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TMA optics for HISUI HSS and MSS imagers

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Abstract — Sagem is presently working on a new project for the Japanese HISUI instrument made from a Hyper Spectral Sensor and a Multi Spectral Sensor, both including a Three Mirror Anastigmat (TMA) main optics. Mirrors are made from Zerodur from Schott but also from NTSIC, the New Technology Silicon Carbide developed in Japan. This report is also the opportunity to show to the community Sagem recent progress in precision TMA optics polishing and alignment.

Index Terms—Zerodur, NTSIC, lightweighting, polishing, testing, TMA, HISUI

I. INTRODUCTION

HISUI, standing for Hyperspectral Imager SUite, is the successor in Japan of the Advanced Spaceborne Thermal Emission and Reflection radiometer (ASTER) that was placed on-board TERRA. HISUI is dedicated to enable most advanced data gathering for environment and disaster monitoring, geodata update, fishing conditions survey.

HISUI is a sensor developed by NEC, jointly with the Japan Resources Observations System and Space Utilization Organization (JAROS) under the guidance of METI.

HISUI consists in 2 main instruments (see Figure 1):

- The Multi Spectral Sensor (MSS) giving images in four spectral bands within the 450-900 nm domain with a ground resolution of 5-m over a swath of 90 km.

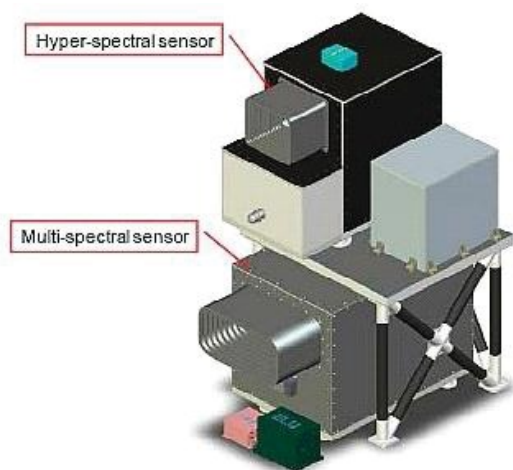


Figure 1 : HISUI architecture

- The Hyper Spectral Sensor (HSS) giving images with 30-m ground resolution over a 30 km swath. 57 spectral bands of 10-nm spectral resolution are spread within the 400-970-nm VNIR spectral domain and 128 bands of 12.5-nm spectral resolution are spread within the 900 – 2500-nm VNIR spectral domain. This sensor is also fitted with an entrance pointing mirror allowing it to explore the 90-km ground swath of the MSS instrument.

II. MSS AND HSS OPTICAL DESIGNS

Both MSS and HSS main optic is a TMA which provide high quality achromatic images over a flat image surface. Entrance aperture is in the 250-300 mm range. MSS has been tuned to high resolution and wide angle for the 90 km swath; therefore its mirror spacing is longer than for HSS which has been tuned for lower resolution and lower field but higher F/N for optimal detector sensitivity.

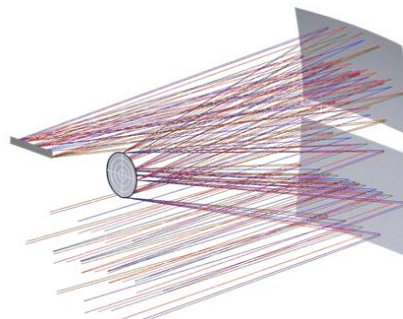


Figure 2 : MSS TMA

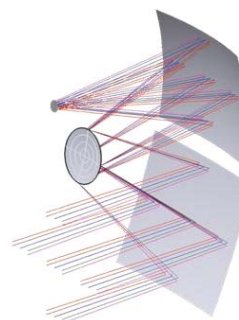


Figure 3 : HSS TMA

III. SAGEM BACKGROUND IN TMA AND OFF-AXIS OPTICS

Sagem pioneered French precision optics work on off-axis aspheric optics more than 25 years ago with many components made for astronomy or laser. By the year 1990, TMA optics came to the attention of the Centre National Etude Spatiale (CNES) and of other space agencies as a family of optics with very high potential for multispectral high resolution observation instruments from space and much R&D work on their design, manufacturing and testing was conducted. In 1993 we were proud to supply the Indian Space Research Organization (ISRO) with its first TMA optics for IR-1C mission. In 1995, we built for CNES a demonstrator of a TMA optics exhibiting 2X better performance over a 2X larger field view in an instrument volume 2X smaller than the SPOT family state of the art at that time. Other precision off-axis optics like the ISRO CARTOSAT TMA or the CNES COROT instrument off axis parabolic pair of mirrors were built and have proven the maturity of such skill and expertise.

Our masterpiece in the domain is the giant pair of off-axis entrance mirror of the European Space Agency (ESA) GAIA astrometric instrument. These world-record off-axis pieces measure 1540 x 490 mm made from Silicon carbide were successfully produced to the huge performance of 9-nm RMS residual surface error.



Figure 4 : CNES TMA demonstrator



Figure 5 : One of GAIA entrance mirror

A recent key reference is the optics developed for the Near InfraRed Spectrograph instrument (NIRSpec), one of the European contributions to the James Webb Space Telescope (JWST) major space mission. This optics is made from three successive TMA, all made from SiC Mirrors components assembled with a SiC structure. This all-SiC design has shown extremely stable and hysteresis-free performance down to cryogenic environment. The Figure 6 and Figure 7 below shows the fully assembled fore optics (FOR), the collimator optics (COL) and the camera optics (CAM). More details about this project have been given in ref [1] and [2].



Figure 6 : NIRSpec FOR TMA



Figure 7 : NIRSpec COL and CAM TMA

IV. THE HSS AND MSS MIRROR SUBSTRATES – NTSIC MATERIAL VALIDATION

Most of the HISUI mirrors are made from glass ceramic material Zerodur from Schott, now widely used for such type of applications. Sagem pioneered the art of lightweighting mirror substrates made from Zerodur by diamond milling and developed high skill in designing optimum rib patterns for such structures.

But the HISUI project has also been the opportunity to qualify the space use of the New Technology Silicon Carbide material (NTSIC). This is a high strength reaction sintered SiC material developed by combining key technologies and expertise of several Japanese manufacturers [3], [4]. NTSIC is pore-free and can be polished without cladding material like Chemically Vapour

Deposited (CVD) SiC. Such additional layer enables obtaining excellent polishing quality but requires large special furnaces. Another concern is the bimetallic effect that may appear when applying such polishing layer and the risk of going through this layer during the lapping and polishing process.

The customer decided to have M1 and M3 of the MSS TMA be made from NTSIC material. This choice was also dictated by the fact that these two mirrors were quite of the same dimension of nearly 300 x 500 mm.

An important part of our work and responsibility under this project was therefore to validate the ability of making precision space mirrors from this NTSIC material. The material is of course not absolutely dense like a glassy material and achieving less than 3 nm micro-roughness level on these aspheric off-axis surfaces without any polishing layer was the main challenge. This was the subject of a polishing development program conducted on small samples, a 160-mm circular piece and a 300x300-mm square piece.

We tried many polishing procedures based on our state of the art and set up one polishing strategy leading to micro-roughness level in the range of 1.5 to 2.5 nm RMS micro-roughness.

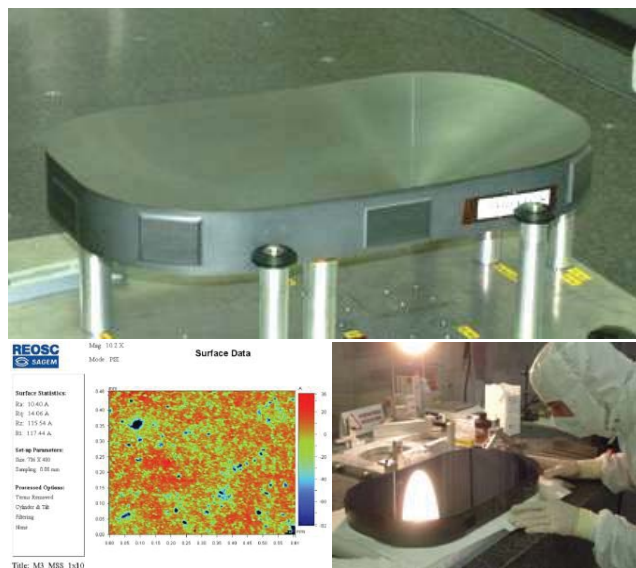


Figure 8 : NTSIC substrate - 1.5-nm microroughness measurement – The polished M3 MSS mirror

On the other side we also performed a test of cladding a NTSIC blank with CVD-SiC. The coating has been successful but some doubts remained wrt the final geometry of the part. It could not be demonstrated that a 500mm blank would not distort when undergoing the high temperature of the CVD-SiC furnace.

Based on all these results, the decision was finally made with our customer to polish the M1 and M3 bare without any polishing layer.

V. WORK ON THE INDIVIDUAL MIRROR ASSEMBLIES

Each of the six mirrors of the MSS and HSS TMA instruments has to be delivered to the customer fully lightweight, polished coated, equipped with electrical grounding straps, fitted with pads and Mirror Fixation Devices (MFD), integrated on a tooling plate in a transport container.

The individual Zerodur mirror lightweighted structure design is now a rather straightforward work to balance mirror substrate stiffness under its own weight and 0g sag release, the strength under launch conditions, the front surface quilting under polishing pressure, and the complexity of the milling operations. The gravity effect is very low, allowing to guarantee no degradation between the on-ground performance and the 0g conditions (see Figure 9).

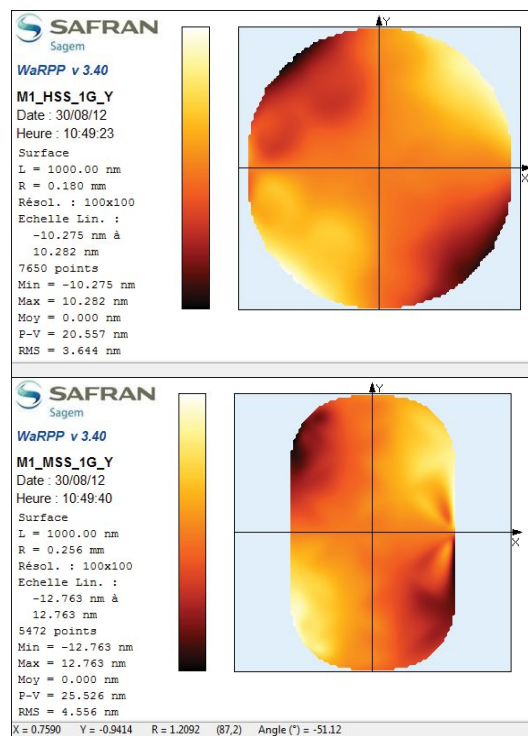


Figure 9 : Surface deformation for HSS and MSS M1 mirrors under 1g Y gravity load : 3.6 nm RMS / 4.5 nm RMS

The two NTSIC mirrors lightweighted structure was discussed and iterated with the customer and its manufacturing constraints and limitations. Final mirror substrate designs were agreed with the customer so that each party could feel safe with respect to its responsibilities in this part of shared activities of the project.

Pads and pads bonding joints were optimized for both substrate materials taking into account the specificities of each Zerodur and NTSIC materials. The MFD were designed to withstand the required requirements (typically 270 Hz first eigenfrequency for the mirror assembly, 23°C

+/- 3° operational temperature and 20°C +/- 30°C storage temperature, 30g quasi-static load level during sine vibrations, etc...) according to our internal state of the art.

All mirrors substrates were precision lapped and polished, directly off axis, i.e. without cutting them out of a parent mirror, with an edge margin of 10 mm only between mechanical contour and useful optical area contour thanks to our latest progresses in precision off axis optics polishing technology. This direct off-axis polishing skill is important to enable maximum programmatic flexibility during fabrication and remove potential constraints during TMA system design phase. Of course, this is also economically more attractive and generating lower programmatic risks than cutting the pieces from a large parent mirror.

The mirrors were polished to optical surface quality in the range of 8 to 28 nm RMS, in line with the constructed error budgets. The requirement for the surface error of the mirrors at the end of the polishing is derived from the initial overall budget error of the TMA. However, this requirement is based on statistical approach and turns out to be generally pessimistic. This is the reason why when the mirrors are close to the requirement, the measured WFE of the mirrors is used to build an optical model of the TMA to check that the performance will be met (see §VII).

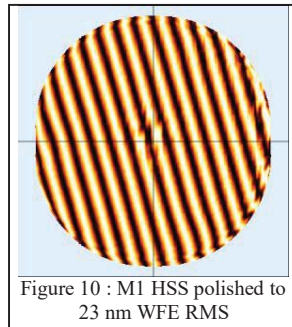


Figure 10 : M1 HSS polished to 23 nm WFE RMS

As an example of polishing result, the Figure 10 shows the fringe pattern of the M1-HSS Zerodur mirror. To be noticed are the low edge effect and the smooth overall surface structure resulting from our latest efforts to keep at lowest level the mid and high spatial frequency residuals.

The roughness achieved on the Zerodur mirrors is well in spec (between 0.5 and 1.5 nm RMS). For the NTSIC mirrors, the achieved micro roughness is slightly higher but still in the requirement (3nm RMS for M1 and 1.5nm RMS for M3).

The mirror assemblies were mechanically tested on a shaker to verify all their mechanical properties. First eigen frequencies are typically found around 260 Hz, with only a 5% discrepancy with respect to the design value.

Finally, an enhanced protected silver coating was deposited ensuring highest reflectivity over the 0.45 – 2.5 μm spectral domain. The performance of the TMA is derived from the individual measurements of the mirrors. The Figure 11 shows the transmission curve of the full TMA taking into account the reflectivity of the 3 coated mirrors.

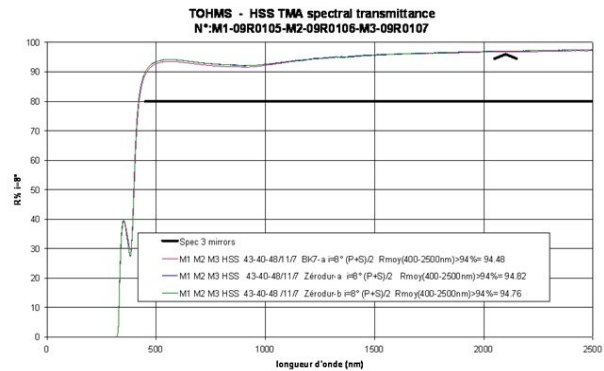


Figure 11: Reflectance curve of the deposited reflective coating for the full HSS TMA

Some straps are then glued on the coating to connect the mirror to the grounding of the instrument to allow the charges draining in the satellite.

VI. GLOBAL TEST AT TMA LEVEL

Once the individual mirrors polished and coated, and prior to their delivery to the customer, we performed an integration within a dummy TMA structure and an alignment of the three mirrors of the MSS and HSS in order to evaluate the global optical performance at TMA level. This is a global cross-check of all previous measurements.

For this purpose we designed a global test structure shown on Figure 12 below, representative of the flight structure and including:

- A global frame with a plate receiving M1 and M3 mirror, a second plate receiving M2 mirror, both linked with metering bars.
- Mounting interfaces for each of the three mirrors and adjustment devices along 6 degrees of freedom
- An auto-collimation flat on a 2-axis tip-tilt mount
- The interferometer installed on a stage for exploring the rectangular field of view
- A control bay allowing to perform all alignment and optical measurement operations in a semi-automated way.

The entire set-up was installed in clean room conditions in order to preserve the cleanliness level of the freshly coated mirrors and their MFD's.

The WFE of the TMA is measured across the whole FOV. The maps are processed using the sensitivity of the mirrors and the motions needed to correct the WFE are derived. The alignment of the HSS TMA has been almost immediate thanks to the efficient alignment procedure and the less tight specification. The focal length requirement was also met.

Unlike for the first TMA, the alignment of the MSS TMA has been more difficult because of the very stringent MTF requirement. The WFE requirement was reached rather easily but it turned out the MTF was not fully met.

This has required an improvement of the alignment in order to minimize some Zernike coefficients (mainly astigmatism 0° and astigmatism 45°).



Figure 12 : the global TMA structure HSS TMA / MSS TMA

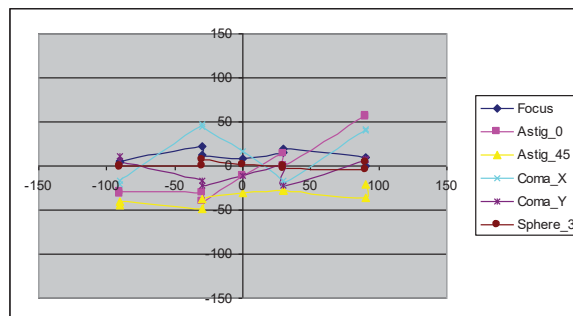
Finally the WFE achieved for the TMA was below 35nm RMS for the whole FOV and the MTF@50 lp/mm was above 0.55 for the required depth of focus. The Figure 13 shows the final performance of the TMA at the end of the alignment at Sagem's premises.

Sagem has now delivered all the mirrors and has supported its customer for the alignment of both the HSS and MSS TMA in the flight structures. The alignment operations have been successful and even better performances have been reached. The TMA are now ready for further integration (spectrograph, sensors, thermal and electronic hardware...).

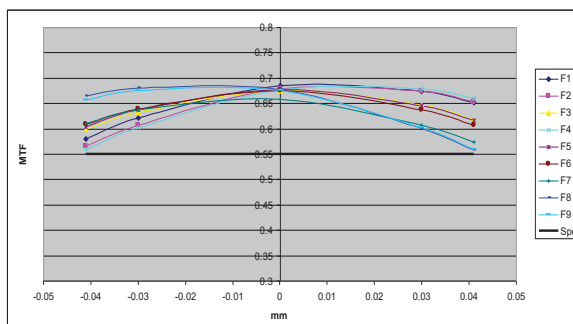
VII. OPTICAL MODEL

For the prediction of the performance, Sagem has built an optical model of the TMA. This was made on the basis of the Code V optical model of the first assembled HSS TMA. The measured optical surface residuals were injected into the model with the tilts and decenters corresponding to the

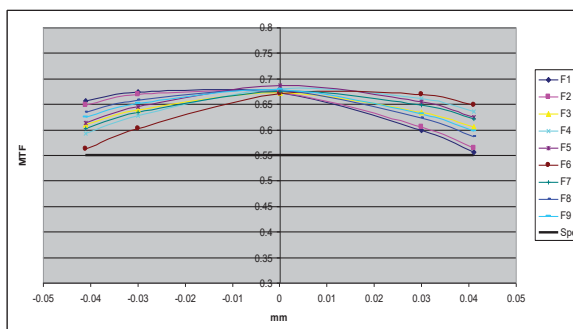
mechanical design. Then, it was proceed to a virtual alignment sequence so that the WFE residuals through the various points of the field of view fitted to the best with the as measured WFE residuals.



Zernike coefficients < 50nm over the full FOV



Tangential and Sagittal MTF > 0.55 @ 50lp/mm and for 485-900nm wavelength



Tangential and Sagittal MTF > 0.55 @ 50lp/mm and for 485-900nm wavelength

Figure 13 : MSS TMA final performance

The model came out conform to the measurements within 3% accuracy only.

Another comment is that the predicted WFE at TMA level made on the basis of the individual mirror measurements is conform to the observed TMA measurement within 10% error only.

The Figure 14 shows the good correspondence through the various field points from design to computer model of the real hardware.

The main conclusion of this work is that the individual mirrors are correct, the predicted TMA level performance is correct and the alignment operations have been correctly done

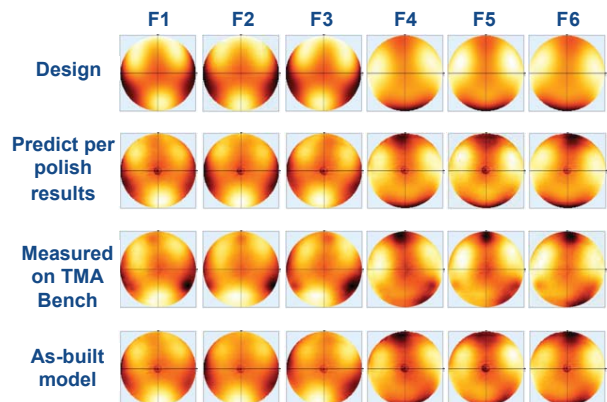


Figure 14 : comparison designed-predicted-observed-modeled

VIII. CONCLUSION

Sagem has built through the years a strong experience and capabilities in the domain of large off axis aspheric optics and Three Mirror Anastigmats systems. This project has shown that NTSIC material is appropriate for manufacturing precision space optics for visible-IR application without application of any polishing layer. This is not only true for the polishing operation but also for the pad bonding and for the optical coating operations.

All mirrors have been delivered fitted with their pads and MFD's on a tooling plate after extensive

optomechanical qualification and verifications. However, Sagem is ready to undertake the integration of the mirror assemblies in the global instrument flight structure, if the customer is wishing to place this global responsibility in our hands.

A global bench has been designed and manufactured to conduct semi-automated performance evaluation and alignment work at TMA level. This is now routine work at SAGEM as shown by the confirmation of the predicted performances by the observed one.

ACKNOWLEDGMENT

We take this opportunity to thank all Sagem technical staff and our customer for the confidence he placed in our hands. We hope that HISUI will deliver soon valuable multi-spectral and hyper-spectral data.

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