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LABORATORY EXPERIMENTS OF OFF-AXIS MIRROR OPTICS OF ALUMINUM FOR SPACE INFRARED MISSIONS

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ABSTRACT

We report our research on aluminum mirror optics for future infrared astronomical satellites. For space infrared missions, cooling the whole instrument is crucial to suppress the infrared background and detector **noise**. In this aspect, aluminum is appropriate for cryogenic optics, because the same material can be used for the whole structure of the instrument including optical components thanks to its excellent machinability, which helps to mitigate optical misalignment at low temperatures. We have fabricated aluminum mirrors with ultra-precision machining and measured the wave front errors (WFEs) of the mirrors with a Fizeau interferometer. Based on the power spectral densities of the WFEs, we confirmed that the surface accuracy of all the mirrors satisfied the requirements for the SPICA Coronagraph Instrument. We then integrated the mirrors into an optical system, and examined the image quality of the system with an optical laser. As a result, the total WFE is estimated to be 33 nm (rms) from the Strehl ratio. This is consistent with the WFEs estimated from the measurement of the individual mirrors.

Key words: instrumentation: high angular resolution - methods: laboratory - telescopes

1. INTRODUCTION

Astronomical satellites require lightweight optics, while infrared (IR) observations require cooled optics. The latter is because cooling the whole instrument is important to suppress the IR background and detector **noise**. For space IR missions, therefore, optics made of aluminum is one of the most important technologies; it can realize lightweight optics and avoid optical misalignment due to thermal contraction by fabricating the whole structure of an instrument including optical components with the same material. In addition, a reflecting optical system can cover a wide wavelength range with high optical throughput and without chromatic aberration.

Instruments with aluminum mirrors have been designed for the future infrared astronomical satellite SPICA. Among the instruments, the SPICA Coronagraph Instrument (SCI; Enya et al. 2011) has the most stringent requirements on a wave front error (WFE) and thus requires highly accurate optics at low temperatures.

In this study, we investigate applicability of aluminum mirrors to optics for space infrared observations. We set our goal for **a** WFE to be that required by the SCI. Using an interferometer, we evaluate the WFEs of the aluminum mirrors fabricated by ultra-precision machining. We then **integrate** the aluminum mirrors into an optical system to **evaluate** the imaging performance of the system.

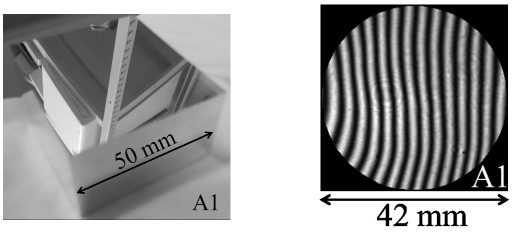

Figure 1. (Left) Off-axis mirror A1 and (Right) a fringe pattern of the mirror.

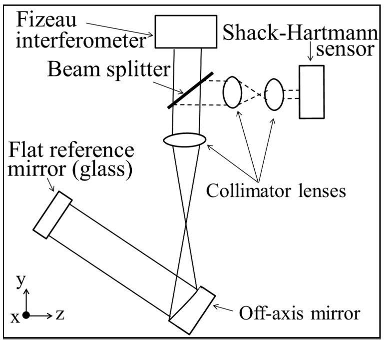

Figure 2. Measurement system for the off-axis parabolic mirrors.

2. METHOD

First, we measured the surface figures of six off-axis parabolic mirrors (A1, A2, B1, B2, V2R1 and V2R2) and a flat mirror (F1), which **are** integrated into an optical system as **described** below. Figure 1 (left) shows one of the off-axis parabolic mirrors, A1. We used a Fizeau interferometer (FUJINON F601) to measure the mirrors. The light source is a He-Ne laser with a wavelength of 633 nm. The aluminum flat mirror is measured directly by the interferometer without additional optics. Figure 2 shows the measurement system for the off-axis parabolic mirrors. We used a Shack-Hartmann sensor with additional optics to coarsely adjust the optical alignment because the measurement system has multiple degrees of freedom in alignment.

An off-axis parabolic mirror was put on an optical stage which is movable in five axes (three shifts and two tilts). We first made optical alignment of the mirrors using the Shack-Hartmann sensor, which allowed us to align the mirrors with accuracies of ∼250 μm (shift) and ∼3' (z tilt). We then **adjusted** the alignment finely based on a fringe pattern **measured** with the Fizeau interferometer **to the** accuracies of 6 μm (shift), 2' (z tilt) and 20" (x tilt). Figure 1 (right) shows one of the fringe patterns thus measured. **For each mirror, we synthesized the surface figure from the fringe pattern, and estimated the WFE from the difference between the measured and ideal surfaces.** Since the WFEs can include not only surface figure errors but also alignment errors, we calculated WFEs with ZEMAX to estimate the sensitivity of the alignment errors to the measured WFEs.

Table 1

WFEs measured for the mirrors.

	WFE [nm] (rms)						
Region	A1	A2	B1	B2	V2R1	V2R2	F1
entire	39	65	65	62	26	74	20
center (14 mm)	@6	8	6	8	4	8	10

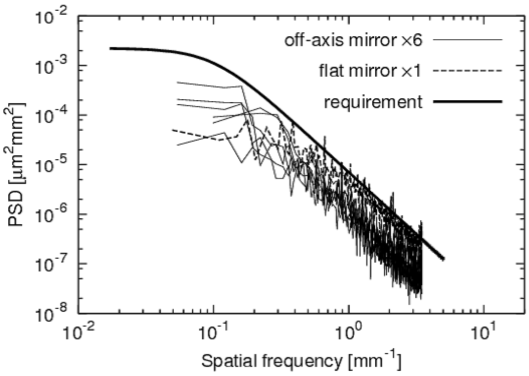

Figure 3. **PSDs** of the WFEs measured for the mirrors. The solid thick line **corresponds to** the SCI requirement.

Next, we integrated the above seven mirrors **into** an optical system to evaluate the imaging **performance** of the system as a whole. We used the optical bench developed for the cryogenic chamber, PINOCO (Enya et al. 2012). We installed the mirrors in the mirror holders on the optical bench, **adjusted** the tilts. We placed a CCD camera (BJ-40L, BITRAN) at the focus position. We evaluated the optical system with a He-Ne **laser**. We simulated an incident light from **the** telescope using a spatial filter with a pinhole (25 μm **in** diameter). The incident light reaches the CCD camera through the six off-axis parabolic mirrors and the flat mirror with the maximum beam diameter of 14 mm. We compared the point spread function (PSF) measured with the optical system with that predicted by our simulation.

3. RESULTS AND DISCUSSION

We show the WFEs measured for all the aluminum mirrors in Table 1, which range from 20 to 74 nm (rms). Figure 3 shows the power spectral densities (**PSDs**) calculated for central parts of the WFE maps (14 mm in diameter), the areas of which are used for **reflection** of the **light** in the optical system. As a result, we confirm

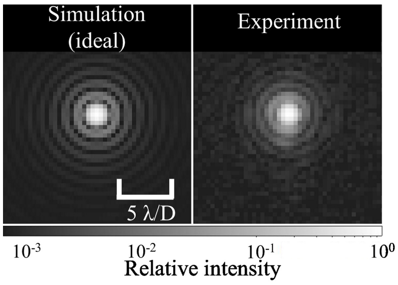

Figure 4. (Left) Simulated PSF. (Right) PSF measured **with** the optical system.

that all the PSDs satisfy the SCI requirements. The WFEs measured from the central parts of the mirrors are also shown in Table 1.

For the result of the measurement **with** the optical system consisting of the seven **mirrors**, figures 4 (left) and (right) show the PSFs predicted by the simulation and measured by the experiment, respectively. We estimated the total WFE of the system to be 33 nm (rms), based on the measured Strehl ratio (i.e., the peak value of the measured PSF relative to that of the simulated PSF). The square root of the sum of the squared WFEs measured for the central parts of the individual mirrors amounts to the WFE of 39 nm (rms). Therefore, both WFEs are consistent with each other within the uncertainties **caused by** the alignment **errors**.

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