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The TROPOMI Telescope

Design, fabrication and test of a freeform optical system

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Abstract—**In this paper, we discuss the two-mirror pushbroom telescope for TROPOMI. Using freeform optics, it has unprecedented resolution. The complete cycle of freeform optical design, analysis, manufacturing, metrology and functional test on a breadboard setup is described, focusing on the specific complexities concerning freeforms. The TROPOMI flight telescope will be manufactured in summer 2012.**

freeform optics; asphere; metrology; TROPOMI; NANOMEFOS

I. Introduction

The TROPOspheric Monitoring Instrument (TROPOMI) is an advanced absorption spectrometer for Earth observation, developed in the Netherlands under contract to NSO and ESA in the frame of the ESA GMES space Component Programme [1]. It is a pushbroom instrument that combines a very large field of view of 2600 km with a 7 km resolution and a spectral range encompassing UV, UVIS, NIR and SWIR bands. It is scheduled for launch in 2015. The telescope has aperture f/9 x f/10 and is capable of imaging the entire 108° swath with a resolution nominally better than 0.02°. This corresponds to a sub-km spot size on earth. The high resolution allows assembly of the telescope with mechanical tolerances, without the need for alignment. The unprecedented viewing angle and resolution are realized with an optical system consisting of only two mirrors. In order to correct the geometric aberrations and maintain the resolution over the entire viewing angle, both mirrors are freeform mirrors without any rotational symmetry.

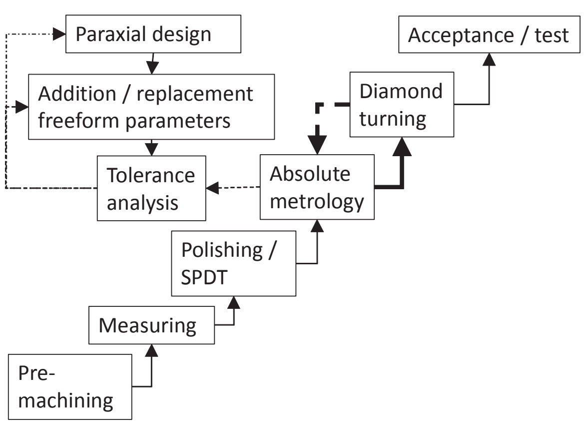

Figure 1. Freeform manufacturing value chain. The bold arrows indicate an iterative loop

The application of freeform mirrors as opposed to conventional surfaces makes it possible to arrive at a telescope design consisting of a minimal amount of elements yet with a superior performance, which is advantageous from the point of view of stray light, throughput, mass and opto-mechanical complexity. Yet with the benefits of using freeforms come disadvantages of a more complex design, analysis and manufacturing process.

At TNO, we are involved in the total chain of design, tolerance analysis, manufacture and test, including freeform designs, see Fig. 1. In this paper, the full cycle of the manufacturing process of the TROPOMI telescope from design to test will be presented. The design and tolerance analysis of the unconventional surface forms will be described. A prototype of the telescope has been built. The fabrication and measurement steps of the freeform surfaces will be reported and the telescope performance will be demonstrated.

II. Design of the telescope

The TROPOMI mission is the successor of OMI [2]. The measurement principle is illustrated in Fig. 2. TROPOMI is a push broom instrument imaging a very wide field of view on earth on a rectangular slit. The slit is relayed to four spectrometers for four different channels (UV, UVIS, NIR, and SWIR). In one direction, the spatial information is resolved

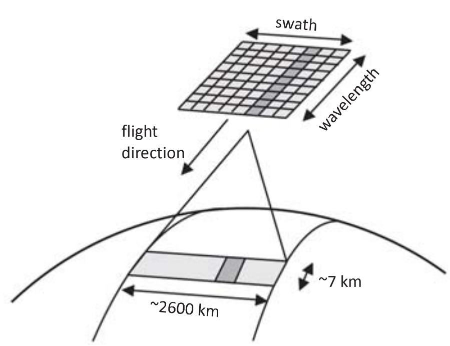

Figure 2. TROPOMI measurement principle

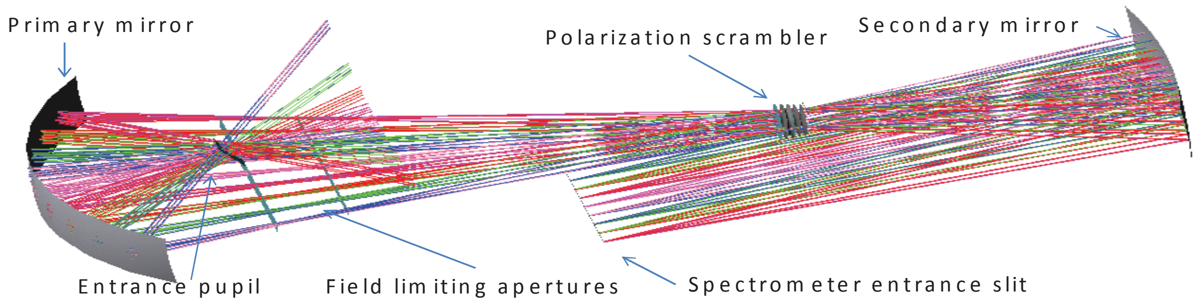

Figure 3. 3D view of TROPOMI telescope

over the long direction of the slit. This direction is referred to as the swath direction. In the other direction, spatial information is resolved by 'sweeping' over the earth surface as the telescope orbits the earth at orbit height of circa 800 km. This is the flight direction. In this paper, the focus will be on the layout of the telescope; the remainder of the instrument will not be discussed. Telescope design and analysis was done with the optical simulation software CodeV.

A. Design with freeform mirrors

The telescope is shown in Fig. 3. Light from earth passes the entrance pupil and is reflected by a concave primary mirror that forms an intermediate focus. The intermediate focus is imaged by a second concave mirror on the spectrometer entrance slit. The entrance pupil is imaged in the focal plane of the second mirror, where the physical pupil stop is located. This has the advantage that the light beams leave the telescope nearly parallel (i.e. the image is telecentric), which eases the design of the spectrometers, keeping the dimensions small. Near the pupil stop a polarization scrambler is placed to make the telescope polarization independent. In the vicinity of the intermediate focus, two field limiting apertures are present: one limits the field in the swath direction and functions as an actual field limiter. The other limits the field in the perpendicular direction (referred to as flight direction). The latter functions as a baffling aperture. The telescope is an almost perfect f-θ system: the angle in the swath direction in the entrance pupil depends linearly on the position in the slit. In the flight direction, the angle in the entrance pupil depends quadratically on the position in the slit. This latter effect is called 'smile', after the shape of the field of view in the entrance pupil.

For future reference we define a coordinate system in which the x-axis points substantially outside the drawing plane (along the broad direction of the primary mirror) and the y-axis lies substantially inside the drawing plane (along the narrow direction of the primary mirror).

A telescope with two conventional spherical mirrors was applied in OMI [3]. It has comparable field of view and a nominal resolution of circa 0.5°. TROPOMI could only be realized with a telescope that has an order of magnitude improvement in the nominal resolution. One notable change in the mirror shape is the application of toroidal mirrors, i.e. mirrors with different radii of curvature in two perpendicular directions. This enables the realization of an anamorphic telescope (i.e. a telescope with a different focal length in the spatial and spectral direction), in which the spatial and spectral resolution performance can be optimized separately. This change alone does not improve the performance of the telescope, but it is advantageous for spectrometer dimensioning. The TROPOMI telescope has an anamorphotism of two: the focal length in the spectral direction is twice the focal length in the spatial direction.

The major improvement in resolution is realized by investigating the aberrations in more detail. For clarity it is advantageous to consider the optical train from slit to earth. In this approach, the slit is imaged by the secondary mirror, and the dominant aberration in the intermediate image is astigmatism (which is also evident from the large distance between the two field limiting apertures). Note that this would also be the case for spherical mirrors because of the high angles of incidence. The astigmatism in the intermediate image is atypically field dependent: the blur does not increase quadratically with field angle, which is common for third order astigmatism. By virtue of the location of the primary mirror in the optical train, this mirror is especially suited to correct this aberration. It is located close to the field such that different field points are spaced relatively far apart yet for individual field points different ray intersection points on the mirror do not coincide. As such, the astigmatism can be corrected locally by introducing additional toroidicity on the primary mirror, and furthermore, the corrective toroidicity is even allowed to vary over the field. The means of correction works especially well because of the anamorphotism of the telescope, that requires a basic toroidicity in the first place. The correcting shape that is superimposed on the toroidal primary mirror resembles a x-cylinder with power that depends linearly on the y-coordinate. The surface shapes of both the primary and secondary mirrors are represented by means of a xy polynomial,

$$z = \frac{cr^2}{1+\sqrt{1-(1+k)c^2r^2}} + \sum_{m,n} c_{m,n}x^m y^n \qquad (1)$$

in which c and k represent the curvature and conic constant.

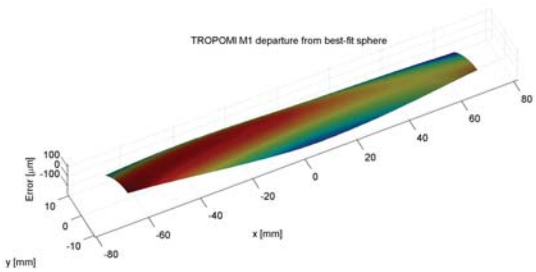

Figure 4. Deviation of nominal primary mirror surface with best fit conic

The size of the mirrors is approximately 100 mm. The deviation from a sphere is several tenths of mm. For the primary mirror, the deviation from a conic is shown in Fig. 4.

The performance gain from using freeform mirrors and an anamorphic telescope is shown in Fig. 5, where rms spot size is plotted versus field angle. It is seen that the resolution of the freeform telescope is a factor of 10 to 30 better and remains much more constant over the field. The resolution in terms of full-width 50% value is better than 0.02° in the swath direction and better than 0.01° in the flight direction, over the full field. Note that 7 km resolution at an orbit height of 800 km corresponds to 0.5°. In the instrument breakdown, a contribution of 0.05° to the resolution is allocated to the telescope. It is evident that the conventional spherical OMI telescope would not meet this requirement, especially taking into account the inevitable alignment and fabrication errors.

The magnification of the telescope is 0.6 mm/° in the swath direction and 1.2 mm/° in the flight direction, e.g. a separation of 0.6 mm in the long direction of the slit corresponds to an angular separation of 1° in the entrance pupil. Being an f-θ system, the focal length in the swath direction remains constant throughout the field. The magnification in flight direction drops to about 0.9 mm/° at the edge of the field. The focal lengths are 34 mm and 68 mm, respectively. The freeform telescope is described in more detail in [4].

B. *Tolerance analysis*

To progress from the nominal design, which is only the first step towards a fully functional system, first a tolerance analysis must be done to investigate the impact of misalignments and errors in fabrication. Most software packages provide standard means to investigate the influence of alignment tolerances. Surface errors are often described in terms of a deviation of regular or cylindrical power, typically expressed in terms of peak-valley surface figure deviation. Thus, low spatial frequency errors are addressed. This analysis was executed for the TROPOMI telescope in a conventional approach.

On the other hand, for freeform surfaces that are fabricated in a non-conventional way, it is important to address higher spatial frequency terms as well. These midspatials are typically surface form errors that have a few to tens of periods over the work piece. Surface roughness is not included in this frequency regime. To analyse the impact of these form deviations, we made use of CodeV advanced features of user defined surfaces and user defined tolerancing. Surface errors are described as a sag error added to the nominal surface. The nominal surface is an *xy*-polynomial with up to eight higher order terms. The sag error is a periodic cosine-shaped concentric or linear ripple with arbitrary period and amplitude. The surface consisting of *xy*-polynomial including ripple is implemented by means of a compiled user defined surface. CodeV allows a concentric ripple as a tolerance in its standard tolerance analysis, but not in the elaborate user defined tolerancing that is needed to perform the full tolerance analysis of the telescope.

The performance degradation resulting from midspatial errors can be evaluated by computing the metric of performance (e.g. resolution) for a number of amplitudes (typically from 0 to 1 micron) and periods (a few to tens of periods over the clear aperture). It is thus assumed that the actual midspatial surface errors that can be expected from the fabrication process can adequately be represented by an idealized ripple when also varying the period ripple over a large interval.

It was seen that the performance metric (resolution) increased proportionally with the amplitude of the ripple, and inversely proportional with the spatial period. Thus it appears plausible to put a requirement on the maximum slope of the surface error rather than maximum amplitude (or peak-valley surface figure deviation) when targeting an estimated total performance (i.e. including nominal performance, fabrication errors and alignment errors).

The tolerance analysis predicts that misalignments on the order of 100 µm can be tolerated without compensating means, which is in line with the desire to mitigate complexity of the assembly of the telescope, i.e. **post-assembly alignment is not necessary**. For the primary and secondary mirror the tolerance analysis predicts an allowed slope error of 0.2 mrad and 0.04 mrad, respectively. With these tolerances, and including the alignment tolerances, the requirement of 0.05° resolution is met.

As a final verification step, the performance was computed for a large number of spatial periods while maintaining the fixed maximum allowed slope error. From these analyses, the surface shape tolerances were determined and converted to a form consistent with the standard for optical drawings. For the purpose of discussion here, it is sufficient to consider the maximum allowed slope error.

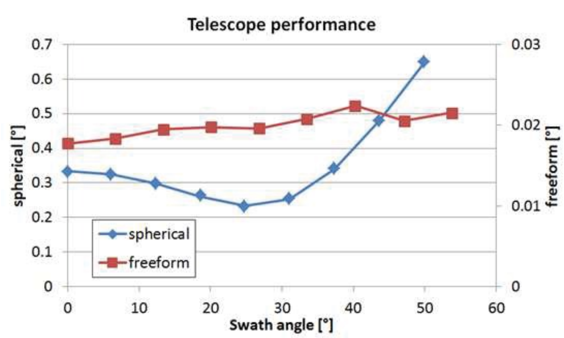

Figure 5. Comparison between conventional and freeform telescope

III. MANUFACTURING

A prototype of the telescope was built to verify the freeform manufacturing process, the performance of the telescope, and the tolerance for alignment. In this section, details of the manufacturing process will be reported.

A. Diamond turning

The freeform mirrors cannot be manufactured using conventional tools. They are both non-spherical and have no axis of symmetry. The sag of the non-rotational symmetric terms varies on the order of 1 mm. In addition to requirements on resolution, which dictates the form and the tolerances on the surface shape, other issues to deal with are throughput and stray light, dictating requirements on reflectivity and roughness, respectively.

The material of choice for the freeform mirrors is Aluminium-6061. It can be machined by diamond turning, and it allows the realization of an athermal design. Manufacturing is done on a Precitech 700A single point diamond turning (SPDT) machine. The work piece is rotated and translated, the diamond turning tool moving relatively in the perpendicular direction to follow the contour of the surface. An important disadvantage is the residual surface roughness: after diamond turning, a roughness of typically 7 nm (Rq rms) remains. This is unacceptable for the application.

The solution can be found in Nickel Phosphorous plating pre-turned Aluminium bodies. The amorphous NiP layer of approximately 100 micron thickness can be finish turned to a roughness of Rq 2 nm. A subsequent light hand-polishing operation will remove the toolmarks of the turning process, without changing the overall shape. The resulting roughness will be below Rq of 1 nm. The mismatch in thermal expansion may cause bi-metallic bending, but for the present case the detrimental effects are limited in the operating temperature range and can be accepted.

In view of the large deviations from spherical shape, the diamond turning machines could not be used in fast servo mode but rather in slow servo mode. Slow servo mode allows larger deviations at the cost of longer processing times: with a rotation speed of 20 to 50 revolutions per minute, a processing time of up to 30 hours was necessary for these freeform surfaces. Long processing times adversely affect the form accuracy because of e.g. thermal and mechanical stability of the machine setup.

In addition to the rotation speed, the step over distance per revolution (groove distance) is a tuneable parameter to optimize the manufacturing process. Large step over gives shorter processing time (and consequently better figure accuracy) yet increased surface roughness. Small step over leads to better surface roughness at the cost of form accuracy, as well as tool wear. Balancing surface figure and roughness, the telescope mirrors were turned at an intermediate step over of circa 10 micron. A final manual polishing step reduced the roughness to 1 nm while maintaining surface figure.

Finally, a bare aluminium coating will be applied on both surfaces for reasons of reflectivity and polarization sensitivity.

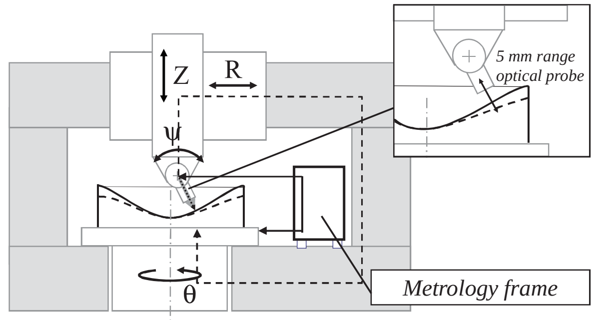

Figure 6. NANOMEFOS machine concept with long range optical probe and separate metrology frame

B. Measurement

Suitable absolute metrology is a key ingredient in the freeform production chain. Specifically for freeform measurement we have developed a unique absolute metrology tool called NANOMEFOS that has the capability of non-contact measuring surfaces with an uncertainty better than 15 nm rms [5]. It is fast, universal, and can accommodate large work pieces. Typical sampling speed is as high as several tens of thousands of points per minute. Its measurement volume is ∅500 mm x 100 mm. The NANOMEFOS machine scans the surface with an optical probe, and therefore has variable point spacing. Sampling point distance is in practice limited by measurement time. For measuring form, ~0.1 to 1 mm is usually applied, but also line scans with µm point spacing can be applied, thus giving the possibility to perform measurements over a very large spatial frequency range.

The measurement concept resembles a giant cd-player (see Fig. 6). The product is mounted on a spindle, rotating at typical speed of a few rpm around a θ axis. As the product rotates, the non-contact optical distance probe moves in radial and vertical (RZ) direction. Mounted on a rotation axis ψ it is continuously being positioned perpendicular to the best fit (rotationally symmetric) aspheric fit of the product. The probe follows focus with an additional stage with a range of 5 mm. Thus, NANOMEFOS is able to measure any freeform surface with a that has up to 5 mm (PV) maximum deviation with respect to the best fit aspheric (convex or concave) surface.

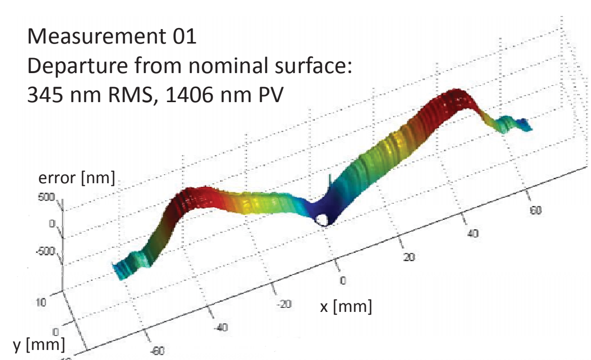

Figure 7. Primary mirror departure from nominal surface

Figure 8. Setup of the telescope breadboard

From the absolute metrology data, the departure from the nominal surface is obtained by fitting the data to the nominal surface, allowing translations and rotations as degrees of freedom. In Fig. 7, the measurement of the first prototype primary mirror is shown, after diamond turning and polishing. The plotted surface is the departure from the nominal surface shape. A substantial low spatial frequency ripple is seen. The slope error is on the order of 0.06 mrad. Thus, the requirement for the primary mirror is met, and we are already close to the requirement for the secondary mirror without corrective machining.

The surface roughness was measured on a Wyko NT9300 using phase shifting interferometry.

IV. Breadboard setup

Even though corrective machining steps are necessary to meet the requirements for the secondary mirror, the fabricated mirrors are used in a breadboard setup without further iteration. The breadboard setup is used to demonstrate the performance of the telescope, which is possible since we are already close to the surface form requirement. Also, the important step that the telescope can be assembled without any post-alignment steps can be verified.

For the breadboard setup, an optical table was designed on which primary and secondary mirror, slit plate and pupil stop can be mounted at their nominal positions, with tolerances dictated by the tolerance analysis. A perfect collimated HeNe laser beam is positioned in front of the telescope and functions as a light source, mimicking the light from earth. The optical table is mounted on a rotation stage and a tilt stage. The rotation stage is used to perform measurements at different swath angles. The tilt stage is used to follow the ‘smile’ of the telescope. The setup is shown in Fig. 8. The laser beam illuminating the primary mirror is visible.

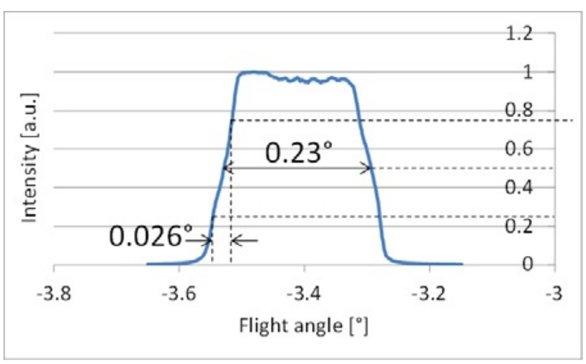

Figure 9. Spot scan in the flight direction, central field

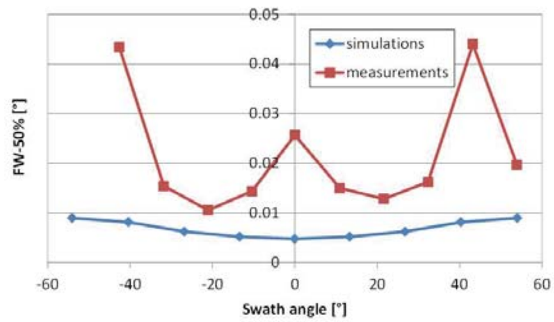

Figure 10. Resolution (FW-50%) of breadboard telescope measurement and simulation

The slit plate contains several square apertures with side 280 μm. This corresponds to the width dimension of the spectrometer entrance slit. Performing a scan with the rotation and tilt stages, the spot profile of the telescope can be measured in swath and flight directions. All measurements are performed with an angle resolution of 0.001°. In Fig. 9 for the central field a spot scan in the flight direction is shown. The FWHM width is 0.23°, which is consistent with the magnification of 1.2 mm/°. The FW-50% is 0.026°. This is considerably worse than the nominal performance of 0.01°, which is to be expected in view of the surface form error and alignment errors, yet it is well within the requirements for the telescope, and fully consistent with the budget allocated for the telescope, as mentioned above in the tolerance analysis section. The performance over the full field is shown in Fig. 10. Note that this is ten times better than the conventional spherical design used in OMI, moreover considering no alignment was applied.

V. Conclusion

For TROPOMI a pushbroom telescope was designed that combines a very high resolution of better than 0.1° with a large field of view of 108° and a f/9 x f/10 aperture. Applying fully freeform surfaces, the telescope could be realized using no more than two mirrors. The improvement over predecessor OMI would not have been feasible without the freeform design.

A rigorous tolerance analysis has been performed, focusing on manufacturing errors of the freeform surfaces (i.e. surface figure deviation) over a broad spatial frequency range. Also alignment errors were taken into account. It was shown that the required performance can be met.

The freeform mirrors were manufactured using single-point diamond turning Nickel plated Aluminum in slow servo mode and a manual post polishing step to level off the tops of the turning pattern and obtaining a surface roughness of 1 nm rms. A crucial step in the manufacturing process is the metrology to verify the surface figure. For this step, we applied our specially developed unique absolute metrology tool NANOMEFOS.

The freeform mirrors were used in a breadboard telescope setup to test the performance including the surface figure deviations and realistic alignment errors, as they will also appear in a flight telescope (the alignment tolerances for the breadboard setup and the flight telescope design are similar, and no compensators are used.)

The resolution performance requirements were met in the breadboard setup, giving confidence on the feasibility of the freeform telescope in TROPOMI. The flight telescope mirrors are similar but not identical to the breadboard mirrors because of later optimization steps in the telescope, including polarization scrambler and minor changes in the dimensions. The mirrors for the flight telescope are scheduled for manufacturing in summer 2012.

ACKNOWLEDGMENT

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