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S.O.F.I.A. Ligthweighted Primary Mirror.

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ABSTRACT

Thanks to its experience in ligthweighting ceramic glass mirrors by machining, R.E.O.S.C. won the contract for designing and manufacturing the primary mirror and its lateral fixations of the 2.7 m. SOFIA telescope which will be installed aboard a 747 SP Boeing aircraft to constitute the Stratospheric Observatory for Infrared Astronomy (S.O.F.I.A.).

Keywords: SOFIA, Ligthweighted mirror, Large optics.

1. SOFIA PROGRAM

The Stratospheric Observatory For Infrared Astronomy (SOFIA) installed aboard a 747 SP Boeing aircraft will be the next generation airborne observatory. SOFIA will cover the spectral range 0.3-1600 micrometers which is a range relatively unexplored despite of its great interest from the planet formations, stars and galaxies up to the evolution of organic molecules in the interstellar space. This flying infrared observatory will be 10 to 1000 times more powerful than the KUIPPER AIRBORNE OBSERVATORY thanks to its 2.7 m. telescope instead of the 0.9 m. instrument which equips the Kuipper Observatory. The flight altitude of the 747 plane will be 12 to 15 km. that is to say at the atmosphere limit avoiding like this the presence of water vapor and its absorption bands.

This program has been conceived by NASA in cooperation with the German Space Agency (D.A.R.A.). NASA will supply the plane and DARA the telescope. The Consortium KAYSER THREDE/ MAN TECHNOLOGIES has been selected by DARA for telescope design and manufacture.

As the result of an extremely competitive call for tenders, REOSC won the contract for designing and manufacturing the parabolic primary mirror and its supports systems.

2. MIRROR AND SUPPORT SYSTEMS SPECIFICATIONS

These specifications are the following:

- spectral range	300 nm -16000 µm.
- outer diameter	2705 mm.
- useful diameter	2690 mm.
- edge thickness	350 mm.
- central hole diameter	420 mm.
- focal length	3200 mm.
- F number	1.19
- radius tolerance	+/- 7 mm.

- optical specifications for 633 nm.:
    . residual fabrication defects shall allow 80% of light to be concentrated in :
        - 0.65 arc second for a diameter of 2650 mm.
        - - 0.80 arc second „ „ 2640 mm.
        - - 1.00 arc second „ „ 2690 mm.
    . residual defects introduced by the mount, support and gravity elevation shall allow :
        80% of light to be concentrated in 0.4 arc second.

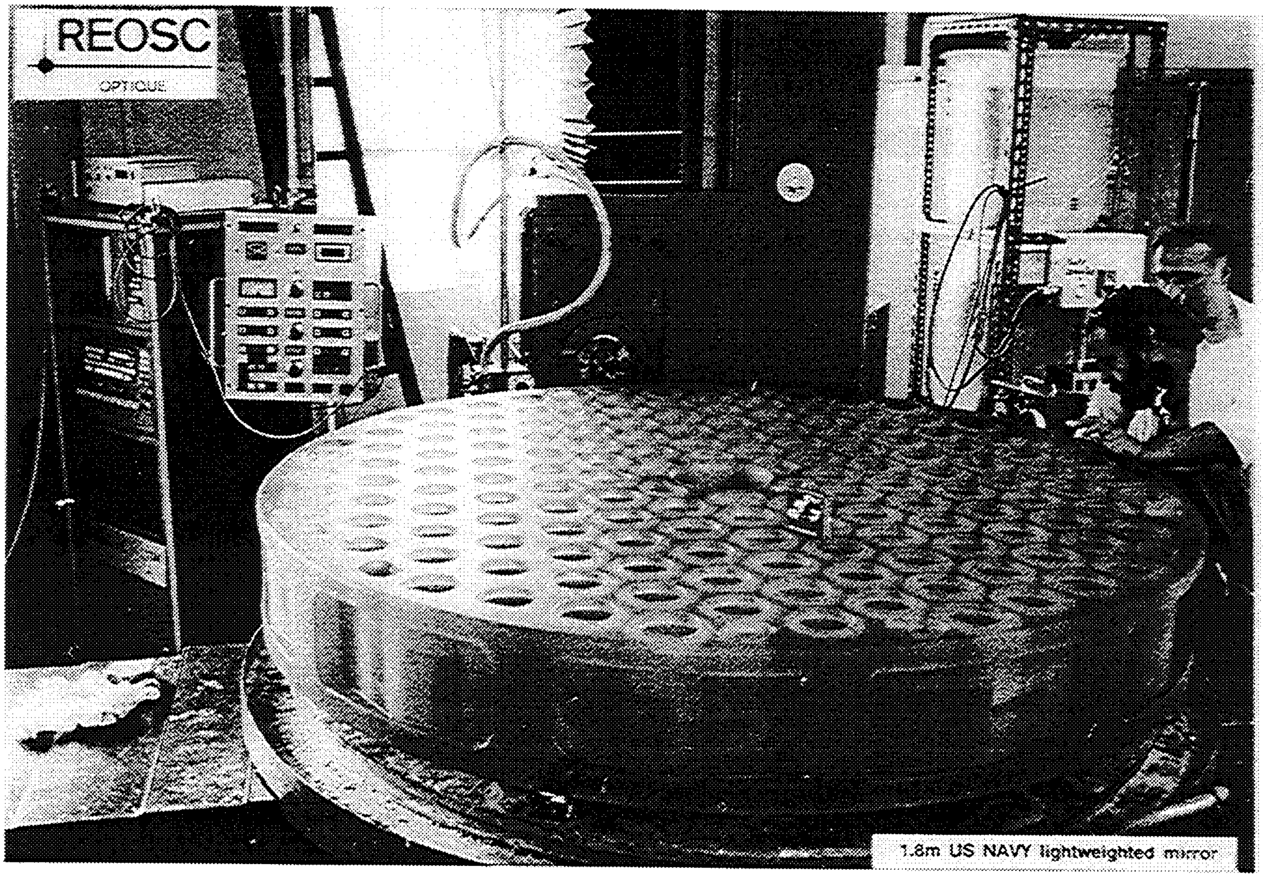


Fig. 1 : 1,8 m lightweighted mirror for the US Sea Lite Program

. residual defects introduced by thermal expansion and cooling shall allow
80% of light to be concentrated in 0.4 arc second.
. polished surface microroughness : lower than 2 nm. RMS.
. working temperature range :
- 60° C to + 40° C
. mechanical specifications:
- mass less than 850 kg.
- stiffness greater than 200 Hz. With a design margin: 20%
- handling positions: possible in vertical and horizontal positions

3. DESIGN DRIVING FACTORS

From the specifications we can conclude that the mirror weight and stiffness combined with the optical quality drive to design a ligthweighted mirror well supported and carefully polished. The ligthweighting concept must avoid mirror surface quilting which generally introduced very important slope errors.

Since 30 years R.E.O.S.C. has solved this problem by setting up its original ligthweighting process which allows to combine mirror weight, stiffness and very reduced surface quilting.

4. THE R.E.O.S.C. LIGTHWEIGHTING PROCESS

It is well known that the best ligthweighted mirror structure comprises an upper plate linked by a welded egg crate to a lower plate. Since 1967, this basic principle has been currently used by Corning Glass for many ligthweighted mirrors among them, the more famous being the Hubble Space Telescope mirror. These mirror structures are very effective if the egg crate welding to the plates is almost perfect but this is not an easy thing to do as many manufacturing sequences take place in a furnace at very high temperature and with a stringent tolerance on the temperature value. For this reason some of these structures have a very irregular welding along the egg crate walls. This defect results in a faulty mechanical behavior of the mirror which presents, after polishing, a prohibitive amount of astigmatism.

To avoid part welding at high temperature in order to reduce the cost, another techniques have been tried like gluing or frit. Generally glues have a very huge coefficient of thermal expansion (CTE), something like five thousand times greater than the mirror material one's. The ligthweighted structures so obtained have prohibitive deformations when temperature varies. Frit technique could give satisfying results only if the frit agent and the mirror material have very close CTE, but in this case high temperature processes are requested and the manufacturing cost is not lowered.

For the above reasons, REOSC ligthweighting process starts from a solid blank made of a low thermal expansion material like Zerodur or Ultra Low Expansion fused silica and it consists in drilling blind holes inside the blank. This drilling is performed from the mirror blank rear face. At first the drilled holes are cylindrical, then by using a milling tool having the same diameter as the blind holes, these holes are enlarged and the final shape of this ligthweighting pocket can be hexagonal, triangular or circular.

The very important features of this process are:

- all the process is performed at room temperature,
- a good reliability thanks to the use of a well proven technique which is hole drilling by using a diamond tool,
- all the machining is performed on a CNC machine and in this process there is no possible mistake after having checked the programs on a dummy mirror made of plastic material,
- ligthweighted mirror design is very flexible, any kind of holes can be used and furthermore thickness for upper and lower plates as well as ribs thickness can be determined to comply with the mirror stiffness requirement,
- mirror stiffness is well ensured by the partial presence of the back plate, the continuity of which being interrupted only by the presence of the first drilled holes needed to pass the milling tool.

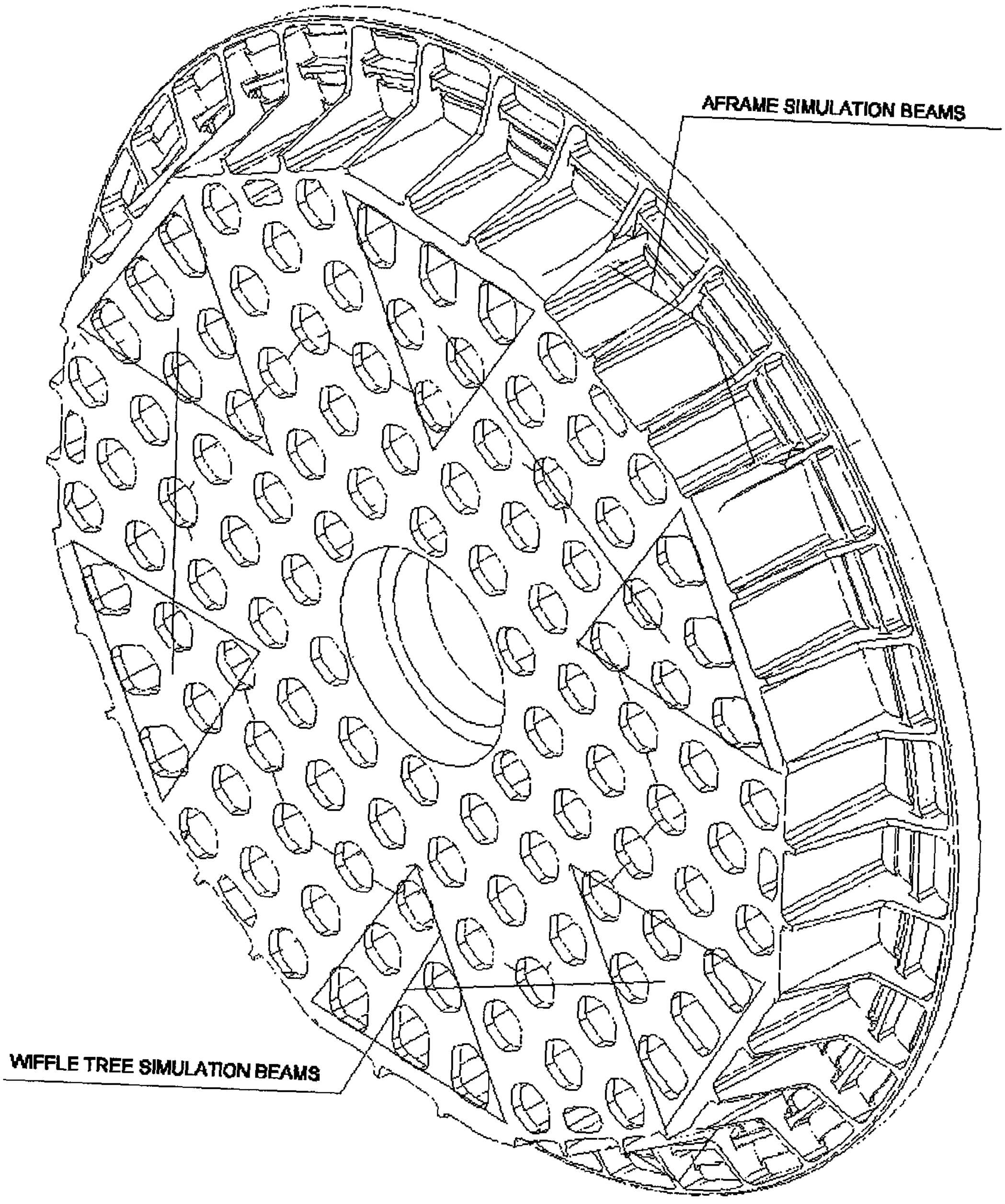


Fig. 2 : SOFIA Mirror Geometry

Since 1968 plenty of ligthweighted mirrors of this type have been manufactured by R.E.O.S.C. as for example the mirrors for many optical European satellites (SPOT, METEOSAT, HIPPARCOS, Infrared Space Telescope etc..), for the U.S. and European ORFEUS program which flew in the shuttle and also for high energy laser weapons like Sea Lite which is a U.S. Navy program. For this program the ligthweighted mirrors delivered have a diameter of 1.8 m. and a mass of 450 kg. The F number is F/1.7 and the RMS mirror surface error is lower than W/30 for W= 1 micrometer. In this error are included the errors due to mirror surfacing, mounting and supporting. The attached picture (fig. 1) shows one of these mirrors.

This process allows to obtain ligthweighting ratios from 70 up to 75% in relation to a solid mirror blank.

5. S.O.F.I.A. PRIMARY MIRROR DESIGN

The mirror geometry is shown on the attached drawing (fig. 2) . The material chosen for the mirror is Zerodur produced by Schott. This material gives reliable results for ligthweighted mirror thanks to its very low thermal expansion coefficient (0.5E-7), its good Young modulus value (90000 Mpa.) and its good homogeneity.

At first the general mirror shape looks like a doubled arch shaped mirror but ligthweighted by expanded cavities.

The basic ligthweighting pattern is a plano concave shape with holes milled from the mirror blank rear face according to a quasi honeycomb pattern, but this design leads to a too heavy mirror. In order to reduce the mass, a large bevel of 45 cm. has been introduced at the mirror edge. This removed mass improved mirror inertia without any disturbing effect on its overall stiffness. In this area the optical front surface requests to be supported in the most effective manner and in order to do so the typical ligthweighting geometry of open back structures with straight ribs has been adopted. Although the best ligthweighting pattern known is triangular ribs, this pattern does not allow an easy connection with the remaining geometry of the mirror and for this reason a radial rib pattern has been adopted. A further advantage of this large bevel is that it fits well with the telescope volume and rotation constraints in the plane. Furthermore, some mass has been removed around the center hole where it also does not contribute to the blank overall stiffness.

The axial support can be fixed onto the remaining plano rear face.

The key parameters of mirror geometry are :

- the overall thickness acting with a power 3 on the stiffness, but also on the milling tool fatigue,
- the thickness of the upper plate and pocket size affecting the optical residual surface quilting,
- the rib thickness which is mainly governed by its resistance to the milling tool pressure during ligthweighting process machining.

The plano parallel raw blank mass is 3400 kg. and the ligthweighted blank mass is 850 kg. The ligthweighting ratio so obtained is 75% .

The main data of the structure are :

- outer diameter	2705 mm.
- inner diameter	420 mm.
- hexagonal pocket size	185 mm.
- upper plate thickness	15 mm.
- total thickness	350 mm.
- plano rear face diameter	2300 mm.
- rib thickness	7 mm.
- rear face mean thickness	25 mm.

The computed first eigen frequency of the mirror when it is free is 230 Hz. and 160 Hz. when it is resting on its lateral and axial supports. The thermal time constant of the structure is around 20 minutes.

6. AXIAL SUPPORT DESIGN

The axial support is based on the well proven concept of whiffletree. Starting from three fixed points required for isostatism there are many possibilities to obtain a uniform load repartition, but in the present case the number of balances which composed the whiffletree must be minimized in order to obtain the stiffness support system. Due to the fact that the telescope angle elevation is only 45° the gravity effect on the mirror is divided by square root of 2 with respect to a telescope working at the zenith. Thus an eighteen point support has been chosen and optimized. Each of the three main support points is equipped with a lever arm. At each end of this lever arm is placed a triangular plate with a support point at each summit. Then, in total there are 3x (3+3)=18 support points.

In order to obtain the best stiffness as possible all the rotation axis and ball joints are made with flexible blades devices. This concept avoid the presence of looseness which will have a disturbing effect on the first eigen frequency value.

Mirror deformations are minimized for the following axial support configuration :

- 12 outer support points located on a diameter of 1100 mm.
- 6 inner support points „ „ „ 542.7 mm.

With these characteristics the encircled energy inside a diameter of 0.4" is 73% and 80% of energy are inside a diameter of 0.5".

It must be noticed that these results take into account the lateral support which is described hereafter.
The wave front error map is shown on the attached figure 3 (SO2 1 EW T3 file)
The axial support is manufactured by Kayser Threde.

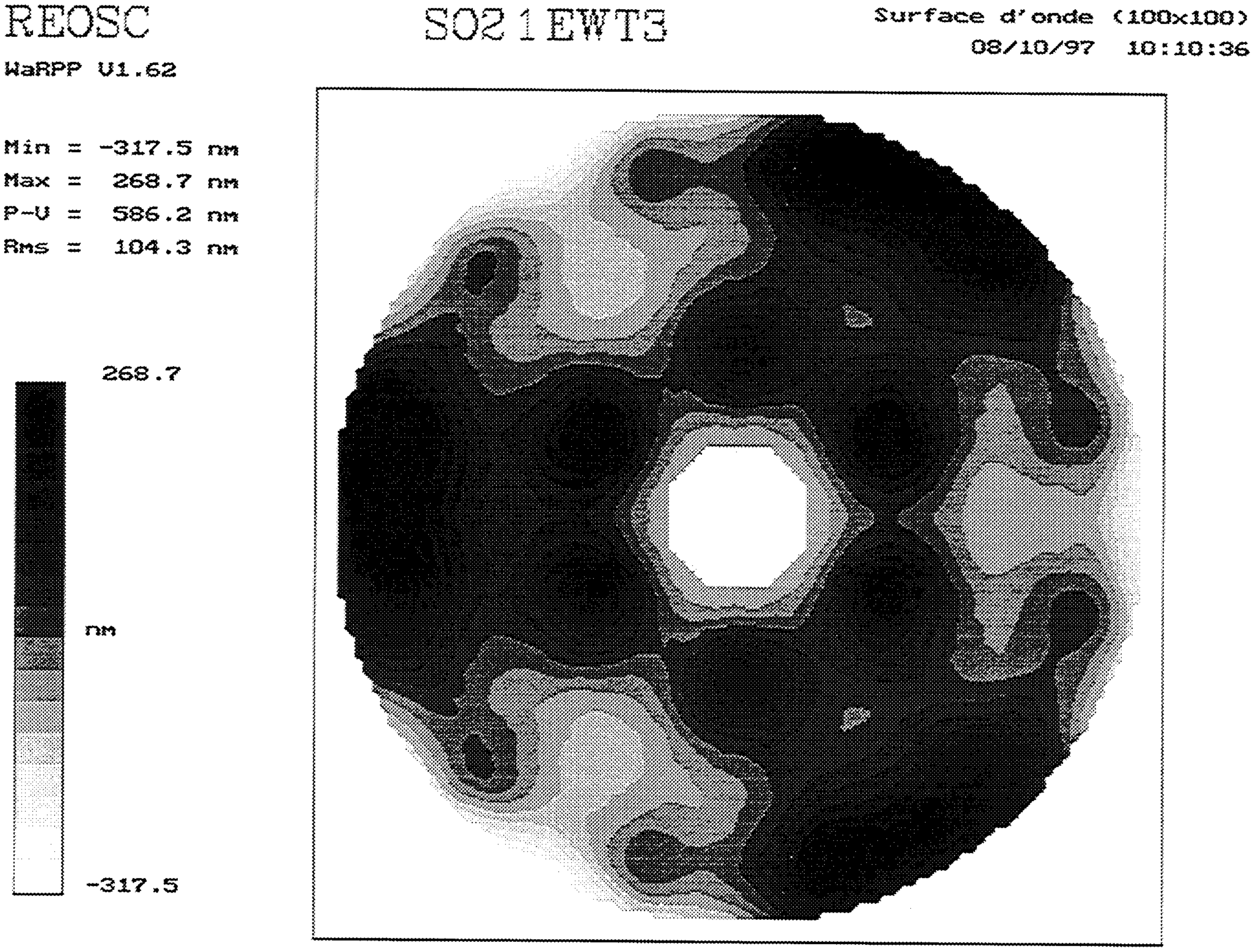
7. LATERAL SUPPORT DESIGN

The lateral mirror fixations are three flexible frames having the shape of the letter A, so they are called A frames. The A frames are made of stainless steel and they are linked to the mirror by means of invar pads glued on the mirror outer ribs while each foot of the A are fixed to the invar pads by means of 4 screws. The summit of each A is fixed on the mirror cell manufactured by MAN. On the figure 2 the A frame are simulated by beams.

The geometry of the A frame is such that this device allows the mirror to move slightly along its optical axis and in the perpendicular direction too but it does not allow the mirror to rotate. The amplitude of these motions have been determined in such a way that no probithive stress will be generated into the mirror during the very important temperature changes. Another important role played by this device is the filtering of parasite torques at the mirror interface and it also decreases the stress generated to the mirror fixation thanks to its two glued pads instead of the unique fixation point if a tangential bar solution had been adopted.

The attached finite element model (figure 4) shows the role played by the flexible blades. At the two ends of the A are its feet screwed to the invar pads glued to the peripheric mirror rib.

With the help of a A frame detailed model, dynamic computations have been performed and show that the mirror first eigen frequency linked to its axial and lateral supports is 160 Hz.


REOSC
WaRPP V1.62

SO21EWT3

Surface d'onde (100x100)
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Min = -317.5 nm
Max =  268.7 nm
P-V =  586.2 nm
Rms =  104.3 nm
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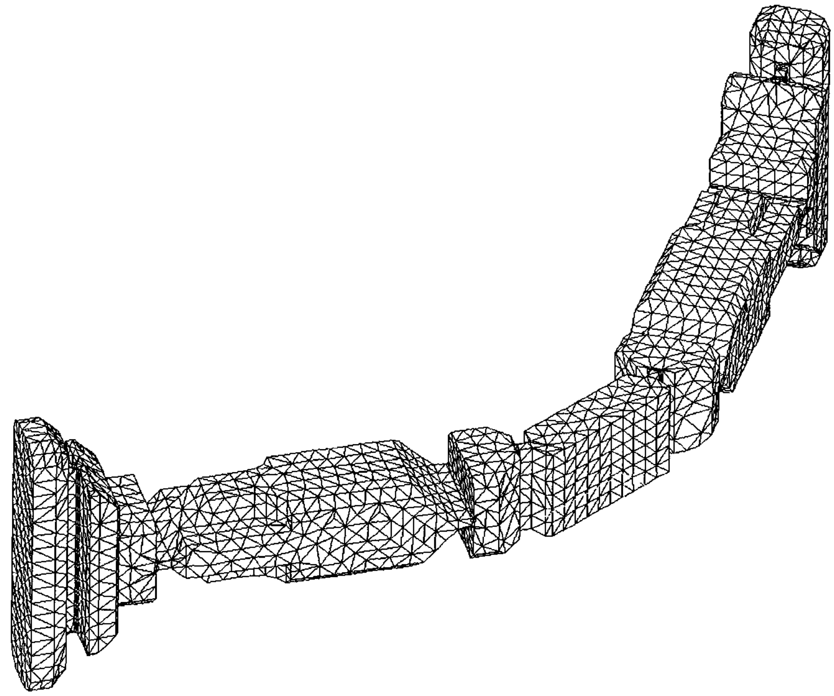
Fig. 3 : Mirror wave Front Marge Error



A Frame

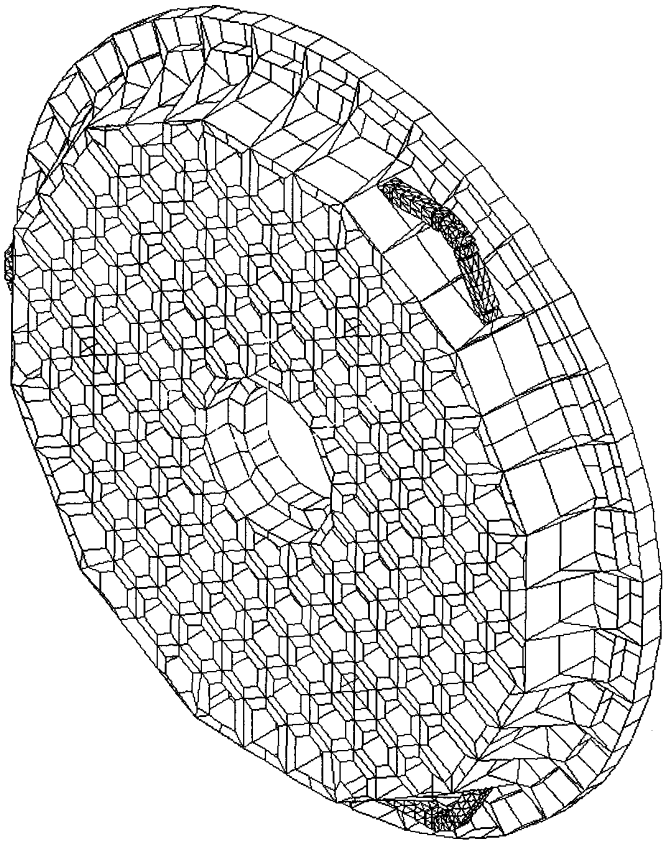


Fig 4 : Mirror + A Frame

8. PRIMARY MIRROR ASSEMBLY PERFORMANCES

8.1. Optical performances. Light concentration versus quilting.

This evaluation is related only to the quilting generated by the various fixation points of the lateral and axial supports and not to the quilting which could be generated by ligthweighting.

At first, it is assumed that the mirror is resting on its axial support and for a polishing pressure of 15 g/cm². the Wave Front Error RMS (WFE) is 63 nm. when tilt and focus are removed. 80% of energy is encircled inside 0.37" and inside 0.4" there is 81% of energy.

These performances are improved if during the polishing stage it is taken into account of the mirror figure in its working conditions that is to say when the telescope axis is at 45° above the horizon. In this condition the WFE mirror map is shown on the figure 5 (SOF2 1-45 file) here attached. As the mirror will be polished by using REOSC computer controlled polishing technique, it is easy to compensate this quilting or at least to minimize its amplitude. When this hypothesis is taken into account, **the WFE RMS is 19 nm. tilt and focus removed, 80% of energy is encircled in 0.18" and in 0.4" there is 90% of energy.**

For various elevation angles WFE RMS and energy concentration have been computed in the two cases where the WFE is or not compensated. These results are summarized in the following tables and graphs.

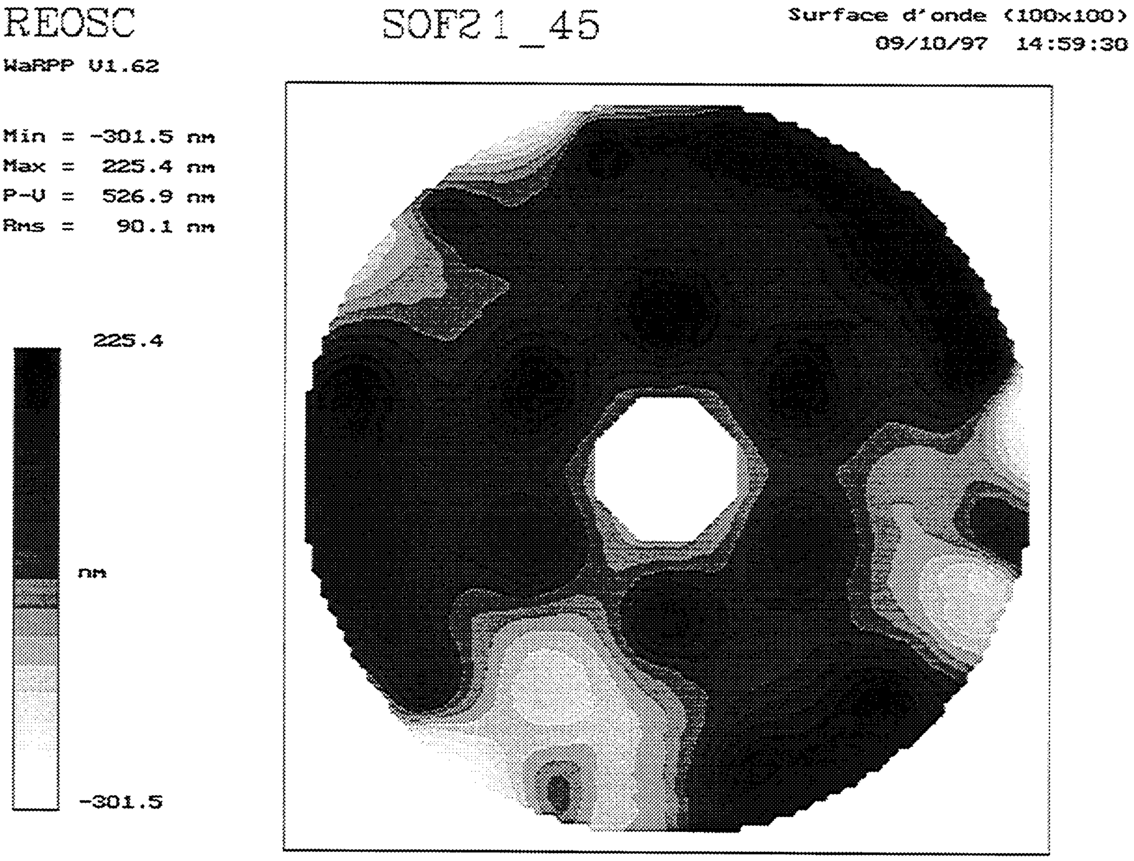
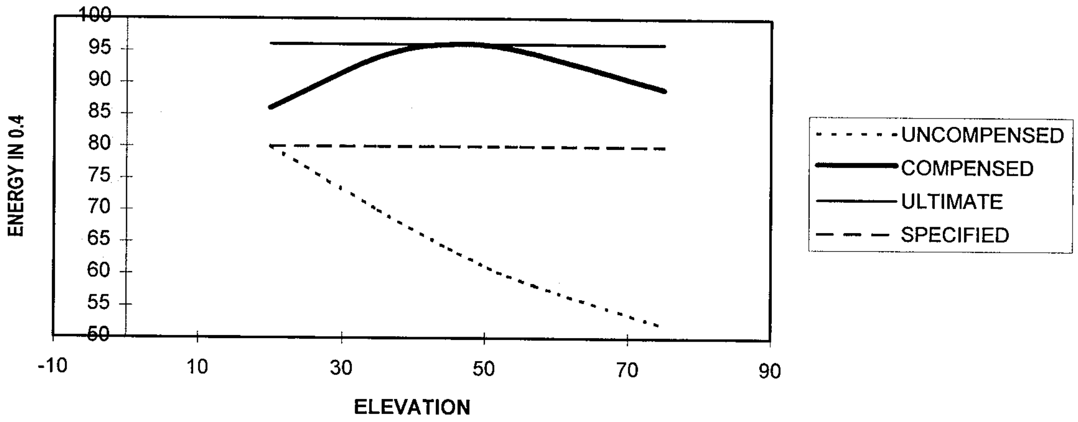


Fig. 5 : WFE improvement by taking into account the mirror working position

ELEVATION	RMS COMPENSATED	% in 0,4" UNCOMPENSATED	% in 0,4" COMPENSATED
15	-	-	84
20	42	80	86
35	16	70	94
45	0	64	96
55	15,5	59	95
75	44	52	89



8.2. Mechanical performances

Mirror life duration: under an operational load of 1.5 g. there is no risk of failure and for a maximum load of 9 g. life duration for a probability of 10E-6 is 5.2 h.

Safety factors (SF) for crash conditions: (pure acceleration loads are considered)

- for the A frame the SF is 5 and for the glued pad 3.9
- if pure acceleration loads are combined with thermal loads for a temperature variation of -80°, the SF becomes 2.7 for the A frame and 2.3 for the pad.

Margin of safety (MoS) in Zerodur and glue from -60° up to +40°: computations have been made for various load conditions for:

- lateral fixations: in worst case MoS is 0.9
- axial fixations : in worst case MoS is 2.2

9. CONCLUSION

The design of the ligthweighted mirror and of its lateral and axial supports fulfills with the requirements.