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Lightweight cold mirror and fixation

J. Espiard, J. Paseri

REOSC, 10 rue des écoles, Ballainvilliers 91160 Longjumeau FRANCE

G. Cerutti-Maori, C. Singer

AEROSPATIALE, 100 boulevard du Midi, B.P. 99, 06322 CANNES LA BOCCA CEDEX FRANCE

Abstract

This paper presents the main results of a feasibility study (ESTEC contract n° 6122/84/NL/GM with AEROSPATIALE and REOSC) of a cold lightweight mirror. This is the primary mirror of a RITCHEY-CHRETIEN telescope for the ISO satellite, diffraction limited at 5 µm (λ/14 RMS). The following points are the main difficulties which must be taken into account to define the mirror :

- Choice of mirror material, based on the best optical suitability, homogeneity of the thermal expansion coefficient and straylight characteristics. The available materials are ZERODUR optical grade and fused silica HERASIL 1 grade. Fused silica seems to be the best material because there is no deformation of a sample under radiations and no hysterisis during temperature cycles, opposite to ZERODUR.
- Lightweighting, REOSC know-how with numerical machine tools allows to reach a weight of 20 kg (instead of 57 kg) and in terms of aspherical coefficient, the wave front error is about λ/86 in RMS value at 5 µm.
- Mirror fixation device, based on a patented fixation for ambient temperature, does not introduce torque in the mirror and take up the differential thermal expansion between the mirror and the optical support structure. A calculation gives a wave front error of λ/70 RMS at 5 µm.
- Mirror cooling, temperature of the mirror in space has to be less than 10° K. It is necessary to bond thermal straps at the rear of the optical surface of the mirror in lightweighting holes. The number of straps necessary to cool down to 10° K the mirror in 48 hours must be over 40. The number of holes in the mirror is 57.

Introduction

The infrared Space Observatory (ISO) is an European satellite with cooled instrumentation (telescope and focal plane experiments) which will be launched in 1992 to carry out infrared astronomy. The telescope of a RITCHEY-CHRETIEN type is diffraction limited at 5 µm (wave front error λ/14 RMS) and the sensitivity limit will be due to the background radiation on the detector.
This paper discusses the feasibility of the primary mirror of the telescope, the specifications of which are :

- Effective aperture	600 mm
- System focal length	9000 mm
- System focal number	15
- Mirror separation e	854 mm
- Focal distance g	460 mm
- Plate scale	2.618 mm/arc min
- Spectral range	2 - 120 um

Exit pupil on secondary mirror.

The characteristics of the primary mirror are the following :

- Outer diameter	640 mm
- Free diameter	634 mm
- Central thickness	74.8 mm
- Central bore dia.	145 mm
- Radius of curvature	2000 mm
- Numerical aperture	1.577
- Asphericity	0.66 E-13
- Material	Fused silica (Herasil 1)
- Coating	Gold

- Mass	20 kg (machined lightweighting)
- Surface accuracy (wave front error for λ = 5 µm)	λ/86 RMS
- Support system	3 fixations at 120° on the periphery of the mirror
- Operating temperature	around 10 K.

To achieve our study on the feasibility of the primary mirror , we first present a preliminary image quality budget which points out the parameters which induce a degradation of the image quality :

- structure stability (decenter, tilt, despace)
- mirror blank stability (radiations, homogeneity, ageing, thermal cycles 300 K ⟷ 10 K)
- mirror fixations
- mirror figuring.

The figure 1 presents the wave front error budget. The allocations for structure and blank stabilities are the most important, but pessimistic calculations were made for these wave front errors.

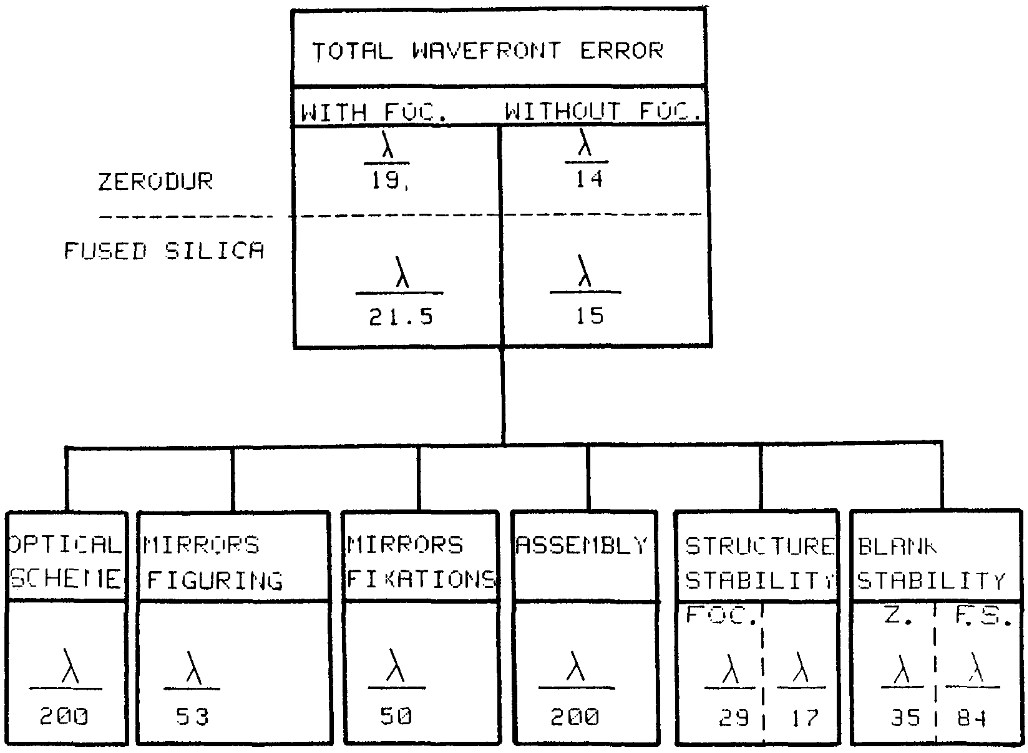

Figure 1. Wave front error budget (specification : λ/13.6 RMS)

Mirror material and structure

The mirror material must enable to obtain a good mirror figure in spite of the lightweighting pattern and also to keep the same figure when the temperature is lowered down to 10° K.
These two important points are satisfied when the material has :

- a low thermal expansion coefficient to avoid mirror figure defects just over the lightweighting cavities bottom and just over the ribs. These defects originate in the thermal behaviour difference which exists between these lightweighting structure elements ;

- a perfect material homogeneity to ensure a good uniformity of the T.E.C., over the mirror blank and consequently, a good mirror figure behaviour at 10° K.

For the ISO telescope, the blank size is :

- diameter : 640 - 0/+ 2 mm
- thickness : 96 - 0/+ 2 mm
- concave radius : 2000 + /-20 mm.

For a diffraction limited mirror, metallic materials such as aluminum or beryllium which are often chosen for mirrors can not be used for cryogenic applications[1] : their thermal expansion coefficients are large so they induce dimensional changes, and these metals need nickel coating to reach optical surface quality, but this coating produces high amount of thermally induced stress which leads to deformation of the mirror when it cools down, and results in hysteresis and ageing effects. The two following materials comply with the above requirements :

- ZERODUR ceramic glass optical grade
- fused silica.

The choice between these two glassy materials is made after consideration of the hysteresis of zerodur (ISO primary mirror will have to withstand about 50 cycles 300 K ←→ 10 K) and of radiation effect (radiations induce a deformation on zerodur samples and have no effect on Herasil samples. The ISO orbits which are actually considered are partially inside the radiation belts).

The lightweight mirror will have to have the major quality of space telescope and also to withstand constraints imposed by cryogenic temperatures. It means that the mirror will have the following properties :

- sufficient stiffness to enable satisfactory polishing and also proper withstanding of the launch environmental conditions at cryogenic temperature ;
- structure homogeneity to avoid constraints in the mirror when it is cooled ;
- the mirror has to be made of a material which can be polished with great precision and most important without local defects ;
- the possibility to enable an easy and strong linkage with the satellite structure ;
- to be as little sensitive as possible moments perpendicular to the mirror surface ;
- to ensure great feasibility to obtain a manufacturing reject ratio lower than 1 or 2 %.

The table hereafter shows the different criteria of choice on mirror material and structure.[2]

	MATERIAL			STRUCTURE		
	METALLIC	GLASSY		MACHINED	ASSEMBLED	
		Zerodur	Fused Silica		Welding	Frit Bonding
Surface smoothness	Bad	Good		/	/	
TEC	High	Low		/	/	
Homogeneity	Bad	Good	Good	Good	In general, problems between core and plates	
Ageing	Bad	No effect	Low effect	/	/	
Hysteresis	/	Yes	No	/	/	
Radiations	/	Yes	No	/	/	
Conductibility	Good	Bad	Bad	/	/	
Manufacture	/	/	/	Well known		
Price	/	Low	High	Low	High	

For the ISO primary mirror, REOSC-AEROSPATIALE recommendation is a mirror manufactured on a machined lightweight fused silica blank. According to REOSC know-how, a wave front error for this mirror of $\lambda/86$ RMS is expected.

Mirror fixation device (MFD)

Mirror mount and attachment for use in space

The mounting of a mirror is a very important problem which is encountered every time a mirror is used. For example, astronomical mirror characteristics have to be considered with the mirror mounted in its cell because the mirror figure effectively employed is that one resulting from the mirror's behaviour when working in its cell. The same concept has to be applied for space lightweight mirrors. Thus, the mirror fixation device (MFD) which links the mirror to the satellite structure is carefully studied in close connection with lightweight mirror determination. For MFD determination, the following factors must be taken into account :

- lightweight structure stiffness
- launch conditions
- satellite structural behaviour under the launching conditions
- mirror's figure accuracy when working in space conditions
- mirror tolerances in tilt and shift to maintain the optical system's qualities to required level
- variation of temperatures
- etc...

It is well known that a mirror is extremely sensitive to any torque which is perpendicular to its optical surface and the baseline concept of the linkage device used in the MFD must avoid any transmission of these spurious torques. To meet all these requirements, REOSC and AEROSPATIALE have developped for French space programs an original device well suited for maintaining large mirrors in correct optical conditions and withstanding the space environment conditions.[3]

In the particular case of ISO, the MFD must :

- protect the mirror against vibrations, accelerations and shocks during ground tests at ambient and cryogenic temperatures and launch at cryogenic temperature ;
- maintain the mirror in its right position as well on ground as in orbit ;
- tolerate a slight structure deformation (mainly due to the difference between the thermal expansion coefficients between mirror and structure) but without any distorsion effect on the mirror.

MFD concept

The mirror, which weighs 20 kg, is supported by three points at 120° on the periphery (configuration based on REOSC know-how on large space mirror).
In each of these points, a patented blade spring system is fixed which maintains the mirror with a good stability and a good stiffness without constraining it.
The figure 2 shows the MFD in details with its pad fixation on the mirror.
This invar pad received a conical split ring (B) which is pressed against the mirror by the screws (C). This pressure induces only local deformations on the mirror without any influence on its global quality. The slight T.E.C. difference between fused silica and invar is taken into account by the pad elasticity. This solution enables an easy MFD disassembly. To avoid important stress at low temperature, the fret will also be glued. The main features of the MFD are the following :

A system of two crossed spring blades (E) made of steel which links two clamps (F) and (G). The clamp (F) is fixed on the pad (A) by means of a nut (H).These blades allow a slight rotation (around the axis of intersection of the two blades) of (F) with respect to (G). This rotation avoids to transmit to the mirror the radial torque induced by the deformation of the structure.

A system of crossed blades (I) which links the clamps (G) and (J) These blades allow a slight rotation (around the axis of intersection of the blades) of (G) with respect to (J)

This rotation avoids to transmit to the mirror the tangential torque induced by the deformation of the structure.

<u>A system of two parallel blades</u> (K) which links the clamps (J) and (L). These pieces constitute a flexible parallelogram allowing the big radial deformation of the structure (about 1 mm) induced by the big difference of temperature (about 280°C). The only constraint on the mirror is the action of a radial force.

<u>A clamp</u> (L) for the fixation of the MFD on the structure. The fixation is ensured by two screws (M). These screw axes are aligned with the intersection point of the blades to ensure a right mirror position.

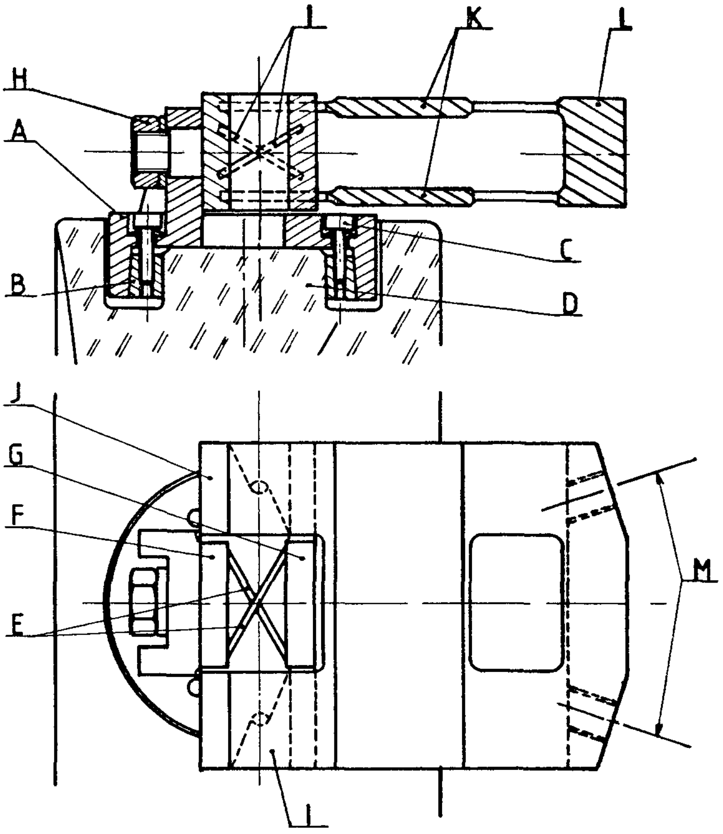

Figure 2. MFD concept

<u>Performances</u>

- The total mass of the MFD is 5 kg.
- The eigenfrequency is 200 Hz.
- The whole support system is able to withstand at 300 K or 10 K, 20 g loads in any direction as well as vibrations.
- The stresses induced in the mirror by differential thermal expansion and thermal gradient of the optical support structure (OSS) are less than 160 N for radial force, 0.015 mN for tangential torque and 0.0013 mN for radial torque. The radial force can be reduced by applying a press-stress at 300 K and it is within (- 80 N, 80 N) on the temperature range. A simplified model with NASTRAN layered composite element program has been used. Calculation outputs showed that the MFD must not induce constraints higher than 200 N for radial force 1.2 mN for tangential torque and 0.7 mN for radial torque to remain within a wave front error of about $\lambda/70$ RMS.

<u>Mirror cooling</u>

All studies done on different cryogenic infrared telescopes have concluded to the necessity to implant thermal straps on the rear optical surface of the primary mirror to cool it

down to temperatures about 10 K.
This part deals with the cooling down of the primary mirror of ISO, stating the number of connections, and the preliminary design and implementation of straps. Thermal straps must not induce deformation on mirror surface.

Thermal calculation

The temperatures inside the cryostat are 18 to 30 K above the mirror (baffle) and 8 K below (OSS). Without straps, our first calculations have shown that it is impossible to cool the mirror down to 10 K.
The maximal duration set as a practical goal to cool down the mirror is 48 h. The figure 3 shows the total thermal conductance (braids, straps, thermal paths in the mirror) versus time, for a mass of mirror equal to 20 kg and a final mirror temperature of 10 K.
So, to cool down the mirror in 48 hours, the thermal conductance must be over 0.06 W/°K. According to the figure 4, which gives the mirror conductance versus the number of straps, we have immediatly that the number of straps must be over 20.
In this calculation, we had not taken into account the thermal resistance of straps. So, the minimal number of contact points to cool down the mirror to 10 K in 48 hours must be over 40.

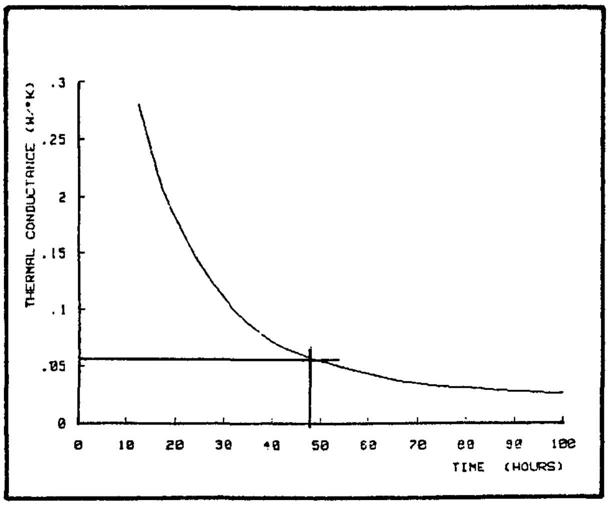

Figure 3. Influence of thermal conductivity on cold down time

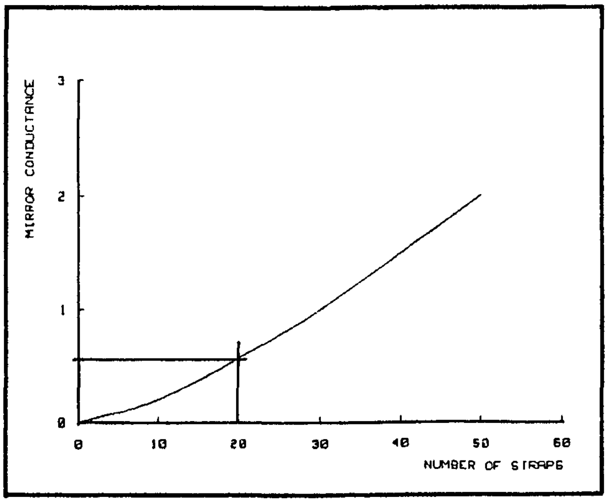

Figure 4. Mirror conductance versus number of straps

Implantation and definition of straps

In 1982, SIRFT, the primary mirror of which is the most similar to the ISO one (material and size), had copper braids and invar bottoms soldered to a vacuum evaporated chromium-nickel film on the mirror back plate.[4]
During tests at cryogenic temperature, source failures of the thermal conductor connections occured. SIRTF project recommended a design modification, using flexible polyurethane as a bonding agent, saying that metallic bond was not really necessary. In 1984, Kodak and Ames research center used a mixture composed with dust copper and rubber cement[5,6] achieved satisfactory.
Consequently, we defined a strap fixation as described in figure 5 : a strap in invar or copper which is bonded to the rear face of the optical surface in lightweighting holes.
The number of holes (57) is sufficient to cool down the mirror to 10 K in less than 48 hours

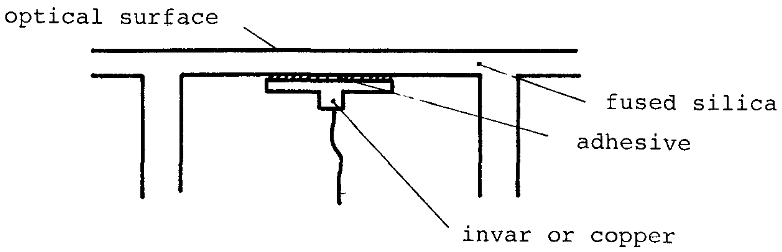

Figure 5. Strap fixation in lightweighting hole

Conclusion

We recommend for the ISO primary mirror :

- fused silica blank Herasil
- lightweight structure machined with the REOSC technology
- fixations which do not introduce important torque in the mirror at ambient or cryogenic temperatures. These fixations are on the periphery of the mirror at 120° (cryogenic adjustment of REOSC/AEROSPATIALE patented fixation).
- cool down the primary mirror with thermal straps bonded at the rear face of the optical surface to minimize thermal gradient.

This study will be pursued with an experimental step to corroborate these first results:

- tests on strap samples (conductivity at 4°K)
- mechanical tests on peg samples at 4°K
- manufacture of a mirror sample to test optical surface deformation.

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