Journal of the Optical Society of Korea
Vol. 13, No. 2, June 2009, pp. 178-183

DOI: 10.3807/JOSK.2009.13.2.178

Accuracy Assessment for Measuring Surface Figures of Large Aspheric Mirrors

Young-Soo Kim*, Ki-Beom Ahn, and Kwijong Park
Korea Astronomy & Space Science Institute, Daejeon 305-348, Korea

Il Kweon Moon and Ho-Soon Yang
Korea Research Institute of Standards and Science, Daejeon 305-340, Korea

(Received May 19, 2009 : revised June 17, 2009 : accepted June 18, 2009)

At the time that the Keck-I 10m telescope was constructed in 1993, the era of Very Large Telescopes (VLTs) was opened. Now thirteen VLTs are in operation, and the largest of the monolithic mirrors is 8.4 m in diameter. Such monolithic mirrors are mostly aspheric and require high accuracies on the surface figures, reaching up to the diffraction limit. At present, next generation telescopes, Giant telescopes, are being developed. One is the GMT (Giant Magellan Telescope) whose size is 25.4 m in diameter. The primary mirror consists of seven segments figuring elliptical shapes on the surface. The surrounding six segments are off-axis and the edges are steep, as the fast focal ratio is adopted. It means that testing of the mirrors is a challenging task. In this paper, testing methods for the GMT primary mirror are reviewed, and accuracy of measuring devices is assessed. Results and discussions follow.

Keywords: Telescope, Mirror, Surface, Accuracy, Aspheric

OCIS codes : (110.6770) Telescopes; (120.3180) Interferometry; (120.3940) Metrology; (220.4840) Optical testing

I. INTRODUCTION

Since Hans Lippershey invented the first refracting telescope in 1608 [1] and the first astronomical telescope by Galileo Galilei appeared on the following year, discovery and understanding in astronomy have advanced rapidly. After Sir Isaac Newton developed the first reflecting telescope, making larger telescopes become possible with ease.

Starting from Mt. Palomar's 200 inch telescope in 1949, the era of 4 m class large telescopes was opened. Since then, after 50 years, 8 m class very large telescopes (VLTs) appeared, starting from the Keck telescope[1] in 1993. Soon after more than a dozen VLTs were constructed and are being operated at Chile, Hawaii, Canary islands, America, etc. There are two types of telescopes according to the constitution of the primary mirror. The first type has a single, monolithic mirror like that of a conventional telescope, but with diameter around 8 m or less. The second type has a primary mirror which consists of several dozens of small mirrors, whose diameter is between 1 m and 2 m and whose shape is usually hexagonal.

TABLE 1 shows optical characteristics of several VLTs, each of which has a monolithic primary mirror. The telescope types are Ritchey-Chrétien (RC), Cassegrain, or Gregorian, which means that the mirrors are figured to parabola, hyperbola, or ellipse on either convex or concave surface. Such aspheric mirror surfaces are more difficult to produce than spherical ones.

Those very large telescopes require high accuracy on the image size reaching the diffraction limits. In case of the Gemini telescopes, 50% of the energy (θ_{50}) should fall within a circle of 0.1 arcsec at the wavelength of 2.2 μm [2]. The image size of ESO (European Southern Observatory) VLTs[2] should be 0.038 arc-seconds in the 1.5 arc-minutes field of view. Requiring such high accuracy means that the telescopes, including the mirrors, should

---

*Corresponding author: ykim@kasi.re.kr
[1] http://www.keckobservatory.org
[2] http://www.eso.org

TABLE 1. Characteristics of very large telescopes with monolithic primary mirror.

	Gemini	ESO VLT	Subaru	LBT	Magellan
No of telescopes	2	4	1	2	2
Diameter	8.1 m	8.2 m	8.2 m	8.4 m	6.5 m
Type	RC	RC	RC	Cassegrain	Gregorian
f/# Primary	1.8	1.8	1.8	1.14	1.25
Conic const	-1.003756	-1.004616		-1.0	-1.0
Image size [arcsec]	0.1 (θ_{50}) at 2.2 μm	0.038 / 1.5 arcmin	0.17 (θ_{50}) at 0.5 μm	0.23 FWHM	
Remarks				In one structure	

TABLE 2. Basic concept data of GSMTs.

Name	Diameter (m)	Optical system	Expected Completion (year)	Participants
GMT	25 (7×8.4 m)	Gregorian	2018	USA : Carnegie Institution of Washington, Harvard Univ., Smithsonian Institution, Univ. Arizona, Texas Univ. at Austin, Texas A&M Univ. Korea : KASI Australia : Australia Nat'l Univ., AAL (Astronomy Australia Limited)
TMT	30 (492 segments)	RC	2017	USA : California Institute of Technology, Univ. of California Canada
E-ELT	42 (1,000× 1.4 m)	5 mirrors	2018	EU : ESO (European Southern Observatory)

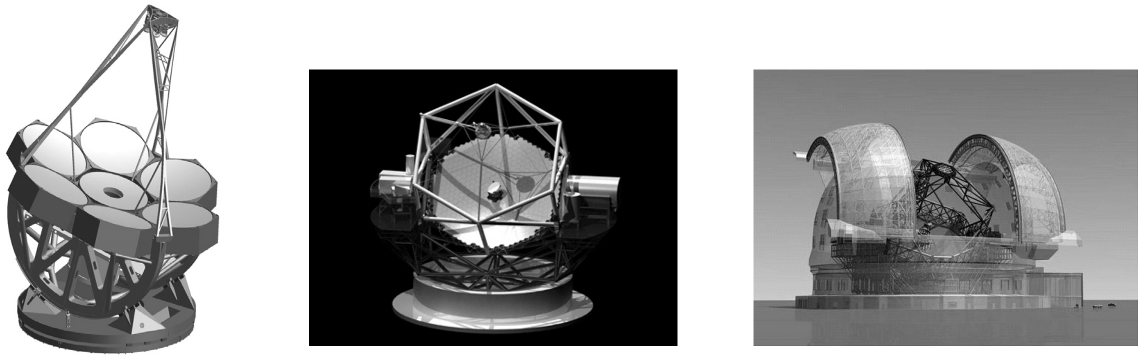

FIG. 1. The three GSMTs: from left GMT, TMT, and E-ELT.

be made very precisely. In order to produce mirrors precisely, test methods should be very accurate. Otherwise, it cannot be judged whether the mirror is produced precisely or not.

After producing the 8~10 m VLTs, the next generation telescopes are being developed. Those are three or more times bigger than VLTs and are called GSMTs (Giant Segmented Mirror Telescopes). There are three GSMTs presently being developed, GMT[3] (Giant Magellan Telescope), TMT[4] (Thirty Meter Telescope), and E-ELT (European-Extremely Large Telescope). TABLE 2 presents the conceptual data of the GSMTs. GMT inherits the Gregorian type of 6.5 m Magellan telescopes, and both primary and secondary mirrors have elliptical surfaces. TMT is RC type and E-ELT has a five mirror scheme.

FIG. 1 shows the conceptual drawing of the GSMTs. The primary mirror of the GMT consists of seven 8.4 m mirror segments, whereas the others consist of several hundreds of hexagonal shaped small mirrors. Those tele-

---

3) http://www.gmto.org
4) http://www.tmt.org

scopes are being developed competitively, and aim for similar completion years. Korea officially joins the development of GMT from year 2009.

II. TESTING METHODS OF LARGE ASPHERIC OFF-AXIS MIRRORS

Large telescopes are required to have better image quality than smaller telescopes. Though adaptive and active optics can correct the degradation of the image quality caused by inaccurate figure of the telescope mirrors, the optical system should be as perfect as possible, so that deformed mirror figures can be corrected simply and easily.

Testing methods for large mirrors are not very different from those for small mirrors in principle, but there are more things to consider. Large telescopes require high accuracy reaching up to the diffraction limit, therefore more precise tests should be performed. The area of the mirror being tested becomes larger and the size can cause difficulty in testing as well. Bigger space is needed and the detector should have a big enough field of view together with sufficient resolution. Environmental factors such as air flow, thermal change of the atmosphere, and ground vibration, should also be considered and controlled carefully [3].

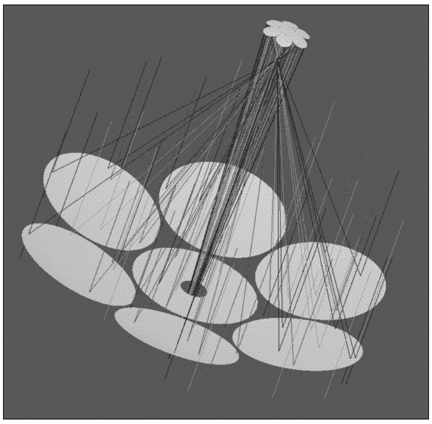

FIG. 2. Optical layout of the GMT optics. It is composed of seven primary and matching secondary mirrors.

In order to measure the figure errors of large aspheric mirrors, several methods have been developd. In order to compensate the aspheric beam, a null corrector or a CGH (Computer Generated Hologram) has been adopted [4, 5, 6]. Using two wavelengths with phase-shifting interferometry [7, 8, 9, 10, 11] or directly measuring aspheric surfaces by profilometry [6, 12] were also developed. When it is difficult to test the whole area at once, methods of testing local areas and stitching the results were also developed [13, 14, 15]. Detailed descriptions can be found in the documents [3, 16].

Off-axis configuration adds more difficulty to the fabrication and test of aspheric large mirrors. The primary mirror of GMT forms an ellipsoidal curve [17]. The surrounding six mirrors should have an identical off- axis aspheric shape, as shown in FIG. 2. The focal length of the primary mirror is 18.0 meters and the diameter is 25.4 meters. These make up f/0.7 focal ratio. The fast focal ratio contributes to the compactness of the GMT structure and reducing the size of the secondary mirror. The optical specifications of GMT are listed in TABLE 3.

As for testing the GMT off-axis aspheric primary mirrors, three methods have been devised. The first and main method is a phase-shift interferometry together with null correcting fold mirrors and CGH. It is a full-size high-resolution measurement of the optical figure. Though the test method needs a large area, there is a spatial restriction in the laboratory at The University of Arizona,

TABLE 3. Optical prescription of GMT.

Primary Mirror (M1)		
Configuration	segmented	Seven(7) × 8.4 m dia. Segments.
Diameter, D1	25.448 meters	Non-circular aperture. Ellipse.
Radius of curvature, R1	36.000 meters	
Conic constant, K1	-0.99829	
Segment diameter, D_c1	8.365 meters	Circular clear aperture. Off-axis segments tilted 13.522°
Center hole diameter	1.78 meters	
Secondary Mirror (M2)		
configuration	7 segments	Conjugated with M1 segments
Diameter, D2	3.2 meters	Pupil stop. Non-circular aperture.
Radius of curvature, R2	4.2058 meters	
Conic constant, K2	-0.71087	
Segment diameter, D_c2	1.063 meters	

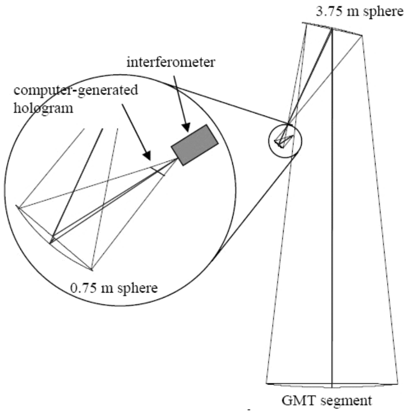

FIG. 3. Interferometry for the off-axis mirrors of the GMT Primary.

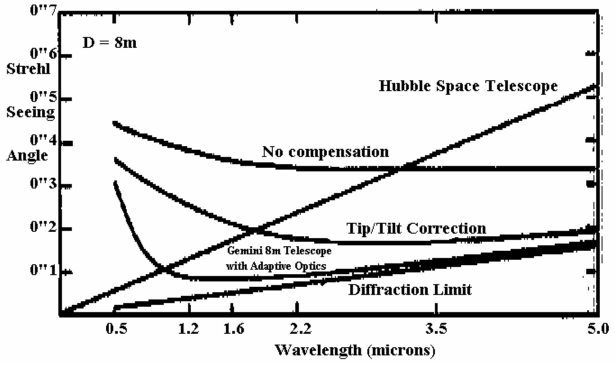

FIG. 4. Expected image quality of the Gemini telescopes [18].

where fabrication and test are conducted. Therefore a folding mirror of 3.75 m in diameter is adopted. Another 0.75 m folding mirror is also employed to reflect the rays to the interferometer. The folding spheres also act as null correctors, as illustrated in FIG. 3. Figure error of the 375 m sphere would bring large impact in the GMT test, so the sphere is also tested from its radius of curvature at the same time with the test of the GMT segment. And the error of the sphere is subtracted from the measurement of the large off-axis mirror.

The interferometry would be able to measure the figure and the geometry of the GMT segments to the required accuracy. However, a possibility of making a mistake in the performance of the test still exists. So it is necessary to have an independent measuring method, and a scanning pentaprism measurement is prepared. It measures slope errors in one-dimension across the mirror. A collimated laser beam is bent at 90 degrees and directed toward the off-axis test mirror by a pentaprism. The bent beam is set to be in parallel to the optical axis. The reflected beam by the off-axis test mirror is focused on the detector which sits at the focus, as the off-axis mirror is figured near parabolic. Deviations of the focused spot indicate slope errors on the mirror surface. The pentaprism moves linearly, and one-dimensional slope errors along one diameter can be measured.

The third method is a laser tracker measurement. This one is used when the mirrors are at the stages of grinding and initial polishing. It is a commercial device which combines a distance-measuring interferometer with angular encoders and servo-controlled pointing. The accuracy of the distance measurement is less than 1 μm and that of angular encoder is about 1 arc-second, which are not accurate enough to measure large mirrors. However the method is still useful during the grinding and initial polishing, as it provides a quick look at the mirror surface, in about 15 minutes. Detailed description of the methods can be found in the Conceptual Design Review of GMT [17].

III. SURFACE ACCURACY ASSESSMENT OF LARGE MIRRORS

In order to test large aspheric mirrors, highly accurate test methods should be developed. In this chapter, required accuracy of testing devices is assessed. The Gemini telescopes are studied to find an appropriate accuracy of large mirrors. The Gemini telescopes are twin 8.1m telescopes, located on Hawaii and in Chile, to observe both northern and southern hemispheres by using the identical telescopes. The primary mirror is f/1.8 meniscus mirror with a central hole of 1.2 m diameter.

The image quality was specified to be better than 0.1 arc second at near infrared wavelengths and near diffraction limit at shorter wavelengths with adaptive optics [18]. In the infrared bands, 50% of the energy will be concentrated within a circle of 0.1 arc second at the wavelength of 2.2 μm [2]. In the optical region, 80% of encircled energy shall be fallen into 0.1 arc second at the wavelength of 550 nm [19]. In fact, the Gemini sites merely show median natural seeing of 0.4 arc seconds FWHM, and in the best condition the image quality is better than 0.25 arc seconds in near IR wavelength [20].

FIG. 4 [21] shows the expected image quality of the Gemini telescopes in several cases: no compensation, tip/tilt correction, and adaptive optics. By applying adaptive optics, the image quality can reach the diffraction limit in the infrared band, and can be better than that of the Hubble Space Telescope at the wavelength of longer than 1 μm.

Three kinds of accuracy measures can be considered for the figure error of a mirror. They are slope error, rms (root-mean-square) surface error, and p-v(peak-to-valley) surface error. The tolerance of slope error can be simply calculated from the image size specified for the Gemini telescopes. In order for the image size to be 0.1 arc second, the primary mirror should have the slope error of $\pm 2.4\times10^{-7}$, if the secondary mirror is regarded as perfect. Therefore, the actual tolerance would be within the order of 10^{-7}.

TABLE 4. Relationship between Strehl ratio and rms wavefront error, and the difference.

Strehl ratio	RMS wavefront error [λ]	Difference [λ]
1.0	0	
0.9	0.050	0.050
0.8	0.071	0.021
0.7	0.087	0.016

The rms wavefront error can be converted from Strehl ratio. Between the rms error and Strehl ratio, there is an approximate relationship as shown [22]:

$$\text{Strehl ratio} \sim 1\text{-}4\pi^2(\text{rms}/\lambda)^2, \quad (1)$$

where λ is the wavelength to observe and rms is rms wavefront error. Precise telescope optics normally require the Strehl ratio to be about 0.8 [22]. The Gemini telescope is also required to be 0.8 of the Strehl ratio at the wavelength of 1.6 μm [23]. When the Strehl ratio is 0.8, the rms wavefront error is 0.07λ. TABLE 4 shows the relationship between Strehl ratio and rms wavefront error. The last column, 'Difference', means the difference of the rms at every 0.1 change of the Strehl ratio. The difference value is about 0.02λ or more in the interval of 0.1 in Strehl ratio. The wavefront error is half the height error on a mirror surface. Therefore, if a testing method has the accuracy of about 0.01λ in rms height error, the Strehl ratio of the tested optics would have the accuracy of 0.1.

Concerning the accuracy of peak-to-valley (p-v), a useful data can be found at COSTAR (Corrective Optics Space Telescope Axial Replacement) in Hubble Space Telescope. The mirrors achieved λ/8 in p-v wavefront error on each Zernike term, where λ is the wavelength of 632.8nm [5]. The tolerance of p-v surface error can simply be estimated to be λ/20 (0.05λ), which is less than half the p-v of COSTAR. As a rule of thumb, rms is assumed to be one fourth or one fifth of p-v [24]. Determining the measuring accuracy of p-v by 0.05λ seems adequate when rms is measured to an accuracy of 0.01λ. The primary mirror of Gemini has the surface accuracy of about 15 nm rms. That is about 0.03λ at the wavelength of 500 nm, which is sensible and matches the above assessments nearly.

IV. RESULTS AND DISCUSSIONS

As Astronomy and opto-mechanical technology become advanced, larger telescopes have been developed. From last decade, more than a dozen 8 m class telescopes have been constructed and being operated. As the size of mirror becomes larger, the accuracy is required to be higher reaching up to the diffraction limit. Now next generation telescopes of 30 m class are being designed, with expected completion by next decade. GMT contains seven 8.4 m aspheric mirror segments as a primary mirror. Six of the GMT primary mirrors are off-axis aspheric, which is more difficult to test. Three test methods for the off-axis aspheric mirrors are reviewed.

Required accuracy of the test methods is assessed for the large aspheric mirrors. Gemini 8.1 m telescopes are selected as a case study. Three kinds of measuring entities are considered, which are slope error, p-v error, and rms error. Measuring devices would be good to have slope error within the order of 10^{-7}, p-v error to an accuracy of 0.05λ, and rms error about 0.01λ. Test methods should be more accurate than the surface accuracy of the mirror to be produced.

Such test methods are also widely applied to other applications, such as wafer inspection, testing camera system, 3-D reconstruction, etc. [25, 26, 27]

REFERENCES

1. A. Isaacs, E. Martin, J. Law, and F. Alexander, *The Macmillan Compact Encyclopedia* (Macmillan Publishers Ltd., London, UK, 1994).
2. F. Gillett and M. Mountain, "A scientific overview," The Gemini Newsletter **12**, 10-18 (1996).
3. Y.-S. Kim, "An improved geometric test for optical surfaces," Ph.D. Thesis, London University (1998).
4. L. Furey, T. Dubos, D. Hansen, and J. Samuels-Schwarz, "Hubble Space Telescope primary-mirror characterization by measurement of the reflective null corrector," Appl. Opt. **32**, 1703-1714 (1993).
5. L. Feinberg and M. Wilson, "Hubble Space Telescope COSTAR asphere verification with a modified computer-generated hologram interferometer," Appl. Opt. **32**, 1786-1788 (1993).
6. J. H. Burge, "Measurement of large convex aspheres," Proc. SPIE **2871**, 362-373 (1997).
7. Y.-Y. Cheng and J. C. Wyant, "Two-wavelength phase shifting interferometry," Appl. Opt. **23**, 4539-4543 (1984).
8. K. Creath, Y.-Y. Cheng, and J. C. Wyant, "Contouring aspheric surfaces using two-wavelength phase-shifting interferometry," Optica Acta **32**, 1455-1464 (1985).
9. J. Kandulla, B. Kemper, S. Knoche, and G. Bally, "Two-wavelength method for endoscopic shape measurement by spatial phase-shifting speckle-interferometry," Appl. Opt. **43**, 5429-5437 (2004).
10. Y. Bitou, "Two-wavelength phase-shifting interferometry with a superimposed graing displayed on an electrically addressed spatial light modulator," Appl. Opt. **44**, 1577-1581 (2005).
11. D. S. Mehta, S. K. Dubey, M. M. Hossain, and C. Shakher, "Simple multifrequency and phase-shifting fringe-projection system based on two-wavelength lateral shearing interferometry for three-dimensional profilometry," Appl. Opt. **44**, 7515-7521 (2005).
12. J. G. Dil, W. Mesman, and J. C. Driessen, "High-precision

measurement of aspheric surfaces," Proc. SPIE **235**, 85-90 (1980).

13. M. Melozzi, L. Pezzati, and A. Mazzoni, "Testing aspheric surfaces using multiple annular interferograms," Opt. Eng. **32**, 1073-1079 (1993).
14. X. Hou, F. Wu, B. Lei, B. Fan, and Q. Chen, "Testing large aspheric surfaces with complementary annular subaperture interferometric method," Proc. SPIE **7018**, 70183K-1-70183K-8 (2008).
15. J. H. Burge, P. Su, and C. Zhao, "Optical metrology for very large convex aspheres," Proc. SPIE **7018**, 701818-1-701818-12 (2008).
16. Y.-S. Kim, "Developing an optical testing method for space telescopes," J. Opt. Soc. Korea **5**, 33-36 (2001).
17. GMTO, *Giant Magellan Telescope Conceptual Design Review* (Pasadena, CA, USA, 2006).
18. P. S. Osmer, *Gemini science requirements*, version 1.1 (1992).
19. E. Hansen, "Gemini telescopes f/16 optical design summary," in *Gemini 8-M Telescopes Project Report, RPT-O-G0047* (Gemini Project Office, Tucson, AZ, USA, 1994).
20. P. Puxley, "Classical and queue scheduling of the gemini telescopes," The Gemini Newsletter **13**, 10-16 (1996).
21. M. Mountain, "What is beyond the current generation of groundbased 8m-10m class telescopes and the VLT-I?," Proc. SPIE **2871**, 597-606 (1997).
22. M. Born and E. Wolf, *Principles of Optics*, 5th ed. (Pergamon, Oxford, UK, 1975).
23. J. Oschmann and D. A. Simons, "Gemini 8 meter telescopes performance estimates update," Gemini Preprint **6**, 1-12 (1996).
24. W. J. Smith, *Modern Optical Engineering* (McGraw-Hill Book Co., New York, USA, 1990).
25. J. H. Lee, Y. Kim, J. Kim, and Y. Yoo, "Bare wafer inspection using a knife-edge test," J. Opt. Soc. Korea **11**, 173-176 (2007).
26. H.-J. Yang, J.-S. Cho, and Y.-H. Won, "Reduction of reconstruction errors in kinoform CGHs by modified simulated annealing algorithm," J. Opt. Soc. Korea **13**, 92-97 (2009).
27. D. Kim and Y. J. Cho, "3-D surface profile measurement using an acousto-optic tunable filter based spectral phase shifting technique," J. Opt. Soc. Korea **12**, 281-287 (2008).