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Sensitivity analysis of test methods for aspheric off-axis mirrors

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Abstract

Following the Hubble Space Telescope (HST), the next generation James Webb Space Telescope (JWST) is being developed to be launched in a few years. JWST will be a segmented mirror telescope with a design much like that developed for ground-based telescopes over the past 20 years. Several segmented mirror telescopes are currently in operation, and next generation ground-based telescopes of the 30-m class are also being designed using segmented primary mirrors. Regardless of size, segmented primary mirror telescopes often require the use of aspheric segment mirrors. One of the key factors in fabrication of aspheric segment mirrors is feasibility of testing off-axis surfaces with high accuracy. A couple of test methods have been investigated for aspheric off-axis segments. As a case study, we apply these test methods to secondary segmented mirror models of the Giant Magellan Telescope. We derive required dimensions of test set-ups and assess sensitivity of optical alignment. Characteristics of the test methods are also discussed.

Keywords: Telescope; Mirror; Aspheric; Test; Measurement; Surface quality

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1. Introduction

The lifetime of the Hubble Space Telescope (HST) is coming to an end and the next generation James Webb Space Telescope (JWST) is being developed to take its place. The JWST will be 6.5 m in diameter providing more than seven times the collecting area of the HST. JWST is planned to launch in 2014 (Ohl et al., 2009) and will settle in the L2 orbit 1.5 million km from Earth. As the diameter is too big to fit into a launcher, the primary mirror is designed as an array of mirror segments that are folded into a compact assembly during launch.

The primary mirror of JWST consists of 18 hexagonal mirror segments with a dimension across the flats of 1.3 m each. As the parent surface of the primary mirror is aspheric, the segments can be divided into three different groups according to their surface shapes. The inner most six segments comprise the first group, while the second group consists of those segments arranged at the vertices of the hexagonal layout. Finally, the remaining segments form the third group (Fig. 1). All six segments in a given group have the same surface form. All 18 segments are aspheric and off-axis since the optical axis goes through the center of the primary mirror where no segment exists in the array.

Furthermore, 1–2 m off-axis aspheric mirrors are prearranged for many future space missions, which include Space Infrared Interferometric Telescope (SPIRIT) (Leisawitz et al., 2007) and Super-Earth Explorer (SEE-COAST) (Schneider et al., 2009). SPIRIT is a spatial and spectral interferometer operated by two telescopes and has the interferometric baselines from 6 m to 36 m. The optical system for SPIRIT is off-axis Cassegrain and a focal collector telescope with 1 m off-axis parabolic primary mirror, as depicted in Fig. 2. The off-axis optical design was selected to prevent diffraction effect. SPIRIT is designed to operate over the range of wavelength between 20 μm and 400 μm. SPIRIT will be launched in 2023 and located in the Sun–Earth Lagrange point L2 (see Fig. 2).

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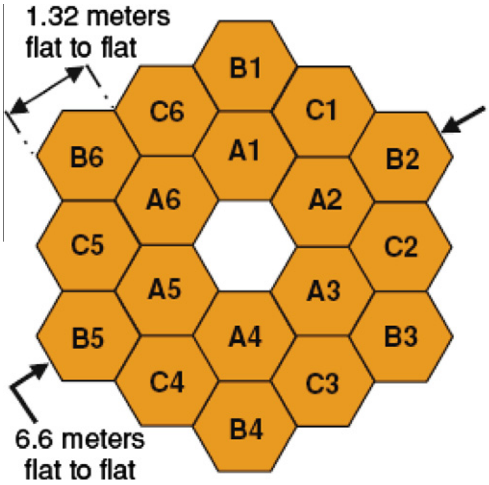

Fig. 1. Primary mirror segments of JWST (Gardner et al., 2006).

SEE-COSTA is also an off-axis Cassegrain with 1.5 m off-axis parabola, as shown in Fig. 3. SEE-COSTA will cover the wavelength range from 0.4 to 1.25 μm. This telescope consists of two channels, a visible channel covering a range of wavelength between 0.4 and 0.85 μm and a near-infrared channel covering 0.85–1.25 μm. It has two focal plane instruments, an imaging spectro-polarimeter with FOV of $3'' \times 3''$, and a pick-up mode camera with FOV of $30'' \times 30''$. SEE-COSTA is scheduled to be launched in 2020 and will take its place at L2 Lagrange point.

Many ground based telescopes employ segmented mirror designs. The two Keck telescopes are both 10 m in effective diameter and their primary mirrors consist of 36 segments of 1.8 m hexagonal mirrors. The parent surface is parabolic, which means that each segment has off-axis aspheric form. Following the success of the Keck telescopes, three similar segmented telescopes have been produced; Hobby–Eberly Telescope (HET), South Africa Large Telescope (SALT), and Gran Telescopio Canarias (GTC). In addition, three next generation telescopes are adopting segmented mirrors for their primaries ranging in size from 25 m to 42 m in diameter; the Giant Magellan Telescope (GMT), the Thirty Meter Telescope (TMT), and the European Extremely Large Telescope (E-ELT). Table 1 lists some details of these telescopes whose primary mirrors are off-axis mirrors or segmented aspheric off-axis mirrors.

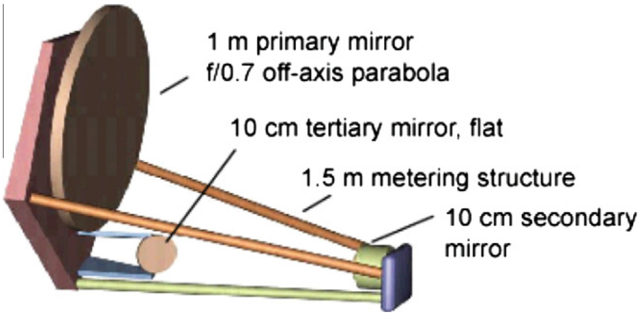

Fig. 2. Optical system of SPIRIT with 1 m off-axis parabolic primary mirror (Leisawitz et al., 2007).

The most important part in fabrication of precision optics listed in Table 1 is the measurement of the surface form. If the measurement is not of sufficient accuracy, the optics cannot be produced with the required precision. There are a number of established test methods for spherical mirrors, from which several methods have been derived for aspheric mirrors. However, the practical measurement of aspheric surfaces is known to be more difficult than that for spherical surfaces (Kim, 2001; Kim et al., 2009).

The use of a null corrector is the most popular method for testing aspheric mirrors. The basic idea of null correction is to change the wavefront from aspheric to spherical, so that test methods for spherical optics can be applied. However, the null corrector itself should be verified first to avoid problems similar to those encountered on the HST. The primary mirror of HST was tested using a null corrector with errors in its own profile (Furey et al., 1993; Bottema, 1993). The resulting errors in the primary took three years and additional corrective optics to repair.

Fortunately, there are many alternatives to null correctors for testing aspheric mirrors. Options include computer generated holograms (CGH) utilizing hologram disk optics (Wyant and Bennett, 1972; Burge, 1997; Martin et al., 2006), Hartmann tests (Ghozeil, 1992; Malacara-Hernandez et al., 2005), and quantized Foucault tests (Vandenberg et al., 1993; Kim, 1998). Of these, CGH testing has lately been dominated in null corrector tests in popularity for testing aspheric mirrors. Several other approaches have been developed; e.g. making more accurate profilometers (Dil et al., 1980; Su et al., 2009), dividing area of the mirror to be tested into several sections and stitching the sectional results (Melozzi et al., 1993; Hou et al., 2008; Burge et al., 2008), and measuring at two longer wavelengths and combining the results to reach the required accuracy (Cheng and Wyant, 1984; Kandulla et al., 2004, Singh Mehta et al., 2005).

This proliferation of test methods is testament to the difficulty of testing off-axis aspheric mirrors. This paper examines two methods of testing off-axis aspheric mirrors and evaluates their feasibility. The methods would be appropriate for small mirrors of less than 2 m in diameter. As a case study, we apply the competing methods to the secondary mirrors of GMT.

2. Test methods of off-axis aspheric mirrors

Aspheric form, such as parabola, ellipse, hyperbola, has one or two foci geometrically. Testing of an aspheric surface basically exploits this characteristic of their geometry.

2.1. Case study – test methods for GMT secondary mirrors

We performed a case study to find out which method is good enough to test large and aspheric off-axis mirrors. A GMT secondary mirror is selected as an example since it is