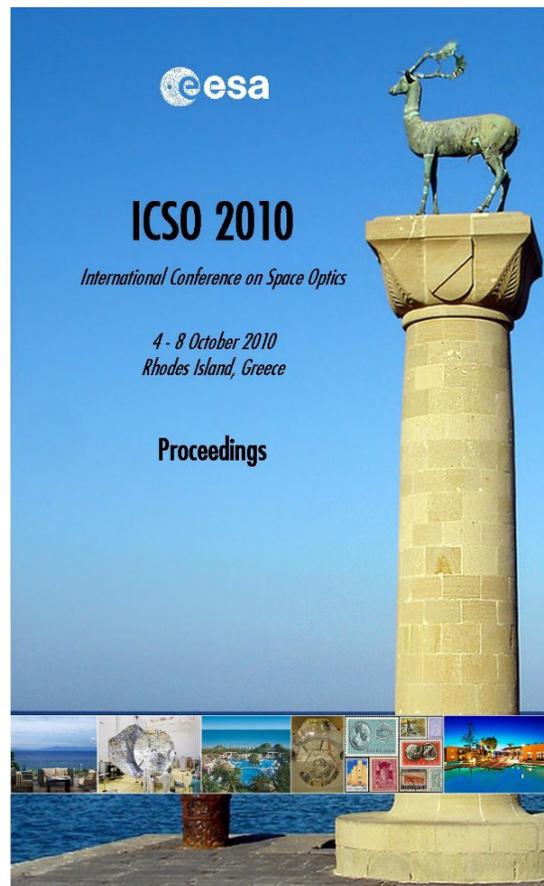


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DESIGN, MANUFACTURING AND TESTING OF A FOUR-MIRROR TELESCOPE WITH A WIDE FIELD OF VIEW

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I. INTRODUCTION

Regarding Earth observation missions, it has become unnecessary to point out the importance of making available wide field of view optical instruments for the purpose of spectral imaging.

Taking advantage of the pushbroom instrument concept with its linear field across the on-ground track, it is in particular relevant to consider front-end optical configurations that involve an all-reflective system presenting inherent and dedicated advantages such as achromaticity, unobscuration and compactness, while ensuring the required image quality over the whole field.

The attractiveness of the concept must be balanced with respect to the state-of-the-art mirror manufacturing technologies as the need for fast, broadband and wide field systems increases the constraints put on the feasibility of each individual component.

As part of an ESTEC contract, AMOS designed, manufactured and tested a breadboard of a four-mirror wide field telescope for typical Earth observation superspectral missions.

The initial purpose of the development was to assess the feasibility of a telecentric spaceborne three-mirror system covering an unobscured rectangular field of view of 26 degrees across track (ACT) by 6 degrees along track (ALT) with a f-number of 3.5 and a focal length of 500 mm and presenting an overall image quality better than 100 nm RMS wavefront error within the whole field.

II. SYSTEM SPECIFICATIONS

Table 1 summarizes the system specifications, taken as the baseline for the feasibility study.

Table 1. System specifications

Spectral range	400 nm- 2400 nm
Focal length	500 mm \pm 10 mm
Aperture	f-number 3.5, unobscured
Field of view (FOV)	Rectangular, 26 degrees ACT by 6 degrees ALT
RMS wavefront error	Lower than 100 nm RMS within the whole FOV; flat focal plane
Smile (distortion)	Lower than 0.15 mm
Telecentricity on image side	Better than 1 degree
Mass	45 kg
Allocated volume	750 x 750 x 600 mm ³
Operational temperature range	293 K \pm 5 K
Vibration testing	Against ESA PSS-01-802

III. OPTICAL DESIGN

On the basis of a first survey of potential solutions backed by optical design simulations and manufacturing considerations, preliminary features of the wanted three-mirror system were put forward:

- for compactness reasons, a pure three-mirror anastigmat (TMA) solution should be preferred with a concave-convex-concave sequence
- the aperture stop is preferably placed on the secondary mirror (M2)
- regarding the order of precedence within the specifications, the priority is put on the image quality over the required field and aperture

The optical configurations were analysed using design optimisation softwares (ZEMAX and CODEV). Different sets of merit functions were considered, the best results being obtained by switching from the standard RMS wavefront error to the standard PTV spot radius, characterized over a rectangular grid of 21 points within the FOV.

Other operands were used to put boundaries to the values of relevant parameters such as focal length, telecentricity, distortion and mirror/focal plane curvature.

Distance between the mirrors, decentring and tilts were limited to avoid vignetting.

Despite a lot of simulations, we were unable to find a suitable solution with three mirrors within the specified volume. In that case, the best maximum value for the residual RMS wavefront error in the FOV was still near 350 nm.

In order to get additional free parameters for the optimisation, a fourth mirror was included in the simulations. The most convenient way to proceed is to add this mirror in front of the other ones, keeping the stop on the same mirror as before (which becomes the tertiary mirror), the drawback being that a fairly large convex mirror is unavoidable (primary or secondary mirror). Despite the difficulties to manufacture a large convex off-axis asphere, this solution was preferred to drastically reduce the size of the primary mirror and control the overall telescope mass.

The study was concluded on a four-mirror configuration, which was very near coping with all the requirements, although some vignetting appeared for the full size field along track (from $\pm 2^\circ$ to $\pm 3^\circ$), nevertheless keeping the optical quality acceptable.

A lay-out of the selected optical configuration is presented in **Fig.1**.

On a half FOV of 13° by 4° , the residual wavefront error is illustrated in **Fig.2**; the FOV WFE residual map is symmetrical with respect to the telescope vertical axis.

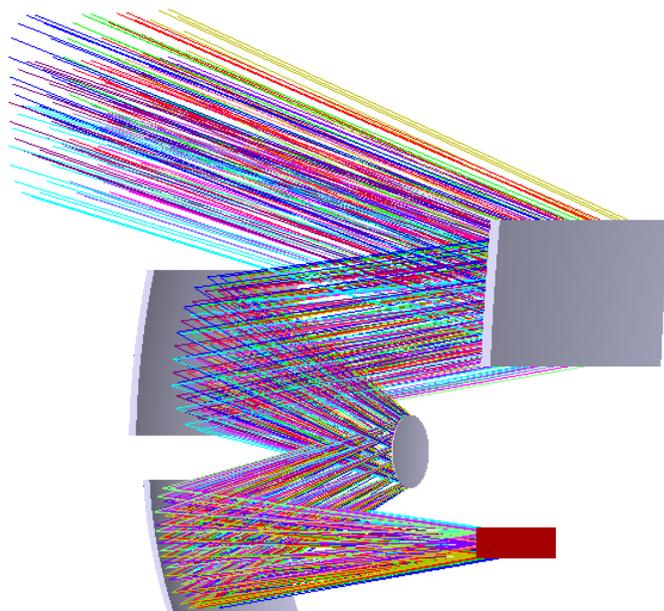


Fig.1. Four-mirror optical lay-out

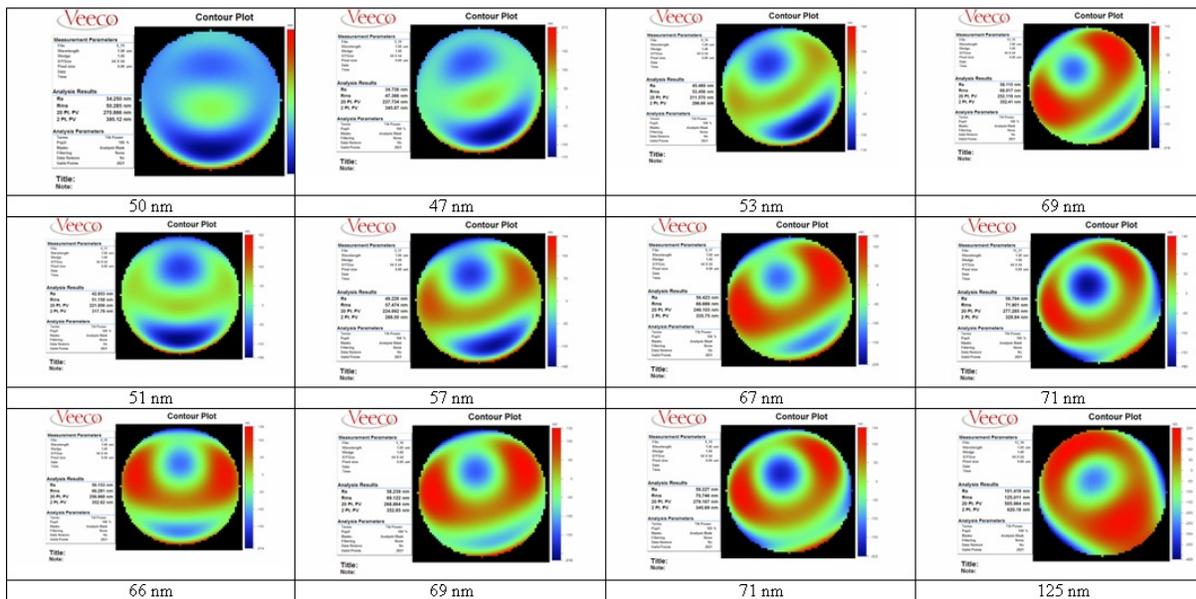


Fig.2. Wavefront error design residuals in nm RMS within the FOV (0 to13°; -2°to 2°)

The values for the other parameters (telecentricity, smile) are within the targets.

IV. MANUFACTURING ASSESSMENT

A first assessment is given by the steepness of mirror asphericity, which can be expressed by the mirror sag and slope departure to best fit sphere.

From that point of view, it appears that M1 and M2 off-axis mirrors are the most challenging to produce. In particular, M1 is a convex mirror of 560 mm by 240 mm and has the following features:

Best fit sphere departure : 625 μ m
Slope departure : 13 mrad

Regarding those parameters, it is clear that specific manufacturing and control techniques had to be developed.

Considering the objective of mass optimization in balance with the critical aspects of mirror manufacturing and testing , it was decided in agreement with ESTEC to adopt a conventional approach involving lightweighting operations within standard materials for the telescope mirrors and structure.

Mirror substrate was chosen to be ZERODUR within an INVAR structure.

We nevertheless selected silicon carbide for the substrate of one mirror (M4) as a specific manufacturing aspect to be treated as part of the development.

A detailed error budget was first established regarding the telescope WFE performance, which included the relevant contributors; the telescope alignment procedure was built in accordance with a global tolerance analysis. An ASAP straylight analysis was also performed to guarantee the design adequacy with state-of-the-art radiometric requirements of such a telescope. Direct stray paths to the focal plane were identified with the aim to be blocked by baffles.

It was considered that the gravity deflection at the mirror and structure levels had to be included in the overall budget as a contribution to image quality degradation. In this sense, the 0-g release contribution was not to be taken into account during telescope alignment. In counterpart, the mirror mounting scheme had to be analysed in detail to demonstrate that the gravity deflection in the testing configuration could be rendered acceptable.

A lightweighting configuration for mirrors M1, M2 and M4 was determined. This was not needed on M3, due its geometry and low mass contribution. The compromise held on the lightweighting scheme was to save mass as much as possible while keeping under control the quilting effects due to polishing pressure and the gravity deformation within the on-ground testing configuration.

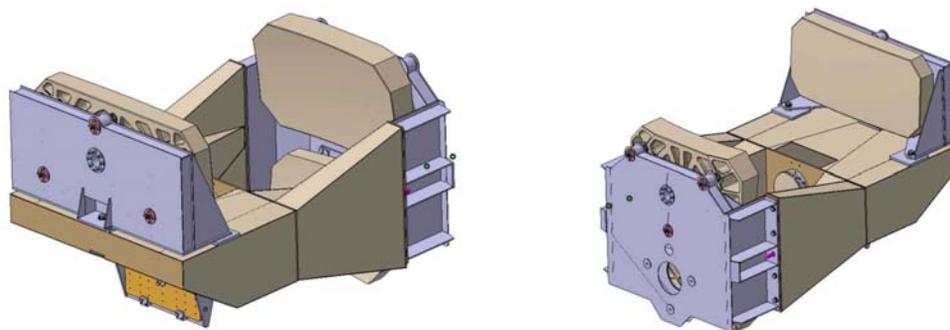


Fig. 3. Telescope opto-mechanical concept view

A mirror mounting scheme and a telescope structure able to cope with the gravity deflection during testing, the thermal operational environment and the launch vibration environment were defined.

The mass figure we obtained after the whole set of optimisation runs for an Invar- Zerodur design is 80 kg. When considering the vibration testing requirements, we checked the effect of the required spectrum on the telescope structure. The calculated efforts were taken into consideration for sizing the mirror cells. From the upper considerations and after detailed analyses, the telescope optomechanical design was frozen. It is illustrated in **Fig. 3**.

V. MANUFACTURING

Mirror manufacturing showed a lot of challenges due to the high degree of asphericity presented by the mirrors. Specific direct off-axis techniques were used with computer-controlled mechanical polishing for Zerodur mirrors and ion beam figuring for the CVD-SiC mirror.

The mirror main manufacturing characteristics are given in **Table 2**.

The design of the test benches involved detailed analyses and in particular, the large M1 convex mirror required the development of a specific equipment devoted to stitch several subapertures to reconstruct the full aperture phase map.

The M1 mirror is manufactured with respect to an off-axis concave master, which is the reference face of the test plate component.

This test plate also has the purpose of giving the correct illumination angles to the mirror, through its toric entrance face.

The concave master is measured in a null test with a computer-generated hologram (CGH).

Mirror M1 is controlled afterwards against its concave counterpart in a Fizeau test configuration.

The specific character of this bench is that it is only acting on nominal 320 mm diameter subapertures of M1 and that it allows a stitching operation to be performed between the M1 subapertures through a dedicated rotation capability.

This configuration was imposed by the unusual aspect ratio of M1 (560 mm by 240 mm) to avoid the manufacturing and the use of a huge test plate.

The test bench configuration of the mirror M1 is presented in **Fig. 4**.

Table 2. Mirror characteristics

	<i>Substrate</i>	<i>Manufacturing</i>	<i>Sizes</i>	<i>Test</i>
M1	Zerodur	Convex, direct off-axis	Rectangular 560 mm x 240 mm	computer-generated hologram + test plate and stitching interferometry
M2	Zerodur	Concave, from parent shape	Rectangular 472 mm x 272 mm	computer-generated hologram
M3	Zerodur	Convex, on-axis	Circular, diameter 120 mm	computer-generated hologram + test plate
M4	Silicon carbide + CVD layer	Concave, direct off-axis	Rectangular 410 mm x 220 mm	computer-generated hologram

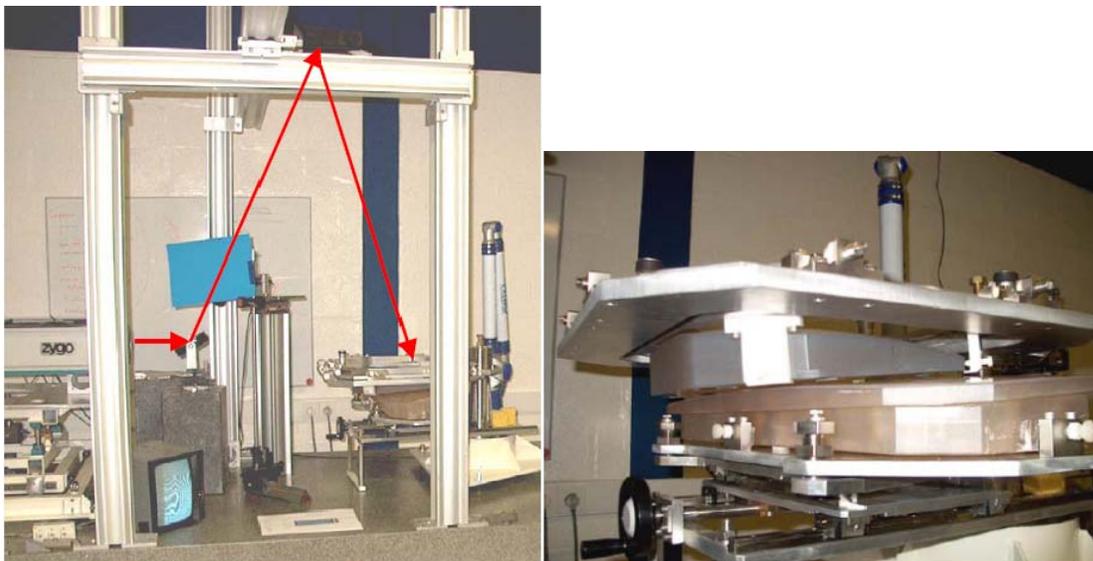


Fig.4. Primary mirror test bench

VI. ALIGNMENT AND TESTING

The as-built error budget for telescope wavefront quality within the FOV before final alignment is shown in **Table 3**.

The aimed average image quality in the field (115 nm RMS) is slightly beyond the initial targeted specification (100 nm RMS).

The mirrors were coated with a protected silver coating and integrated in their respective cells. The alignment process was conducted with the help of a 3D machine (CMM).

The alignment session began with the setting of mirrors M2 and M4; M2 was the reference frame for the whole alignment and M4 was aligned with respect to M2.

Then the telescope main structure was integrated and M3 was aligned with the CMM.

We proceeded afterwards with the M1 integration.

The final step consisted in finely adjusting the M1 position with the telescope controlled in double pass thanks to the use of an ACflat. An aid from an optical software was called for this process.

This step was conducted for three field lines (ACT) over the ALT direction (**Fig.5**).

At the end of alignment, the measured field wavefront error map in a common focal plane was the following (**Fig. 6**):

Table 3. Telescope WFE error budget

Contributors	WFE in nm Rms
M1 final figure	34
M1 test accuracy	15
M1 mounting and gravity	5
M2 final figure (including test accuracy, mounting and gravity)	24
M3 final figure (including test accuracy, mounting and gravity)	19.5
M4 final figure (including test accuracy, mounting and gravity)	23
Alignment	55 nm
Design residuals (average)	85 nm
TOTAL RSS	115 nm



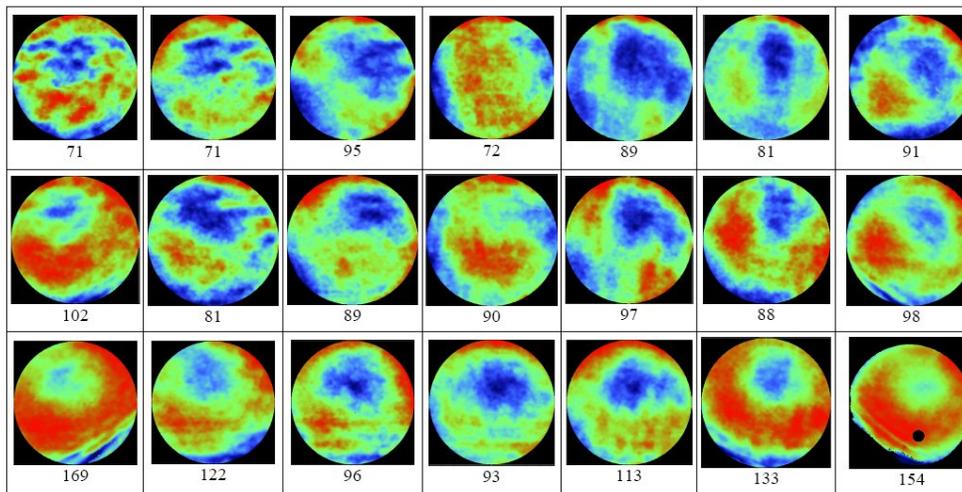
Fig.5. Telescope alignment set up

The average value stands below 100 nm RMS, well inside the as-built budget of 115 nm RMS. After integration and alignment, the telescope underwent vacuum thermal cycling and vibration testing with success, keeping the overall image quality within the budget.

VII. CONCLUSION

The feasibility of the wide field telescope was finally demonstrated with a four-mirror configuration. The most critical steps in the development were the manufacturing and the control of the convex primary mirror (stitching interferometry) and the telescope alignment process, which was a lengthy operation. Despite those difficulties, AMOS succeeded in bringing forth the required hardware and technology to meet the initial objectives of the project.

A potential further step would consist in optimising the telescope mass with the use of high performance structural materials in order to get a device adapted for space use. It is expected thereby to gain a 1.5 factor on the mass.



Moyenne : 99.7 nm

Fig. 6. Measured WFE in nm RMS at the end of telescope alignment