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# PERFORMANCE OF LIGHTWEIGHT LARGE C/SiC MIRROR

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## ABSTRACT

Very lightweight mirror will be required in the near future for both astronomical and earth science/observation missions. Silicon carbide is becoming one of the major materials applied especially to large and/or light space-borne optics, such as Herschel, GAIA, and SPICA. On the other hand, the technology of highly accurate optical measurement of large telescopes, especially in visible wavelength or cryogenic circumstances is also indispensable to realize such space-borne telescopes and hence the successful missions.

We have manufactured a very lightweight Φ=800mm mirror made of carbon reinforced silicon carbide composite that can be used to evaluate the homogeneity of the mirror substrate and to master and establish the ground testing method and techniques by assembling it as the primary mirror into an optical system. All other parts of the optics model are also made of the same material as the primary mirror.

The composite material was assumed to be homogeneous from the mechanical tests of samples cut out from the various areas of the 800mm mirror green-body and the cryogenic optical measurement of the mirror surface deformation of a 160mm sample mirror that is also made from the same green-body as the 800mm mirror.

The circumstance and condition of the optical testing facility has been confirmed to be capable for the highly precise optical measurements of large optical systems of horizontal light axis configuration.

Stitching measurement method and the algorithm for analysis of the measurement is also under study.

## 1. INTRODUCTION

It is surely expected that optical and/or infrared telescopes with larger diameter primary mirror will be required increasingly in the near future in order to achieve higher spatial resolution images of earth surface or celestial objects.

We have been studying lightweight large mirrors that are applicable to the next Japanese large infrared telescope, SPICA, and future large telescopes for earth observations from geosynchronous orbit. The SPICA telescope requires a Φ=3.5m primary mirror that can achieve diffraction limited images at 5 μm.

In order to realize such large space-borne instruments, we have to achieve and establish the integration and ground measurement techniques of large (Φ~1.5m or larger) optics as well as the large mirror manufacturing technologies.

We have studied the applicability of silicon carbide mirrors to shorter wavelength observation for the past several years. For the purposes of verifying the designing and manufacturing technologies of lightweight large silicon carbide mirror and employing it as a test mirror used for ground optical measurements under both room temperature and cryogenic condition, a Φ=800mm light weight mirror was manufactured using carbon fiber reinforced silicon carbide composite (C/SiC) material, HB-Cesic®, developed by Mitsubishi Electric Corporation and ECM.

The final goals of our study are as follows; (1) verifying and confirming the manufacturing process of lightweight large silicon carbide mirror, from designing of structure and mixing of raw material to final polishing, (2) developing the methods to evaluate and guarantee the ceramic mirror quality for space use, (3) achieving matured designing technique of thermally stable mirror and optical system and evaluation of its thermal stability, and (4) achieving and establishing highly precise ground optical testing technology for large mirrors and large telescope systems.

The above first three items have been being studied and the preliminary results of these studies are described briefly as below.

## 2. MANUFACTURING C/SiC MIRROR

We have manufactured a Φ=800mm spherical mirror using carbon fiber reinforced silicon carbide (C/SiC). The main purposes of manufacturing this mirror are (1) to verify and establish the technology of designing and manufacturing very light weight mirrors for visible use, (2) to shorten the manufacturing lead time including polishing process of the mirror surface, (3) to confirm the uniformity of the mirror material by applying the mirror to cryogenic surface figure measurement, and (4) to master and establish the technology of ground optical testing by using the mirror.

The material of the mirror, C/SiC (or HB-Cesic®), has been developed and improved from that used for SPICA-BBM Φ=720mm mirror manufactured in 2002. The length of carbon fibers contained in the raw material are shortened in order to avoid the inhomogeneity and unisotropy of the inner micro structure and resulting CTE inhomogeneity that affect surface figure error, and to promote chemical reaction during sintering in order to ensure more homogeneous inner structure (Fig.7).

The weight of the sandblasted mirror after sintering is about 11kg which corresponds to 22kg/m$^2$ of mirror surface density.

The optical bench and the interface structure were also designed and manufactured. They were integrated as a mirror unit (Fig.1) to be installed in the cryogenic vacuum chamber in JAXA. The mirror is supported at three points on the backside using the C/SiC interface cups and invar stress relief supports (Fig.2). The interface cup is cut out from the same material block as the mirror for the purpose to reduce CTE mismatch between the mirror and the interface cup.

The mirror surface is silicon vapor deposited so that the mirror surface can be polished in a short time and also the surface roughness can be ensured within the specification. Silicon vapor was deposited after lapping and rough polishing. Before the process, the effect of the silicon vapor deposition to the mirror surface stress was tested using small samples. It was confirmed that the process would not affect the surface figure. After the deposition, the interface cups were glued to the mirror, and the final polishing was done with the configuration that the interface cups and stress relief supports are attached to the mirror.

As a result, the mirror surface figure is about 58nm (rms) and the surface roughness is around 0.8-1.2nm (rms) . The results are shown in Fig.4 and Fig.5, respectively. The total manufacturing lead time, from designing and mixing raw materials to final integration of the mirror unit, was 11 months. The net time spent for polishing including lapping was about 6 months, which is comparable to that needed for glass mirrors of this size.

The typical figures of the mirror are summarized in Tab.1.

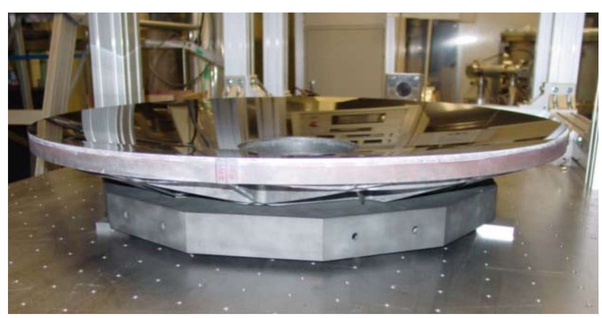

Fig.1 Mirror unit (with supports and optical bench)

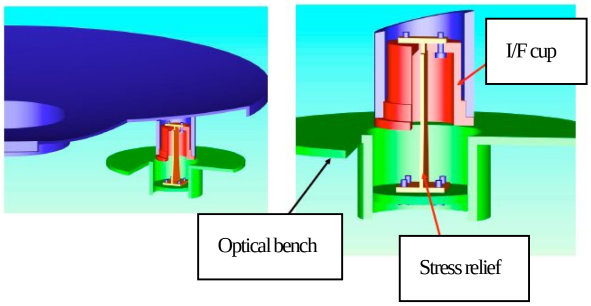


Fig.2 Structure of supporting interface

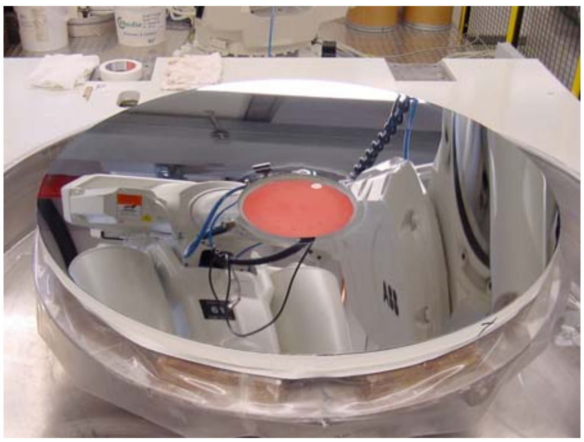

Fig.3 Polished mirror

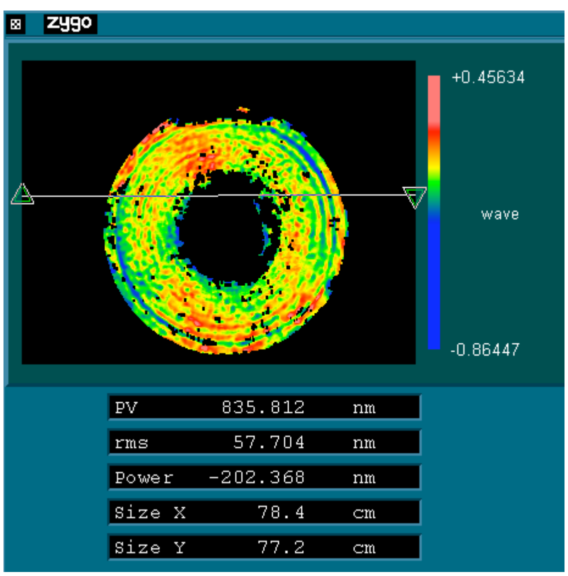


Fig.4 Surface figure error after integration

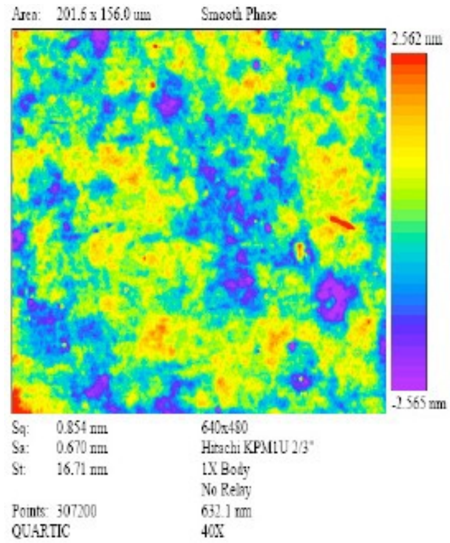


Fig.5 Surface roughness

Tab.1 Specification of the mirror

| Items | Specifications |
|---|---|
| Diameter | 800mm |
| Substrate | Carbon fiber reinforced silicon carbide |
| Mirror surface | Silicon vapor deposited |
| SFE | 60nm (290mm-740mm) (rms) |
| Surface roughness | 0.8-1.2nm (rms) |
| Weight | ~ 11kg |

## 3. SAMPLE EVALUATION

In order to evaluate the homogeneity of the 800mm mirror, 201 sample coupons are cut out from various parts of the same material block as the mirror (Fig.6). They were cut out after sintering. Using these samples, physical properties such as thermal expansion coefficient, Young's modulus, bending strength, etc. are being measured according to the JIS standard. Fig.7 shows the inner structure of the sintered material. Homogeneity has improved compared to that used for SPICA-BBM manufactured in 2002. The Weibull modulus obtained from 120 samples is 12.1, which is higher than other types of silicon carbide (Fig.7). The Weibull modulus for those cut out from the center region is 12.2, and for those from the outer region is 16.2. The results of the measurements suggest that the physical property of the large C/SiC material block seems to have slight gradient from the central area to the rim area (Fig.8).

The quantitative thermal expansion measurements for dozens of sample coupons are being carried out. Also the highly accurate CTE measurements (order of $10^{-9}$) down to liquid helium temperature are being done for several samples.

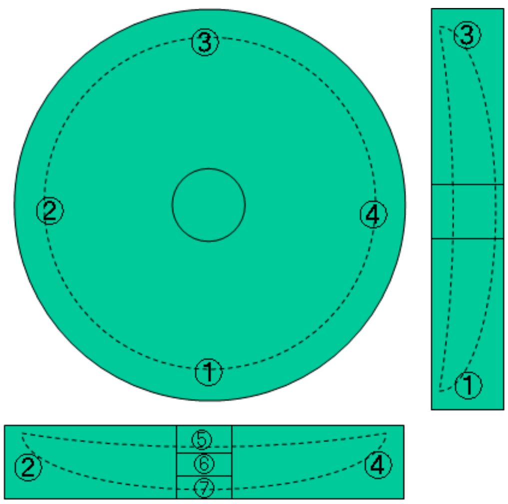


Fig.6 Areas for sample coupons

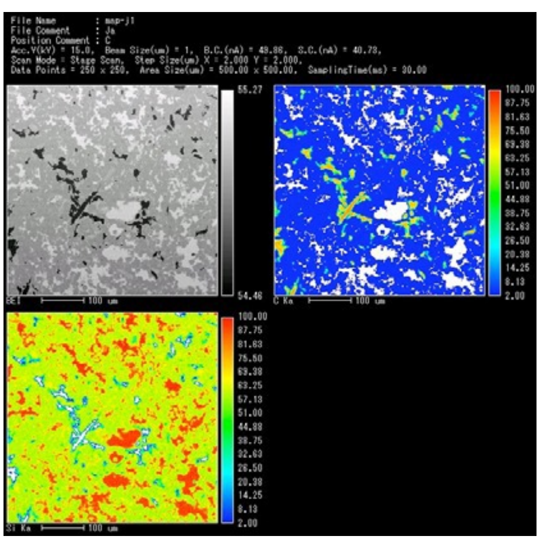

Fig.7 Microstructure of the C/SiC substrate material

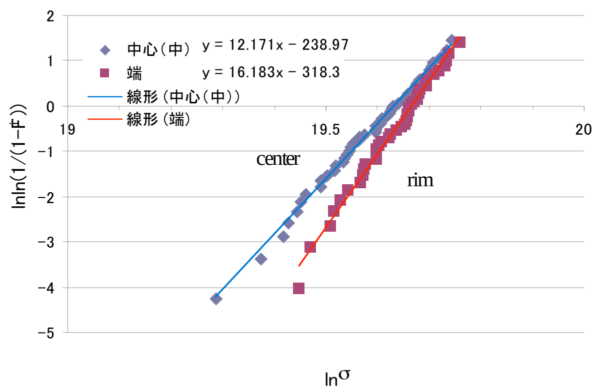


Fig.8 Deviation in strength

In order to confirm and evaluate the performance of the material precisely by optical method, a Φ=160mm small mirror was also manufactured which is cut out from the central part of the 800mm mirror. If the variation of CTE is large, it can be easily confirmed by cryogenic mirror surface figure measurement. The small mirror was cooled down to 17K and its surface figure error was measured at several temperatures during the cooling. The surface figure deformation caused by the inhomogeneity of CTE was derived as 0.027λ (rms) by subtracting the surface figure error at 17K from that of 290K. Comparing the cryogenic deformation of Φ=160mm mirror made of the old C/SiC material used for the SPICA-BBM, the surface figure error for this size has been improved by one order of magnitude. This result also means that the homogeneity of the CTE of the substrate is improved.

The cryogenic optical measurement of the surface figure error of 800mm mirror is also planned.

Combining these results of sample coupons and cryogenic mirror surface figure deformation, analytical models of the microscopic structure to explain the measured results (uniformity or ununiformity) and to evaluate, guarantee, and estimate both the mechanical quality and the optical performance of C/SiC mirrors will be studied and developed. Very preliminary analytical example for the 160mm mirror is shown in Fig.10 by using FEM model dividing the mirror into 19 cells (Fig.9).

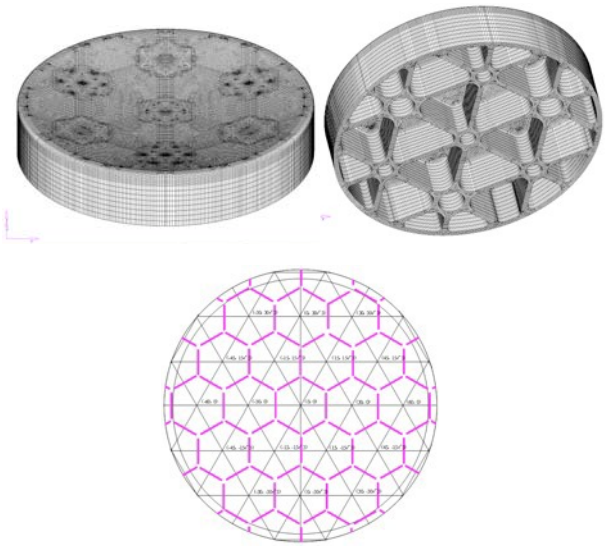

Fig.9 160mm mirror structure and FEM model

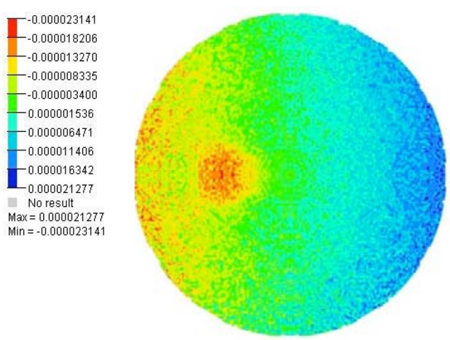


Fig.10 A case of CTE difference between inner and outer of a cell

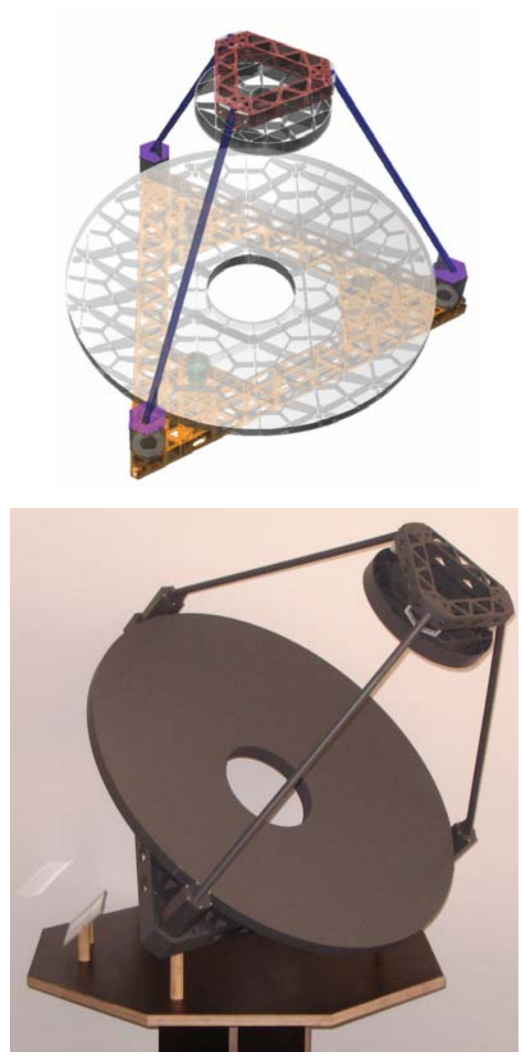

Fig.11 FEM mode (upper) and 1/1 scale plastic model (lower)

Fig.12 Integrated support structures and its 3D measurement

## 4. MANUFACTURING All C/SiC OPTICS MODEL

On the purpose of mastering and establishing ground optical performance testing method and relating know-how for large optical systems, an all C/SiC optics model using the 800mm mirror as primary was designed (Fig.11) and its components were successfully manufactured (Fig.12).

The secondary mirror is a high order convex (Fig.13). It is also silicon vapor deposited. The secondary mirror support will be bipod structure that enables optical alignment easier during the testing.

The optics model will be integrated next year after the cryogenic measurement of the primary mirror. After the integration, the model will be employed for the ground testing simulations to develop the optical measurement technologies.

Fig.13 Secondary convex mirror (being polished)

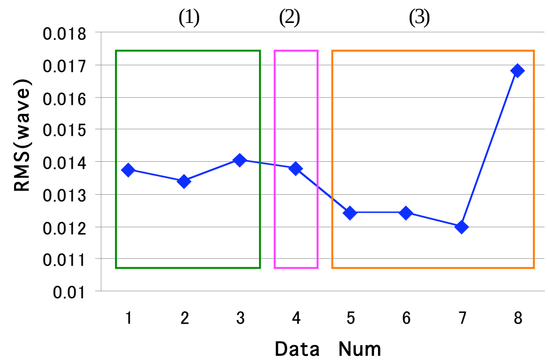


Fig.14 Surface wavefront errors under various conditions

## 5. GROUND TESTING ENVIRONMENT

Basically the optical system will be set with its optical axis is horizontal in the 6m vacuum chamber in Tsukuba Space Center of JAXA. The vibration environment of the facility was measured to evaluate and confirm the availability and capability for highly precise optical tests.

In order to eliminate or reduce the vibration effect to the optical measurement, a new instrument of high-speed laser interferometer that is robust to vibrations was used. The tests were performed under the three environments and conditions, (1) atmospheric pressure at room temperature (RT), (2) vacuum at RT, and (3) vacuum at liquid nitrogen temperature of which vibration environment is the worst while all pumps and cryo-coolers are working. Using this interferometer, the measurement accuracy was confirmed to be high enough (better than 0.02λ rms) for our purpose even under the worst vibration condition (Fig.14). Herewith this result, we confirmed that the 6m chamber facility at Tsukuba Space Center can be used for highly precise optical measurement of future large optical systems.

Concerning the measurement method and its analysis, stitching method will be applied to larger (Φ>~1m) optical systems, especially for SPICA of which aperture is 3.5m. This method will be tried and established using the 800mm optics model. The algorithm for stitching measurement analysis is being developed, that should be applied to very high resolution optical telescopes and very large optics such as SPICA, by iterating the stitching measurement trials and analysis.

## 6. SUMMARY

A Φ=800mm very lightweight mirror was manufactured using the carbon reinforced silicon carbide composite material improved and developed by Mitsubishi Electric Corporation and ECM. As the results derived from mechanical tests and observations of sample coupons and optical cryogenic measurement of 160mm sample mirror, the homogeneity and uniformity of the substrate of the mirror, that is equivalent to the variation in CTE, are confirmed to have been improved by one order of magnitude in surface figure deformation. The mirror will be tested under cryogenic condition to confirm the optical performance at cryogenic temperature and the homogeneity of the substrate.

A optics model using the 800mm mirror and the same composite material for all other parts was designed and all the parts have been manufactured successfully. This model will be assembled next year after the cryogenic measurement of the primary mirror and will be employed to establish the measurement method and know-how of the large optics such as SPICA telescope and also high spatial resolution optical sensors, by applying the stitching measurement method. The algorithm to analyze the stitching measurement is also under development.

This project is currently schedule to be completed by the end of March 2010 in order to hand over the lessons learned to each projects.

## 7. REFERENCES

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