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THE 3,5M ALL SIC TELESCOPE FOR HERSCHEL

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ABSTRACT

Placed on the L2 Lagrangian point, **Herschel** operates in the spectral range between 80 and 670 µm wavelength and is devoted to astronomical investigations in the far-infrared, sub-millimetre and millimetre wavelengths.

The **Herschel** Telescope is an **“all Silicon Carbide” Telescope**, based on a 3.5-m-diameter Cassegrain design. The driving requirements are the large diameter (3,5m), the WFE to be kept below 6µrms despite the operational temperature (70K), and finally the mass to be kept below 300kg.

The size of the Telescope has put some challenges in the manufacturing and the tests facilities installations. At this stage, the major critical phase which is the brazing of the primary mirror has successfully been passed.

The development and manufacturing of the Herschel Telescope is part of the Herschel Planck program funded by the European Space Agency (ESA).

1 INTRODUCTION

Based on the 1,35m FIRST demonstrator experience, the Herschel “all-SiC” Telescope, using Boostec (Bazet, France) Silicon Carbide material for the reflectors and the major Telescope structure, and joining/bonding technologies developed by Astrium/Boostec, is under manufacturing.

Its architecture allows to comply with the specification of light weight (300kg) and low sensitivity to thermal environment, which guarantees a WFE of less than 6µ, with purely passive thermal control.

2 TELESCOPE DESCRIPTION

The Herschel Telescope is a pure Cassegrain design composed of a fast and large parabolic primary mirror and a hyperbolic secondary mirror.

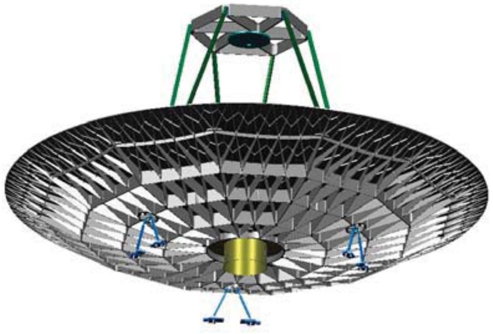

Figure 2-1: Herschel Telescope view

The Telescope focal length is 28,5m, the F/number: 8.68, with a field of view of 0,25°. The secondary magnification is 16.29.

The total height is 2m from the top to the interface plane. The focus is 800mm after the interface plane.

Primary reflector (M1)	
Radius of curvature	3500 mm
Conic constant	-1
Distance to M2	1587.998 mm
Secondary reflector (M2)	
Radius of curvature	345.2 mm
Conic constant	-1.279
Diameter	308.12 mm
Image surface	
Radius of curvature	-165 mm
Conic constant	-1
Diameter	246 mm
Distance to M1	-1050 mm

Figure 2-2: Telescope optical design parameters

The Telescope major constituents are:

- The **primary reflector** (M1), 3.5m diameter, made of twelve silicon carbide segments brazed together at high temperature. The optical coating, deposited after polishing, is Aluminium with a protective layer of Plasil. Invar inserts are screwed on the primary reflector SiC interfaces. The inserts lower side interface with the bipods and the upper side with the hexapod invar fittings

- 3 Quasi-isostatic bipods, made of titanium, supporting the primary reflector, interfacing with the rest of the satellite.

- The **secondary reflector** (M2), also made of SiC, mounted on its SiC barrel by tilt and focus adjustment shims.

- The **hexapod assembly**, also made of SiC: The hexapod legs are equipped with invar fittings glued on both ends. They are connected to the primary reflector inserts by screwing and to the M2 SiC barrel by gluing.

- The **passive thermal control** based on low emissive shields (kapton VDA) protecting the back side of M1, the hexapod legs, and the barrel. The low external emissivity is driven by the straylight considerations. A set of heaters, hanged to the back side of the primary mirror are operating at the beginning of the life for decontamination process.

- In order to avoid the Narcissus effect on the detectors, the central part of the secondary mirror is shaped in such a way that no parasitic reflected beam can enter back in the focal plane

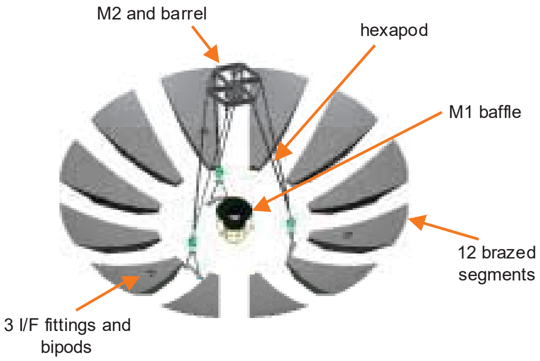

Figure 2-3: Exploded view of the Telescope

3 TELESCOPE PERFORMANCES

The main performances predicted for the Telescope at this stage are:

- The **WFE budget** at nominal focus (for the complete FOV): 5,3 µm rms in the Herschel range 80 µm to 670 µm, in cold conditions,

The major contributors of the WFE budget are the polishing tolerances of the primary mirror, specified to 3µrms, and the cool-down effect, evaluated to 2,5µrms. This last contributor covers the global effect of the cool-down from ambient to the operational temperature (70K), and the local effects coming from the different materials behaviour. The thermal gradient effects are very low, due to the good conductibility of the SiC.

- The **overall transmission**: 0.975 EOL, which has been verified through qualification environmental tests on samples,

- the **roughness**, of less than 30nm rms, directly obtained by polishing, without CVD layer,

- The self emission is better than 10%,

- The occultation ratio is 7,7%,

- The **alignment figures**: the on axis best focus position is kept inside a cylinder of height +/-5 mm and diameter +/-5 mm, the pupil (M2) is positioned with an accuracy of +/- 2 mm in lateral,

the major contributors of the Telescope alignment are the accuracy of the secondary mirror integration, and the wave front sensor accuracy.

- The **mass** is predicted to be below 300kg, with an optical skin thickness of 2,5 to 3mm,

This budget takes into account the integration positioning constraints on segments before brazing, as some optimisation between mass, curvature radius, and brazing parameters has to be done.

-The **first frequency** is predicted to 97Hz in longitudinal, 45Hz in lateral,

-The quasi-static loads, that can withstand M1 and M2 respectively are 12g and 12g in longitudinal, and 10g and 35g in lateral,

4 INDUSTRIAL FACILITIES

- SiC parts manufacturing: To manufacture and test such a large piece as the primary mirror, adaptation of existing facilities and procurement of new ones have been done. All these new facilities have been verified through intensive campaigns, and have followed a formal qualification process before operations on the flight hardware.

The main efforts have been done in the SiC production for which an extension of the Boostec facilities has been done. The most significant investments have been a sintering oven, able to sinter 2 segments together, and a brazing oven, 4m diameter capacity. Large milling and grinding machines, able to cope with the segments length (1,5m) and reflector diameter have also been procured. These facilities are fully operational, and have produced the flight primary reflector, now ready for polishing.

Figure 4-1: sintering oven

Figure 4-2: brazing oven

- primary mirror polishing: A new polishing facility has also been installed at Opteon (Finland) allowing to control and polish the primary mirror. 3 major devices have been installed:

- The polishing machine, of 4m capacity.

- The swing arm profilometer, used during the lapping phase, allowing to measure the WFE with an accuracy better than 1µrms.

- The pentaprism device, used during fine polishing, allowing to measure the WFE with an accuracy better than 0,5µrms.

These facilities have been tested, using the 1,35m demonstrator, and have successfully passed their qualification review.

Figure 4-3: Opteon polishing facilities

Figure 4-4: the 4m polishing machine

- coating: As only astronomical observatories have the capacity to operate such sizes, the coating is realized in the existing Calar-Alto Observatory facilities (Spain), using a specific Aluminium coating procedure qualified by Astrium, with a protective layer of Plasil.

- Optical tests facilities: The optical tests of the Telescope have required the adaptation of a vacuum test chamber at CSL (Belgium) of 6m diameter, called Focal XXL. This chamber is compatible with Helium cooling and allows the implementation of the Telescope alignment tower, also used in clean room.

Figure 4-5: vacuum chamber Focal XXL

5 DEVELOPMENT POLICY AND QUALIFICATION APPROACH

The **model policy** consists in the delivery of 1 proto-flight Telescope model, and strategic spare pieces among them another blank for the primary mirror which is the main critical piece of the Telescope program. No development model has been found necessary as the qualification of the FIRST 1,35m demonstrator was successfully performed under vibrations and thermal vacuum.

The lessons learnt from the demonstrator have been completed on local scale-1 mock-ups and samples to verify the local behaviour in cryo-environment (bipods connections mock-up, CTE measurements and technological qualifications on samples).

Figure 5-1: bipods connection mock-up

Dedicated **process qualification** reviews have been held for each new process or facility. The performances of each machine has been tested through full scale representative mock-ups:

- complete segments for the milling, flat grinding, sintering, brazing, and circular grinding operations,
- the FIRST 1,35m demonstrator for the polishing, and for the coating.
- full scale external shape mock-up, representative in dimensions and interfaces, built for training on handling, transportation, and facilities installation.

Figure 5-2: full-scale mock-up for handling and transportation rehearsal

Stringent **manufacturing controls** have been defined in order to secure the ceramic pieces at each manufacturing or assembling step. A specific incremental control sequence has been defined, from the powder production up to the final Telescope assembling and testing:

- The ceramic powder batches are characterized on sintered samples and tested before the machining of each flight piece. At this step, the powder batch is accepted or rejected on the criteria of mechanical strength and of properties dispersion, expressed in Weibull modulus.
- For each SiC piece, a static proof-test, covering the dynamic stresses, is performed. Combining the proof-test results and the powder properties, the qualification of the pieces can be assessed.
- Once brazed, the M1 reflector is equipped with its flight bipods and submitted to a vibration proof-test after final grinding. This control approach guarantees the safety of the reflector for its integration on the Telescope, and its testing.

- The M2 support structure, once assembled by gluing, is also proof-tested in order to cover the qualification loads.

The **qualification of the product** is obtained by tests, on the Telescope and on samples, for technologies as gluing and coating. After assembly and alignments, the Telescope is qualified under environmental conditions:

- acoustic and sine tests at qualification level.
- thermal cycling between 70K and 323K
- thermal balance at around 110K in the flight configuration including the thermal insulations.

The WFE performances are measured before and after the environmental tests, and at operational temperature during the thermal cycling. The optical transmission is measured on samples, in cryo environment, in the Herschel band.

The technological procedures (gluing, grounding) are qualified separately on samples between 55 and 323K.

6 TELESCOPE INTEGRATION AND ALIGNMENT

The alignments sequence starts since the segments assembling on a dedicated tool. Each segment is precisely positioned with respect to the adjacent ones, the aim being to guarantee the geometrical adjustments for the brazing process, and to define the relative positions which minimize the final mass of the reflector, while keeping a final skin thickness higher than 2mm.

Figure 6-1: segments alignments

The next alignment step is the grinding operation of the primary mirror. The bipods mounting must guarantee the perfect positionning of the mirror on the grinding machine, in order to get the optical axis and the mechanical axis identical. A fine translation adjustment of the mirror allows to minimize the reflector thickness differences, and then minimize the mass of the reflector once ground. As an order of magnitude, 1mm uniform thickness of the optical surface represents 30kg in mass.

During the grinding, the reflector is maintained by the 3 bipods and several supporting points that allow to minimize the distortions under the grinding efforts. As the mass is decreasing during the grinding, the height of these supporting points is calibrated to take the surface release into account. At the end of this stage, the M1 radius is known, and the M2 optical parameters can be adapted accordingly to optimise the Telescope combination.

The polishing operation conserves the same initial alignment than for the grinding. During the polishing, gravity compensators are installed in order to simulate the Og surface.

The coarse alignment of the M2 wrt the M1 is performed thanks to 3 possible adjustments:

- 2 rotations at M1/ hexapod interface (tilts)
- 1 translation at M2 barrel/ hexapod interface (coarse focus)
- 3 translations and 2 tilts for M2 adjustment with respect to the barrel (tilts, focus, decenter)

Due to the high magnification of the secondary mirror (265 magnification), the resolution of M2 adjustments is very tight: translations: 5µm, tilts: 100µrad.

7 OPTICAL PERFORMANCES VERIFICATION

The wave front error performance is controlled under ambient conditions with a Shack-Hartmann method.

The principle is to measure at the Telescope focus the aberrated and distorted wavefront generated by the Telescope. It is working in auto collimation on a flat reference mirror set in front of the Telescope.

The Telescope pupil is re-imaged by mean of an auxiliary optics on a sampling mask, which defines a grid of sub-aperture over the pupil. An array detector is located in front of the sampling mask, and each sub-aperture produces a spot on the detector. The spot centroïd measurement provides the average wavefront slopes error over the sub-aperture area. The wavefront map is then reconstructed from slope measurements by means of a wavefront reconstruction algorithm, which must be understood as a mathematical integration algorithm, since the ray slopes simply provides the wavefront map derivatives (averaged on the sub-apertures).

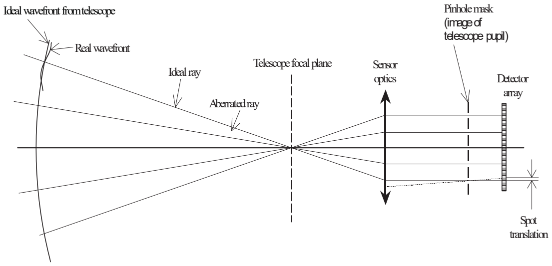

Figure 7-1: wave front sensor principle

Manufacturing a large reference mirror would be challenging and expensive. The auto collimation mirror is simply made of several **liquid mirrors** placed on the integration site floor, while the Telescope is looking down. The wave front sensor at the Telescope focal plane provides with the functions of emission, reception, and post-processing of the measurements. The test is performed in the visible range (He-Ne laser wavelength 0.633 µm) over the whole field-of-view.

A high sampling rate of 64x64 is required for allowing a correct over-sampling of the primary mirror major cells. That provides with a sampling period of 55mm which allows to control the Telescope low order aberrations as well as high spatial frequency deformations. A zoom function will also allow to get very high sampling and to get mapping under mirror cells scale. Quilting effect can then be controlled.

The liquid mirrors are realized by oil-filled tanks which prevents from micro-vibrations and surface distorsions.

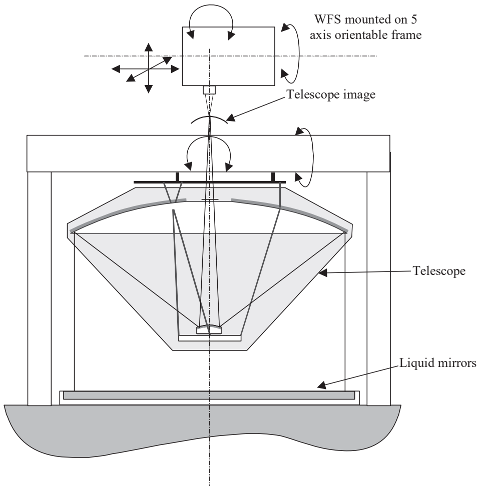

Figure 7-2: clean room optical tests configuration

In order to reduce the gravity effect, **gravity compensation** devices are installed at the rear face of the mirror. That allows to reduce the gravity distortion WFE (17µrms without compensation) down to 1µrms. The basic concept is to apply a vertical force on the back face of 9 segments in order to produce the 0g shape (more precisely the wave front error map in-orbit). The accuracy of this compensation is linked to the mass distribution knowledge and to the force application accuracy. The global error must be kept below 1%.

The compensator effect calibrations is dependant on the finite element model accuracy. It is then verified in clean-room by producing a calibrated force on each compensator. The corresponding WFE distortion is measured with the wavefront sensor, and correlated with the FEM model predictions. Maps controled during polishing (+1g) and integration (-1g) are also processed to validate the 0g performance.

The WFE is measured on several points in the field, with an accuracy of 0,15µrms.

The **WFE test under operational cold vacuum conditions** is performed in the new XXL chamber of CSL, with He shrouds which can allow the whole Telescope to reach the [70, 90K] range. In order to come to a realistic test duration (the effective cool-down in orbit will take some months down to 70K), the Telescope protective thermal layers are removed to reduce the time constant. That does not affect the thermal maps representativity as the spatial gradients are very low in orbit, as well as in test.

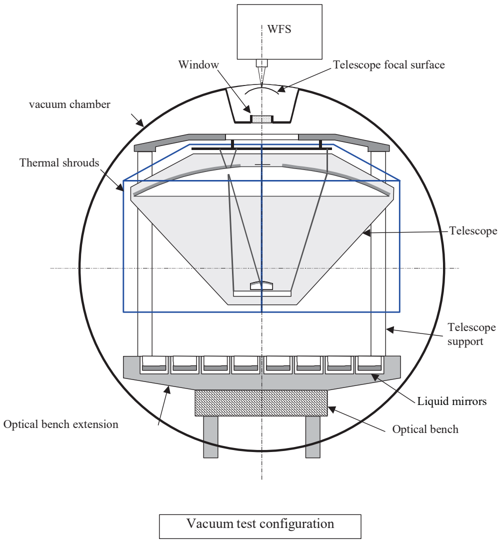

Figure 7-3: Vacuum optical tests configuration

In the vacuum test configuration, the pupil sampling is reduced to 8x8 with respect to the ambient test configuration as only the changes in low order aberrations in cold are necessary for deriving the WFE in cold conditions. This reduced number of mirrors leaves enough room to implement a removable insulation on the mirrors which prevents from freeze the liquid used. The zoom function is also used to check locally the high spatial frequencies of the Telescope.

For this test also, the gravity compensator are mounted.

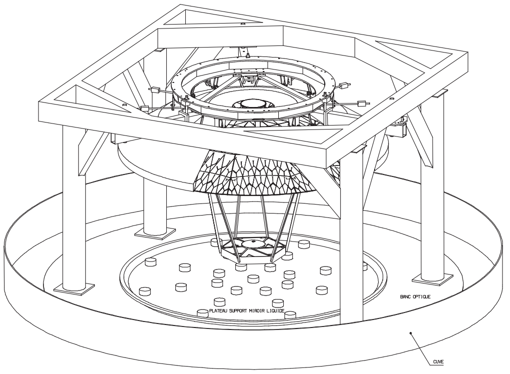

Figure 7-4: Telescope supporting tool for optical performances under vacuum

The **Telescope transmission** is verified on samples after the mirrors coating. A complete qualification campaign has previously been performed, which has shown that the process developed is compatible with the ground storage and L2 environments (adherence, humidity, thermal shocks, thermal cyclings, radiations, UV exposure). The reflectivity performance is measured at ambient and operational temperature in the whole Herschel wavelength at LEMTA laboratory of Nancy University (France) with a Bruker spectrometer. The absolute accuracy on reflectivity is better than 0,005 at ambient.

The results are in good accordance with the theory, and give a predicted coating performance at the end of life of more than 0,990. Emissivity is therefore expected to be lower than 0,005. This value has also been confirmed by absorptivity method performed at the Delft University in the framework of the Herschel/ Planck program.

8 PRESENT STATUS AND FURTHER ACTIVITIES

The flight primary reflector has been successfully brazed in November 2003. That represents so far the largest ceramic piece ever produced in the world, for the largest space-borne Telescope.

The reflector is presently under grinding in order to remove the front face stiffeners, and reduce the thickness of the optical surface down to 3mm only, and reach the final parabolic shape. At the end of this stage, the reflector will weigh about 240Kg. Before going further, it will be submitted to the qualification vibration proof test and will be ready for the polishing operation, and finally the coating.

The reflector is planned to be ready for assembling on the Telescope by the end of the year 2004.

Figure 8-1: Herschel flight reflector under preparation for grinding

Figure 8-2: Herschel Telescope flight reflector

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