

International Conference on Space Optics—ICSO 2018

Chania, Greece

9–12 October 2018

Edited by Zoran Sodnik, Nikos Karafolas, and Bruno Cugny



Freeform optics design, fabrication and testing technologies for Space applications

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ABSTRACT

The introduction of freeform optical surfaces in a space instrument offers the possibility to improve its performance, its volume and weight or a combination of both. This is shown to be valid for either imaging systems or spectroscopic systems. At Safran Reosc we master freeform robotic polishing technology since more than 25 years and we will show how we continue to improve it in term of quality, productivity and adequacy to ceramic materials like Silicon Carbide. Surprisingly, the conservative space industry evolved slowly from spherical to rotationally symmetric aspherical and off-axis optics during the last decades. This is no more valid today and we are proud to contribute to MicroCarb and IASI NG, two recent innovative projects taking benefit of such freeform optics designs enabling more cost-effective advanced missions. These projects will be briefly presented with their status of progress of work at the company. We will also take this opportunity to present our work on the extreme off-axis optics used within the MERLIN lidar project, produced with the same freeform technology.

Keywords: freeform optics, space optics, MicroCarb, IASI-NG, MERLIN,

1. INTRODUCTION

Freeform optical surfaces were previously generally seen as a disruptive evolution of optical systems for new, low resolution applications like virtual reality lenses. However, when implemented in a more incremental way to refine a high performance optical system for imagery or spectro-imagery, freeform optical surfaces constitute a new powerful tool offering the possibility to enhance the performance volume or to reduce the instrument volume and weight for the same level performance, or a combination of these two attractive features, especially for space instrumentation. Freeform optical manufacturing technique is available at Safran Reosc since decades and still under continuous improvement. Today we are proud to use it for the real freeform optical systems of the advanced projects MicroCarb and IASI-NG.

2. DESIGN: THE BENEFITS OF FREEFORM OPTICS

2.1 Imaging optics: Variations on Pleiades' optics

We have previously shown to the community ^{[1], [2]} the benefits of using freeform optics within high resolution space camera in term of compactness and/or increase of design performance (image quality and/or field of view). This was done with some academic design variations of the of the Pleiades's payload which are summarized in the figure 1 below.

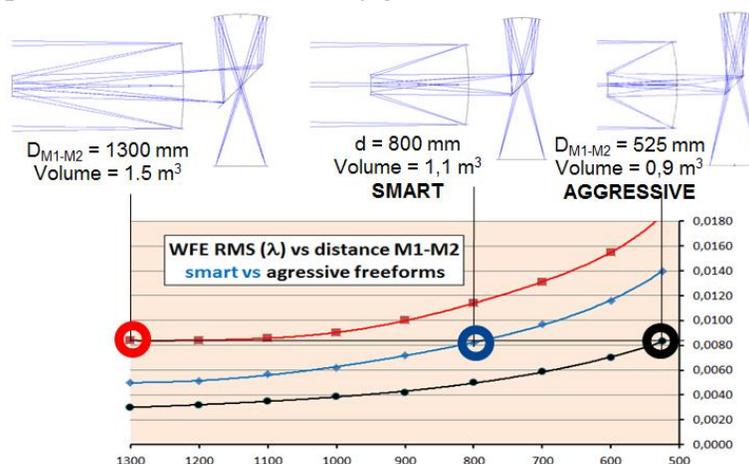


Figure 1. Pleiades telescope WFE RMS versus D_{M1-M2} and type of freeform deformation introduction.

We showed how the design performance (worst WFE RMS residual through the telescope field of view) is degrading when one reduces the D_{M1-M2} distance separating the two main mirrors, but also how it is improving when smart or more aggressive freeform surfaces are used in the design instead of conventional aspheric on or off-axis. The introduction of freeform surfaces within such a conventional optical system clearly opens new horizons in terms of compactness and/or level of performances. However, considerations on error budget and position tolerances raised by system level analysis may refrain to go too far in such direction. But we will show below that manufacturability of such optics is no more a show-stopper for Safran Reosc.

2.2 Variations on spectrometer instruments

A similar exercise has been made recently by some researchers from the University of Rochester, Institute of Optics but on a spectrometer instrument instead of imager^[3]. The outcome is exactly the same, i.e. the introduction of freeform optics enable higher performances in the same volume or similar performances in a smaller volume.

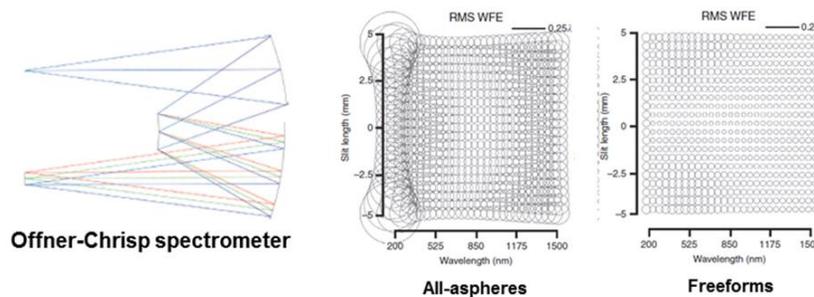


Figure 2. Benefits of freeform within a spectrometer: Better performance in same volume

The introduction of freeform surfaces within such type of optical imaging of spectrographic instrumentation is generally done with the addition of polynomial terms beyond the conventional aspheric, on- or off-axis, optical prescription. The most used functions are X^m, Y^n , Zernike or Forbes polynomials. Zernike have the advantage to remain ‘close’ to the natural third and higher order aberration terms.

2.3 Let’s exchange in the early phases

At Safran Reosc we also master the lens design of precision optical systems for space application and have developed solid knowledge about how, and on which optical surface introducing such type of freeform deformation and how to manage the lens design process in order to limit the amplitudes and slopes of the freeform surface so as to keep it with our best domain of manufacturability and testability. We therefore invite our potential customers to exchange with us as soon as possible in the instrument design process in order to reach common understanding and to give us an opportunity to refine the design in terms of performance, manufacturability and testability. For example:

The use of Zernike polynomials is highly preferred because all our robotic manufacturing and testing software chain are all based on this mathematics. Remaining with Zernike avoids the development of software upgrades and the associated potential risks.

Except the case of off-axis parabola, we recommend to develop optics prescriptions with opto-mechanical referentials simply located at the physical center of the component optical surface.

We recommend considering a reasonable edge margin around the clear aperture in order to minimise costs. Very low edge margin between mechanical contour and useful optical area contour is of course possible but at higher cost, schedule and risk.

We remain open to explore really disruptive freeform designs and think that tight exchanges in the early phases of such project can only contribute to consolidate its success.

3. MANUFACTURING TECHNOLOGIES FOR FREEFORM OPTICS

3.1 Lightweight glassy mirror substrates

Safran Reosc holds more than 4 decades heritage in lightweight mirror substrate design and manufacturing with diamond milling technique out from glassy materials like Zerodur from Schott, ULE from Corning, Fused Silica, etc.

This started in the early 70's with first French defense projects followed by METEOSAT satellites optics. Pockets were made with hexagonal contour and "semi-closed back" shape thanks to diamond wheels attached at the end of a rod allowing to proceed to under-cutting of glass and to end-up with a near honeycomb sandwich structure. Many mirrors were designed and fabricated according to this technology like those of the SPOT family, HELIOS or ISO.

The pocket design evolved to open-back structure with triangular cells in order to ease the machining work while further reducing weight and improving stiffness-to-weight ratio. The balloon borne SUNRISE telescope primary mirror was accurately designed to a lightweight structure quite as efficient as Silicon Carbide optics thanks to thin ribs machined down to 3.5 mm, lightweight pockets bottoms following the optical surface profile, advanced acid etching and a sophisticated rear surface trefoil shaping in order to get maximum stiffness to weight performance. Lightweighting areal density was brought below 40 kg/m² and lightweighting ratio around 90% from the initial solid blank

Presently we work at Safran Reosc on meter-class ultra-lightweight optics for Kompsat-7 project and on the unique, highly off-axis aspheric primary mirror for the receiver telescope on-board the Methane Remote Sensing Lidar Instrument. MERLIN is a scientific mini-satellite jointly developed by France & Germany dedicated to measure with unprecedented accuracy spatial and temporal methane emissions all over our planet. Its 745 mm aperture mirror is one of the most lightweighted optics ever made by Safran Reosc with a mass of only 11.9 kg, i.e. an areal density of as low as 26 kg/m².

The front surface of the MERLIN main receiver mirror is an off-axis section of a very steep parabola as shown on the sketch below. The aspheric departure from its best fit sphere is as high as 16 mm. This optical surface will be generated, polished and figured thanks to our freeform technology presented below.

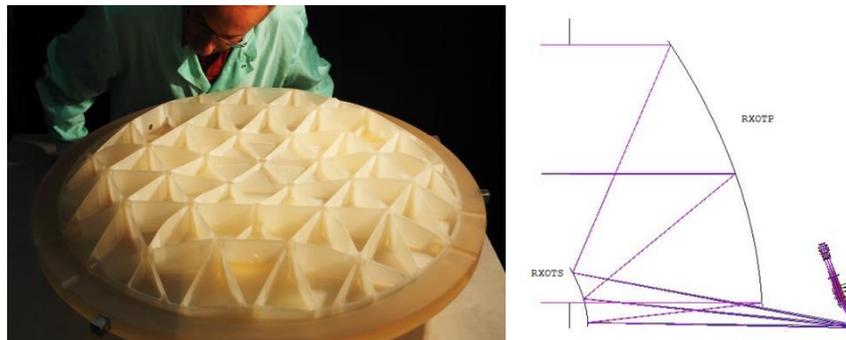


Figure 3. The MERLIN receiver's main mirror after lightweighting operations and optical sketch

3.2 A long heritage in (freeform) robotic grinding and polishing

Safran Reosc initiated its development in robotic optical manufacturing technique back in the 80's, taking immediate advantage of the multi-degrees of freedom offered by the robot systems more and more used in the car industry. In fact our robotic systems are inherently adapted to freeform optics since the beginning but, surprisingly, we were only asked to produce conventional aspheres and off-axis optics during these past 25 years due to some conservatism affecting the space industry. The key examples of off-axis space optics made 'directly off-axis' during all these years and that could be quite considered as freeform optics are listed herebelow and shown on figure 4:

- 1987 A 450 mm off-axis telescope demonstrator
- 1988 The PRONAOS sector mold for CNES
- 1993 The IRS 1C 250 mm TMA optics for ISRO
- 1999 The IRS P5 Cartosat 500 mm TMA optics
- 2010 The 27 highly aspheric optics in SiC for the JSWT NIRSpec instrument
- 2011 The two 1.5-m GAIA instrument main mirrors

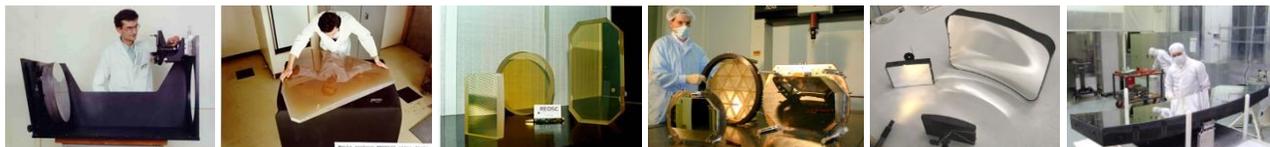


Figure 4. Some off-axis optics made directly off-axis with freeform robotic technology in the past

Today we also prepare ourselves for the production in the SAFRAN plant of Poitiers of the 931 1.45 m off-axis hexagonal segments of the European Southern Observatory (ESO) Extremely Large Telescope (ELT). The production rate has to go up to of 1 segment/day to finish the production by 2023. This world unique optical production project will be fully based on our freeform technology that proved its capability with seven proto segments made 8 years ago.

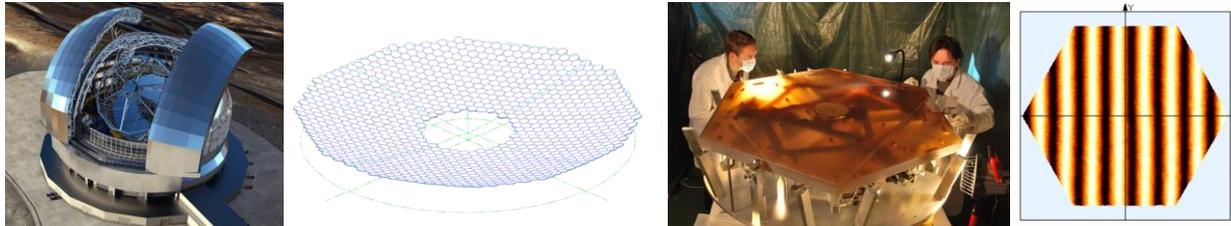


Figure 5. The ESO ELT, its segmented 39-m primary and proto segment polished to 10 nm RMS WFE

3.3 Recent development in robotic polishing: Double robot configuration

In order to gain in productivity for large optics the company recently developed a multi-head technique with double robot configuration as shown on the figure below. The optics to be processed is presenting its surface to two robots, each one driving a polishing tool. In fact there are two possible ways to use such configuration:

Case 1: Two robots - One process: Both robots are operating the same type of tool and simply execute the same processing run for a net double processing speed. The target is simply to gain time and productivity.

Case 2: Two robots - Two processes: In this configuration, the two robots are driving different types of tools, each one having its own specificity in term of correction efficiency. The goal is therefore to have a more efficient run able to work on two types of defects at the same time. The net result is again faster convergence and better productivity.



Figure 6. One optics – Two robots for better efficiency

3.4 Recent development in robotic polishing: Robotic polishing Nanostation

With freeform optics the payloads can become more compact and thus, the optical components smaller. Our large robot solution appeared then less well adapted and the need of smaller size machinery perfectly adapted to small freeform optics has emerged. Therefore our process team elaborated a new concept of machinery. In the frame of a three years program a new type of machinery based on a small size robot system fitted with new 'polishing heads' was developed. However, the man-machine interface fully remains the same in order to minimize the training time required for our optical technicians. The main characteristics are: a capacity to handle up to 400 mm optics, full freeform technology and adaptation to glassy or ceramic materials.

The MicroCarb project presented below stimulated the rapid implementation of 3 so called Nanostations which are now operational and used daily to process these advanced freeform optical elements.



Figure 7. Our small robot 'Nanostation' for 0–400 mm optics

3.5 Ion Beam Figuring

Ion Beam Figuring is a technology originating from the semiconductor industry. Argon ions are projected under vacuum onto the optical surface with the appropriate energy and remove some atoms from the substrate by sputtering effect. Its key advantages are:

- Non contact process, thus not generating any edge effects or quilting
- Simple electric driven process and gaussian removal function, therefore highly deterministic and accurate
- Quite good removal rate. Combined to its accuracy, IBF it is a productive tool.

At Safran Reosc we have set-up a 1.3-m IBF machine in the mid of the 90's and delivered our first meter class accurate optics in 1998. This machine has been recently refurbished with new features and new command-control system.

For the Gran Telescopio Canaria segmented telescope project we set-up in 2001 a 2.5-m large Ion Beam Figuring chamber. It helped us to finish its demanding off-axis / freeform optics to exceptional high quality with a production rate of one 1.8-m hexagonal segment every 2 weeks.

We also conducted work in the domain of semiconductor optics and, for this, we set-up a third IBF machine dedicated to 300 mm class optics. This one is equipped with a specific IBF gun delivering a footprint down to 2 mm.

All these IBF machinery are fitted with a command-control system able to manage aspheric and freeform optics in term of Zernike polynomials up to Z36.



Figure 8. 130 cm, 250 cm and 30 cm IBF machinery

3.6 Metrology

For metrology we use precision 3D Coordinates Measuring Machines (CMM) to evaluate the shape of our optical parts in the early stages of the process: milling, grinding and lapping operations. Large pieces may require long time of measurement which are running through the night.

Once the optical surface is shiny, Computer Generated Holograms (CGH) are used to assess the surface deviations from ideal profile with nanometer accuracy. In the past years we spent deep energy to standardize the process, improve and make more rapid and accurate the alignment of the fiducials with respect to the part so as to reach shortest turn-around time and better productivity.

More recently we also introduced in our optical shop the use of deflectometry. This method show some attractive advantages: it is non contact, offers high spatial resolution with a large dynamic range. The method is well sensitive to high spatial frequency defects and well complementary to classical interferometry and therefore can contribute to overall efficiency of our metrology. However, its implementation and data processing remains not very simple if high absolute accuracy is targeted.



Figure 9. Deflectometry test set-up development

We conducted a 3 year R&D internal program on deflectometry which ended with a set-up dedicated to small size optics. The work was quite successful and was the winner of the 2017 SAFRAN innovation award. The methodology developed was declared OK for production and we used it recently during the processing of one of the Meteosat Third Generation entrance telescope main mirror.

3.7 The case of Silicon Carbide: From CVD SiC to R-SiC polishing layer

Recently^[4] we presented how Safran Reosc is pushing its precision manufacturing technologies for the case of Silicon Carbide. SiC is a ceramic material combining high specific stiffness, high thermal stability as well as high strength. It is therefore well adapted to the construction of mono-material telescope systems with structural elements and mirror bodies made from SiC. Temperatures changes do not affect the proper focusing of the optics and thermal gradients are rapidly reduced thanks to the high thermal conductivity.

The difficulty with SiC lies in its polishing because it remains porous or show variations of local hardness in the case of Silicon infiltrated material. To overcome this problem a dense layer of CVD SiC is deposited on the substrate. However CVD SiC is very hard and very difficult to polish. Through the years we have made one of our specialties in the processing of aspheric and off-axis SiC optics with our robotic freeform technology.

Available CVD furnace to perform such CVD deposition process have a limitation in size to about 1-m. The process itself is also not free of risks. There is therefore a demand for alternate solutions to the CVD SiC layer. We conducted R&T work on the subject and proposed an alternate technique with our R-SiC polishing layer. This R-SiC layer can be already deposited on optics up to 1.6 m and show several key advantages:

- Lower deposition costs than CVD SiC
- Potential for larger size up to 3-m
- Compatible with robotic polishing, IBF and MRF
- Net gain in optics overall production schedule
- Lower risks with easy removal and repair in case of problem
- Low CTE mismatch with bare SiC and cryo qualification.

Our R-SiC polishing technology has been subject to a deep qualification process under ESA contract and is now fully mature with TRL 8 reached for 350 mm class optics. Work is going on to reach TRL 7 up to 1.5-m class optics.

3.8 Improving SiC polishing efficiency – A generic effort

As indicated above, SiC material is more difficult to polish. This is put in evidence on the below diagram showing the material removal rate versus the achievable form error for the various optical fabrication stages of large aspheric optics. SiC is clearly to be 5 to 10 time slower, or more difficult to process than Zerodur.

The dark grey arrow is the shortcut offered by the R-SiC polishing layer which allows the processing of the optics as if it would be glassy. But this is possible only after aspherical lapping of the surface.

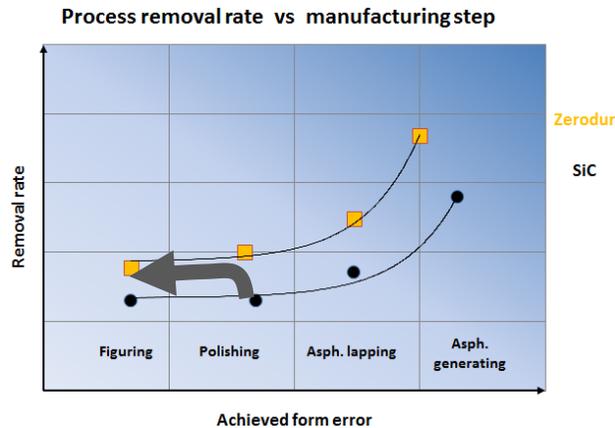


Figure 10. Process efficiency for Zerodur & SiC (arbitrary scale)

Today Safran Reosc process team is working hard on each of the SiC optical fabrication steps represented by a black dot on figure 7 to improve its removal rate and have it approaching the one of Zerodur. We cannot give much detail about all these various activities which remain confidential but our goal is definitively to have “*SiC as fast to polish than Zerodur*”.

4. ON-GOING FREEFORM SPACE OPTICS PROJECTS

Safran Reosc is resently working on two space optics programs involving real freeform optics for imagery and spectroscopy, one for the IR domain, the other down to visible domain and therefore with demanding specifications.

4.1 IASI NG optics

The Infrared Atmospheric Sounding Interferometer (IASI) is a Fourier Transform Interferometer sounding instrument conceived by Cnes and developed by Thales Alenia Space for installation on-board the METOP satellite. The variation of the OPD in the interferometer is performed by moving lightweight hollow corner cubes delivered by Safran Reosc.

Today IASI NG, the successor of IASI, is under development by Airbus Defense and Space. It is targeting improved SNR and spectral resolution and broader spectral range from 3.6 to 15.5 μm thanks to a new original concept of Mertz Type Interferometer. This is involving precision KBr prisms offering a high transmission domain. One of our contributions to IASI NG is the supply of these delicate prism elements made from the hygroscopic KBr material.

The IASI NG interferometer is working with some telescope optics as shown on the figure below:

An Afocal Telescope Assembly (ATA) feeding light into the interferometer

An Imager Telescope Assembly (ITA), from the imager companion of the instrument.

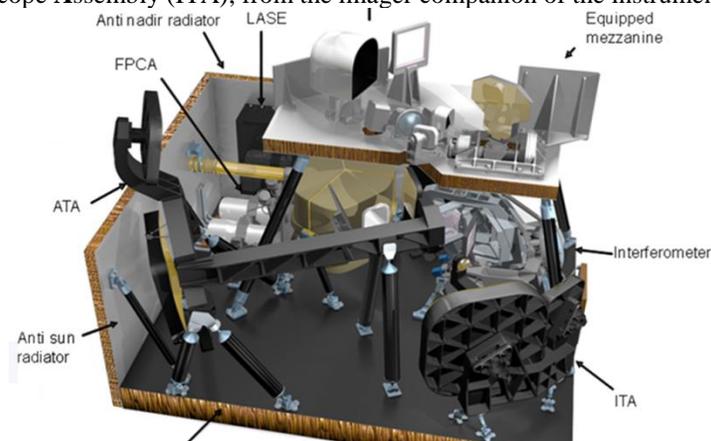


Figure 11. The IASI NG instrument with ATA & ITA telescope optics (Image Airbus)

From the 6 curved mirrors involved within ATA and ITA 2 are fully freeform with Zernike terms up to 36 and 4 are off-axis aspheric. The mirror sizes varies from 7 to 38 cm. The freeform or aspheric departure from best sphere varies from 100 to 1500 μm PTV and the figuring specification is in the range of 150 nm RMS. All mirrors are made from SiC material. They remain bare, without CVD polishing layer du to they use in in the infrared domain only.

4.2 The Microcarb instrument optics

MicroCarb, also named the CO₂ cartographer, is a mission conceived by Cnes and decided at the occasion of the COP 21 conference on the climat in Paris. Its mission is to perform the mapping, on a global scale, of the sources and sinks of CO₂, the most important greenhouse gas. It is the first European program on the subject and is designed for reaching a high accuracy of 1ppm. The instrument is in fact a multiband, high resolution spectrometer ($R \approx 25.000$), tracking the many fine spectral lines corresponding to the CO₂ gas within the 700-2100 nm spectral domain.

To keep the mission budget low the instrument will be launched on the Myriades microsat platform. Therefore, the instrument has to be squeezed within a compact volume. To keep the instrument's performances under compact volume Airbus engineers designed a unique compact multiband spectrometer concept thanks to the use of freeform optics as shown on the figure below. See ^[5] and ^[6] for more details on the mission and the instrument.

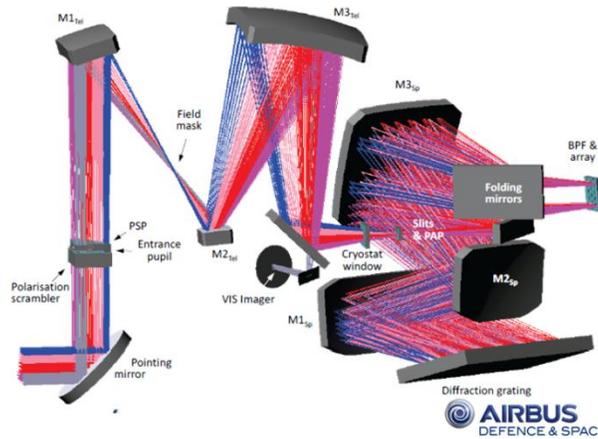


Figure 12. The MicroCarb instrument with 6 freeform optics (Image Airbus)

Microcarb requires medium size optics in the 5 to 20 cm range of size, with high freeform amplitudes varying from 100 to 1000 μm PTV with Zernike terms up to 36, precise figure down to of 20 nm RMS WFE and 2 nm microroughness.

4.3 Progress in IASI NG and MicroCarb optical fabrication

Safran Reosc is proud to have been selected by Airbus for the supply of these two challenging sets of freeform optics: 3 sets of flight optics for IASI NG and 1 proto-flight set of optics for MicroCarb.

At the time of preparation of this manuscript two Microcarb mirrors have been pre-polished down to ≈ 150 nm RMS and will receive soon their R-SiC final polishing layer. Some SiC substrates are still to be delivered to us by Mersen. The full set delivery is planned in the first half of 2019.

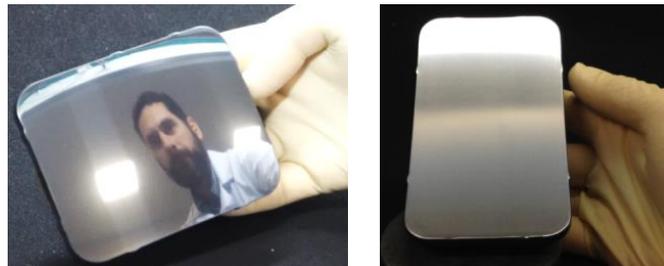


Figure 13. The MicroCarb first two mirrors prepared for R-SiC polishing layer deposition

The IASI-NG FM1 & FM2 sets of optics are finished and delivered to spec. The FM3 is in good progress with nearly 50% of the work completed.



Figure 14. The IASI-NG ATA FM1 set of optics: M1 – M2 – M3 (from left to right)

5. CONCLUSION

We have shown that freeform optics offer new opportunities to improve space instrumentations in term of image quality and distortion as well as volume and mass. More compact optics contribute to reduce the total cost of the system and its launch thanks to the possibility to use smaller platforms. Such advantages are valid for imaging systems as well as for spectrographic instruments.

In this second category, Microcarb is the first European ‘hi-res’ space instrument fully based on freeform optics with severe departure from best sphere up to 1000 μm on 5-20 cm size optics. It is a high-return advanced scientific mission with limited budget that became affordable to CNES thanks to Airbus innovative concept and Safran Reosc skills and capabilities in SiC freeform optics optical manufacturing.

We are also proud to contribute in a similar manner to IASI NG, the next generation of atmospheric sounding instrument to be implemented on-board METOP-SG.

Our robotic polishing technology appears to have been conceived ‘freeform’ right from the beginning more than 25 years ago and it is surprizing that the demand for such freeform optics is only arising recently. We still pursue our efforts to improve our manufacturing and testing processes to become more productive, more accurate and more freeform.

Efficient concurrent engineering and exchanges with our customers in the early stage of the projects are essential for such type of optical instrumentation in order to precisely align both engineering teams on all the details of the optical prescription and to refine all assessments on feasibility and testability of the various optical components.

We are convinced that ceramic freeforms optics will become a state-of-the-art in space optics, enabling more and more advanced instrumentation at better mission cost.

We want to thanks to CNES, Airbus for placing their confidence in Safran Reosc.

REFERENCES

- [1] R. Geyl & al, Safran Reosc, “Recent development for advanced space optics at Reosc”, OPTRON conference, Paris, 2016.
- [2] R. Geyl, Safran Reosc, "Advanced space optics development in freeform optics design, ceramic polishing, rapid and extreme freeform polishing", International Conference on Space Optics (ICSO) 2016.
- [3] J. Reimers & al, University of Rochester, “Freeform spectrometer enabling more compactness”, Light Science & Applications, 2017-6.
- [4] R. Geyl & al, Safran Reosc, “Pushing SiC polishing technology for advanced applications”, SPIE Optical System Design, 2018-5.
- [5] V. Pascal, CNES, "An improved MicroCarb dispersive instrumental concept for the measurement of greenhouse gases concentration in the atmosphere", International Conference on Space Optics (ICSO) 2014.
- [6] L. Georges, Airbus Defense & Space, "The MicroCarb instrument"; International Conference on Space Optics (ICSO) 2016.