SILICON CARBIDE TECHNOLOGY FOR SUBMILLIMETRE SPACE BASED TELESCOPES
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ABSTRACT
Silicon Carbide (SiC) provides simultaneously excellent optical, mechanical and thermal properties, an ability to work over a very wide temperature range (0 K to above 1800 K) and a very low sensitivity to environmental effects (no acid or alkali attack, no humidity effects). One of its most interesting application in the visible or in the infrared wavelength range is the realisation of athermal, fully passive and stable space telescopes, where both optics and structural parts are made of silicon carbide. Submillimetre telescope needs are analysed through the example of FIRST telescope, which is now a 3.5 m Cassegrain telescope working at about 80 K. The need for polishing the primary reflector is developed and the effect of cool-down discussed. Then, it is shown that SiC material is most appropriate for all specific aspects of FIRST: mass, stability, cool-down distortions, achievable performance and coating. A design of the 3-meter FIRST telescope is presented, the primary reflector being made of 12 segments brazed together. The realisation of a 3.5 meter telescope would use exactly the same technology, which is being validated through the development of a 1.35 m spherical reflector made of 9 brazed segments. The overall wavefront error can be driven below 6 µm rms and is practically driven by the primary reflector polishing.

1- ANALYSIS OF SUBMILLIMETRE TELESCOPE REQUIREMENTS
Since atmospheric transmission is rather poor in the submillimetre wavelength range (λ ~ 50 µm to 1 mm), science observations are or will be performed with balloon-borne or space based telescopes. PRONAOS is an example of submillimetre balloon-borne telescope, which was built by MMS-F in 1991 for the Centre National d’Etudes Spatiales (France). Its diameter is 2-meter and the primary reflector is made of CFRP and is actively controlled during the balloon flight. The overall telescope is diffraction limited above 530 µm wavelength (WFE < 38 µm rms). FIRST and Planck are two major submillimetre programmes of the European Space Agency (ESA), which may be merged in the near future in a single programme called FIRST/Planck. Although FIRST and Planck have many common areas, their science objectives and instruments are different and their telescopes will be separated on the satellite. Both are more demanding than PRONAOS telescope, but FIRST telescope is certainly the most challenging. It will therefore be considered in the following discussion for deriving from the telescope requirements some criteria for the material selection and impacts on the design, manufacturing and test. Most of the analysis can however be transposed for Planck case.

1.1- Wavefront error requirement
FIRST telescope diameter was recently increased to 3.5 meters (Table 1). The telescope design goal is to be limited by diffraction (i.e. Strehl ratio > 0.8) over the operating wavelength range. Therefore, the overall WaveFront Error (WFE) should be below λ/44 in root-mean-square value (rms), which corresponds to a WFE = 6 µm rms for a wavelength λ = 85 µm.

<table>
<thead>
<tr>
<th>Primary reflector diameter</th>
<th>3.5 m, f/0.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Telescope focal length</td>
<td>27 m</td>
</tr>
<tr>
<td>Operating wavelength</td>
<td>85 µm to 600 µm</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>60 K to 100 K</td>
</tr>
<tr>
<td>Eigen frequency</td>
<td>&gt; 45 Hz lateral</td>
</tr>
<tr>
<td></td>
<td>&gt; 60 Hz axial</td>
</tr>
<tr>
<td>Overall height</td>
<td>&lt; 1.7 m</td>
</tr>
<tr>
<td>Overall mass</td>
<td>&lt; 260 kg</td>
</tr>
<tr>
<td>WFE requirement</td>
<td>&lt; 10 µm rms</td>
</tr>
<tr>
<td></td>
<td>Goal : &lt; 6 µm rms</td>
</tr>
</tbody>
</table>

Table 1- FIRST Cassegrain telescope specifications.

1.2- Straylight requirement and operating temperature
The telescope detection sensitivity can dramatically be degraded by the background photon noise and it is of the utmost importance to
minimise the optics self-emission by firstly lowering as far as possible the telescope temperature and secondly minimising the reflector emissivities. In parallel, the collecting area must be of course as large as possible, within affordable mass and cost figures.

About a year ago, the orbit selected for FIRST was a low inclination, 24-hour elliptic orbit (i.e. of major axis equal to the geostationary orbit diameter, or 71 600 km), with a perigee altitude of 1000 km. The detailed design performed by MMS at that time showed that, with an appropriate thermal design, the telescope could be cooled passively down to 100 +/- 20 K, the temperature fluctuation depending on the relative position of the sun with respect to the orbit.

The new orbit selected for FIRST/Planck is around \( L_2 \) Lagrange stationary point, which located on the sun-earth axis, at \( 1.5 \times 10^6 \) km distance behind the earth. The system analyses of FIRST/Planck satellite are running today and the results will be available in the coming months. It is however clear that \( L_2 \) orbit is in favour of a much more stable thermal environment, and of a lower temperature, since the heat loads are practically constant with time and earth heat inputs (albedo and thermal at perigee passage) are now negligible. The natural equilibrium temperature will probably be below 80 K.

### 1.3- Impacts on telescope manufacturing and test

It is interesting to compare FIRST requirements to those of more « classical » telescopes working in the visible or thermal infrared range, for highlighting the specific difficulties related to FIRST.

The WFE accuracy requirement (~ 6 µm rms) is about two orders of magnitude less stringent than in the visible range. Nevertheless, the following discussion shows that FIRST telescope manufacturing is a real challenge, because 1) the WFE accuracy still requires a « rough » polishing step for the primary reflector, 2) the telescope height limitation makes the secondary reflector positioning tolerances practically comparable to those of telescopes working at shorter wavelengths, and 3) the telescope low operational temperature adds some complexity to the telescope manufacturing, integration and test.

![Figure 1- View of FIRST telescope.](image)

**Primary reflector polishing**

The first question one may raise is whether the primary reflector can be achieved without including a polishing step. With an overall WFE of 6 µm rms, the primary reflector allowable surface error can hardly be above 2 µm rms (corresponding to a WFE ~ 4 µm rms a detailed WFE budget is provided below for the 3-meter telescope).

To MMS knowledge, such an accuracy can hardly be guaranteed by a surface grinding and 3-D measurements over a piece of 3 or 3.5 meter diameter, and MMS approach is to include a « rough » polishing step, controlled by optical measurements, which would unambiguously guarantee the reflector performance at room temperature. Obtaining the surface accuracy by grinding may be a plausible approach if the overall error budget is degraded by a factor 4 or so, but this factor 4 is precisely crucial for science observations, since it is mandatory for getting a diffraction peak for a point source image at wavelengths below 300 µm.

The polishing step also allows to lower the surface roughness, say below 30 nm, without significant extra-costs (the surface shape errors being still specified at 2 µm rms). This can only improve the coating reflectivity, and therefore reduce the self-emission of the reflector. But this has also a very important impact related to the reflector assembly and test: the reflector test, the telescope integration in clean room and the cold test in vacuum can then be made by using visible light, which considerably simplifies the tests and improves the measurement reliability.
Secondary reflector positioning tolerance

The positioning tolerance relaxation provided by the use of large wavelengths is balanced by the large telescope diameter. A 3.5 meter reflector is rather unusual in space: since the overall satellite mass and envelope are limited by the launcher capability, and because a significant part of the available room is taken by the cryostat, the telescope height is limited to about 1.7 m, which corresponds to an f-number for the primary reflector about f/0.5.

As a consequence, the secondary reflector magnification and the ray incidence angles are unusually high, and the tolerance requirements on the secondary reflector positioning are about 10 µm in focus and 50 µm in lateral, i.e. comparable to that of telescopes working at much shorter wavelengths.

Impacts of low operational temperature

Having a low operational temperature (~ 80 K) for the telescope is not « unusual » in the infrared. Again, what is specific to FIRST is rather the combination of low temperature with a large telescope. There is of course an impact on the thermal design but the most important impacts are probably the constraints induced on the telescope manufacturing and test.

Actually, the telescope parts will be first manufactured and tested separately, then assembled at room temperature. Then, the whole telescope will be cooled-down in vacuum and tested at operational temperature. Two situations can happen:

i) The telescope alignment and the overall wavefront error are not significantly affected by the temperature variation of ~ 200 K,

ii) The primary reflector cool-down distortions are not compatible with the overall WFE budget.

In the second event ii), one needs to 1) dismount the telescope, 2) re-figure either the primary or the secondary reflector and 3) re-do the cold test verification. Such situation should preferably be avoided for FIRST for many reasons:

- The planning and cost impacts are considerable. Vacuum tests (wavefront measurement, decontamination, thermal cycling) at cold temperatures can last more than one month and represent a significant part of the overall telescope cost.

- There is a significant risk that the correction loop does not properly converge in one step, because accurate measurements of large distortions at cold temperature are difficult to achieve, and also because of error propagation.

- The telescope dismounting and re-alignment will also be a potential source of confusion, in particular in the case of cool-down distortions which are not axi-symmetric.

The idea of re-figuring or « post-shaping » only the secondary reflector (which is a small mirror) is certainly more viable than re-figuring the large primary reflector. It was first proposed by MMS in 1993 for the CFRP telescope. However, it was also shown that the compensation is efficient over the whole field of view only for large scale distortions (e.g. third order aberrations).

It is therefore quite important to determine what conditions should be met for being in situation i) and avoiding unacceptable cool-down distortions. These are physically due to non-equal thermal elongations of the reflector parts, i.e. to spatial inhomogeneities of the Coefficient of Thermal Expansion (CTE). Numerical Finite Element Model simulations show that the cool-down distortion WFE can be written:

$$\langle \text{WFE} \rangle = L_c \Delta \text{CTE} \Delta T$$

where:

- $\langle \text{WFE} \rangle$ is the statistical average of the cool-down distortion WFE, expressed in meters,
- $L_c$ is the CTE spatial fluctuation scale (or correlation length), in meters,
- $-\Delta \text{CTE}$ is the amplitude of CTE spatial variations (peak-to-valley)
- $-\Delta T$ is the temperature variation (~ 200 K)

The way formula (1) is derived will clarify what is meant by correlation length $L_c$. The reflector is divided into elements of dimensions $L_c$, and each element is affected by a CTE variation randomly distributed in the interval ($-\Delta \text{CTE}/2$, $+\Delta \text{CTE}/2$). Clearly, the cool-down WFE will slightly depend on the CTE distribution (i.e. first and second order statistics) and on the reflector design but the order of magnitude of the distortion can safely be evaluated with eq. (1).

From (1), one can see that large scale CTE fluctuations have a dramatic impact on the telescope quality. By making $L_c = 1.5$ m, $\Delta T = 200$ K, and $\text{WFE} = 3 \, \mu m$ rms, the maximum allowable CTE fluctuation is 0.01 ppm/K.
Conversely, equation (1) also shows that very short scale CTE fluctuations (say below few mm or so) are not critical and self-compensated.

The tolerance on CTE fluctuation is independent of the actual value of the CTE, and the lower is the CTE, the less demanding is the relative CTE fluctuation requirement.

**What should be the ideal material properties for FIRST telescope?**

From the preceding discussion, one can derive what should be FIRST ideal material properties:

i) The material should be polishable, and allow metal coating deposition if needed,

ii) Its CTE should be as low as possible, isotropic, and ultra-homogeneous (large scale variations below 0.01 ppm/K).

iii) It should preferably provide structural properties and a good thermal conductivity: in that way, the tripod can be made of the same material, and the ground tests are simplified since the alignment at room temperature will be preserved at operational temperature during cold tests or in orbit (we exclude here launch effects). The good thermal conductivity ensures that thermal gradient amplitude and effects are made negligible.

iv) It should withstand low temperatures (~ 80 K) and moderately high temperatures (~ 80 °C, for decontamination), without degradation or physical evolution.

v) Finally, it should provide a good lightweighting capability compatible with the mass requirement.

**2- SICSPACE SILICON CARBIDE TECHNOLOGY**

**2.1- Material manufacturing**

Silicon Carbide (SiC) is an emerging technology for space applications with a high growth potential. The material can be obtained by several processes, which can significantly affect either its physical properties or its cost. We shall only consider here the sintered silicon carbide manufactured by Céramiques & Composites (C&C, located at Tarbes, France) according to a well-defined and cost-efficient process.

MMS and C&C have been working in close collaboration since about 5 years for developing SiC technology for space applications. The material properties and the manufacturing process of large structural or optical pieces are now fully mastered. As a consequence of this successful collaboration, both companies have recently created a commercial company, called SICSPACE, which purpose is to efficiently promote the technology.

C&C SiC is not a new material for ground applications: The material is not toxic and has been used for many years in various industrial domains, such as fluid pumps in car or chemical industries and heat exchangers. Most often, it is used for its good mechanical and thermal properties (high strength, no fatigue, high thermal conductivity) and/or its insensitivity to hard environmental constraints (no acid or alkali attack, ability to work over a very wide temperature range (0 K to 1800 K) and to withstand thermal shocks, no humidity effects).

A considerable amount of experience and test results have been acquired by SICSPACE, and the following data are not exhaustive, but mainly limited to FIRST purpose.

![Figure 2: Major manufacturing steps for sintered silicon carbide.](image)

The major manufacturing steps of a SiC blank are shown on figure 2:

i) SiC powder preparation: Silicon carbide fine powder is mixed with organic binders and some sintering adds elements.

ii) Green body manufacturing: The powder is isostatically pressed at a high pressure (> 1400 bars).

iii) Green body machining: The green body is machined to the desired shape. For reflectors, the rear face lightweighting is performed on the green body.
iv) Sintering: The machined green body is pressureless sintered at high temperature, about 2000 °C.

The organic binders are removed during sintering process and the material is then composed of SiC over 98.5%. With the standard C&C process, the composition is controlled within 200 ppm.

The pressureless sintering of SiC makes possible to reach a densification level which is over 97%. As a consequence, the ceramic exhibits a residual porosity of less than 3% and typically 2% in volume. The sintering gives an isotropic shrinkage of SiC parts. The length contraction is about 20% and C&C know-how allows to accurately master this phenomenon and therefore the size of the sintered component.

2.2- Material basic properties

We now turn attention to Silicon Carbide properties and show that it is most appropriate to the FIRST telescope. Some key figures, measured by MMS, are provided in Table 2.

<table>
<thead>
<tr>
<th>Material Characteristics</th>
<th>R.T.</th>
<th>110 K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density ( \rho ) (kg/m(^3))</td>
<td>3160</td>
<td>3160</td>
</tr>
<tr>
<td>Young modulus ( E ) (GPa)</td>
<td>420</td>
<td>420</td>
</tr>
<tr>
<td>Ultimate bending strength ( \sigma_r ) (MPa)</td>
<td>374</td>
<td>405</td>
</tr>
<tr>
<td>Toughness ( K_{IC} ) (MPa.m(^{1/2}))</td>
<td>2.75</td>
<td>2.83</td>
</tr>
<tr>
<td>Weibull modulus ( m )</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>CTE ( \alpha ) (ppm/K)</td>
<td>2</td>
<td>0.65</td>
</tr>
<tr>
<td>Thermal conductivity ( \lambda ) (W/m/K)</td>
<td>190</td>
<td>180</td>
</tr>
<tr>
<td>Specific heat ( C_p ) (J/kg/K)</td>
<td>700</td>
<td>135</td>
</tr>
</tbody>
</table>

Table 2: Some basic physical properties of SiC, from MMS measurements.

**Thermal properties**

The coefficient of thermal expansion is already quite low at room temperature and drops to 0.6 ppm/K at 100 K (see figure 3). In parallel, the material thermal conductivity is also very high, comparable to that of metals.

**Mechanical properties**

SiC is a ceramic which presents good strength properties. Several hundred tests made by MMS and C&C experience for ground applications show...
that C&C SiC can safely withstand stress levels as high as 250 MPa. This allows the use of silicon carbide for building structures.

In-built stresses of as-sintered pieces are very low, < 0.1 MPa. No difficulty (e.g. variable distortions) was encountered for grinding or polishing of numerous pieces manufactured so far without any thermal treatment after sintering, even when a substantial amount of material was removed.

No fatigue of the material was detected, even after $10^6$ stress cycles of maximum amplitude 300 MPa.

**Optical properties**

The surface roughness of as-sintered silicon carbide is typically $Ra < 0.5 \mu m$, which is already satisfactory for FIRST. Fine grinding allows to reduce this roughness below 0.1 $\mu m$.

C&C silicon carbide is polishable (polishing convergence as good as for glass) and the surface roughness can be made as low as 1 nm. The material can therefore be used for applications in the visible range.

Because of the residual porosity of the material, micro-holes are visible on a polished surface under microscope inspection. The above roughness figures should be understood « micro-holes excluded ». The micro-holes are not visible by the naked eyes since their average diameter is 2 $\mu m$. The total hole surface ratio is typically 3%.

When the wavelength is large in comparison to micro-hole size, these holes are not seen by the electromagnetic wave and the reflection factor is practically not affected (in the same way that atomic fine structure is not seen by visible radiation). This is the case for FIRST and this was confirmed by emissivity measurements made at JPL on aluminium coated samples.

For short wavelengths (near infrared and visible radiations) the micro-holes generate a light loss, of amount equal to the obscuration ratio (~ 3%). The lost light is scattered over wide angles (nearly Lambertian diffusion), which may be a problem either when a large number of mirrors is used, because of light loss, or when dealing with applications very sensitive to scattered straylight. Although this paper is devoted to the submillimetre range, it is worth noting that the micro-hole scattering can be overcome : the solution demonstrated at MMS is to deposit a thin layer (~ 50 $\mu m$) of Chemical Vapour Deposited Silicon Carbide (SiC CVD, non porous material) prior to polishing. SiC CVD physical properties are very close to that of C&C sintered SiC, its adherence on C&C SiC is excellent. This is best demonstrated by the fact that the separation line between the SiC CVD layer and the sintered SiC is not visible by microscope inspection : only the absence of micro-holes in the CVD thin layer SiC allows to « guess » the border line.

SiC can be metal-coated by using the same process as for silica glass. Indeed, under air contact, SiC naturally exhibits a very thin oxidisation layer made of silicon oxide (SiO$_2$). The thickness of this layer can be increased by an appropriate thermal treatment but experience has shown that this was not necessary : aluminium coating obtained by vacuum deposition on as sintered/polished SiC pieces showed performance equivalent to that obtained with glass samples.

**Comparison to some other materials**

<table>
<thead>
<tr>
<th></th>
<th>SiC</th>
<th>Be</th>
<th>Zerodur</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density $\rho$ (g/cm$^3$)</td>
<td>3.16</td>
<td>1.85</td>
<td>2.53</td>
<td>2.73</td>
</tr>
<tr>
<td>Young Modulus $E$ (GPa)</td>
<td>420</td>
<td>303</td>
<td>91</td>
<td>71</td>
</tr>
<tr>
<td>CTE $\alpha$ (ppm/K)</td>
<td>2</td>
<td>11.4</td>
<td>0.05</td>
<td>24</td>
</tr>
<tr>
<td>Thermal conductivity $\lambda$ (W/m/K)</td>
<td>190</td>
<td>180</td>
<td>1.6</td>
<td>237</td>
</tr>
<tr>
<td>Specific heat $U$ (J/K/kg)</td>
<td>700</td>
<td>1880</td>
<td>821</td>
<td>900</td>
</tr>
<tr>
<td>Ratio $\alpha/\lambda$</td>
<td>0.011</td>
<td>0.063</td>
<td>0.03</td>
<td>0.1</td>
</tr>
<tr>
<td>Ratio $E/\rho$</td>
<td>133</td>
<td>164</td>
<td>36</td>
<td>26</td>
</tr>
</tbody>
</table>

*Table 3: Material comparison at room temperature.*

Table 3 provides a comparison between silicon carbide and some well-known materials. Two classical figures of merit have been added :

**Thermal distortion ratio $\alpha/\lambda$ :** The lower is the better. It physically reflects that thermal distortions are not only proportional to the CTE, but also to the thermal gradients, which, under given thermal environment, drop down when the thermal conductivity ($\lambda$) increases.
Specific stiffness \( E/\rho \): The higher is this value, the better is the material lightweighting capability, for equal mechanical behaviour (e.g. equal first resonance frequency). However, a comparison only based on specific stiffness is rather theoretical, since it does not include manufacturing limitations such as the aspect ratio (rib thickness/height). Actually, such limitations are not very constraining for SiC: an aspect ratio about 20-25 can easily be reached, and values as high as 80 with a rib thickness of 1.8 mm have been achieved.

Both figures of merit show silicon carbide advantages: except for Beryllium, which is not far from SiC, the material provides a much better lightweighting capability than others. It is also the best choice for minimising thermal distortions.

2.3- Joining techniques for manufacturing large pieces

Available facilities allow to manufacture monolithic silicon carbide pieces of dimensions up to 1 m x 1.6 m. This covers practically most of the needs. Manufacturing larger monolithic pieces would require a significant industrial investment.

Therefore, the cost effective and safe approach for the realisation of large pieces, such as FIRST primary reflector, is to assemble together smaller pieces, which are well within manufacturing capabilities. Several techniques can be envisaged and have been investigated:

i) Mechanical bonding, by bolting with shear pins.
ii) Glass bonding
iii) Epoxy bonding
iv) Brazing

Mechanical bonding is a straightforward technique which is probably the most efficient for joining structural parts. Its use for optical reflectors working in the visible is not recommended, because of potential micro-slippering between assembled parts. However, it may be envisaged for FIRST.

Glass and epoxy bonding are both mastered but they provide rather poor strength properties (~ 20 MPa): using these techniques often means a loss of interesting properties of SiC, such as SiC high strength value or its un-sensitivity to humidity. However, epoxy bonding (SiC/SiC or SiC/metal) is sometimes the most simple and cost efficient technique, in particular for connecting SiC to metallic parts (e.g. fittings) or gluing small pieces on a SiC structure.

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**Figure 5**: Microscope inspection of a brazing joint. Brazing is non-reactive and ultra thin joints of few \( \mu \)m are achievable.

Brazing technique consists of adding a material between two SiC pieces. MMS technique is a high temperature brazing which provides several remarkable properties:

- Its CTE can be matched to that of Silicon Carbide, say within 0.1 ppm/K or so,
- The brazing joint can be very thin: few \( \mu \)m to few tens of \( \mu \)m (figure 5). But thick joints of thickness as high as 300 \( \mu \)m have been achieved. For thin joints, the brazing strength is comparable or better than for SiC. It drops with the thickness, but remains above ~ 70 MPa even for joint thickness as high as 200 \( \mu \)m. Numerous tests performed at liquid nitrogen temperature showed that brazing strength is practically not affected at low temperatures.
- The brazing is non-reactive, i.e. SiC is not attacked. Therefore, de-brazing is possible (for example by re-heating) without any damage of the SiC parts.

One can group the various bonding techniques (i) to (iv) in two parts:

- Glass (ii) and epoxy (iii) bonding, which degrade some of the SiC properties,
- Bolting (i), and brazing (iv), which preserve the most interesting SiC properties.

For the case of FIRST reflector, the two most interesting techniques are bolting and brazing. Brazing technique was finally selected by MMS,
because it is robust, well-mastered, and it allows to avoid stress concentrations. It requires a brazing oven, of diameter ~ 4 meters.

2.4- Some examples of realisations

A large number of SiC pieces have been realised so far. The pieces are extremely variable in shape and size, going from C&C ring serial production (hundreds manufactured per day) to small shims of very high accuracy for optical alignments, or to medium size reflectors or blanks. We have selected here some reflector realisations, which are somehow related to FIRST telescope needs.

Figure 6- Polished optical reflector for visible wavelengths. Size : 720 mm x 350 mm. The reflector design is based on SPOT Zerodur steering mirror and illustrates SiC lightweighting capability. The reflector mass is 5.9 kg, more than twice lighter than the equivalent Zerodur reflector, while still providing much better mechanical performance.

Figure 7- Large blank manufactured under ESA contract (1200 mm x 420 mm). This breadboard demonstrates MMS/C&C capability for manufacturing complex large SiC pieces.

Figure 8- Circular blank made of two brazed pieces (rear face represented), diameter 630 mm. This blank was developed for demonstrating brazing technique.

3- FIRST « ALL-SIC » TELESCOPE

3.1- Telescope Design

We now detail the design proposed for FIRST telescope using Silicon Carbide, when the diameter was fixed to 3-meter. Going from 3 m to 3.5 m does not represent a technological step since the primary reflector is made of brazed segments. Therefore, most of the following can be transposed to the 3.5 meter telescope.

The telescope is represented on figure 9, and is composed of :

- A primary reflector (parabola), made of 12 brazed SiC segments, with pie-segmentation (as on figure 11). The brazing area height is 85 mm. The brazing joint thickness is driven by the grinding accuracy of the separate pieces and is expected to be below 50 µm. For
analyses, a conservative value of 100 µm is taken. The reflector provides 3 interface points where invar inserts are fixed. There is no need for gluing the inserts: they can simply be bolted and centred on the silicon carbide.

- A secondary reflector (hyperbola), also made of SiC.
- A tripod assembly, made of 3 legs connected on one hand to the primary reflector interfaces (via invar fittings) and on the other hand to a barrel holding the secondary reflector. The tripod legs and the barrel are made of SiC. This is mandatory for ensuring the secondary reflector alignment w.r.t. the primary reflector.
- Isostatic mounts made of titanium
- A triangle interface mount. The triangle is made of 3 SiC tubes connected by titanium fittings.

![Diagram of telescope elements](image)

\textit{Figure 9: FIRST telescope elements.}

The primary reflector mass is 120 kg while the telescope mass is 154 kg.

<table>
<thead>
<tr>
<th>ITEM</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary reflector</td>
<td>120</td>
</tr>
<tr>
<td>Secondary reflector</td>
<td>1.8</td>
</tr>
<tr>
<td>Tripod and barrel</td>
<td>21.3</td>
</tr>
<tr>
<td>Mounts</td>
<td>7.3</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>3</td>
</tr>
<tr>
<td>Total</td>
<td>154</td>
</tr>
</tbody>
</table>

\textit{Table 4 - Telescope mass budget evaluation.}

The primary reflector segments are brazed in one step. The reflector lightweighting was optimised for obtaining a gravity distortion below 5 µm rms, the reflector being horizontal and mounted on its bipods, while meeting the eigenfrequency requirements. This enables a simple and robust removal of gravity distortion during ground test measurements without additional supports for gravity compensation, since gravity distortion can be safely predicted by a model with an accuracy better than 10% (in fact few %).

The telescope first eigenfrequencies are 47 Hz in lateral and 147 Hz in axial (figure 10). Both are within the specifications (Table 1). The high value of axial frequency is directly connected to gravity distortion. Therefore, there is still some room for further mass reduction if one slightly relaxes the gravity distortion goal.

Although the 3.5 meter telescope is not yet designed, we identify here the major differences. The number of segments may be increased to 13 instead of 12, and the primary reflector mass is evaluated at less than 200 kg while the total telescope mass will be about 250 kg.

![Diagram of telescope modes](image)

\textit{Figure 10 - First modes of the telescope assembly.}
### 3.2- Performance analysis

A detailed performance analysis has been performed and is summarised in Table 5. As usual, root-sum-square rule is used for combining independent contributors.

<table>
<thead>
<tr>
<th>Contributor</th>
<th>WFE (µm rms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reflector manufacturing</td>
<td>4</td>
</tr>
<tr>
<td>Assembly, Integration and test (AIT)</td>
<td>1.7</td>
</tr>
<tr>
<td>Cool-down distortions</td>
<td></td>
</tr>
<tr>
<td>In-orbit distortions</td>
<td>1.5</td>
</tr>
<tr>
<td>Telescope integration on PLM</td>
<td>1</td>
</tr>
<tr>
<td>TOTAL (RSS)</td>
<td>4.7 µm rms</td>
</tr>
</tbody>
</table>

**Table 5 : WFE major contributors**

Each contributor is split in several sub-contributors, which are not detailed here.

- **Reflector manufacturing**: The figure is mainly constituted by the primary reflector surface error, at room temperature, after polishing.

- **AIT**: The figure includes gravity distortion prediction error, wavefront measurement error in cold temperature, and reflector alignment errors at room-temperature. The 3 contributors have approximately equal weight.

- **Cool-down distortions**: The figure represents the additional WFE when the telescope is cooled down to 80 K. Telescope alignment is not perturbed since the design is athermal. Simulations show that the distortions due to the presence of brazing are negligible, even with a joint thickness as high as 100 µm and with a conservative CTE mismatch between the brazing and SiC of 1 ppm/K. This is due to the fact that SiC parts are homogeneous (same CTEs) and drive the overall reflector distortion (SiC part stiffness largely dominates).

- **In orbit distortions**: This figure includes thermal distortions in orbit and a provision for misalignments induced by the satellite launch. The telescope being athermal, the figure is in fact practically equal to launch effect provision.

- **Telescope integration on the PLM**: The figure represents the additional WFE which may be generated by the telescope mounting on the PayLoad Module.

The overall WFE budget is 4.7 µm rms, and is practically driven by the primary reflector polishing specification.

### 3.3- FIRST 1.35 meter demonstration model

For validating the whole manufacturing process proposed for FIRST primary reflector, a 1.35 meter spherical reflector is currently being manufactured by MMS/C&C in the frame of an ESTEC contract.

The demonstration model is made of 9 segments brazed together. The height of brazing areas are deliberately made representative of that of the 3.5 meter reflector. The demonstration model will be ground and polished to FIRST specifications, and then tested at cold temperature. The cold test is planned by June 98, and represents a « proof test » which will unambiguously confirm the suitability of the proposed technology for FIRST.

![Figure 11 - FIRST demonstration model: diameter 1.35 m, 9 brazed segments, pie segmentation. Under manufacturing.](image)

**Figure 11 - FIRST demonstration model: diameter 1.35 m, 9 brazed segments, pie segmentation. Under manufacturing.**

### ACKNOWLEDGEMENTS

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