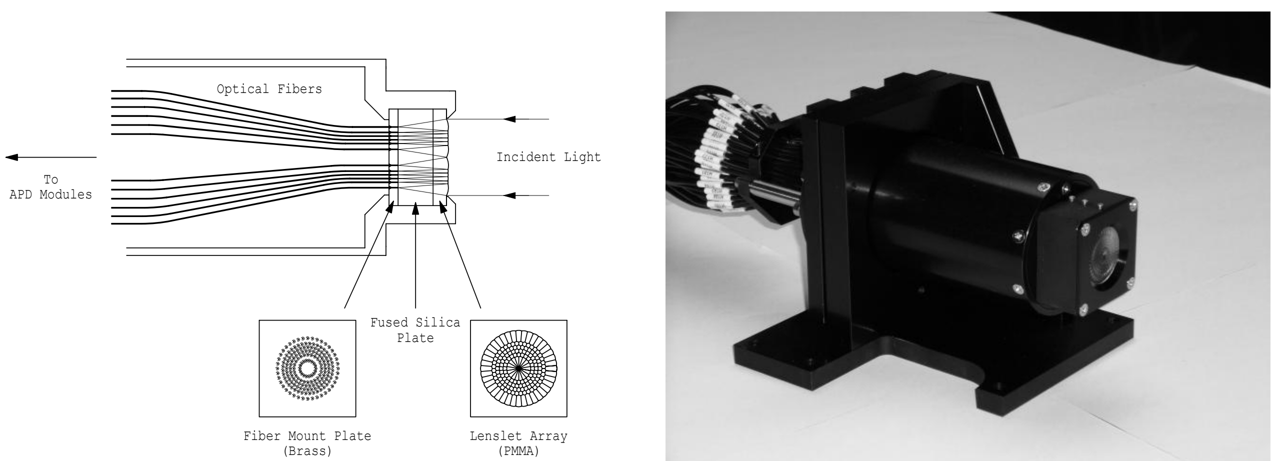

Figure 4. 188-element lenslet array unit assembly.

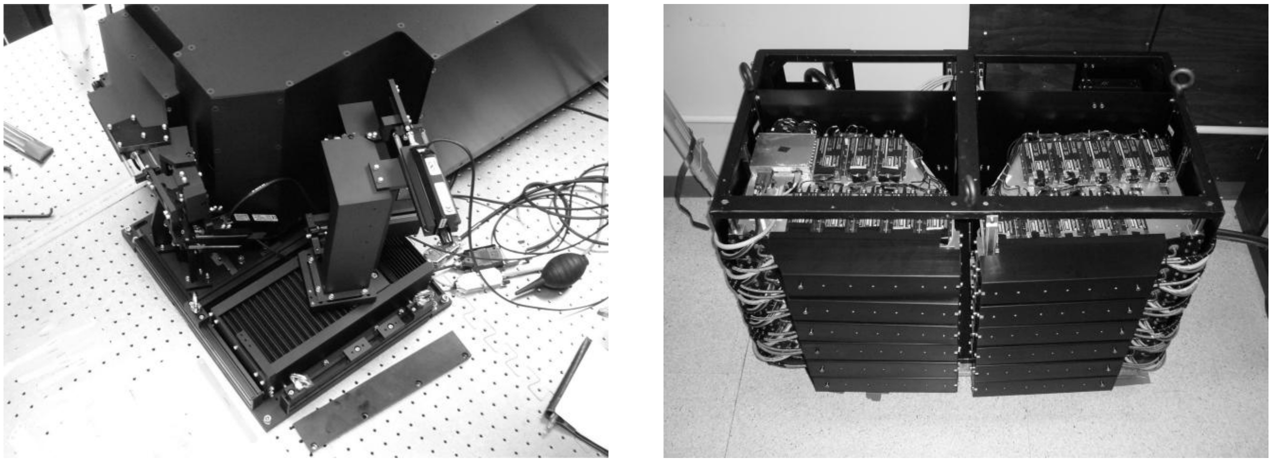

Figure 5. Photographs of the guide star acquisition unit in the front of the HOWFS enclosure (left) and the APD enclosure before installation into the AO module (right).

to compensate the focal shift at the LGS mode.[6] These mirror motions (five degrees of freedom) are controlled very precisely to maintain the registration between the deformable mirror and lenslet array.

Several commercial or custom motorized linear and rotation stages (totally 14 motion axes) are installed inside the enclosure for changing aperture sizes, insertion of beam splitter cubes, filters, atmospheric dispersion corrector (ADC), opening/closing of shutter. The components after the M7 mirror (including the lenslet array unit) are mounted on the pupil focusing stage with a 100 mm stroke, and the bandle of the optical fibers from the lenslet array is held with a slider at the side of the enclosure.

The lenslet array is a plastic lens molded from a copper mold, which was machined precisely by diamond tool.[6,9] Each lenslet focuses the incident light into an optical fiber placed at the back surface of the fused silica plate (Figure 4). The optical fibers were mounted on a brass plate by epoxy adhesive. The plate has mounting holes drilled precisely to align well with the focusing positions of lenslets. The ends of optical fibers were polished to flash the surfaces of the plate after mounting of fibers. Index matching oils were used between the lenslet array, fused silica plate, and fiber mounting plate to avoid the reflection.

The APD modules were installed into the APD enclosure located below the optical bench of AO module. The right photograph of Figure 5 shows the APD enclosure. The APD enclosure has twelve shelfs, and one shelf has eighteen APD modules. Totally, 216 APD modules, which includes sixteen modules for the low-order wavefront sensor and twelve spares, are installed. The shelfs have a coolant piping internally and are cooled by water circulation. The length of the optical fibers between the lenslet array unit and the APD modules is 3.2 m, and the custom aspherical mold lens is used for fiber-to-APD coupling.[6]

3. CALIBRATION UNIT

The calibration unit is a source simulator for optical alignment, calibration, control matrix creation, and diagnostics of the AO system. It provides two beams with the same f-ratio as the telescope for two point sources, simulating the NGS and LGS beams, simultaneously, with and without turbulence. The unit also simulates the shift of telescope focus, tip/tilt motion, and spread of LGS.

3.1 Optics

Figure 6 shows the optical layout of the calibration unit. For a NGS point source, we used the combined light of 0.655 and 1.55 μm laser diodes through a 5 μm pinhole. For a LGS source with a size of 0.5" at the sky, we used the light from a yellow LED through a diffuser plate and 100 μm pinhole. To simulate the tip/tilt motion of LGS, the LGS path has a first steering piezo tip/tilt mirror. The shift of telescope focus for LGS (difference between NGS and LGS) is reproduced by using two beam splitter prisms (left of Figure 7).

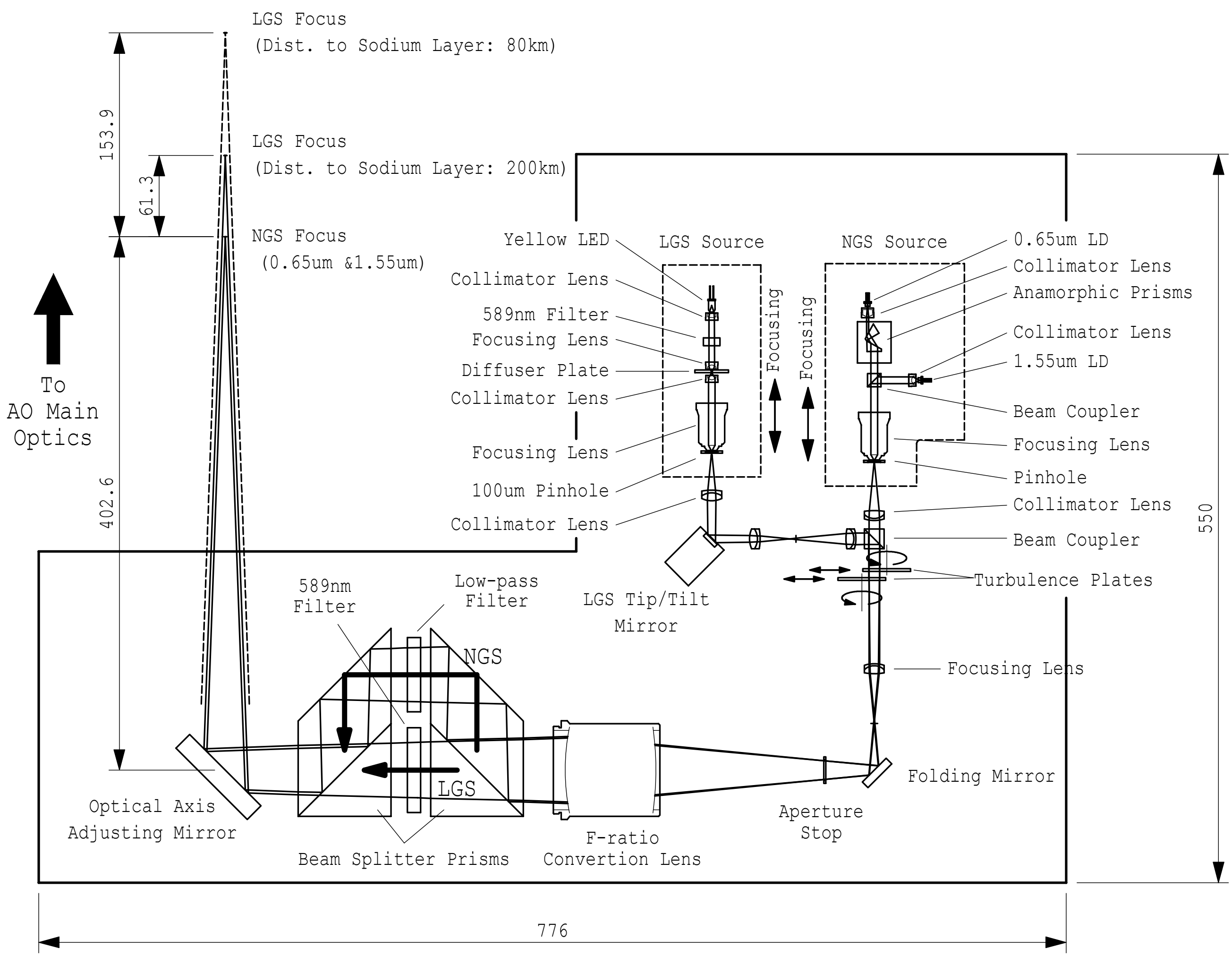

Figure 6. Optical layout of calibration unit.

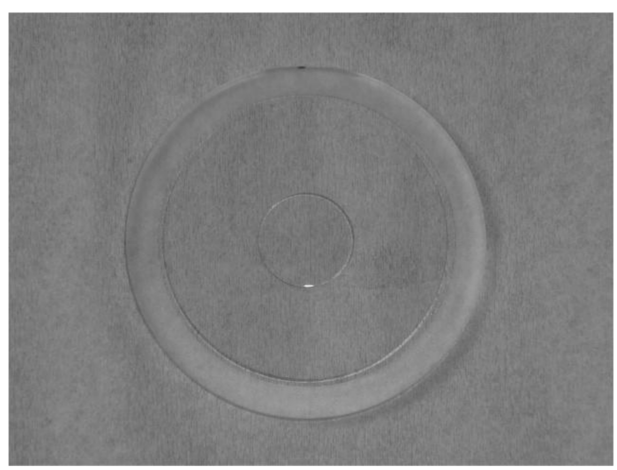

Figure 7. Photograph of the beam splitter prism (left) and turbulence plate (right) of the calibration unit. The size of prism is 142 × 70 × 70 mm. The diameter of turbulence plate is 36 mm and thickness is 2 mm.

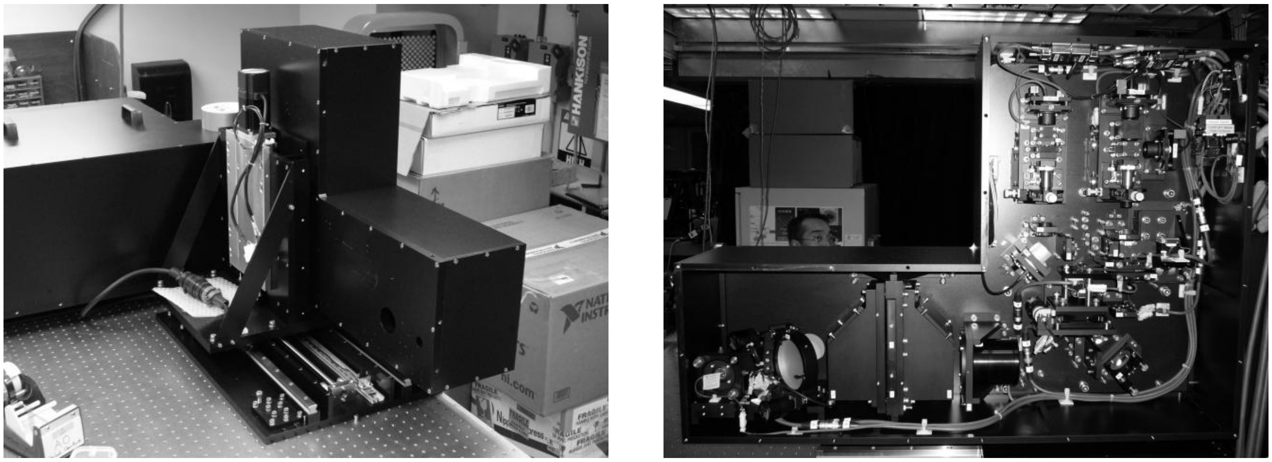

Figure 8. Photographs of the calibration unit mounted on the XZ stage (left) and the inside of enclosure of calibration unit (right).

The atmospheric turbulence by two turbulence layers at about 0 an 6 km altitudes is simulated by inserting two rotating turbulence plates into the common path of NGS and LGS. The turbulence plate is identical to that of the 36-element Cassegrain AO system.[4] It is a molded plastic plate with a deformed surface to produce a wavefront error with Kolmogorov statistics (right of Figure 7). The beam diameter is 8 mm, and the annular region from about 9 to 28 mm diameter is the deformed area while the center area is flat for no turbulence operation.

3.2 Opto-Mechanics

All optical components are mounted on a vertical base plate with an enclosure box (right of Figure 8). The beams are provided through a hole on the vertical base plate. The box is mounded on a large XZ stage with a 280 mm stroke along the X (horizontal) axis and a 100 mm stroke along Z (vertical) axis (left of Figure 8). The box is insertable in the front of the image rotator unit of the AO module, and the unit covers the field of view of the AO science path with a 2.7' diameter by sliding of the XZ stage. The NGS and LGS foci are adjusted by sliding of the internal stages. The weight of the box including all internal components is 40 kg and the overall weight of the calibration unit including XZ stage is 86 kg. The calibration unit is mounted at four points of the optical bench of AO module. The one point is the fixed point and other three points have a flexure mechanism to reduce the mechanical stress due to the difference of the thermal expansion/construction between the calibration unit (made with aluminium) and the optical bench (made with stainless steel) when the temperature changes.

4. SUMMARY

We built a 188-element curvature-based wavefront sensor with APD modules and a calibration unit that simulates NGS and LGS beams with and without atmospheric turbulence for the Subaru laser guide star AO system. Many improvements about opto-mechanics were made after the first light observation on October 2006. The second light observation is scheduled around July of 2008.

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REFERENCES

[1] Hayano, Y., Takami, H., Gaessler, W., Takato, N., Goto, M., Kamata, Y., Minowa, Y., Kobayashi, N., and Iye, M., "Upgrade plans for Subaru AO system," in [*Adaptive Optical System Technologies II*], P. L. Wizinowich and D. Bonaccini, eds., *Proc. SPIE* **4839**, 32–43 (2003).

[2] Takami, H., Iye, M., Hayano, Y., Saito, Y., Kamata, Y., Arimoto, N., Takato, N., Colley, S., Eldred, M., Kane, T., Guyon, O., Oya, S., Watanabe, M., Hattori, M., Goto, M., Kobayashi, N., and Minowa, Y., "Laser guide star AO project at the Subaru Telescope," in [*Advancements in Adaptive Optics II*], D. B. Calia, B. L. Ellerbroek, and R., Ragazzoni, eds., *Proc. SPIE* **5490**, 837–845 (2004).

[3] Takami, H., Takato, N., Otsubo, M., Kanzawa, T., Kamata, Y., Nakashima, K., and Iye, M., "Adaptive optics system for Cassegrain focus of Subaru 8.2 m telescope," in [*Adaptive Optical System Technologies*], D. Bonaccini and R. K. Tyson, eds., *Proc. SPIE* **3353**, 500–507 (1998).

[4] Takami, H., Takato, N., Hayano, Y., Iye, M., Oya, S., Kamata, Y., Kanzawa, T., Minowa, Y., Otsubo, M., Nakashima, K., Gaessler, W., and Saint-Jacques, D., "Performance of Subaru Adaptive Optics System," *PASJ* **56**, 225–234 (2004).

[5] Takami, H., Hayano, Y., Oya, S., Hattori, M., Watanabe, M., Guyon, O., Eldred, M., Colley, S., Saito, Y., Itoh, M., and Dinkins, M., "The First Light of the Subaru Laser Guide Star Adaptive Optics System," *Proceedings of the Advanced Maui Optical and Space Surveillance Technologies Conference*, S. Ryan, ed., E68 (2007).

[6] Watanabe, M., Takami, H., Takato, N., Colley, S., Eldred, M., Kane, T., Guyon, O., Hattori, M., Goto, M., Iye, M., Hayano, Y., Kamata, Y., Arimoto, N., Kobayashi, N., and Minowa, Y., "Design of the Subaru laser guide star adaptive optics module," in [*Advancements in Adaptive Optics II*], D. B. Calia, B. L. Ellerbroek, and R., Ragazzoni, eds., *Proc. SPIE* **5490**, 1096–1104 (2004).

[7] Oya, S., Guyon, O., Watanabe, M. Hayano, Y., Takami, H., Iye, M., Arimoto, N., Colley, S., Eldred, M., Kane, T., Hattori, M., Saito, Y. Kamata, Y., Kobayashi, N., Minowa, Y., Goto, M., Takato, N., "Deformable mirror design of Subaru LGSAO system," in [*Advancements in Adaptive Optics II*], D. B. Calia, B. L. Ellerbroek, and R., Ragazzoni, eds., *Proc. SPIE* **5490**, 1546–1555 (2004).

[8] Hayano, Y., Takami, H., Guyon, O., Oya, S., Hattori, M., Saito, Y., Watanabe, M., Murakami, N., Minowa, Y., Ito, M., Colley, S. A., Eldred, M. P., Golota, T. I., Dinkins, M. C., Kashikawa, N., and Iye, M., "Current status of the laser guide star adaptive optics system for Subaru Telescope," in [*Adaptive Optics Systems*], N. Hubin, C. E. Max, and P. L. Wizinowich, eds., *Proc. SPIE* **7015** (2008) [7015-35].

[9] Takami, H., Colley, S., Dinkins, M., Eldred, M., Guyon, O., Golota, T., Hattori, M., Hayano, Y., Ito, M., Iye, M., Oya, S., Saito, Y., and Watanabe, M., "Status of Subaru laser guide star AO system," in [*Advances in Adaptive Optics II*], B. L. Ellerbroek and D. B. Calia, eds., *Proc. SPIE* **6272**, 62720C-1–10 (2006).