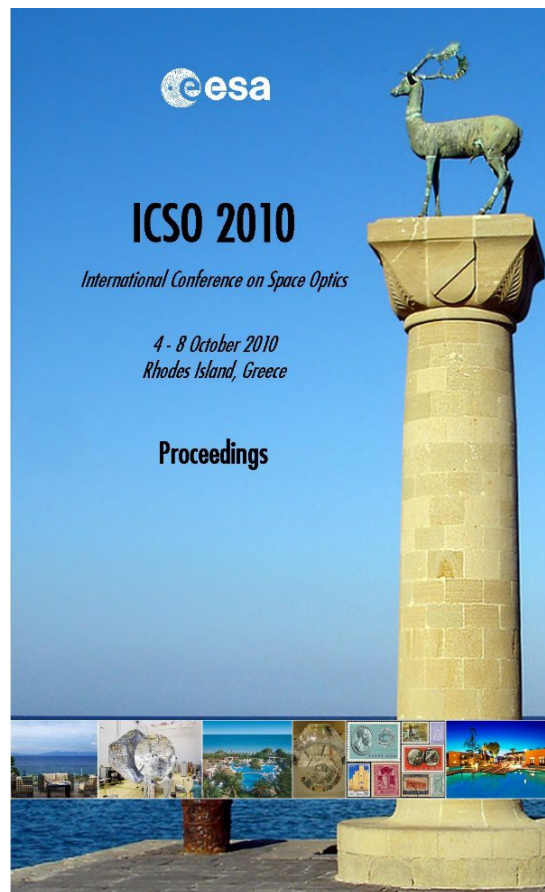


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## *Optical testing of lightweight large all-C/SiC optics*

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## OPTICAL TESTING OF LIGHTWEIGHT LARGE ALL-C/SiC OPTICS

M. Suganuma<sup>1</sup>, T. Imai<sup>1</sup>, H. Katayama<sup>1</sup>, M. Naitoh<sup>1</sup>, Y. Tange<sup>1</sup>, Y. Y. Yui<sup>1</sup>, K. Maruyama<sup>1</sup>  
H. Kaneda<sup>2</sup>, T. Nakagawa<sup>3</sup>, M. Kotani<sup>4</sup>

<sup>1</sup>*Japan Aerospace Exploration Agency, 2-2-1 Sengen, Tsukuba, Ibaraki, 305-8505 Japan*  
[suganuma.masahiro@jaxa.jp](mailto:suganuma.masahiro@jaxa.jp), [imai.tadashi@jaxa.jp](mailto:imai.tadashi@jaxa.jp), [katayama.haruyoshi@jaxa.jp](mailto:katayama.haruyoshi@jaxa.jp), [naitoh.masataka@jaxa.jp](mailto:naitoh.masataka@jaxa.jp),  
[tange.yoshio@jaxa.jp](mailto:tange.yoshio@jaxa.jp), [yui.yukari@jaxa.jp](mailto:yui.yukari@jaxa.jp), [maruyama.kenta@jaxa.jp](mailto:maruyama.kenta@jaxa.jp);

<sup>2</sup>*Nagoya University, Furo-cho, Chikusa-ku, Nagoya, Aichi, 464-8602 Japan*  
[kaneda@u.phys.nagoya-u.ac.jp](mailto:kaneda@u.phys.nagoya-u.ac.jp);

<sup>3</sup>*Japan Aerospace Exploration Agency, 3-1-1 Yoshinodai, Sagami-hara, Kanagawa, 229-8510 Japan*  
[nakagawa.takao@jaxa.jp](mailto:nakagawa.takao@jaxa.jp);

<sup>4</sup>*Japan Aerospace Exploration Agency, 6-13-1 Osawa, Tokyo, 181-8588 Japan*  
[kotani.masaki@jaxa.jp](mailto:kotani.masaki@jaxa.jp)

We carried out various tests of 800-mm-diameter aperture, lightweight optics that consisted wholly of carbon fiber-reinforced SiC composite, called HB-Cesic. A cryogenic optical test was performed on the primary mirror to examine any CTE irregularity as a surface change, and only small deformations were observed. The primary mirror was assembled with a convex secondary mirror into an optical system and tested under vacuum at the 6-m-diameter radiometer space chamber at Tsukuba Space Center of JAXA, where we have prepared interferometric metrological facilities to establish techniques to test large optical systems in a horizontal light-axis configuration. The wavefront difference between under vacuum and under atmosphere was confirmed to be less than  $0.1 \lambda$  at  $\lambda=633$  nm, if we realigned the optical axis of the interferometer and flat mirror under vacuum. We also demonstrated a stitching interferometry using the  $\Phi 800$ -mm optics by rotating a mask wheel of subapertures in front of the optical reference flat. The wavefront stitched from eight individual measurements of  $\Phi 275$ -mm subapertures differs from the full-aperture measurement without the mask by about  $0.1 \lambda$  nm RMS, which showed the technique could be applied to test large telescopes especially for infrared wavelength region.

### I. INTRODUCTION

Owing to its high specific stiffness and high thermal stability, silicon carbide (SiC) is becoming an outstanding material applied especially to large, spaceborne optics. The current design of the Space Infrared Telescope for Cosmology and Astrophysics (SPICA), a Japan-led international infrared astronomical mission, will use SiC for its 3-m class aperture telescope. The telescope should be operated at below 6 K and have diffraction-limited performance at a wavelength of  $\lambda=5 \mu\text{m}$  [1, 2]. SiC is also a candidate material for 2-m aperture optics to be used in future Earth observation missions in visible to infrared wavelengths from a geostationary orbit.

SiC composite materials consisting of SiC reinforced with carbon fibers (C/SiC) possess sufficient fracture toughness to significantly mitigate its brittle nature; a serious problem for large spaceborne mirrors. Among the various types of carbon fiber-reinforced SiC materials, HB-Cesic is a material that was developed jointly by ECM and Mitsubishi Electric Corporation (MELCO) [3, 4] and is not only very strong but also has improved uniformity and homogeneity. We selected this material for our large optics study program and manufactured 800-mm-diameter aperture, lightweight optics to verify and establish the technology of designing and manufacturing very lightweight mirrors for visible use, to shorten the manufacturing lead time including the polishing process of the mirror surface, to confirm the uniformity of the mirror material by applying the mirror to cryogenic surface figure measurement, and to master and establish the technology of ground optical testing using the mirror [5].

In addition to the manufacturing of large-aperture and lightweight telescopes, it is indispensable to acquire technologies of highly accurate optical measurements of such telescopes under vacuum or cryogenic circumstances. We are preparing interferometric metrological facilities and establishing techniques to test large optical systems using the  $\Phi 800$ -mm C/SiC optics. These were developed under the same framework as JAXA's large optics study program for astronomy and Earth observations. We are demonstrating techniques for optical alignment, metrology under a vacuum environment, and subaperture stitching interferometry.

In this paper, we present recent results of our optical testing activity using the  $\Phi 800$ -mm C/SiC optics. § 2 introduces the  $\Phi 800$ -mm all-SiC optics we manufactured. § 3 presents the cryogenic test of the  $\Phi 800$ -mm primary mirror. § 4 shows the test in the 6-m radiometer vacuum chamber at JAXA's Tsukuba Space Center,

which we modified to test large aperture optics of up to a 3-m class. Subaperture stitching interferometry experiments for the  $\Phi 800$ -mm optics are introduced in § 5.

## II. $\Phi 800$ -mm C/SiC OPTICS

The material of our  $\Phi 800$ -mm optics, C/SiC (or HB-Cesic®), was developed by ECM, Germany, and Mitsubishi Electric Corporation (MELCO). It is improved over similar C/SiC used for the SPICA-BBM  $\Phi 720$ -mm mirror manufactured by MELCO. For the HB-Cesic, the length of carbon fibers contained in the raw material is shortened in order to avoid the inhomogeneity and anisotropy of the inner microstructure and that affects surface figure error. The improvement also promotes chemical reaction during sintering, resulting in more homogeneity of the inner structure.

The weight of the primary mirror after sintering is about 11 kg, corresponding to 22 kg/m<sup>2</sup> of mirror surface density. The mirror is supported at three points on the backside using the C/SiC interface cups and invar stress relief supports. The interface cup is cut out from the same material block as the mirror to reduce CTE mismatch between the mirror and the interface cup. About 40 nm of silicon vapor was deposited on the mirror surface so the mirror surface could be polished in a short time. This also ensured the surface roughness to be within the specification. The silicon vapor was deposited after lapping and rough polishing. The mirror surface figure is about 0.1  $\lambda$  RMS (here and hereafter,  $\lambda$  is the He-Ne laser wavelength of 632.8 nm) and the surface roughness is around 1 nm RMS. The typical figures of the mirror are summarized in Table 1. Photos of it are shown in the top of Figure 1. For details on HB-Cesic material and the manufacturing of the primary mirror, see [3, 4, 5].

To master and establish a ground optical performance testing method for large optical systems, an all-C/SiC optics model using the  $\Phi 800$ -mm mirror as primary was designed and its components were manufactured. The secondary mirror is a high order convex, and is also silicon vapor-deposited. The secondary mirror support has a bipod structure that enables easier optical alignment during testing. The optics model was integrated after the cryogenic measurement of the primary mirror presented in the next section and was employed for ground testing simulations to develop optical measurement technologies. Photos of the support structures and the assembled optics are shown in the bottom of Figure 1. The focal ratio of the optics is F/3. The wavefront error of the optics achieved about 1.3  $\lambda$  RMS through the integration, which was mainly derived from its cost-effective optical design with a considerable spherical aberration. It also worsened to 1.7  $\lambda$  RMS after an I/F cup was detached and re-attached to the primary mirror.

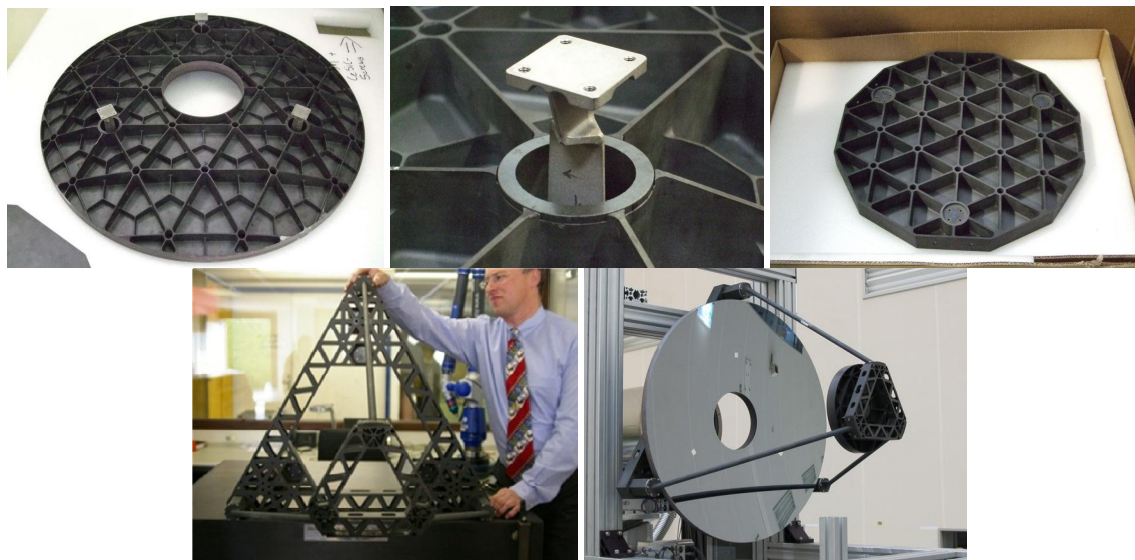
**Table 1** Specifications of the  $\Phi 800$ -mm HB-Cesic Primary Mirror

Item	Results
Surface	Silicon vapor-deposited
Surface figure error	61 nm RMS
Clear aperture	Outer: 740 mm Inner: 280 mm
Surface roughness	0.8-1.2 nm RMS
Weight	11.2 kg

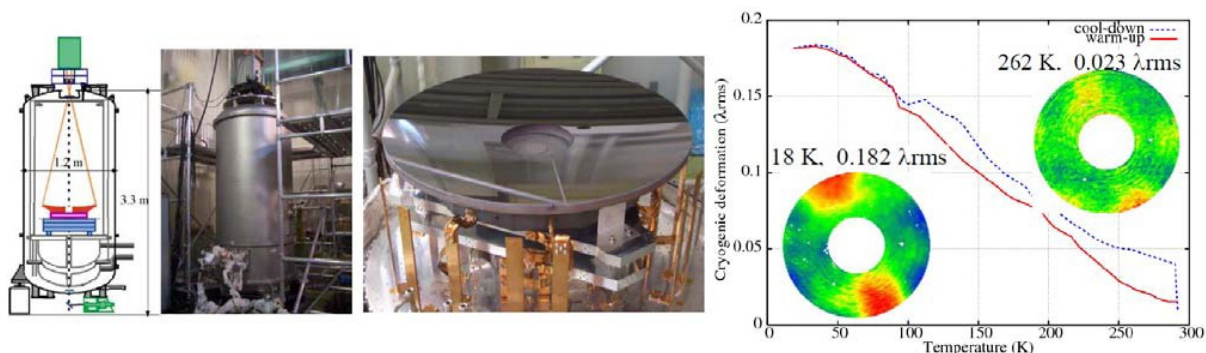
## III. CRYOGENIC TEST OF $\Phi 800$ -mm PRIMARY MIRROR

We tested the cryogenic optical performance of the  $\Phi 800$ -mm primary mirror mounted on an optical bench, which was introduced in the previous section. A liquid-helium chamber was used and the mirror was cooled down to 18 K. The test configuration and results are shown in Fig. 2. We found that the cryogenic deformation of the mirror unit was about 0.18  $\lambda$  RMS. The test results reflect a significant improvement in CTE uniformity and homogeneity of HB-Cesic compared to previous C/SiC composite materials, as well as an excellent CTE match between the mirror and optical bench. We think that the small astigmatism seen in the figure could not be derived from variations in homogeneity of HB-Cesic. Since we found that the variation in thickness of the silicon layer had a larger gradient along the observed direction of the astigmatism, the deformation was likely caused by a non-uniformity of the thickness of the silicon coating. The details are reported in [6].

The requirement on the imaging quality of SPICA telescope is equivalent to a total wave-front error of less than 350 nm RMS, which means that the surface figure error of the primary mirror must not be greater than 175 nm RMS or 0.28  $\lambda$  RMS. According to the results of our cryogenic optical testing, the  $\Phi 800$ -mm HB-Cesic mirror meets this criterion despite the astigmatism. We have successfully demonstrated that HB-Cesic possesses promising applicability for the construction of large cryogenic lightweight space optics components.



**Fig. 1.** (Top left) Backside of the primary mirror. (Top center) I/F cup and stress relief that mounts the primary on the optical bench. (Top right) Backside of the optical bench of the primary. (Bottom left) Support structure of  $\Phi 800$ -mm optics, which is made from the same materials as the primary. (Bottom right)  $\Phi 800$ -mm optics integrated in 6-m chamber at JAXA's Tsukuba Space Center.



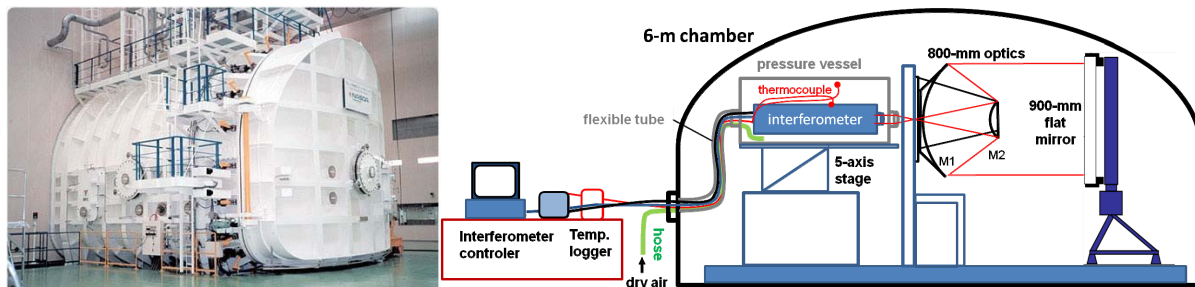
**Fig. 2.** (From left to right) Schematic of the measurement configuration of the primary mirror unit, the cryo-chamber at the JAXA facility used for the optical testing, the mirror unit, and the cryogenic deformation observed for M1.

#### IV. OPTICAL TEST IN 6-M RADIOMETER SPACE CHAMBER

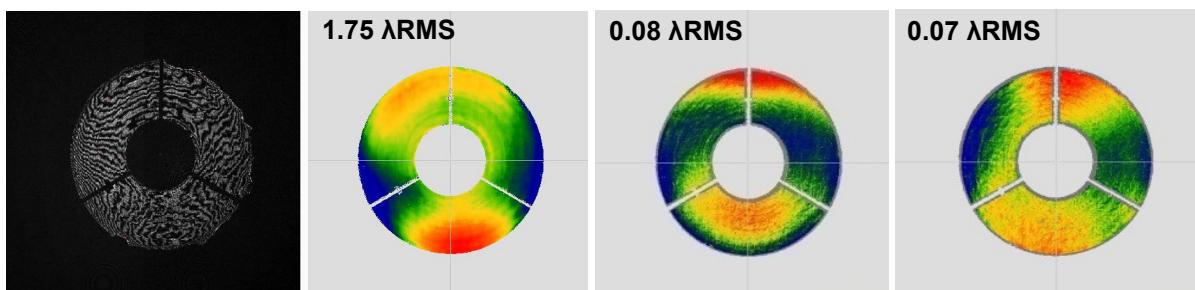
The primary mirror was assembled with a convex secondary mirror into an optical system at the 6-m-diameter radiometer space chamber (6-m chamber) in JAXA's Tsukuba Space Center, where we have prepared interferometric metrological facilities to establish techniques to test large optical systems in a horizontal light-axis configuration.

We developed a test bench for interferometric metrology for large optics with an autocollimation method in the 6-m diameter chamber. This chamber was built for ground tests of optical and infrared space instruments and has a vibration isolation system. Final optical testing of the SPICA telescope and future large space optics is assumed to be performed by JAXA in this chamber. The optical systems should be aligned in a horizontal light-axis configuration within the facility limit to handle a 3.5-m aperture telescope like SPICA. A Twyman-Green interferometer with dynamic phase shift, produced by 4D Technology, was used and vibrations from the pumps and shroud of the chamber were confirmed to be negligible for optical measurement [7]. To avoid considerable facility modification, the interferometer was operated in an aluminum and titan pressure vessel, which was mounted on the five-axis stage in the chamber. A diverger lens with a focal ratio of F/3 was mounted on the front window of the pressure vessel. We aligned the optical axis of the 800-mm optics by an autocollimation test using a 900-mm diameter flat mirror, the result of which was 0.12-0.17  $\lambda$  RMS for single-pass wavefront error (WFE) for the optics. Figure 3 shows a photo of the 6-m chamber and schematics of the test configuration.





**Fig. 3.** (Left) Photo of the 6-m radiometer thermal vacuum chamber (6-m chamber) at JAXA's Tsukuba Space Center. (Right) Schematics of the interferometry test of  $\Phi 800$ -mm optics in the 6-m chamber. For a photo before the setup was carried into the chamber, see Fig.5 (left).



**Fig. 4.** (Left) The fringe obtained for  $\Phi 800$ -mm optics under atmosphere. (Center left) Wavefront measure of the  $\Phi 800$ -mm optics under atmosphere. (Center right) Wavefront difference between under vacuum and under atmosphere, where only tilts of the  $\Phi 900$ -mm flat mirror were realigned to reduce fringes under vacuum. (Right) Similar to center right, but the axis of the interferometer and  $\Phi 800$ -mm optics was realigned to reduce the coma under vacuum. For each measurement, tilt and power shapes were excluded.

An interferometric measurement for  $\Phi 800$ -mm optics under vacuum was conducted. Figure 4 shows the wavefront measurement of the  $\Phi 800$ -mm optics under atmosphere and under vacuum. During the exhaust of the chamber, the optical alignment changed by several tens of fringes, i.e., about 10 arcsec of tilt for the optical system. The WFE was  $1.77 \lambda$  RMS under vacuum, excluding tilts and power shape, while WFE was  $1.75 \lambda$  RMS under atmosphere. The wavefront difference between them was  $0.08 \lambda$  RMS and mainly revealed a coma aberration. The coma should arise from changes in the offset of the interferometer axis at its focus which is a characteristic of the optical design for our  $\Phi 800$ -mm optics.

After we realigned the axis of the interferometer by the five-axis stage under vacuum, the coma was removed and the wavefront difference between under vacuum and under atmosphere decreased to  $0.07 \lambda$  RMS and mainly revealed an astigmatism aberration. The astigmatism change would not be caused by alignment change nor by the interferometer or pressure vessel themselves since similar tests for a small spherical mirror under vacuum showed no astigmatism aberration. It is possible that the  $\Phi 800$ -mm primary mirror or  $\Phi 900$ -mm flat mirror might deform from their temperature uniformity since the temperature in the chamber sharply dove by several degrees during the exhaust. The details are presented in [8].

## V. SUBAPERTURE STITCHING INTERFEROMETRY EXPERIMENTS

Stitching interferometry is a key technique for accurate optical testing of future large telescopes. No space telescope in the past has been tested yet with this method for its final verification. We have studied stitching algorithms based on least squares calculations of pistons and tilts for subaperture wavefronts at their overlapped regions. Numerical simulations have being conducted assuming the test of the SPICA telescope [9].

We are also verifying the feasibility of the stitching interferometry using the  $\Phi 800$ -mm optics at the optical testing facility shown in § 4. For simplicity, we simulated the rotation of small flat mirrors by rotating the subaperture mask in front of the  $\Phi 900$ -mm flat mirror. Figure 5 (left) shows a photo of the test configuration before being carried into the chamber. Between the  $\Phi 800$ -mm optics and  $\Phi 900$ -mm flat mirror, there is a mask rotator that has two  $\Phi 275$ -mm apertures placed at opposite sides of the rotation axis. Figure 5 (right) shows the schematics of the subapertures overlapped on the full-aperture of the  $\Phi 800$ -mm optics.

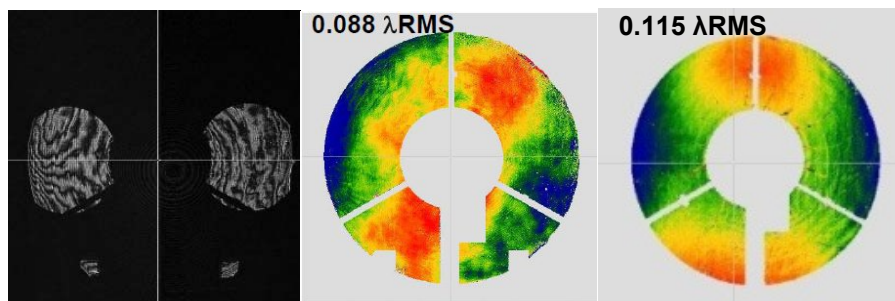
We obtained interferograms for eight pairs of subaperture data by rotating the mask by 22.5 degrees one by one, and stitched the sixteen subapertures into one wavefront that covers the full-aperture of the  $\Phi 800$ -mm optics. An example of interferometric subaperture data thus measured at one rotational angle of the aperture mask is shown in Figure 6 (left). We evaluated the stitching error by comparing a stitched wavefront with the  $\Phi 800$ -mm full-aperture wavefront that was obtained without the mask under atmosphere before and after obtaining subaperture datasets. For both stitched and full-aperture wavefronts, tilts and power components were excluded individually before comparison since these components would have little effect on telescope performance.

At the beginning of the experiment, we tested in atmospheric pressure. Figure 6 (center) is the wavefront difference between a stitched wavefront under atmosphere and a full-aperture wavefront. The difference is below  $0.08 \lambda$  RMS, and mainly shows astigmatism aberration. One of the sources of the astigmatism could be small changes in the focus alignment while subaperture datasets were obtained, since the stitched wavefront had significant astigmatism for another test when we purposely changed focus alignment for each subaperture measurement. The features of atmospheric turbulence, which have smaller spatial scales and are randomly placed, were also seen. A stable environment, especially for focus alignment while obtaining successive subaperture data, would be crucial in the stitching interferometry.

Next, we tested in vacuum pressure in the 6-m chamber. Figure 6 (right) is the wavefront difference between a stitched wavefront under vacuum and a full-aperture wavefront under atmosphere. For each subaperture measurement under vacuum, the interferometer was realigned to reduce the coma. The wavefront difference was a little larger than  $0.1 \lambda$  RMS and shows a small coma and astigmatism. The difference resembles Figure 4 (right), that is, the difference between two  $\Phi 800$ -mm full-aperture wavefronts, under vacuum and under atmosphere. We therefore think that the difference includes not only stitching error but also changes in the wavefront for the  $\Phi 800$ -mm full-aperture itself.



**Fig. 5.** (Left) Photo of the experimental configuration for the stitching interferometry before being carried into the 6-m chamber. From left to right, the interferometer in the pressure vessel mounted on the five-axis optical adjustment stage, the mirror stand, the 800-mm all-HB-Cesic telescope, the aperture mask with a rotation mechanism, and the 900-mm flat mirror with the two-axis adjustable stand. (Right) Schematics of the subapertures overlaid on the full-aperture of the  $\Phi 800$ -mm optics.



**Fig. 6.** (Left) An example of interferometric subaperture fringe data obtained at one rotation angle of the aperture mask. (Center) Difference between stitched wavefront synthesized from the subaperture datasets obtained under atmosphere and full-aperture wavefront without the aperture mask obtained under atmosphere. (Right) Similar to the center, but subaperture datasets were obtained under vacuum.

## VI. SUMMARY

We tested  $\Phi 800$ -mm lightweight two-mirror optics that wholly consists of C/SiC composite, called HB-Cesic®. We observed a very small deformation of  $0.182 \lambda$  RMS ( $\lambda=633$  nm) in the primary mirror on its optical bench at the cryogenic temperature of 18 K, proving extremely uniform CTE of the mirror substrate. The optics were integrated and tested in a 6-m vacuum chamber where we prepared an interferometry facility to test future large aperture optics with a horizontal light-axis configuration. Wavefront measurement for  $\Phi 800$ -mm optics under vacuum at room temperature differed by less than  $0.1 \lambda$  RMS from under atmosphere. We also demonstrated stitching interferometry using a mask wheel with  $\Phi 275$ -mm subaperture and a least squares algorithm and experimentally found the stitching error could be about  $0.1 \lambda$  RMS or less. We therefore successfully confirmed that these techniques should be applicable to test larger aperture optics especially for an infrared observation mission like SPICA.

## REFERENCES

- [1] Nakagawa, T., and Murakami, H., "SPICA, cooled telescope optimized for mid- and far-infrared astronomy," *Advances in Space Research* 40 (5), 679-683 (2007)
- [2] Kaneda, H., Nakagawa, T., Onaka, T., Enya, K., Kataza, H., Makiuti, S., Matsuhara, H., Miyamoto, M., Murakami, H., Saruwatari, H., Watarai, H., and Yui, Y. Y., "Development of lightweight SiC mirrors for the Space Infrared Telescope for Cosmology and Astrophysics (SPICA) mission," Proc. SPIE 6666, 666607-666607-9 (2007)
- [3] Krödel, M. R., and Ozaki, T., "HB-Cesic composite for space optics and structures," Proc. SPIE 6666, 6666E-6666E-10 (2007)
- [4] Krödel, M. R., Ozaki, T., Kume, M., Furuya, A., Yui, Y. Y., Imai, H., Katayama, H., Tange, Y., Nakagawa, T., and Kaneda, H., "Manufacturing and performance test of an 800-mm space optic," Proc. SPIE 7018, 70180A-70180A-10 (2008)
- [5] Yui, Y. Y., Goto, K., Kaneda, H., Katayama, H., Kotani, M., Miyamoto, M., Naitoh, M., Nakagawa, T., Saruwatari, H., Sukanuma, M., Sugita, H., Tange, Y., Utsunomiya, S., Yamamoto, Y., and Yamawaki, T., "Performance of lightweight large C/SiC mirror," 7<sup>th</sup> International Conference on Space Optics (ICSO), October 2008
- [6] Kaneda, H., Naitoh, M., Imai, T., Tange, Y., Enya, K., Katayama, H., Maruyama, K., Nakagawa, T., Onaka, T., Sukanuma, M., Kano, R., Kiriya, Y., Mori, T., Takahashi, A., "Cryogenic optical testing of an 800 mm lightweight C/SiC composite mirror mounted on a C/SiC optical bench," *Applied Optics*, 49, 3941 (2010)
- [7] Katayama, H., Yamamoto, Y., Miyamoto, M., Saruwatari, H., Kaneda, H., and Tange, Y., "Measurement of vibration environment of 6m-diameter radiometer thermal vacuum chamber in JAXA," Proc. SPIE 7436, 7436Q-7436Q-8 (2009)
- [8] Sukanuma, M., Katayama, H., Naitoh, M., Imai, T., Miyamoto, M., Kaneda, H., Tange, Y., Nakagawa, T., "Development and tests of interferometry facility in 6-m diameter radiometer thermal vacuum chamber in Tsukuba Space Center," Proc. SPIE, 7731, 142 (2010)
- [9] Kaneda, H., Nakagawa, T., Enya, K., Tange, Y., Imai, T., Katayama, H., Sukanuma, M., Naitoh, M., Maruyama, K., Onaka, T., "Optical testing activities for the SPICA telescope," Proc. SPIE 7731, 30 (2010)