Prototype Development for the GMT FSM Secondary  
- Off-axis Aspheric Mirror Fabrication -

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A prototype of the GMT FSM has been developed to acquire and to enhance the key technology - mirror fabrication and tip-tilt actuation. The ellipsoidal off-axis mirror has been designed, analyzed, and fabricated from light-weighting to grinding, polishing, and figuring of the mirror surface. The mirror was tested by using an interferometer together with CGHs, which revealed the surface error of 13.7 nm rms in the diameter of 1030 mm. The SCOTS test was employed to independently validate the test results. It measured the surface error to be 17.4 nm rms in the diameter of 1010 mm. Both tests show the optical surface of the FSMP mirror within the required value of 20 nm rms surface error.

**Keywords:** GMT, secondary, mirror, off-axis, aspheric, fabrication

1. INTRODUCTION

Giant Magellan Telescope (GMT) is one of the giant telescopes in the world under development. The diameter of the GMT is 25.4 m and the effective focal ratio is f/8. It will be built at Las Campanas, Chile, and the first light is planned to be held in 2019. The primary mirror consists of seven 8.4 m mirror segments as shown at Fig. 1. The GMT has a Gregorian feature with concave secondaries, which consist of seven 1.05 m mirror segments to be matched one-to-one with the primary segments. The optical prescription is described in Table 1, and the ray traced drawing is shown in Fig. 2. (GMT Organization 2006, 2014)

Two types of GMT secondaries are going to be produced - Fast-steering Secondary Mirror (FSM) and Adaptive Secondary Mirror (ASM). The FSM contains a conventional thick and light-weighted mirrors, but it adds tip-tilt actuators to compensate the structural jitter mainly caused by winds. The FSM will be used as the first light secondary and a back-up when the ASM is completed. The ASM corrects atmospheric turbulences on the secondary mirror directly, which is similar to the adaptive secondaries of the Large Binocular Telescope, the Multiple Mirror Telescope, and the Magellan telescopes (Lloyd-Hart 2000, Wildi et al. 2002, Riccardi et al. 2003, Biasi et al. 2010, Esposito et al. 2011).

KASI joined the GMT development project since 2009 as representative of Korean participants. As part of the Korean GMT project, KASI has developed a prototype of the FSM together with several institutions in Korea and the USA (KASI 2012a, 2012b, 2013).

2. GMT FSM SECONDARY

The GMT FSM consists of seven mirror segments whose
The mother curve has the radius of curvature of 4163.9 mm for the whole diameter of 3.2 m. The seven segments have one-to-one relations to the primary mirror segments. Among the seven segments, the surrounding six segments except the center one are placed at off-axis positions, as shown in Fig. 3.

The baseline of the FSM is the f/11 secondary of the Magellan telescopes. The features between the FSM and the Magellan secondary are compared and listed on Table 2 (Magellan telescopes 1998, KASI 2010, GMT Organization 2014). The diameter of the FSM segment is 1.05 m, which is smaller than that of the Magellan secondary. However, the focal ratio of the FSM is as fast as 0.65, which makes the edge slope steeper than that of the Magellan secondary. It adds the difficulty of the fabrication of the off-axis segments more. Both mirrors are light-weighted and the weights are held by vacuum forces between the mirrors and their mirror cells. Tip-tilt mechanism is implemented by installing piezo-actuators in the three axial supports.

Table 1. Optical prescription of the GMT.

| Items                              | Description          |
|------------------------------------|----------------------|
| Primary mirror (M1)                | D 25.4 m (8.4 m *7 segments) |
| Secondary mirror (M2)              | D 3.2 m (1.05 m *7 segments) |
| M1 conic constant                  | -0.9983 (ellipsoid)   |
| M2 conic constant                  | -0.7169 (ellipsoid)   |
| Effective focal length             | 207.5888 m            |
| Effective focal ratio              | 8.1574                |
| M1-M2 separation                   | 20.2625 m             |
| Back focal length                  | 5.630 m               |

Table 2. Comparison of the GMT FSM and the Magellan secondary.

| Item                        | GMT FSM                  | Magellan secondary |
|-----------------------------|--------------------------|--------------------|
| Diameter                    | 3.2 m (1.05 m * 7 segments) | 1.3 m (single mirror) |
| Radius of curvature         | 4163.901 mm, f/0.65       | 2862.5 mm, f/1.10   |
| Surface form                | Ellipsoid, -0.7169        | Ellipsoid, -0.63349 |
| Weight                      | 93.2 kg (on-axis segment) | 92.1 kg (off-axis segment) | 200.4 kg |

Fig. 1. Schematic drawing of the GMT. The primary mirror consists of seven segments of 8.4 m in diameter.

Fig. 2. Optical ray traces of the GMT. The star lights reflected by the primary segments will be converged first to a plane before the secondary.

Fig. 3. A drawing of the GMT FSM segments. Among the seven segments, the surrounding six segments are placed at off-axis positions.

3. FABRICATION OF AN OFF-AXIS MIRROR

A prototype of the FSM (FSMP: Fast-steering Secondary Mirror Prototype) has been developed, which is a full-size of one segment. The FSMP comprises an off-axis mirror and
tip-tilt test-beds. By developing the FSMP, key technologies of fabricating large optics and precision mechatronics of tip-tilt actuation can be achieved and upgraded.

A consortium is organized by five institutions in Korea and the USA. Among them, mirror design was performed by Korea Astronomy and Space Science Institute (KASI), and analysis was performed by National Optical Astronomy Observatory (NOAO) in the USA. Actual mirror fabrication and tests have been conducted by Korea Research Institute of Standards and Science (KRISS), Institute for Advanced Engineering (IAE) and Gwangju Institute of Science and Technology (GIST) mainly worked on the tip-tilt actuations (Kim et al. 2014).

An off-axis segment was designed from the Zemax data for the GMT, which was provided by the GMT Organization in January 2011. The optical prescription of the GMT has been changed, therefore the FSMP design is not the same as the current design of the FSM. The Zemax data were reproduced to Fig. 4. It can be seen that the off-axis segment is not circular, as the diameter in radial direction is 1042.58 mm, whereas it is 1046.5 mm in cross direction. There is about 4 mm difference in diameters between the two perpendicular directions. However the FSMP mirror was fabricated on a circular shape of 1,064 mm in diameter whose off-axis surface was modified from the design of the center segment with the light-weighting pattern. The center segment is circular with the diameter of 1062.0 mm.

The mirror model was drawn from the Magellan secondary mirror model, and it was analyzed by NOAO and KASI (Kim et al. 2009, Ahn et al. 2011). The results are shown in Fig. 5. Surface deformation by gravity is expected to be 7.6 nm rms at zenith position. When the mirror is in vertical position, i.e. the telescope is 90 degrees inclined, the surface deformation would be 7.7 nm rms (KASI 2012b).

Mirror fabrication was performed by KRISS, starting from light-weighting by drilling 91 holes at the back side of the mirror. The manufacturing drawing for the light-weighting is shown in Fig. 6, and the light-weighted mirror is shown in Fig. 7.

Mirror grinding was followed on the front surface. It was conducted until the surface accuracy is achieved to 5 μm in peak to valley. Fig. 8 shows a surface map during grinding, which was measured by a laser tracker on Oct. 29, 2012. The peak to valley value was about 5 μm excluding the redundant area at edges which was cut down after grinding (KASI 2013).

Polishing and figuring of the off-axis mirror was performed for 9 months to refine the mirror surface to reach the surface error less than 20 nm rms. Fig. 9 shows the surface error map.
announced on July 17, 2013. The surface rms error was 13.7 nm for the diameter of 1030 mm. For the surface testing, two different Computer Generated Holograms (CGHs) were applied to a phase-shift interferometer (KASI 2013). Another two months of smoothing works were continued to remove the ripples but it didn’t make much progress. And another test method was employed to verify the interferometric

![Fig. 6. Manufacturing drawing for the light-weighting.](image)

![Fig. 7. Back side of the mirror after light-weighting. 91 holes were made from the spherical back side.](image)

![Fig. 8. A surface map during grinding. It was the measured data on Oct. 29, 2012. The peak to valley was about 5 μ excluding the redundant edges which were cut down after grinding.](image)
test results. It was Software Configurable Optical Test System (SCOTS), which was developed by The University of Arizona (Su et al. 2010, 2012, 2013, Huang et al. 2013). SCOTS is known as a strong test method in measuring high frequency deformations. Fig. 10 shows the test results performed directly by the team of SCOTS in The University of Arizona. The SCOTS result is 17.5 nm rms, and the interferometer result is 12.9 nm rms in the diameter of 1010 mm (Huang et al. 2014). Both indicate the surface errors were within the required value of 20 nm rms.

4. CONCLUSION AND DISCUSSIONS

GMT FSM consists of seven concave segments which form an ellipsoidal mother curve with a fast focal ratio of 0.65. Each segment is 1.05 m in diameter, and forms off-axis configuration except the center one.

A prototype of the FSM mirror has been developed to acquire the key technology. One is fabrication of highly aspheric off-axis mirrors. Starting from the study of the Magellan secondary mirror, a full-size off-axis FSM segment was developed for five years by designing, analyzing, lightweighting, etching, grinding, polishing, shaping, and testing. The off-axis mirror needs many features to consider from the design to the fabrication and tests. The mirror surface was tested by interferometry with CGHs, and the surface error was measured to 13.7 nm rms in the diameter of 1030 mm. The surface error is less than the required value of 20 nm rms. For comparison, the SCOTS test was conducted, and the results go well within the required value of 20 nm rms in the diameter of 1010 mm.

Fabrication of an off-axis conical surface mirror with fast focal ratio was a challenging task, and the accomplished techniques enhanced our capabilities. Those techniques contribute to the development of the GMT FSM, and would work for the development of other telescopes, space optics, and optics fabrication industry.

ACKNOWLEDGEMENTS

This work was supported by the Large Optical Telescope
Project funded by the Ministry of Science, ICT and Future Planning.

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