First light of the OVLA active mirror with its surface heating system

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ABSTRACT

The Optical Very Large Array (OVLA) project consists in a kilometric-size optical interferometer of 27 mobile 1.5m telescopes designed to provide high-resolution IR and visible snap-shot images. An OVLA prototype telescope has been developed at the Observatoire de Haute-Provence. It features a 1.5m meniscus-shaped f/1.7 primary mirror weighting 200kg including its active cell with 32 actuators. The mirror blank made of 24mm-thick ordinary window glass is very cheap but extremely sensitive to temperature variations because of its large CTE (3 times larger than *Pyrex*). Indeed, the mirror shows a Z11=3150 nm *rms* wavefront error due to a 0.5°C thermal gradient generated between its front and back side by an unbalanced heat dissipation towards the night sky and the ground. This spherical aberration, too large to be corrected by the actuators, is compensated by an uniform electrical current generated through the aluminum coating by 42 peripheral electrodes. We also describe the electrodes control hardware and present some results obtained during the first light of the telescope. Lastly, we propose a possible upgraded surface heating system to adjust thermally other optical aberrations.

Keywords: telescope design, active optics, thermal control, surface heating.

1. INTRODUCTION

The Optical Very Large Array (OVLA)[1] project consists in a kilometric-size optical interferometer 27 or more mobile 1.5m telescopes designed to provide high-resolution IR and visible snap-shot images using the *densified pupil*[2] mode. Each telescope will have to move accurately during the observation, for full flexibility of the array configuration as well as for keeping a zero optical path difference between the beams. This constraint implies compact and light telescope design.
A prototype telescope has been developed and tested at Observatoire de Haute-Provence (OHP) and should be connected in 2001 to GI2T (Grand Interferomètre à 2 télescopes) to form GI3T.
This telescope under tests has unusual characteristics: a spherical mount[3] and a thin active primary mirror[4]. This mirror is a 1.5m meniscus-shaped f/1.7 weighting 200kg including its cell ant its 32 actuators. For cost purposes, the mirror blank is made from a Pilkington, UK, 25mm-thick plan ordinary window glass, slumped in a special oven[5]. The blank costs 40 times less than an equivalent meniscus-shaped *Zerodur* blank. The main counterpart of this low price is the poor thermal behavior of the window glass: its CTE is 9.10^{-6}/°C, 3 times larger than *Pyrex*-like glasses, and at least 2 orders of magnitude larger than *Zerodur* or *ULE* materials.
This paper describes the thermal behavior of the OVLA primary mirror and the surface heating system designed to compensate the mirror deformations, and tested during the first light of the telescope which occurred in September 1999.

2. THERMAL BEHAVIOUR OF THE OVLA PRIMARY ACTIVE MIRROR

2.1. Thermal conditions

Figure 1 shows an astronomical mirror in typical conditions. The terrestrial ground and the atmosphere absorbs a part of the solar radiation and re-emits energy in infra-red during the night. Finally, we can regard the ground as a hot source and the starry sky like a cold source. The possible clouds are also hot sources since they reflect towards the ground a part of the thermal radiation emitted by the Earth. The rear surface of the mirror is thus warmer than the optical surface. A gradient of temperature settles inside glass according to the nebulosity and the solid angle filled by the sky. The mirror becomes curved like does a thermal switch. Thus, longer the tube of the telescope is, weaker the gradient is.

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Some temperature measurements made with the OVLA primary mirror looking at the dark sky have shown that the optical surface is always between 0.45 and 0.85°C colder than the rear surface.

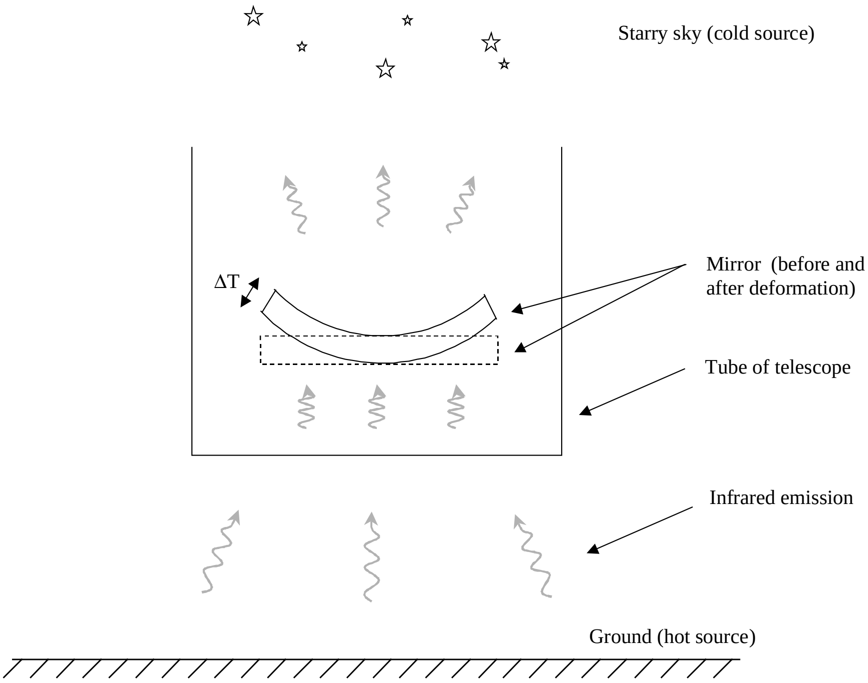

Figure 1: *Thermal conditions of an astronomical mirror looking at the dark sky.*

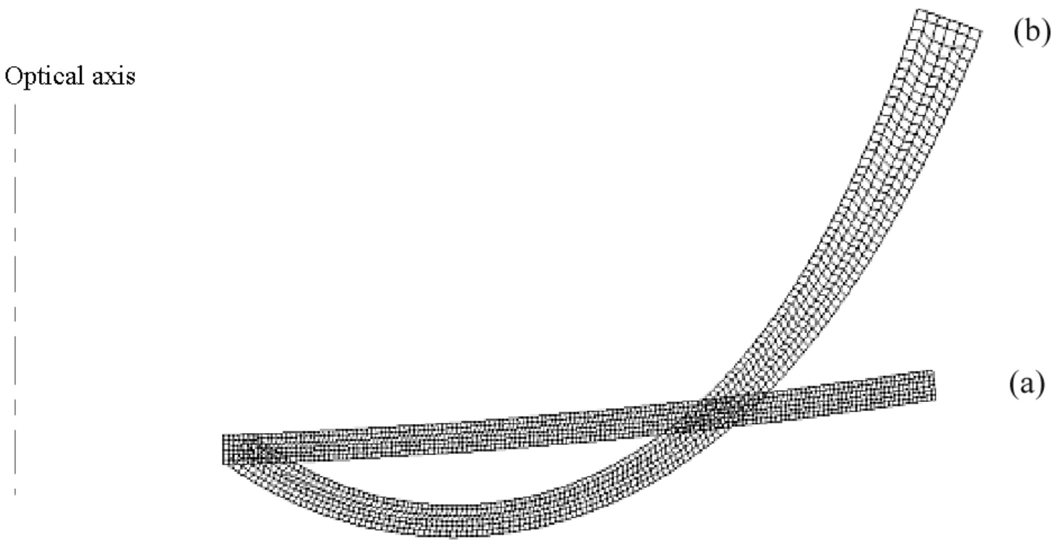

Figure 2: *Half-side view of a mirror blank without (a) and under thermal load (b) computed by FEA with Castem 2000. In (b), a thermal gradient of 1/h °C/m inside the meniscus-shaped blank is considered, where h is the blank thickness (24mm in the case of OVLA primary mirror). The surface deformations generated are essentially Z2=6.56 µm rms (defocus) and Z11=3.15 µm rms (spherical aberration).*

2.2. Thermal deformations of the primary mirror

This thermal gradient coupled with the high CTE of ordinary glass yields large deformations of the mirror. Figure 2 show a profil of the mirror radius computed by finite-elements with and without thermal load. This numerical simulation considers a vertical thermal gradient of 1/h °C/m. The mirror thickness h is 24mm. The main deformations of the mirror surface are defocus (Zernike Z4) and spherical aberration (Zernike Z11) with the following values :

i) Z4=6.56 µm rms/°C
ii) Z11=3.15 µm rms/°C

Z4 term is easily balanced since it generate only an 1.05mm/°C focus translation. But, Z11 is too great to be compensated by actuators. Indeed, such spherical aberration needs high dynamic active support with a 200N force range! Fortunately three alternative methods of correction can be considered[6].

One of them is a thermal control of the mirror optical surface. It seems to be the best solution because it tackles the origin of the problem by providing the heat lost toward the sky. The thermal gradient settled inside mirror glass is simply compensated by heating the optical surface of the mirror. A similar technique has been chosen by the GEMINI team in order to heat the *Zerodur* 8-m primary mirror to avoid local air convection due to temperature difference between the optical surface and the adjacent air[7]. In the case of the OVLA telescope, we not only benefit from a better local seeing, but also from a correction of spherical aberration. The following sections of this paper describe in details the surface heating system developed for the 1.5-m OVLA primary mirror.

3. PRINCIPLE OF THE MIRROR SURFACE HEATING SYSTEM

Outdoor temperature measurements made with several pairs of 100-Ω platinum RTD sensors uniformly spaced on the OVLA primary mirror surfaces have shown a quasi-uniform thermal gradient between the optical and back surface up to 0.85°C. To compensate this gradient, we have to achieve an uniform heating over the whole surface with a standard deviation lower than 0.05°C.

It can be done efficiently by Joule heat dissipation through the aluminum reflective coating because the aluminum layer is extremely thin (about 100 nm) and the thermal conduction toward the glass is much higher than the conduction toward the adjacent air. This requires a constant electric field E_y along the y direction, while E_x=0. To obtain a good uniformity of the electrical field, we should have :

i) an uniform electrical resistivity of aluminum coating (constant thickness, no scratches, no oxidation,…),
ii) an excellent contact between electrodes and aluminum,
iii) numerous electrodes to avoid local hot spots,
iv) an "electrical fill" of the central hole by additive electrodes,
v) an electrode voltage proportional to the distance separating the electrode and the $y=0$ axis.

About the first requirement, we have verified with resistance measurements made one a fresh and a 2-year-old non protected aluminum coatings, that the age of coating has no effects on its electrical resistivity.

Numerical simulations computed by finite elements with *Field Precision* software[8] show that a solution with 42 electrodes and 19 different voltage "slices" is sufficient. In figure 3, the voltage of each electrode is mentioned as a fraction of the maximum voltage. In order to optimize the electrical field uniformity, the electrode width depends of the electrode position in order to equalize each projected electrode height on the $x=0$ axis.

The fill factor of the mirror perimeter by electrodes is 2/3. This value seems to be a good compromise. Indeed, smaller spaced electrodes would generate more hot spots, while wider quasi-joined electrodes would make the mirror perimeter electrically more conductive than the rest of the aluminum coating.

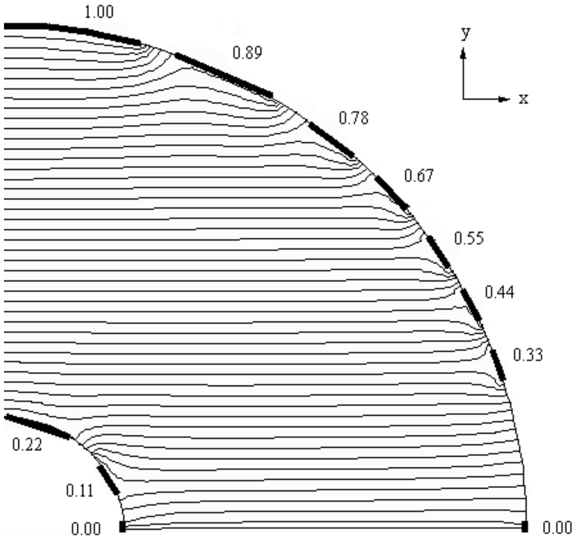

Figure 3: *View of electrical potential lines over the mirror surface obtained with a set of 42 electrodes and 19 voltage levels. The voltage applied on each electrode is given in times of maximum voltage, and varied as the distance separating the electrode with the y=0 axis.*

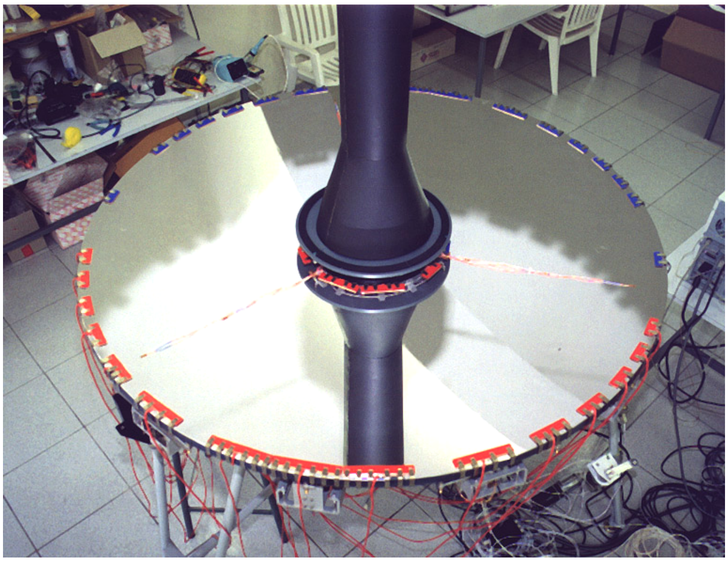

Figure 4: *Photograph of the 1.5-m OVLA primary mirror under testing equipped of its 42 electrodes and its 18 Pt100 RTDs.*

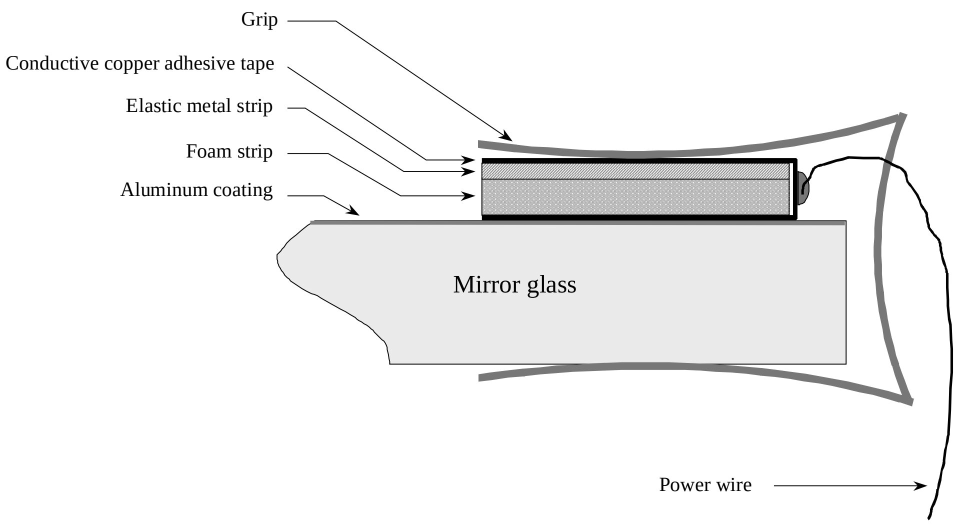

Figure 5: *Detailed view of an electrode interface system.*

4. ELECTRODE DESIGN AND INTERFACE SYSTEM

For easy operations, we chose a system of electrodes which can be installed after aluminizing. Since we have noted any problem of conductivity with old aluminum coatings which could be oxidized.

Figure 5 presents the system of electrodes chosen for the OVLA mirror. The contact between the electrode and aluminum coating is ensured by a grip pressing a foam strip wrapped in an adhesive copper sheet. An elastic metal strip rigidifies the unit. Thus the electrode takes perfectly the mirror shape and ensures an excellent contact. Among all the solutions we have explored (solder pastes, indium, conductive silicones...), it is the simplest and the cheapest one which achieved the desired uniformity and reliability. Moreover, the assembly of electrodes does not damage the mirror coating and requires neither gluing nor welding. Their removing is easy and does not leave any residue on aluminum coating. It is even possible to modify the electrodes distribution during tests if necessary.

5. HARDWARE OF THE SURFACE HEATING SYSTEM

5.1. Power calculations

To impose a temperature difference ΔT between opposite faces of a plate of a surface S, thickness h and thermal conductivity λ, the required heat power ΔQ is given by the Fourier law of heat transfer[9] :

$$\Delta Q = \lambda \frac{S}{h} \Delta T . \tag{1}$$

In the case of OVLA primary mirror, we have :
$\lambda = 1{,}39\ W.m^{-1}.K^{-1}$
$S = 1{,}81\ m^2$
$h = 0{,}0241\ m$

giving $\Delta Q = 100{,}9 \cdot \Delta T$. (2)

A power of 100W is needed to compensate an 1°C thermal gradient due to loss of heat toward the dark sky.
Now, let us calculate the electrical current and voltage required to provide this power. To simplify calculation, we consider a square mirror of the same surface S than the OVLA mirror (S=1,81m^2). The resistance of a square of aluminum coating of resistivity ρ and thickness e is:

$$R_{\square} = \frac{\rho}{e} \tag{3}$$

where $R_{\square}$ is the square resistance usually used in micro-electronics.
With $\rho = 2{,}65.10^{-8}\ \Omega.m$ and $e = 100.10^{-9} m$, we obtain $R_{\square}$=0,265 Ω. The required electrical current to dissipate 100W is :

$$I = \sqrt{\frac{P}{R_{\Diamond}}} = 20\ A . \tag{4}$$

This current, shared between all electrodes, induces a current density of 150 A/mm^2 in the 100-nm thick aluminum coating. But thanks to its large heat exchange surface with the glass, the coating does not fuse.
Lastly, the corresponding voltage U which we have to impose between two opposite edges of the mirror is :

$$U = \frac{P}{I} = 5\ V . \tag{5}$$

These values are only an estimation because the considered mirror is square instead of circular, but that is enough to size the voltage distribution hardware.

5.2. Hardware implementation

To power the 42 electrodes we have decided to use AC voltage for the same reasons than the GEMINI team[10] :

i) The maximum power needed (56W/m^2) is near the threshold where, with DC, metal migration might be a problem.
ii) AC transformers efficiency reaches generally 95%.
iii) The mean dissipated power can be controlled with a single variable transformer or an industrial PID regulator.
iv) The different electrode voltages can be generated by a transformers featuring several secondary windings.

Figure 6 presents the hardware implementation for the surface heating system of the 1.5-m OVLA active mirror. An annular transformer of 200 VA, specially designed for our application, delivers the 19 different voltage ratios necessary to the electrodes thanks to a series of 18 identical secondary windings. The maximum output voltage of the transformer is 12 V between the 2 opposite windings. It is conservative compared to the 5V needed to compensate an 1°C-gradient.
The annular transformer is placed just behind the mirror in order to reduce the length of wires as well as to confine the alternative magnetic field creates by the current loops (windings + aluminum coating) inside the mirror glass where there are no sensitive electronics components.
The total power dissipation can be controlled automatically or manually. In manual mode, a variable transformer (alternostat) supplies the annular transformer with an adjustable voltage from 0 to 220 VAC.
An automatic regulation of the power is also possible in order to correct the possible fluctuations of the thermal gradient due to nebulosity and telescope pointing changes. The feedback loop is closed by a pair of Pt100 RTD sensors measuring the temperature difference between the optical and rear surfaces in a single point located at R/2 from the mirror center, where R is the mirror radius. The error signal is amplified by a dedicated chip (XRT103) and transmitted to an industrial PID regulator through a 4-20mA current loop. A temporal power modulation is done by a 5A solid state relay with a period of several seconds. The successive power pulses are completely smoothed by the large thermal inertia of the mirror and should not degrade the mirror performance even in the infrared.
Additional pairs of Pt100 RTDs measure the thermal gradient in other locations on the mirror, just for checking and monitoring, not for controlling the power. These RTDs are distributed following three radius at 120° in order to stay under the M2 support arms (see figure 4).
We have also developed a dedicated PC-based “thermal active control” software with an user-friendly control panel.

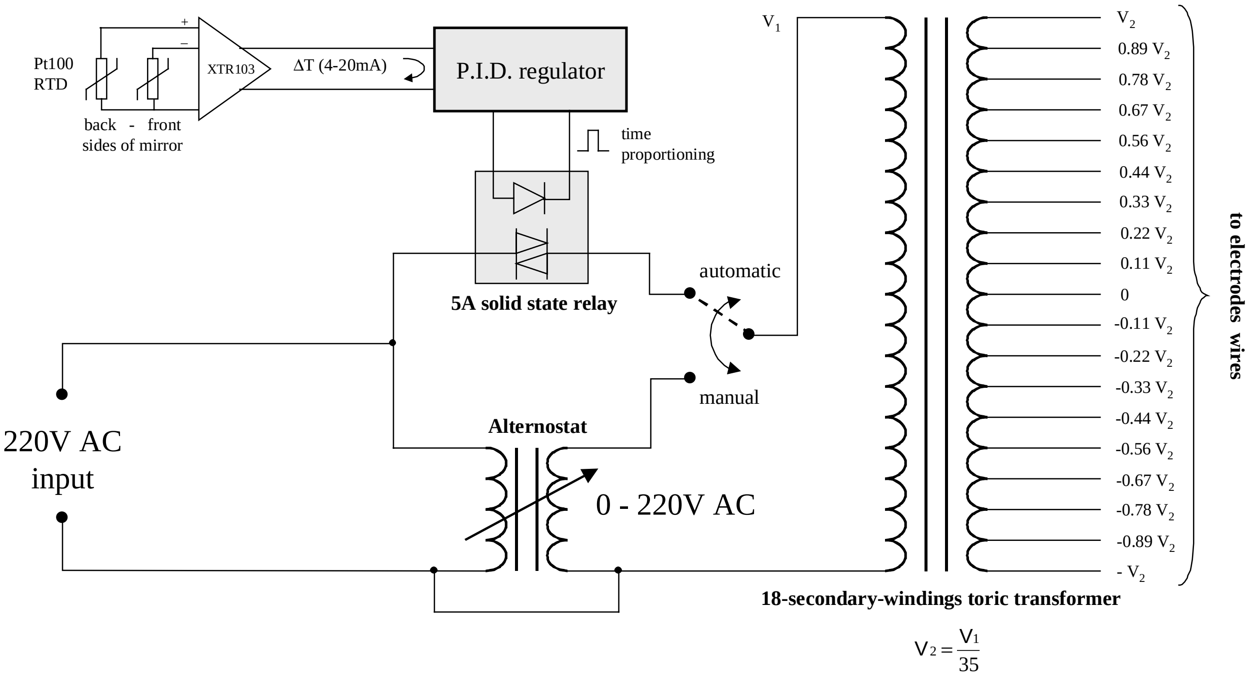

Figure 6: *Schematic view of the hardware implementation for the heating mirror surface system. The power dissipated through the mirror surface can be controlled by a variable transformer (alternostat), or by a PID regulator. An annular transformer featuring a series of identical secondary windings, delivers the 19 different voltages.*

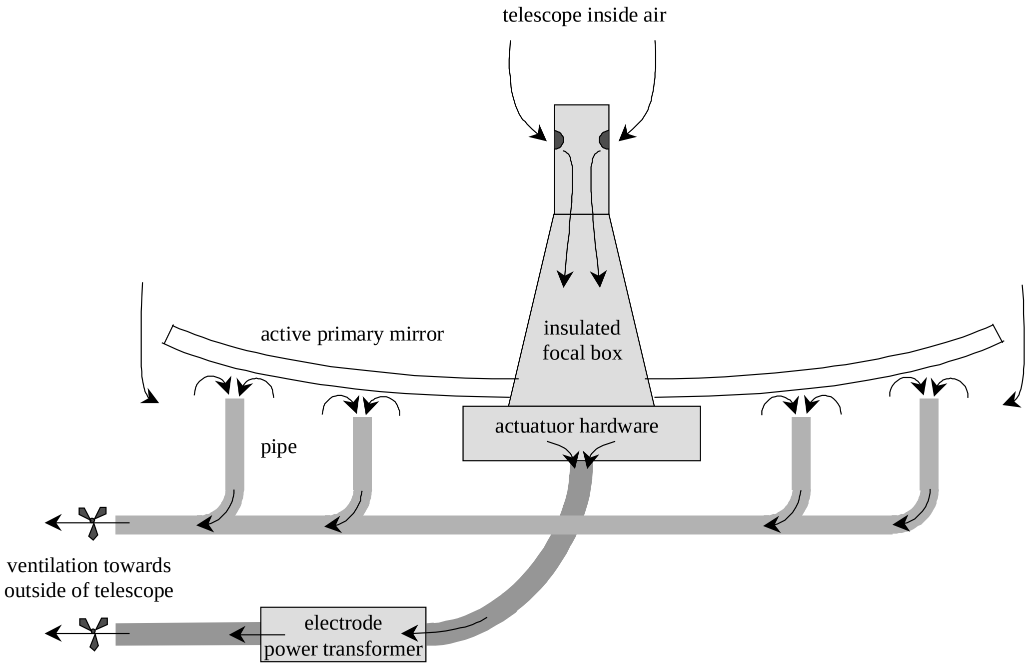

Figure 7: *Fan system installed under the mirror in order to reduce thermal perturbation due to electronics components.*

5.3. Fan system

To minimize thermal perturbation on the mirror, all electronics equipment (guidance and wavefront analysis cameras, tilt-sensor encoders, actuators hardware, electrodes annular transformer) have been located in an insulated and ventilated box (figure 7). Moreover, a set of pipes uniformly distributed under the mirror pumps the air, and helps to reduce the thermal gradient in the mirror thickness.

6. OUTDOOR TESTS AND RESULTS

First light of the OVLA telescope has occurred in September 1999 with an image of Deneb. Figure 9 shows this image before and after astigmatism correction made by the primary mirror active support. The uncorrected image FWHM reaches 30 arc-sec., while corrected image FWHM is from 3 to 5 arc-sec. Residual errors come from coma and trefoil and are yet not completely corrected by the active mirror support which is again under testing and upgrading.
To validate quantitatively the surface heating system, we have started a sequence of wavefront analysis after the heating system was switched off. Thus, we can follow the spherical aberration (Z11) growing with respect to the thermal gradient settling between the optical and back surfaces.
Figure 10 shows that Z11 wavefront error is proportional to the thermal gradient with a gain of 6.26±0.23 µm rms/°C, i.e. 3.13±0.11 µm rms/°C for the mirror surface error. This measured value is in perfect agreement with 3.15 µm rms/°C computed by *finite elements* simulations. Temperature measurements made with the set of RTDs show a standard deviation of the residual thermal gradient lower than 0.04°C.
This satisfactory result proves that our electrodes configuration is well suited for a 1.5-m ordinary glass mirror, and provide an uniform and steady current density through the whole coating surface.

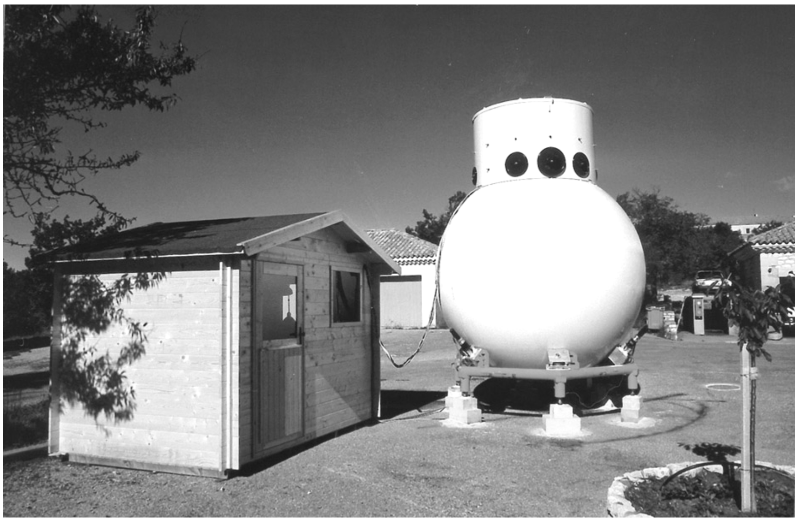

Figure 8: *Photograph of the OVLA telescope ready for its first light with the 1.5-m active primary mirror and its surface heating system. On left, we can see the operating lab containing the control computers.*

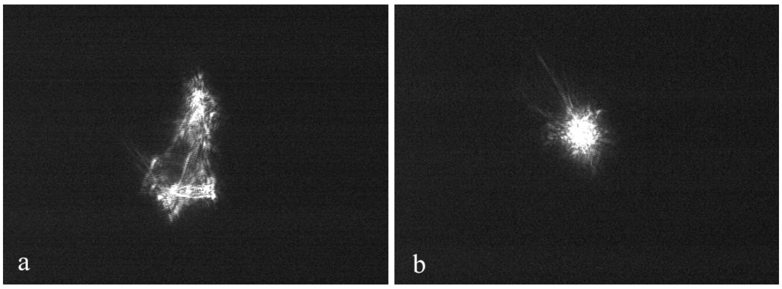

Figure 9: *First light of the OVLA telescope before (a) and after (b) astigmatism correction made by the primary mirror active support. The uncorrected image FWHM reaches 30 arc-sec., while corrected image FWHM is from 3 to 5 arc-sec. The spherical aberration is compensated by the optical surface heating system.*

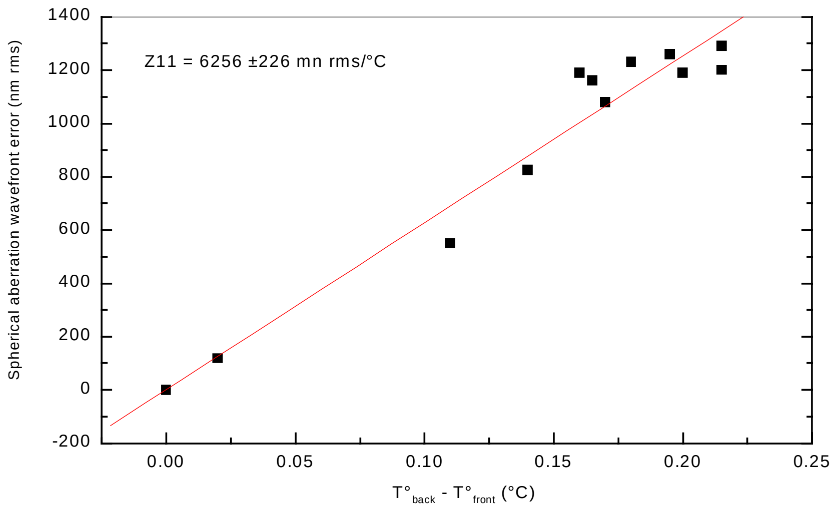

Figure 10: *Spherical aberration wavefront error with respect to the temperature difference between the rear surface and the optical surface of the mirror. As expected by simulations, these measurements show that Z11 wavefront error is about 6.30 µm rms/°C.*

7. TOWARD THERMAL ACTIVE OPTICS

The heating system we have described here allows to control thermally the spherical aberration of the primary mirror. Thereafter, we think to modulate the power dissipated in the mirror coating directly from the wavefront analysis results, instead of from temperature measurements. If we extend this concept further, we can imagine a *thermal active optics* system heating locally the mirror surface in order to compensate other optical aberrations than Z11.

This requires a temporal and spatial low-frequency modulation consisting of a set of commutable electrodes uniformly distributed on the external edge of the mirror and around the central hole. Indeed, it is possible to heat only a part of the mirror surface by applying a voltage between two selected electrodes, and therefore generate (or compensate) a given deformation (aberration)[6].

For example, it is possible to overheat the external edge of the mirror by supplying successively a pairs of peripheral of electrodes. That means to rotate on the mirror surface, a current cord of constant length (this mode is called “rotating voltage” on figure 11). The generated electrical field has a radial profile with a revolution symmetry. Conversely, it is possible to overheat the center of the mirror by imposing a constant voltage between all the electrodes of the central hole and all those of the external edge (this mode is called "center-edge voltage").

Other modulation modes are possible to generate non symmetric heating, as overheating only one half of mirror.

However such system can’t correct high frequency deformations. Ideally, we would need an array of electrodes uniformly distributed on the entire mirror surface, or only in the shadow of M2 support arms.

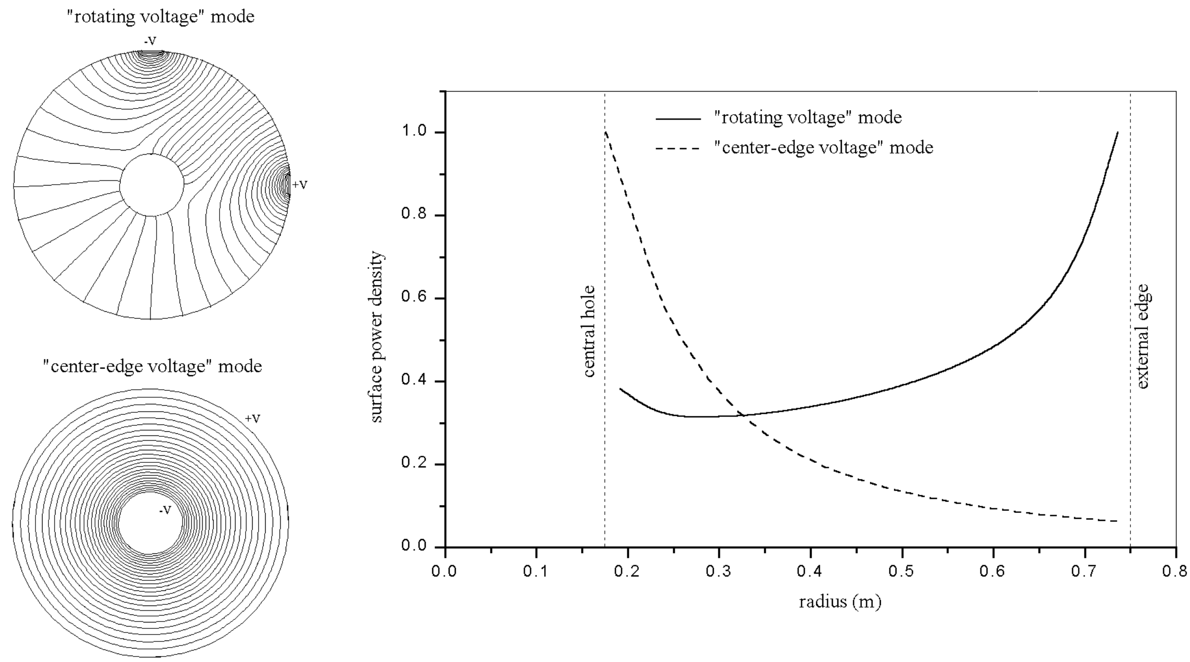

Figure 11: *Two examples of selective heating distribution with temporal low-frequency electrode commutations.*

8. CONCLUSIONS

We have seen that the optical surface of an astronomical mirror is always up to 1°C colder than the rear surface. Under a such thermal load, high CTE ordinary glass mirror surface presents a large amount of defocus and spherical aberration (6.5 and 3.1 µm *RMS* respectively in the case of the OVLA primary mirror).
The defocus can easily be balanced with a classical focuser. An automatic focus correction can be done by measuring the thermal gradient. Spherical aberration was a problem for using ordinary glass in astronomical mirrors. But we have demonstrated that a surface heating system, including only simple and common components, is able to correct this spherical aberration and it becomes possible to use ordinary glass to make very cheap, active or passive, monolithic mirrors or segments for future extremely large telescopes.

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