ICSO 2016

International Conference on Space Optics

Biarritz, France

18–21 October 2016

Edited by Bruno Cugny, Nikos Karafolas and Zoran Sodnik

Advanced space optics development in freeform optics design, ceramic polishing, rapid and extreme freeform polishing

R. Geyl

H. Leplan

E. Ruch

esa icso proceedings cnes

International Conference on Space Optics — ICSO 2016, edited by Bruno Cugny, Nikos Karafolas,
Zoran Sodnik, Proc. of SPIE Vol. 10562, 105623S · © 2016 ESA and CNES
CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2296212

ADVANCED SPACE OPTICS DEVELOPMENT IN FREEFORM OPTICS DESIGN, CERAMIC POLISHING, RAPID & EXTREME FREEFORM POLISHING

R. Geyl, H. Leplan, E. Ruch
Safran Reosc, France

I. INTRODUCTION

In this paper Safran-Reosc wants to share with the space community its recent work performed in the domain of space optics. Our main topic is a study about the advantages that freeform optical surfaces can offer to advanced space optics in term of compactness or performances. We have separated smart and extreme freeform in our design exploration work.

Our second topic is to answer about the immediate question following: can we manufacture and test these freeform optics? We will therefore present our freeform optics capability, report recent achievement in extreme aspheric optics polishing and introduce to the industrialisation process of large off axis optics polishing for the ESO Extremely Large Telescope primary mirror segments.

Thirdly we present our R-SiC polishing layer technology for SiC material. This technique has been developed to reduce costs, risks and schedule in the manufacturing of advanced SiC optics for Vis and IR applications.

II. BENEFIT OF SMART & AGRESSIVE FREEFORM

Beyond axisymmetric aspheric surfaces and off-axis segments of such axisymmetric optics, there are other shapes of optical surfaces generally called freeform. These includes X^m,Y^n, Zernike, Legendre or Forbes polynomials, spline progressive functions or simply optical surfaces described by a step file, … and others !

Up to very recently, the use of such type of optical surfaces within a space optical system was very rare mainly for manufacturing and testing reasons, and consequently costs, but also for lack of skill about the best way to optimize such surfaces toward the goal required by some specific applications. This may change rapidly.

In order to assess the situation and challenge our optical manufacturing skill, REOSC conducted several work on the evaluation of the benefit of such optical surfaces within common optical systems.

We also wanted to analyze the differences in term of benefits and advantages when using ‘smart’ freeforms, i.e. of moderate amplitude and waviness, or ‘agressive’ freeform with more significant departure from best fitted off axis conic.

The specimen we used for this study work is in fact the optical design of the present Pleiades dual use earth observation system, considered as today’s state of the art. Its mains specifications are:

Aperture	650 mm
EFL	13-m
FoV	1.6° in y with 0.1° offset in x

It is a so-called Korsch type Three Mirror Anastigmat (TMA) with 1300 mm distance between M1 and M2 mirrors. The WFE error at worst field point is 0,0083 λ = λ/120 RMS. The volume of the optics is roughly evaluated to 0.65x1.95x1.2 = 1.5 m3

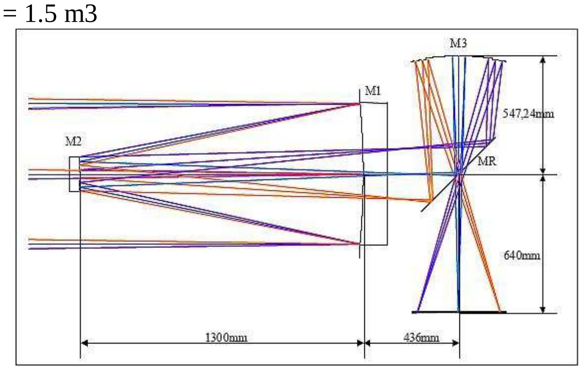

Fig. 1. Pleiades design

The key questions we asked ourselves were:

- Can smart freeforms improve the telescope WFE performance?
- Can they allow to reduce size of the optics?
- Can they allow other improvements?

A. Smart freeform

A first study work consisted in comparing conventional design and design with smart freefrom involved. We also studied the evolution of the wavefront error (WFE) performances when the M1-M2 distance is progressively reduced and the optical formula re-optimized at each step.

During this work the optics behind the primary was intentionally left unmodified in architecture. But all radii and aspheric terms, including freeform, were varied during the investigations. Interesting results have appeared as shown on the Figure 2 below.

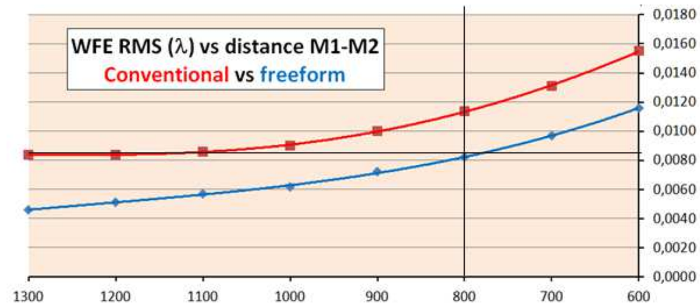

Fig. 2. Performance vs M1-M2 distance and use of smart freeform within the system.

A first comment about the conventional design case is that one could have reduced the M1-M2 distance to 1100 mm without any significant loss in nominal performance. Then, the WFE residuals are progressively increasing up to 0.0160 λ RMS when M1-M2 distance is reduced down to 600 mm.

When smart freeform are used, the previous curve is significantly dropping down by quite 50% for 1300 mm M1-M2 distance with only 0,0045 λ RMS. For 600 mm distance the WFE RMS is only 0,0120 λ.

One sees that, with such smart freeform, the same design performance as the original Pleiades is obtained for only 800 mm M1-M2 distance. This is a nice advantage, because it would mean less volume (0.65x1.45x1.2 = 1.13 m^3), therefore less weight and less inertia for the payload, thus improved satellite agility and/or lifetime. Figure 3 shows the telescope in this configuration.

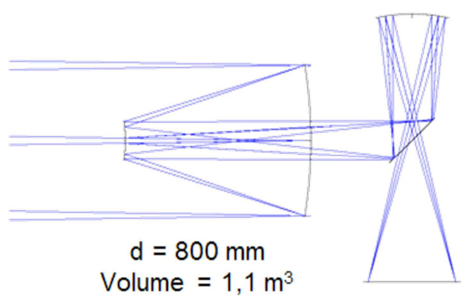

Fig. 3. Compact Pleiades with smart freeforms (same scale as original Pleiades design)

Furthermore, a nice secondary benefit was found with the evolution of the distortion. When reducing the M1-M2 distance from 1300 mm to 800 mm it appears that the distortion is also decreasing significantly from 2% to 1.4% only. This is not a general result but has been obtained 'by chance' on this optical configuration.

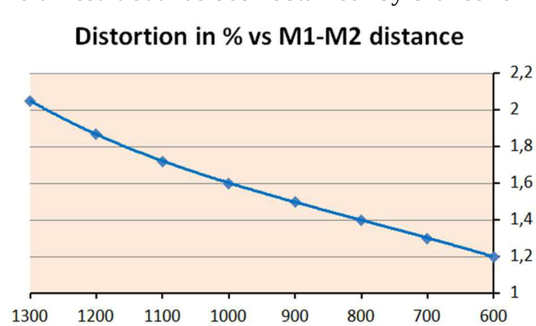

Fig. 4. Distortion reduces with M1-M2 distance

B. Aggressive freeform

In a second investigation work we allowed higher amplitude, or so-called 'aggressive freeform', to develop within the system. This is bringing additional benefits as per the figure below.

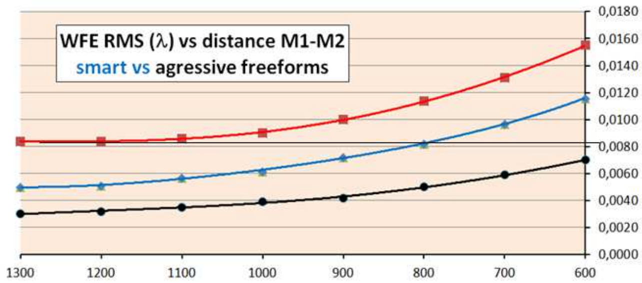

Fig. 5. Introducing extreme freeforms

In this case, the performance for 1300 mm M1-M2 distance is dropping further by 30% to 0,0030 λ RMS only. The 0,0080 λ RMS of the conventional Pleiades design is reached for a M1-M2 distance evaluated to 550 mm only, a very short distance.

Figure 6 below is showing the some freeform surface departures from off-axis aspheric segments. It starts with 1 µm PTV only trefoil shape and can go up to 100 µm or more, but with much unusual optical shape.

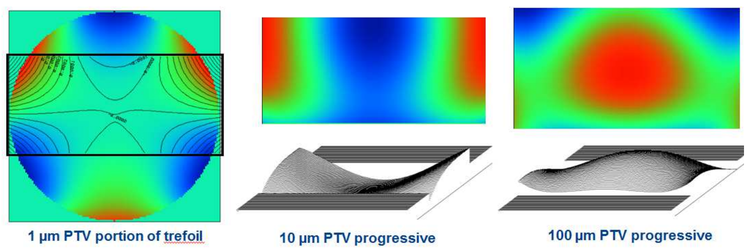

Fig. 6. Some freeform departure from off-axis asphere

This study works has clearly shown that smart and aggressive freeform surfaces can clearly allow to drastically re-visit the whole families of space optical camera designs and to gain either in WFE performance or in volume for the same optical performance, or along both directions.

III. Toward new generation space cameras

Another study work was then conducted at REOSC to develop advanced telescope designs that would bring significant system advantages with:

- Significantly smaller volume
- Low distortion
- 2D FoV for latest generation CMOS sensors

We developed several designs with following characteristics:

- Pupil diameter of 650 mm (same as Pleiades)
- 2D FoV of 2.1° x 0.7°
- Distortion < 0.1%
- Volume <0.5 m3

The exact details of these designs shall remain confidential and, in any case, they shall be adapted to the precise system specifications. But clearly, new trend is now possible thanks to freeform surfaces toward much more compact optical space payloads as shown below.

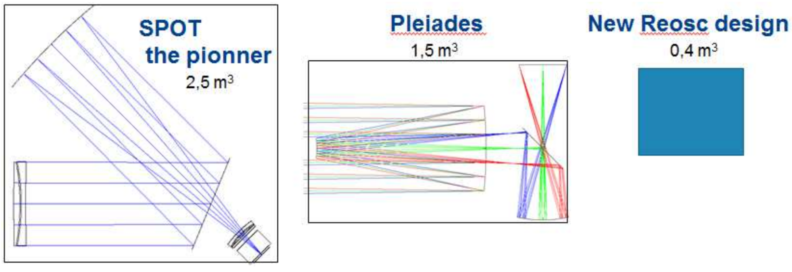

Fig. 7. New REOSC Space Camera design compared to SPOT and Pleiades

IV. Advanced large freeform optics manufacturing

Space optics manufacturing is also a domain where REOSC has recently made significant advances. These progresses were stimulated by three key projects conducted within the company in the past years.

A. Segments for the GTC

In year 2000, REOSC was selected by Gran Telescopio Canarias (GTC) for the optical fabrication of the 36 segments (+ 6 spares) constituting the 10.5-m primary mirror of this telescope. These segments have hexagonal contour with 1.8-m peak to peak dimension. The aspheric departure from best fit sphere is going up to 250 µm and the optics specification was set by GTC below 20 nm RMS WFE.

An additional challenge was to produce these optics at a rate of 2 segments per month, which we did!

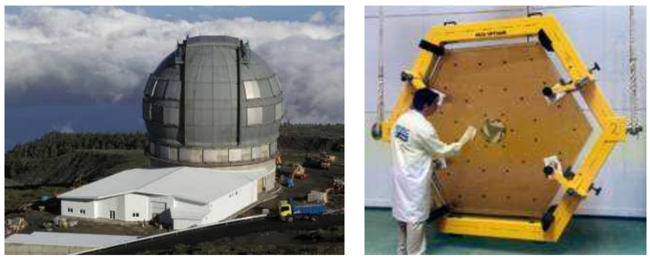

Fig. 8. GTC optics

B. TMA optics for NIRSpec

In 2005, REOSC was selected by ESA for the supply of 3 sets of Three Mirror Anastigmats (TMA) for the NIRSpec spectrograph installed on-board the James Webb Space Telescope (JWST).

In total this project represented 27 small off-axis segments made from Silicon Carbide with typical dimensions in the range of 10 – 40 cm. The aspheric departure went up to 1000 µm and the optics specification down to 20 nm RMS WFE.

These tough optics were produced at a rate of 1 optics per month.

Fig. 9. NIRSpec optics

C. E-ELT proto segments

In 2008, REOSC was selected by the European Southern Observatory (ESO) for the supply of seven prototype off-axis segments of the 39-m primary mirror of the European Extremely Large Telescope (E-ELT).

The giant E-ELT project will in fact need 798 segments (+ 133 spares), of 1.45-m peak-to-peak size, for the construction of its primary mirror. Its construction has been recently decided by ESO Council.

The aspheric departure is going up to 750 µm and the optical specifications ask for low amplitude 10 nm RMS WFE residuals and tight control over the mid spatial frequency residuals. These pieces shall be ultimately produced at a rate of one segment per day!

Fig. 10. E-ELT Proto segment

The roadmap that REOSC is pursuing on the basis of these recent projects is dedicated to produce advanced space and astronomy optics in a completely new industrial manner with:

Dimension	: in the 100 to 1800 mm range
Material	: Zerodur or SiC
Profile	: off-axis asphere or freeform
Aspherization	: up to 1000 µm or more.
Mid spatial	: 5-10 nm RMS smooth surfaces

Productivity is the new paradigm. REOSC has completely revisited its optical production shop with standardized processes and world unique self-developed technology and equipment. Productivity has drastically evolved from one meter-class optics per year to several tens or hundreds per year.

Beyond overall figure, smoothness of the optical surface is becoming more and more important for high resolution optical systems or systems fitted with active optics. This smoothness is the new key performance parameter required for ultimate resolution systems. The E-ELT efforts have led us to significantly progress in this direction.

Today we have organized our production facility with one fab-line dedicated to 100–500 mm optics and a second fab-line for 500–1800 mm optics. Another specific shop area is dedicated to SiC optics processing.

D. Extreme freeform optics demonstration

Laser science is undergoing dramatic evolution with ultra-short pulses going down to the picosecond and femtosecond regime, thus generating very high peak power once focused on the specimen. Laser scientists are targeting peak illumination intensity of 10^{22} W/cm² with multi Petawatt systems presently under construction. The light interaction with matter becomes very strong and opens new domains of physic and material research.

In this fs regime refractive materials are no more allowed because refractive index dispersion of glass is causing a temporal broadening of the ultra-short laser pulse, thus leading to losing the fs regime. Therefore beam transportation and focusing is mainly done with plane mirrors and… off-axis parabolas.

At the focal station, the beam size can go up to 400 mm or more. But a key parameter is the beam deviation angle. With low beam deviation angle, easy to manufacture, the scientists are forced to squeeze their instrumentation in a narrowly constrained volume, while 90° deviation and high output NA would provide some ‘comfort’ and science power.

REOSC decided to manufacture a prototype extreme OAP meeting the ideal demand for new generation multi PW laser system. Its key parameters are presented on the following table:

Clear aperture diameter	500 mm
Beam deviation	90°
Output NA	F/2.5
WFE	λ/10 RMS
Mid spatial frequ. errors	< 1 arcsec or 80% EE in Ø 10 µm
High spatial frequ. errors	µ-roughness < 1.5 nm RM S
Cosmetic defects	S/D : 20/10 (MIL Std)

The parent mirror of such AOP shall have a vertex radius of curvature of 1250 mm and should be produced with a total diameter exceeding 3-m in order to be able to extract the off-axis segment. In clear, such OAP must be produced directly off-axis.

The aspherical departure from best fit sphere is around 11-mm over the 500 mm clear aperture and goes up to 19-mm over the 600-mm mechanical diameter optics fabricated. To our knowledge the optical manufacturing of such an extreme OAP has never been reported.

As expected the extreme aspheric shape of this piece caused some difficulties during its profile generation, its lapping and polishing stages. These required some adaptations of our robotic polishing processes which were however quite rapidly solved. Again, this is showing the robustness and flexibility of the REOSC robotic optical manufacturing technology and its capability to handle extreme off-axis and freeform optics for new scientific instrumentation.

Final achieved performances of the extreme OAP are:

WFE residuals	37.3 nm RMS	
Encircled Energy	80% in Ø 5.2 µm	Slope = 0.93 µrad RMS
Micro-roughness	1.2 nm RMS	
Cosmetics	Scratch/Digs 20/10	

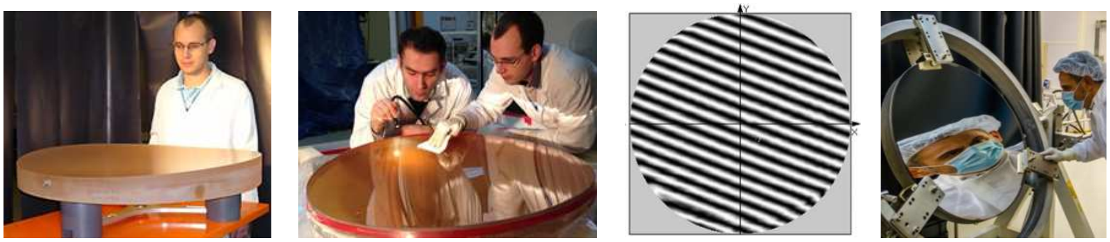

Fig. 11. The extreme OAP as lapped, polished, interferogram and coated

The skill and knowledge gained with this extreme OAP prototyping activity will be re-used soon for the polishing of main mirror of the MERLIN lidar receiver instrument. We hope it will also open the way towards new design concepts within the science community that were not conceivable in the past years.

V. 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 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 antenna, 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 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 dense and can be polished to much better roughness performance.

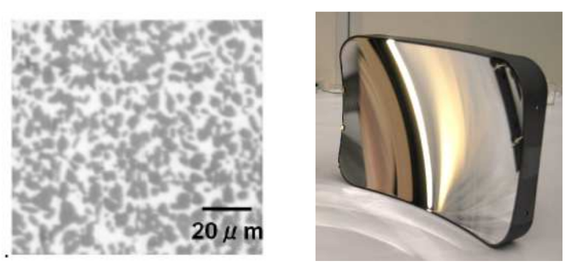

Fig. 12. SiC is porous and needs a polishing layer

But CVD SiC is also very hard and this is a challenge for the optician. This difficulty is fully mastered by REOSC's technicians and the pair of GAIA large primary mirrors, polished down to 9 nm RMS figure are a perfect example of this our unique skill on the subject.

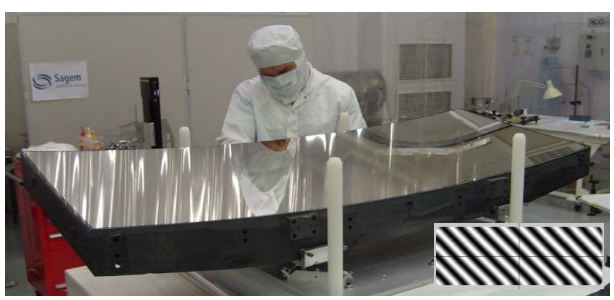

Fig. 13. 150x56 -cm GAIA primary mirror in SiC polished to 9 nm RMS

Another issue is the size limitation of the CVD high temperature deposition chambers. However REOSC team recently developed an alternative polishing layer for SiC mirror substrates we named R-SiC.

This is a specific glassy layer deposited in-house and that is sufficiently thick in order to be post polished with our deterministic robotic polishing technology.

The European Space Agency (ESA) awarded REOSC with a R&T contract where several samples, demonstrator and full qualification process have been conducted.

Fig. 14. R-SiC demonstration

Today the R-SiC technology is mature and offers 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
- Removability and repair in case of problem
- Low CTE mismatch with bare SiC and cryo qualification.

VI. CONCLUSION

REOSC has made new steps in the domain of advanced space optics along various directions:

- Design skill development for very compact new generation optical payloads thanks to smart or aggressive freeform optics surface.
- Maturation and industrialisation of large freeform optics robotic manufacturing technology towards smoother surfaces and higher production rate.
- Capability to produce extreme off-axis (or freeform) optics
- R-SiC polishing layer developed as a new alternative to the CVD SiC layer and offering various cost-schedule-risk advantages during the precision polishing of SiC optics.

VII. THANKS

We thank our customer ESA, ESO, CNES and the various main contractors for the confidence they are placing in Safran Reosc skills and capabilities.

Thank for our lens design team and optical manufacturing team for the efforts in the domain of smart, aggressive and extreme freeform optics.