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VIRGO Mirrors : Wavefront control

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VIRGO Mirrors : Wavefront control

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Abstract

The franco-italian VIRGO program to detect gravitational waves requires large mirrors whose optical properties are extremely severe : absorption and scattering < 1 ppm at 1064 nm, wavefront homogeneity of 9 nm R.M.S. on ∅100 mm.

To achieve this performances on the wavefront, we have developed an experimental method to correct the wavefront shape to be as plane as possible. A thin silica layer is added through a hole, where it is necessary on the surface, on the last layer of the multilayer. A phase retardation is produced. The wavefront is measured before and after correction with a Zygo interferometer. The first test has been done on ∅80 mm mirror at 633 nm.

The wavefront R.M.S. goes from 6 nm to 1.5 nm. At this level, we are limited by the interferometer accuracy and repeatability. The optical properties modifications due to the corrective coating are small (at 1064 nm) or easy to overcome. The corrected wavefront includes at the moment the reference flat of the interferometer, so the measurements are not absolute. But, the feasibility of this correction method is proved and it is powerful.

1 - Introduction

VIRGO is a franco-italian program which goal is to build a giant Michelson type interferometer (Fabry-Perot cavity in each 3 km long arm) to detect gravitational waves. Virgo is based on the following principle.

The gravitational waves which propagates at the speed of light are transverse to the propagation direction [1]. When they propagates, they cause an antisymmetric change of the distance between free masses placed along two orthogonal directions transverse to the propagation direction of the wave. As the gravitational wave propagates across the Michelson interferometer having free suspended masses as mirrors, the interferometer arm lengths are changed antisymmetrically and a variation of the light power transmitted at the interferometer output is observed

As the typical signal to detect is very small (optical path difference about 10^{-18} m), almost perfect optics are required to keep clean the TEM_{00} mode in the arms.

A complete knowledge of the mirrors optical characteristics (Residual transmission, Absorption, Scattering, Surface wavefront) is needed. The absorption level is measured by photothermal deflection spectroscopy [2] whose sensitivity is 0.1 part per million (ppm) at 1064 nm. The scattering level is evaluated with a CASI™ scatterometer from S.M.S. (this is the only system in Europe) : this system is linear over 12 decades and it allows scattering level measurement below 1 ppm. Transmission measurements are also possible. The wavefront is measured with a Mirau type Zygo interferometer Mark IV xp (λ = 633 nm, accuracy 5-10 nm). The optical loss level (absorption + scattering) of each mirror must be known precisely because the interferometer performances decrease immediately : for example, a high absorption in the mirror coatings gives rise to a thermal lens effect and, thus, to a wavefront deformation in the interferometer and a contrast loss.

To meet the VIRGO low-loss requirements for the optical coatings (absorption and scattering in the 1 ppm range), we are using the reactive Dual Ion Beam Sputtering deposition technique (D.I.B.S.). This is the only known technique which guarantees low scattering levels [3]. This statement has been demonstrated in the gyrolaser application. On 80 mm diameter mirrors, we have reached the VIRGO requirements for absorption A and scattering S at 1064 nm [4] (A = 0.5 +/- 0.1 ppm, S = 0.6 +/- 0.2 ppm, average values on the whole surface).

At the moment, the maximal size that can be coated in our home-made coater is 100 mm in diameter which is small as compared to the VIRGO mirrors size (350 mm in diameter). To be able to coat such large samples, a large coater (cube of 2.5 m) will be built in 1998.

The VIRGO requirements on the wavefront uniformity are also very severe. For example, on the ∅350 mm diameter mirror, the wavefront homogeneity must be $\lambda/120$ R.M.S. on ∅100 mm (if the roughness power law is assumed to be $z(f) \approx f^{-1.7}$, $\lambda = 1064$ nm). To reach these requirements, a simple planetary motion of the substrate in the deposition chamber is not enough. So we have imagined a method to modify the wavefront shape, called "Corrective Coating Method", whose performances will be described in the following paragraphs. As the large coater is not ready, the first tests have been done on small ∅80 mm mirrors at 633 nm (working wavelength of the Zygo interferometer). Nevertheless, the methodology to correct the wavefront is easily transposable to large size mirrors at 1064 nm.

2 - Corrective coating method

2.1 - Theoretical approach

To realize high reflectivity mirrors, we have used a classical quarter-wave design $(HL)^n$ HLL (H: high index quarter-wave layer Ta_2O_5, L: low index quarter-wave layer SiO_2). The last half-wave SiO_2 layer has no optical purpose but the aim of this layer is to protect the multilayer for a long term stability.
An experimental method was imagined to obtain a mirror wavefront as plane as possible. To do so, a small amount of SiO_2 is added through a hole (circle or square) on the last low index layer of the multilayer stack where it is necessary. The addition of this thin SiO_2 layer produces a phase retardation (its thickness is variable). It is easy to change locally the wavefront shape and to control the modifications with an interferometer.

Before doing experimental tests, calculations have been done to know numerically how does the multilayer phase in reflection φ vary when the SiO_2 thickness locally increases.
The quarter-wave design $(HL)^n$ H is deposited on a substrate (refractive index n_S). Each layer is represented by a complex matrix [5] :

$$M_H = \begin{bmatrix} \cos(\delta_H) & \frac{i}{n_H}\sin(\delta_H) \\ i.n_H.\sin(\delta_H) & \cos(\delta_H) \end{bmatrix} \quad \text{for } Ta_2O_5 \text{ (refractive index } n_H\text{)}$$

$$M_L = \begin{bmatrix} \cos(\delta_L) & \frac{i}{n_L}\sin(\delta_L) \\ i.n_L.\sin(\delta_L) & \cos(\delta_L) \end{bmatrix} \quad \text{for } SiO_2 \text{ (refractive index } n_L\text{)}$$

The phases δ_H et δ_L are defined by the following formula (e_H and e_L geometrical thickness of the layers):

$$\delta_H = \frac{2.\pi}{\lambda} n_H.e_H \qquad \delta_L = \frac{2.\pi}{\lambda} n_L.e_L$$

Thus, the equivalent matrix of the multilayer stack M_T is defined by the formula :

$$M_T = M_H.[(M_L.M_H)^n.\begin{pmatrix} 1 \\ n_S \end{pmatrix}]$$

To study the influence of the corrective coating on the multilayer phase, we have added a SiO_2 layer (thickness x, matrix $M_{Lf}(x)$) and an air "layer" (thickness E-x, E = constant, matrix $M_A(x)$). With this configuration, we reproduce exactly what is seen by the interferometer. Thus, the equivalent complex matrix M_E of the entire multilayer is defined by the formula :

$$M_E(x) = M_A(x).M_{Lf}(x).M_T = \begin{pmatrix} B(x) \\ C(x) \end{pmatrix}$$

The phase in reflection (in degree) after a round-trip is given by the expression :

$$\varphi(x) = \operatorname{atan}\left(i.\frac{C(x).\overline{B(x)} - B(x).\overline{C(x)}}{B(x).\overline{B(x)} - C(x).\overline{C(x)}} \right)$$

The theoretical phase variation φ_n is expressed in nm to be compared to the one measured with the interferometer.

$$\varphi_n(x) = (\varphi(x) - \varphi(0)).\frac{\lambda}{2.360}$$

The factor 2 in the denominator suppresses the round-trip of the wave reflected by the mirror. Figure 1 shows the typical phase variation due to the addition of silica on the multilayer stack.

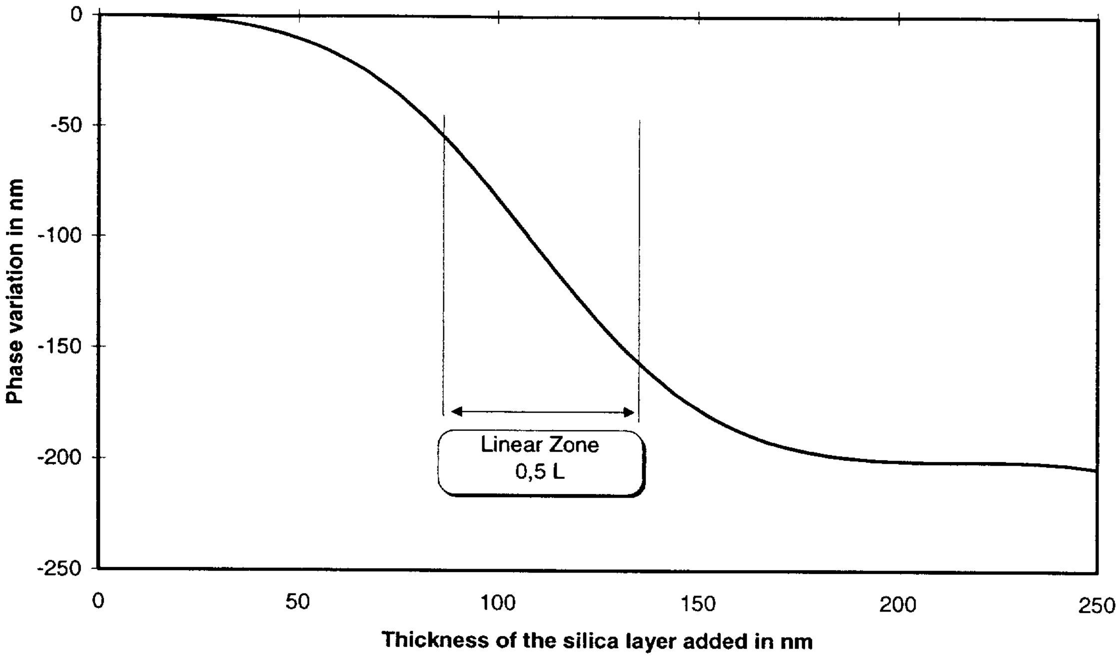


Figure 1 : Variation of the multilayer phase as a function of the silica thickness added at 633 nm

The variation is linear with a slope of 1 only on a small region centered around the inflection point of the curve. The width of this region corresponds to half a quarter-wave SiO_2 layer thickness (500 Å at 633 nm or 900 Å at 1064 nm). This is the maximum wavefront defect that can be corrected. For the corrective coating to be efficient, the starting multilayer design must be **$(HL)^n$ H 0.7L** to be situated at the beginning of the linear zone. The linear variation allows a good control of the wavefront correction and the accuracy will be only limited by that of the interferometer.

These calculations have been checked experimentally. The comparison is shown in Table 1. There is a good agreement between theory and experiment (interferometer accuracy +/- 5 nm).

SiO_2 thickness added (nm)	Measured phase variation (nm)	Calculated phase variation
0	0	0
10	-8	-8.2
20	-13.3	-18.1
30	-26.3	-29.2
40	-35	-40.6
50	-51	-51.3
90	-78	-77.6

Table 1 : Comparison between the calculated phase variation and the measured phase variation.

2.2 - Experimental approach

The corrective coating principle is described on Figure 2. To realize the corrective coating treatment, a robot, working under vacuum, was built in the D.I.B.S. chamber. An home-made software was developed to pilot this robot and to allow every movement in the X-Y plane of the sample. Thus, a 100×100 mm square can be described in this plane. We will describe the corrective coating procedure used to improve the mirror wavefront.

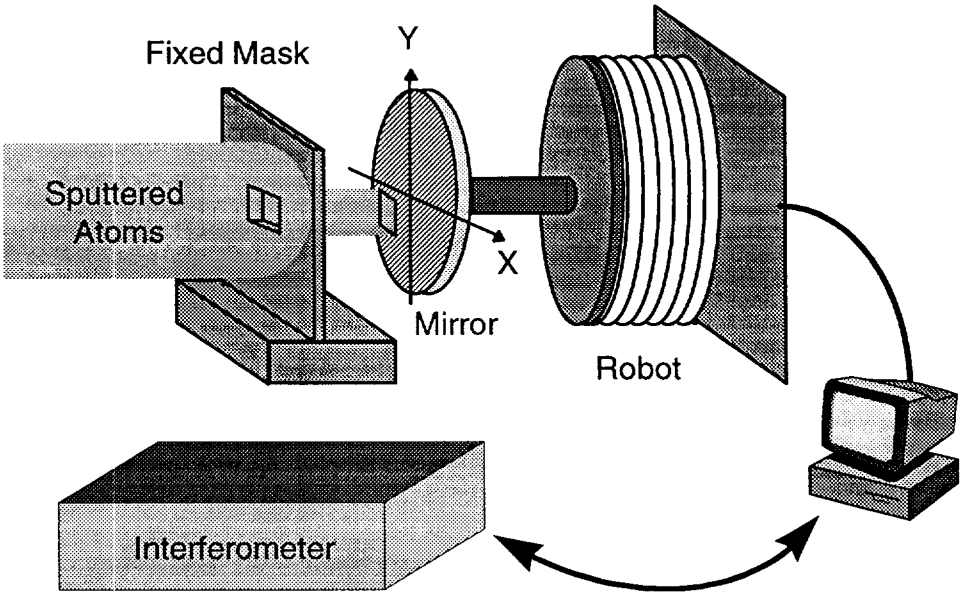


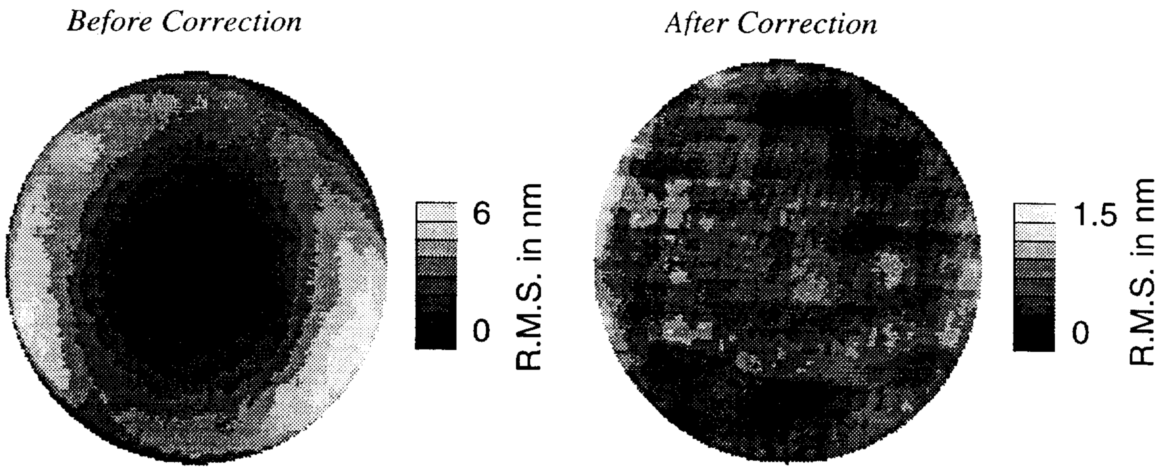
Figure 2 : Principle of the corrective coating method.

The first step is the measurement of the mirror wavefront (design $(HL)^n$ H 0.7L) with the Zygo interferometer. This measurement is done after a thermal annealing of the sample. Indeed, the D.I.B.S. coatings have a lot of compressive stress. It is reduced by a factor 4 with the annealing. The remaining wavefront deformation is due to the thickness inhomogeneity of each layer and to a small remaining stress that can not be suppressed (20% of the total deformation).

The wavefront data are used by an other home-made software to determine what is the necessary silica thickness to be added at each point of the sample to improve the wavefront flatness (the deposition speed of the silica layer through the hole is measured experimentally). This calculation is now automatic. The software generates a file used to pilot the robot. Thus, the corrective coating treatment can start.

Figure 3 shows what can be achieved with this wavefront correction. The R.M.S. wavefront goes from 6 nm to 1.5 nm after correction. At this level of flatness, we are limited by the Zygo interferometer accuracy and repeatability.

The VIRGO requirements on the wavefront are satisfied on ∅80 mm mirror. The corrective coating is a very efficient method to make the wavefront as plane as possible.


Before Correction

After Correction

Figure 3 : Wavefront at 633 nm of a Ø80 mm mirror before and after the corrective coating

Nevertheless, this method can only improve wavefront deformation lower than 50 nm (respectively 90 nm) at 633 nm (respectively at 1064 nm), this is the only limitation. Otherwise, the method accuracy is strongly deteriorated because the phase variation is no more linear (Figure 1).

We checked that the corrective coating has not deteriorated the optical properties of the mirror. Absorption, scattering and residual transmission measurements have been done before and after correction (Table 2) at 633 nm (we have not at the moment an interferometer at the YAG wavelength (1064 nm)).

	Absorption (ppm)	Scattering (ppm)	Residual transmission (ppm)
Before correction	4.7 +/- 3	2 +/- 0.1	7
After correction	7.5 +/- 3	1.9 +/- 0.1	45

Table 2 : Influence of the corrective coating on the optical properties at 633 nm (mirror design with 17 doublets HL)

SiO_2 and Ta_2O_5 are more absorbing in the visible region than in the infrared region (higher extinction coefficients, 633 nm close to the optical band gap). It explains the higher absorption level (5 ppm instead of 0.5 ppm at 1064 nm). The uncertainty on the absorption measurement is also higher (3 ppm which corresponds to the noise of the optical bench) because the pump laser beam of the photothermal deflection system is not powerful enough (35 mW at 633 nm instead of 1.5 W at 1064 nm).

The absorption level has increased after the corrective coating (30% higher). This is due to the fact that the thin silica layer added has not been annealed. But, an annealing will slightly modify the wavefront because of the layer stress relaxation. Nevertheless, the absorption increase will have less effect at 1064 nm because of the very low absorption level : 0.65 ppm instead of 0.5 ppm is acceptable.

The scattering has not been modified by the corrective coating. This is an important result because the more we manipulate the samples, the more we may create defects on the sample surface (holes, rays, particles contamination) which have a direct influence on the scattering level.

At last, the residual transmission has been strongly modified by the corrective coating treatment. To overcome this problem, a simple solution is to add some doublets to the multilayer design : for example, with a design $(HL)^{20}$ H 0.7 L, the residual transmission would be about 6 ppm. But, the drawback of this solution is the deposition time and the total thickness of the multilayer increase. Because of the stress, when the multilayer thickness is too high, the coating may come unstuck from the substrate.

3 - Conclusion and perspectives

We have developed an experimental method to correct mirror wavefronts to achieve the very severe VIRGO requirements. The results are very convincing (1.5 nm R.M.S. instead of 6 nm R.M.S. on ∅80 mm mirrors). The method validity is demonstrated. Some small modifications of the optical properties of the mirrors have been observed after the corrective coating but they can be overcome or neglected at 1064 nm.

The perspectives of this work is to transpose the method to larger substrates (350 mm diameter). To do so, we have to build a new large coater to be able to coat such large samples. To correct larger surfaces, the principle is the same. This is just a question of time : the corrective coating of a ∅80 mm mirror lasts about 10 hours. Moreover, an interferometer at 1064 nm will be purchased to make wavefront corrections at the VIRGO wavelength. The correction methodology does not depend on the wavelength.

The measurements we have presented are not absolute measurements because they include the ∅100 mm reference flat. We have corrected the wavefront defects of the couple reference flat / mirror. So, the next development of the corrective coating method will be to suppress the reference flat contribution. One complicated solution is the "three-flats method" [6-8].

Nevertheless, the feasibility of this correction method is clear and this is a powerful method.

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