PREPARING OPTICAL FABRICATION FOR MICROCARB, FIRST SATELLITE BASED ON FULL FREEFROM OPTICS

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ABSTRACT:

In dec 2015, during COP21, France has initiated the development of the MicroCarb satellite dedicated to better understand the carbon cycle within our atmosphere and to predict its evolution. CNES selected Airbus Defense & Space for the development of the instrument and Safran Reosc has been selected for the optical polishing of the key optical components of this innovative compact spectrometer, the first in EU of its class entirely based on precision freeform optics.

The benefits of freeform optics will be highlighted before introducing to the MicroCarb satellite and instrument optical design.

Our joint design efforts with Airbus Defense & Space towards 'feasible' optics will be presented with the latest technology development at Safran Reosc on freeform optics polishing technology.

1. Benefits of freeform optics

1.1. For imaging instruments

We previously showed to the community[(1), (2)] the benefits of using freeform optics within high resolution space camera in term of compactnes and/or increase of design performance (image quality and/or field of view) with some academic design variations of the of Pleiades payload summerized in figure 1 below.

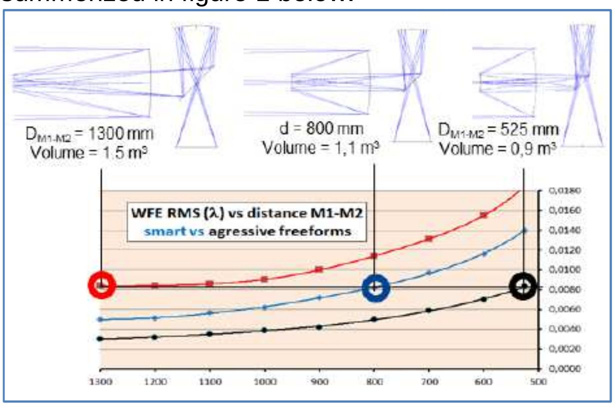

Figure 1. Pleiades WFE RMS vs D_{M1-M2} and freeform

We showed how the design performance (the highest WFE RMS residual through the telescope field fo view) is degrading when one reduces the D_{M1-M2} distance separating the two main mirrors, but also how it improves when smart or more aggressive freeform surfaces are used in the design instead of conventional aspheric off-axis. Freeform surfaces clearly open new horizons in term of lens design for more compact and/or more performance optical system. Other considerations of manufacturability and error budget are not included in this exercise we conducted.

1.2. For spectrometer instruments

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

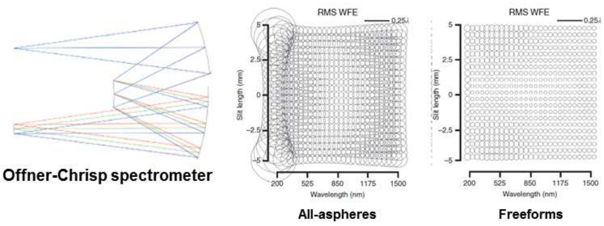

Figure 2. Benefits of freeform within a spectrometer Better performance in same volume (See ref (3))

The introduction of freeform 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, Forbes polynomials which remain 'close' to the natural third and higher order aberration terms. This consideration is no more valid for special applications like illumination which require much more strong deviations from conventional optics and make use of a much wider diversity of surface representations functions.

2. MicroCarb, the CO2 cartographer

2.1. The satellite

The MicroCarb mission was decided during the COP 21 conference on the climate in Paris [(4), (5)].

The project, studied by Cnes since several years, received then the funding for a Phase B study. The phase C/D was initiated a few months later.

The mission of MicroCarb is to perform a mapping of the sources and sinks of the most important greenhouse gas on a global scale. The project is following similar projects like GOSAT in Japan and OCO62 in the US but with:

a) Top level performances

High accuracy	1 ppm
Bias	< 0.1 ppm
Basic pixel on ground	4,5x89 km²
Revisit time	1 week

b) Compactness and low mission cost
Thanks to its implementation on the low profile / low cost Myriade platform developped by Cnes.

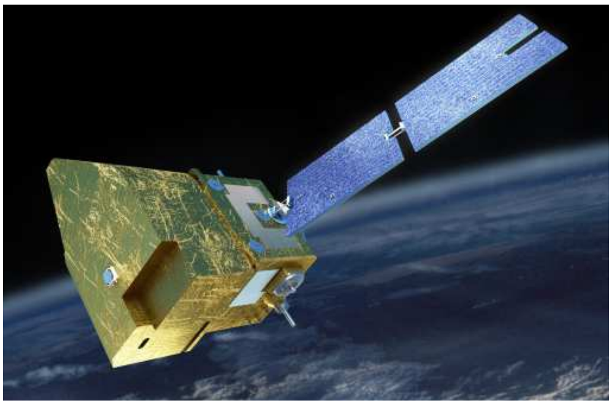
Figure 3. Artist view of MicroCarb satellite

2.2. The MicroCarb Instrument

CNES selected Airbus Defense & Space (ADS) for the development of the MicroCarb instrument. The main principle of the instrument is to measure the absorbed & reflected solar flux in several highly resolved Vis & NIR spectral bands.

MicroCarb is therefore a passive high resolution multiband spectrometer operating with a spectral resolution > 25.000 within four narrow bands around the central wavelengths of 673, 1273, 1607 and 2037 nm respectively.

MicroCarb needing a cooling at low temperature, 150 K for the detector and 220 K for the spectrometer, ADS decided to construct it fully with Silicon Carbide for both the structure and the optical elements in order to reach perfect athermalization.

The spectrometer concept is based on a classical Littrow configuration double pass spectrometer and the multiband capability is performed with a slicing of the entrance pupil and the use of small prisms elements as shown on figure 4.

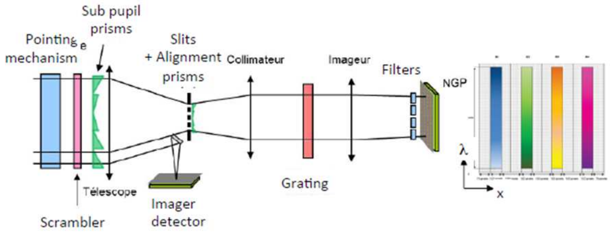

Figure 4. MicroCarb multiband spectrometer concept

A scan mirror, driven by a pointing mechanism, orients the line of sight on the selected ground area during the flight of the satellite.

Several prism elements are slicing the entrance pupil in four subpupils with a slight lateral dviation, thus creating four images of the scene laterally shifted at the focal plane of the telescope.

Several slits are then placed on these images of the scene and are immediately followed by small prisms again to redirect all the beams towards the grating and compacting the spectrometer.

Finally the several spectra are created on the 2D sensor at the camera focal plane behind order separation bandpass filters.

The design of this optical concept with Three Mirror Anastigmat systems for total absence of chromatic aberrations leads to the global instrument sketch shown on figure 5.

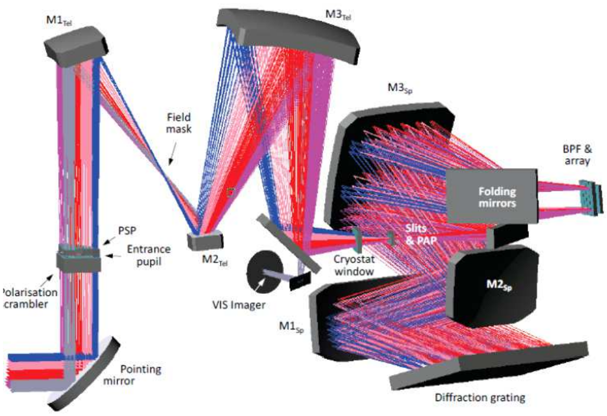

Figure 5. MicroCarb 3D architecture

To keep the instrument compatible with the Myriade microsatellite platform developped by CNES, it appears rapidly to ADS that conventional off-axis optics do not offer the optical performance in the required volume. Therefore the use of freeform mirror design has become an absolute necessity and a key enabler of the mission.

Microcarb is probably the first EU space instrument fully based on high quality multi-freeform optics and is a real breakthrough in space optics. It is also expected that MicroCarb could be the pionneer of a serie of Carbon monitoring instruments at the service of the international community concerned with the greenhouse effect.

3. Manufacturability of MicroCarb optics

Beeing a first of its kind, MicroCarb freeform optics polishing and testing is also representing a new challenge in optical fabrication that ADS placed at Safran Safran Reosc.

A joint engineering phase was conducted between Safran Reosc and ADS in order to well assess the manufacturability and testability of the 6 freeform elements: 3 in the spectrometer optics and 3 in the telescope optics.

3.1. Harmonizing the modelization

The need for modelization harmonization appeared immediately with ADS having designed the optics with X^n, Y^m Taylor expansion while Safran Reosc is more pronoe to use Zernike polynomials for optical design, manufacturing and testing.

It rapidly was shown that the final instrument performance is the same with both type of modelization.

Safran Reosc is using Zernike polynomials in all its metrology software chain as well as in all the robotic polishing equipment running in the company. Switching to Taylor polynomials is of course possible, but would require the rewriting of many software and thus generating new expenses and, above all, risks of software bugs for the project (e.g. wrong freeform shape orientation or term mixing) that could be catastrophic.

After some exchanges with ADS agreement was reached to adjust the freeform optical prescription on the basis of Zernike polynomials.

Other harmonization was made with respect to the optical/mechanical referential linked to the various components.

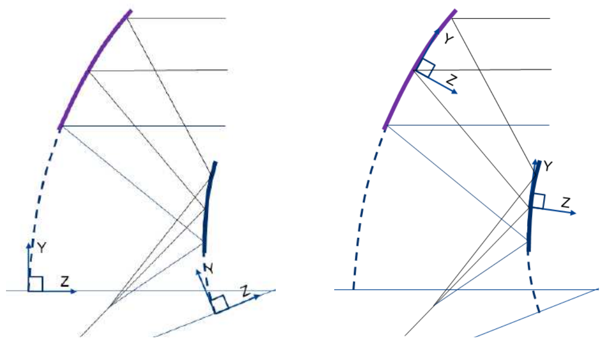

Figure 6. Main optical referential + Tilts & Decenters versus individual referential per mirror

The figure 6 above shows the two possible ways to define the optical axis and mechanical referential into which the optical elements are defined. The traditionnal one is preferrably used by the lens designer while the individual optical referential is more practical during the fabrication. For free-form surfaces, the off-axis definition is no more an advantage for design as it can be compensated by a free-form term. The base radius, the aspheric and freeform terms are thus all defined with respect to the center of the component clear aperture.

Agreement of both parts was reached on the the use of the second method considering it is finally more simple and generating less errors in both design phase and production phase of the optical elements.

3.2. Aspheric departure & Polishing specifications

Several discussions and exchanges have also been conducted on the subject of the aspheric departure, including the freeform terms.

Safran Reosc most similar optics produced in the past are the James Webb Space Telescope Near IR Spectrometer (NIRSpec) optics fabricated in the years 2008-2010. These were 3 sets of 3 TMA systems with similar optics dimensions (10x10 cm to 30x30 cm), also made from Silicon Carbide, but with conventional off-axis optical profile and aspheric departure in the range of 10 to 400 µm.

Figure 7. JWST NIRSpec optics, conventional off-axis

For MicroCarb, the aspheric departures from best sphere are now at a higher level:

PTV asph. departure	450 – 1300 µm
Max slope	30 mrd
Zernike terms	up to 36

The instrument operating from Vis to IR, the polishing requirements specified by ADS remain similar to the one of a visible optics with excellent reflected wavefront error.

These high freeform shape and tight polishing specifications required for this project constitute a real breakthrough in optical manufacturing challenge of this project and are a true 'premiere' for space optics in Europe.

New technologies are therefore to be developped or refined a) at Mersen Boostec for the accurate freform generation of the SiC substrates, b) at Safran Reosc for accurately polishing and testing such small size, highly aspheric optics toward high level of optical specifications and c) at Airbus leve for the full system alignment and testing.

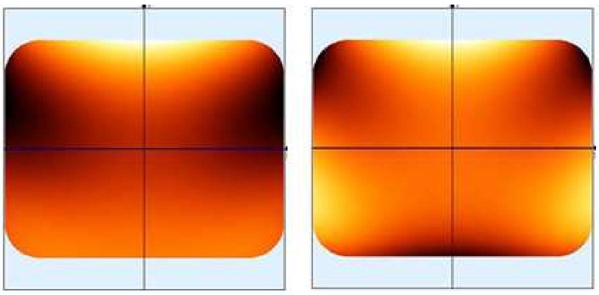

Figure 8. M2 Spectro aspheric profile
Left : wrt best sphere Right: wrt best torus
590 µmPTV 320 µm PTV

As example, we show the main aspheric properties of the secondary mirror of the spectrometer TMA system. The deviation from best torus clearly shows an unusual triangular pattern of high amplitude.

4. R-SiC polishing layer

Silicon Carbide is recognized since several years as a very interesting material thanks to its outstanding characteristics of high Young Modulus and thermal diffusivity leading to very attractive merit factors like specific stiffness E/ρ and Thermal stability under transients α/D. In addition, SiC offers an excellent resistance to harsh environments and accepts high temperatures. Brazing technology allows the realization of large mirror substrates as well as structural components, thus leading to very efficient all-SiC large opto-mechanical architectures.

Airbus Defense & Space (ADS) has developed superb space optics based on Mersen-Boostec SiC technology like the Herschell 3.5-m sub-millimeter telescope, the GAIA ultra-accurate astrometer, the family of NAOMI space cameras and the NIRSpec cryogenic IR spectrograph.

Since the beginning, REOSC has developed all its best efforts to be the European expert in SiC optics polishing. From an optical fabrication perspective SiC has the drawback of remaining porous or inhomogeneous and cannot be polished bare to visible quality, i.e. down to 1-2 nm micro-roughness residuals.

To overcome this difficulty, the today solution is to deposit a layer of Silicon Carbide material under Chemical Vapour Deposition (CVD). This layer is perfectly dense and can be polished to much better roughness performance.

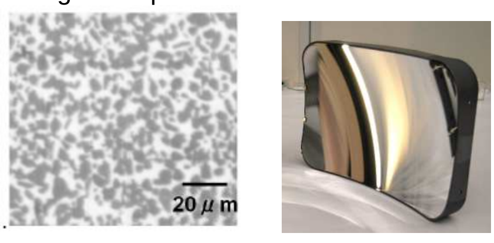

Figure 9.SiC is porous and needs a polishing layer

But CVD SiC is also very hard and this constitutes the challenge for the optician due to a removal rate close to 10x lower than for glass or glass-ceramic. This difficulty is now fully mastered by REOSC's technicians.

To reduce all these difficulties linked to SiC polishing Safran Reosc team has developed an alternative polishing layer for SiC mirror substrates we named R-SiC.

This is a specific glassy layer deposited in-house with a sufficiently high thickness in order to be post-polished efficiently with our deterministic robotic polishing technology. After some internally funded development the European Space Agency (ESA) awarded Safran Reosc with a R&T contract where several samples, demonstrator and qualifications works have been conducted on the subject.

Figure 10.R-SiC demonstration on 20-cm mirror

Today the R-SiC technology is mature and confirms its advantages under many aspects:

- 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
- Easy removal and repair in case of problem
- Low CTE mismatch with bare SiC and cryo qualification.

ADS selected R-SiC as the polishing layer for MicroCarb and this represents another 'première' for the project, beeing the first real space optical program using the R-SiC polishing layer.

5. Specific optical machinery

MicroCarb will make use of recently installed robotic machinery specially designed for small size optics in the range of 5-40 cm. These are driven by exactly the same command-control system than all other robotic equipment in the company.

MicroCarb will also benefit from our small Ion Beam Figuring (IBF) equipment designed for 5-30 cm class optics, fitted with small Ion gun footprint down to 1-mm which will allow Safran Reosc to accurately conduct the final fuguring cycles over all the steep aspheric optics of the instrument.

6. CONCLUSION

Microcarb is an exciting new type of space optics project thanks to its full freeform profiles, high aspheric departure from the sphere, high precision, Silicon Carbide optical elements.

The project is the opportunity to make new steps in advanced space optics along various directions:

- Design skill for very compact new generation optical payloads thanks to smart or extreme freeform optics surface.
- R-SiC polishing layer, a new alternative to the CVD SiC, which offer various cost-schedule-risk advantages during the development of SiC space optics.
- Maturation and industrialization of robotic optical manufacturing toward smoother optics produced at high rate and with small edge margin.

Airbus Defense & Space thank CNES for the confidence they put in theyr respectives company engineers and technician.

7. References

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