(9)

ESO-74-C
July 1998

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SEP 17 1998

Variable Curvature Mirrors for the VLTI

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ABSTRACT

A variable curvature mirror is a powerful device that can increase the field of view of optical interferometers. Such a mirror has being developed for the coherent combined focus of the European Southern Observatory Very Large Telescope Interferometer (ESO VLTI).

The variable focal length permits positioning of the pupil image of an individual telescope at a precise location after the delay-line. This property is necessary to exactly remap homothetically the output pupil configuration at the image beamcombiner.

Given the large zoom range that is needed in the delay line, when the mirror is not stressed the optical surface is a plane while it is convex with f/2.5 at maximum stress. The mirror itself is a very small stainless steel meniscus, with a 300μm thickness, because only the high elasticity of such material allows to achieve the full domain of curvature. The thickness distribution of the meniscus is calculated using elasticity theory in the case of a large deformation.

The realization of this micro-optic active device requires advanced techniques in optical fabrication and in particular high precision manufacturing with numerical command lathe. This article also presents the testing of this highly Variable Curvature Mirror (VCM) and the surface quality obtained within the full curvature range.

Keywords: active optic, mirror, elasticity, interferometry.

ESO-74-C

1. INTRODUCTION

Since the very begining of the Very Large Telescope Interferometer (VLTI) project, it was foreseen that observations with this unique interferometer should not be limited to on-axis objects. The possibility to have a "wide" field-of-view (8 or 2 arcsec) was planned and studied [1,2].

It came out that the "wide" FOV goal cannot be achieved without a precise and homothetic maping of the telescopes array pupils in the recombinaison mode. This led to study and define a pupil management system located in the delay-lines [3], and in the early 90's the European Southern Observatory issued a call for proposal for a variable curvature mirror (VCM) serving for beam management purposes.

While the VLTI is tracking an astronomical object, the delay-lines provide for the equalization of the optical paths of individual telescopes by varying positions in the interferometic tunnel. The optical system of the delay-line, represented at Fig. 1, is a cat's eye mounted on a carriage and whose location in the tunnel is carefully monitored in order to compensate optical path differences (OPD) up to 120m between different telescopes.

This cat's eye system is a Ritchey-Chretien telescope with the VCM as tertiary mirror. The primary and secondary mirrors produce an image of the source on the VCM and, after other reflexions on the secondary and primary, the beams are directed to the recombinaison laboratory through the interferometric tunnel.

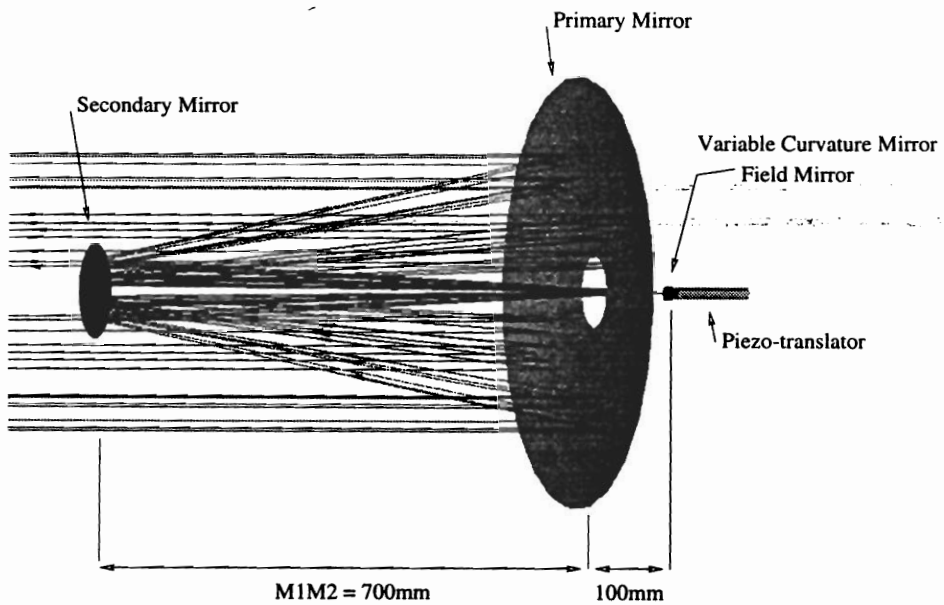

Figure 1: Optical layout of the Ritchey-Chretien delay-line system with the VCM (M15) as the tertiary mirror

The range of radii of curvature required for the VCM is determined by the position of the delay-lines. The distance between the position of the pupil image following the Coudé optics and the entrance of the cat's eye, and the distance between the exit of the cat's eye and the required position of the pupil image in the recombinaison laboratory are the two major parameters for the determination of this range. Considering the FOV planned for the VLTI (2 arcsec) and the OPD to compensate for, the cat's eye secondary curvature must be continuous variable within a range from $(84\text{mm})^{-1}$ to $(2800\text{mm})^{-1}$. This has been thoroughly analysed and described by the authors [4], O. von der Lühe [2,3] and other authors [1,5], including further phase recoveries with the additional VLTI sub-array, 8m Unit Telescopes and Auxiliary Telescopes.

As demonstrated hereafter, the VCM system is critical for the wide FOV operation of the interferometer. For a simpler demonstration we consider an interferometer with a simple Newtonian cat's eye system (Fig.2) using a small plane mirror located at its focus as a secondary, but the results remain the same with a Ritchey-Chretien system used in the VLTI.

For paraxial rays, a $\delta_0/2$ displacement of the delay-line in the tunnel compensates for a δ_0 optical path difference, but for off-axis rays (or "field rays") coming with an angle i this OPD is equal to $\delta_i = \delta_0(1 - i^2/2)$ (see Fig. 2). Then with a small plane mirror, when the OPD is compensated for paraxial rays, it is not for the rest of the field. But a cat's eye system has the great advantage that rays coming from different parts of the field are physically separated on the secondary mirror. Hence, bending the small mirror with $\delta_0.i^2/4$ at the distance $R.i/2$ from the axis compensates for the "field OPD" $\delta_0.i^2/2$ and eliminates the difference between paraxial and off-axis rays (see Fig. 2). This bending corresponds physically to make spherical the small secondary mirror, with a radius of curvature $\rho = R^2/2\delta_0$ where R is the radius of curvature of the cat's eye primary. Then the OPD is compensated for all the FOV and the "field fringes" are eliminated at the combined interferometric focus of the telescopes array. As the radius of curvature ρ of the cat's eye secondary depends of the compensated axial OPD δ_0, it is varying during the movement of the delay line system . This possible compensation for the OPD of "field rays" in a cat's eye interferometer was first noticed by P. Connes [6,7].

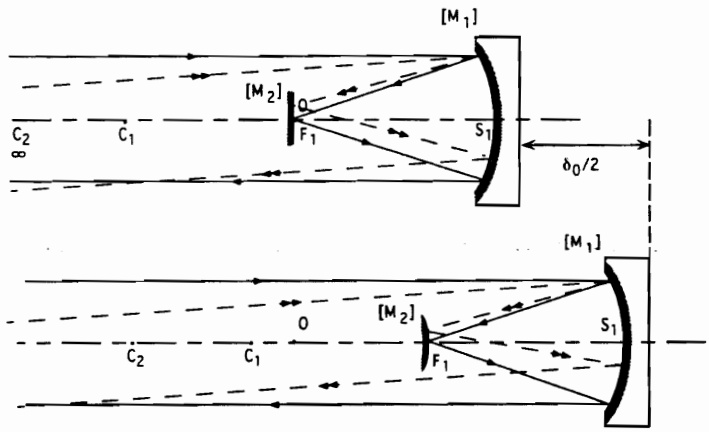

Figure 2: **Field compensation with a Newtonian cat's eye system**

The spherical deformation corresponds also to the one which maintains the center of symmetry O of the cat's eye system at the same location during the movement (see Fig. 2), the variable focal length then permits to keep a pupil image at a precise location while the delay-line carriage is moving.

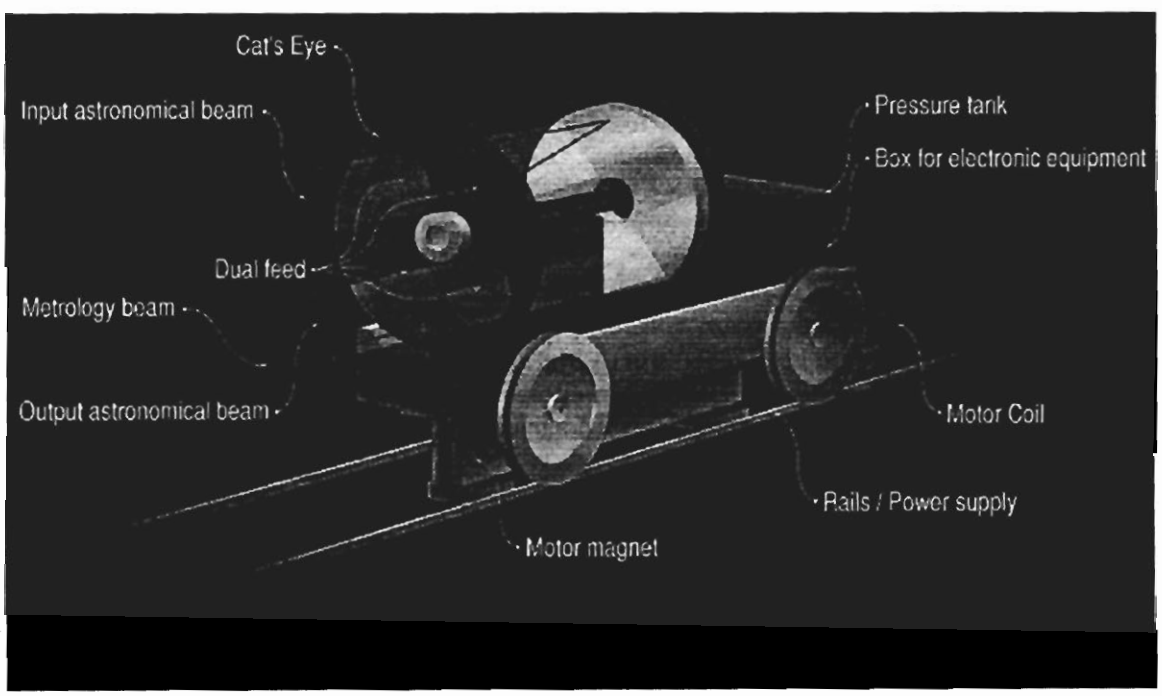

Figure 3: **Artist view of the VLTI delay-lines. The VCM is located behind the primary mirror.**

2. VARIABLE CURVATURE MIRRORS

The first approach to variable curvature mirrors belongs to G. Lemaître [8]. VCM's or *zoom mirrors* are generated by a pure quadratic deflection of the form $w(r) = w_0(1 - r^2/a^2)$, where w_0 is the axial deflection and a the radius at the edge of the mirror. A torque uniformly applied at the edge of a constant thickness meniscus provides exactly such a variation of curvature. But because such a torque is not easy to applied, the case of easier load distributions were investigated and the idea was to actively deforme a small metallic mirror with an uniform loading or a central force. A prototype was developed for the European Synchrotron Radiation Facility and served to increase the field of view of a Fourier transform interferometer. The mirror was 20mm diameter large and the maximal flexure achieved was 31μm, corresponding to a focal ratio varying from $f/35$ to $f/20$.

The major difference, between this first successful attempt and the ESO prototype, is the amplitude of the maximal deformation applied to the mirror. Due to the large range of curvature needed in the delay-line, the simple theory of elasticity was not convenient. We had to extend the theory of elasticity to the large deformations where the total amplitude of the flexure can be of the same magnitude or greater than the plate thickness. The analytic developments of the elastical deformations theory and the numerical results used for the ESO-VCM design have been presented in various papers [9,10,11,12].

The location of the VCM in the delay-line system, on the piezo-translator used for small OPD compensation, led us to minimize its weight and to realize a small mirror with a 16mm diameter. Then, with such a small optical aperture, the range of radii of curvature corresponds to a f ratio from f/∞ to f/2.5, and the maximal central flexion reached is 380μ.

In the VCM system presented here, the curvature is achieved with an uniform loading applied on the rear side of the mirror and produced by a pressure chamber. In order to use easily achievable pressure ($< 10bar$), we choose for the active part of the system a very thin meniscus with a 300μm central thickness t_c. Remembering the amplitude of the deformation achieved at the maximal curvature (W_0=380μm), the flexion ratio W_0/t_c is larger than 1.25, very far from the 1/3 limit of the small deformations approximation. The use of the large elastical deformations theory was obviously necessary. This allowed us to determine the radial thickness distribution of the mirror in order to have constantly, in the 14mm central part of the mirror, a spherical surface during deformations.

Due to the large bending of the mirror, the full domain of curvature is not achievable with a classical optical material as vitroceramic glass (Zerodur). Metal alloys having 100 times higher flexibility than glasses, a stainless steel substrate (AISI 420) has been chosen for this reason and for the fact that deviations to Hooke's law (stress-strain relation) are smaller with such materials.

3. REALIZATION OF THE MIRROR

This micro-optic active device requires advanced techniques in optical fabrication and in particular high precision manufacturing with numerical lathe. The thickness profile, or the back side equation of the meniscus, determined using large elastical deflections theory, must be produced with a 1 micron precision in order to have the required optical shape. Deviation from this profile would product undesired deformations.

The realization of the VCM uses an *holosteric* solution where the edge of the central active meniscus is linked with an outer rigid ring via a very thin collar having a 50μm thickness (Fig. 4), and the air pressure is applied on the back side of the meniscus. This simplifies the mounting and avoids air leak by having the mirror and its outer ring in the same sample.

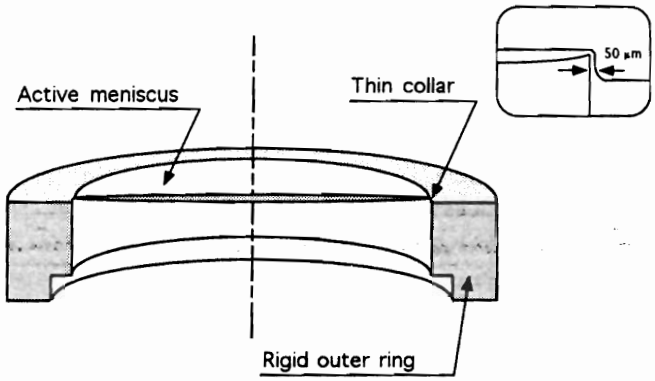

Figure 4: Holosteric concept developed for the VCM

As the deflection depends, among others parameters, of the collar radial thickness, an off-centering coming from a too large amount of loose in the substratum fixation on the lathe and producing an irregular collar thickness distribution, can not be accepted. A best effort has been done to reduce such an effect, and to obtain a minimal off-centering, crucial for the axial symmetry of the mirror's shape.

The last stage of the manufacturing process consists in the final surfacing and polishing, and is a very delicate one. The difficulty comes principally from the small size of the mirrors and the high flexibility of the active meniscus due to its thickness. A know-how has been developed at the LOOM (Laboratoire d'Optique de l'Observatoire de Marseille), the polishing is done without modifying the mirror figure and the achieved roughness is close to 10nm. [13,14]

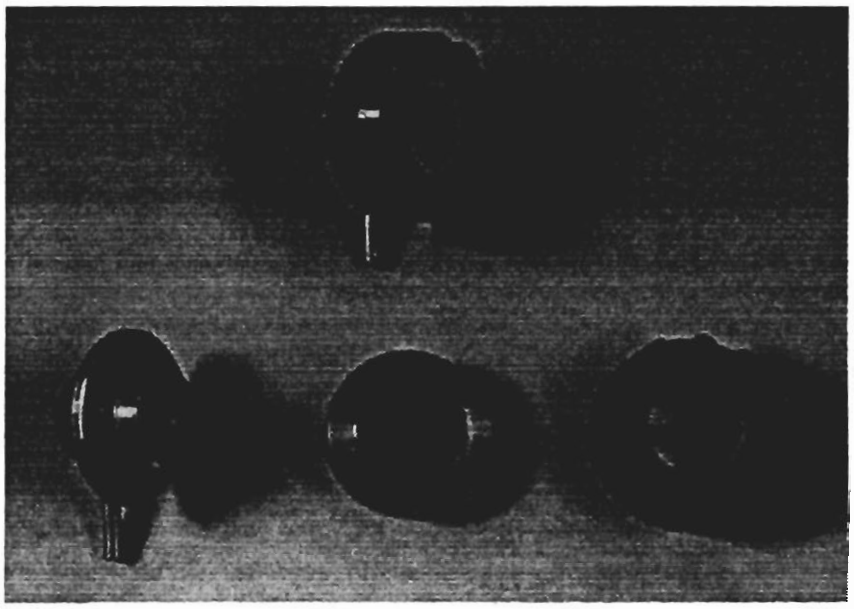

Figure 5: VCM mirror and its support head (mounted and dismounted)

The VCM mirror is represented, mounted and dismounted on its support head, at the Fig. 5. An effort has been done to reduce the total weight of the overall system (Mirror + head) which is only 32g. The small tube at the back part of the head is where the pipe coming from the air pressure chamber is attached.

4. OPTICAL PERFORMANCES OF THE PROTOTYPE

4.1. Optical surface

The ESO requirements asked for the VCM during operation are tight. The main one is to limit the surface deviation from a sphere to less than one wave peak-to-valley (PTV) for λ=632.8nm , but the clear aperture concerned varies during the operation. The deviation has to be minimized on two different diameters according to successive ranges of curvatures. To radii of curvature between [2800 and 230mm] and those between [230 and 84mm] correspond respectively a 14mm and a 6mm clear aperture.

The important result deduced from surface measurements is that the central part of the mirror fulfils the requirements: deviation from a sphere is lower than λ PTV on a 6mm diameter. The analysis shows that on a 6mm diameter the deviation remains below λ during the whole curvature range [14], as proved by the interferogramms in Fig. 6 taken at radii of curvature equal to 2800mm and 84mm. A large curvature variation can be achieved with a reasonable good optical quality on the central part of the surface. Unfortunately, the analysis also shows that this good quality is not achieved on the full aperture. For radii from 2800m to 230mm the outer part of the mirror surface is out of quality requirements, due to an excessive amount of spherical aberration.

Figure 6: Interferograms of the optical surface of a VCM sample for the maximal and mininal achieved radii of curvature: 2800mm (left) and 84mm (right).

Table 1: Wave Front Error of a VCM surface on the whole curvature range

P	*R*	*a*	*Wave Fronf Error* (λ)		
[bar]	[mm]	[mm]	*Sph. Abb*	*rms*	PTV
0.233	2800	7	0.492	0.439	2.271
1.013	420	7	8.098	0.929	4.713
1.815	230	7	16.170	1.481	7.118
1.798	230	3	0.270	0.111	0.588
3.341	140	3	0.219	0.130	0.679
5.082	105	3	0.027	0.146	0.755
7.561	84	3	0.460	0.202	0.849

Table 1 presents the optical quality (rms and PTV) achieved with one of the VCM mirrors on the whole curvature range, the spherical aberration amount is also indicated.

For radii of curvature from 2800mm to 230mm the Wave Front Error (WFE) is evaluated on a 14mm diameter. The spherical aberration becomes rapidly important leading to an out of requirement quality but, as already mentioned, the best results are obtained for a 6mm diameter. At the 230mm radius, the spherical aberration is divided by 60 when we reduce the clear aperture from 14 to 6mm. This amount of spherical aberration remains low within the range [230 - 84mm], and the WFE (PTV) is slowly increasing from 0.59λ for 230mm to 0.85λ at 84mm. This proves that the largest deviations come from the outer part of the mirror and that the spherical aberration amount remains the major problem encountered.

4.2. Curvature control accuracy

The other important point related to the achievement of a coherent field at the combined focus, is the adjustement of a precise curvature during the operation of the VCMs. To evaluate this accuracy, we made numerous scans of the whole curvature range from which we calculated the mean curvatures achieved and deviations to them. This set of mean curvatures is used to modelize a *Pressure/Curvature* relation, using a Lagrange interpolation, which is included in the pressure monitoring software. As the relation depends of the active meniscus and the collar thicknesses, this calibration has to be done for each mirror because of small variation among the samples.

This calibration is crucial for the monitoring of the VCM curvature under an open-loop control. The resulting error on the curvatures is less than 5.10^{-3} m^{-1} which is the limit value accepted by ESO in the control curvature accuracy requirement. This result proves that the *Pressure/Curvature* relation is a tight one and permits to achieve a precise curvature with a high accuracy.

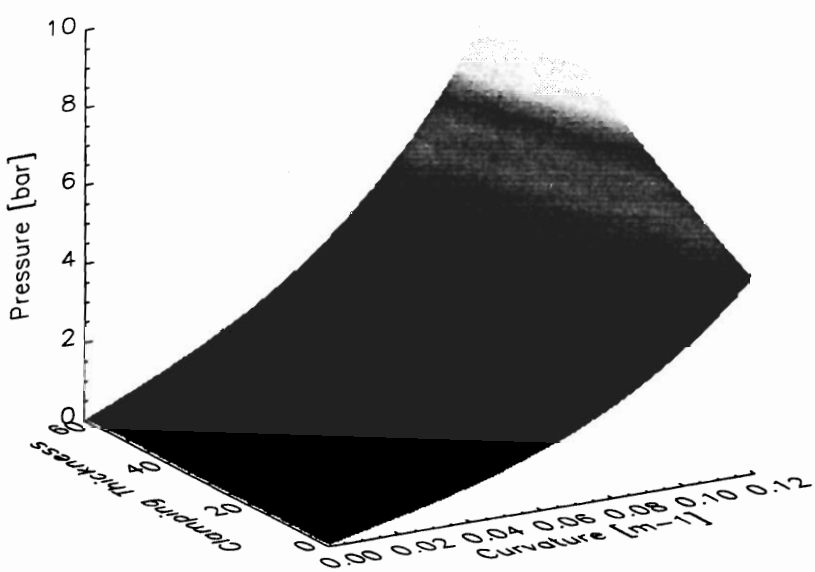

Figure 7: *Pressure/Curvature theoretical law for various collar thicknesses*

The theoretical relation *Pressure/Curvature*, displayed in Fig. 7, include the "semi-clamped edge" effect. This means that when in the free-edge case a pressure P_0 is needed to achieve a given curvature, then a pressure $P_c = P_0.(1+c/t)^3$ is necessary for a meniscus having a central thickness t and a collar thickness c in the semi-clamped case. The Fig. 7 presents this relation for various collar thicknesses from a 0 (free-edge) to 60μm. The good agreement between these theoritical predictions and the experiments proves that the effect added by the collar rigidity has been properly analysed and that the numerical simulation is accurate.

6. CONCLUSION

We have described here, a highly variable curvature mirror, its manufacturing process and the optical quality obtained within the curvature range. Another type of VCM, using a central force instead of a uniform pressure has been also developed at the Observatoire de Marseille [15]. The optical quality is nearly the same, but this type of mirror is easier to actuate and control than the pressure loaded one. ESO choosed the uniform loaded type as, with the second type, it would be impossible to put the DC motor, providing the central force by an axial displacement, on the piezo-translator.

This is the first time that a variable curvature mirror is achieved with such a large range. The optical quality is in accordance with the ESO requirements for a 2 arcsec FOV (WFE $< \lambda$ on a 6mm diam.) and led to the realization of a VCM system fulfilling the goals for the forthcoming optical interferometric array of the VLT. Today this VCM system is being included in the delay-lines in order to setup and calibrate the interfaces with the other devices of the interferometric mode. The integration will be done during this year, and the installation on the Paranal observatory of the first complete systems (delay-lines with VCMs) will occur before year 2000. The VLTI will not be the only one interferometer to benefit of this type of device. A Variable Curvature Mirror system has been integrated in another optical interferometric array.

A VCM is now a major component of the upgraded Grand Interferometer à 2 Telescopes (GI2T) array of the Observatoire de la Côte d'Azur, located in Plateau de Calern (France). This mirror has been mounted in the LAROCA delay-line and is used for pupil management on the REGAIN recombinaison table. The complete system has been tested in observing conditions during the 97 year in a close collaboration between D. Mourard and the GI2T team and the ESO VLTI group[16].

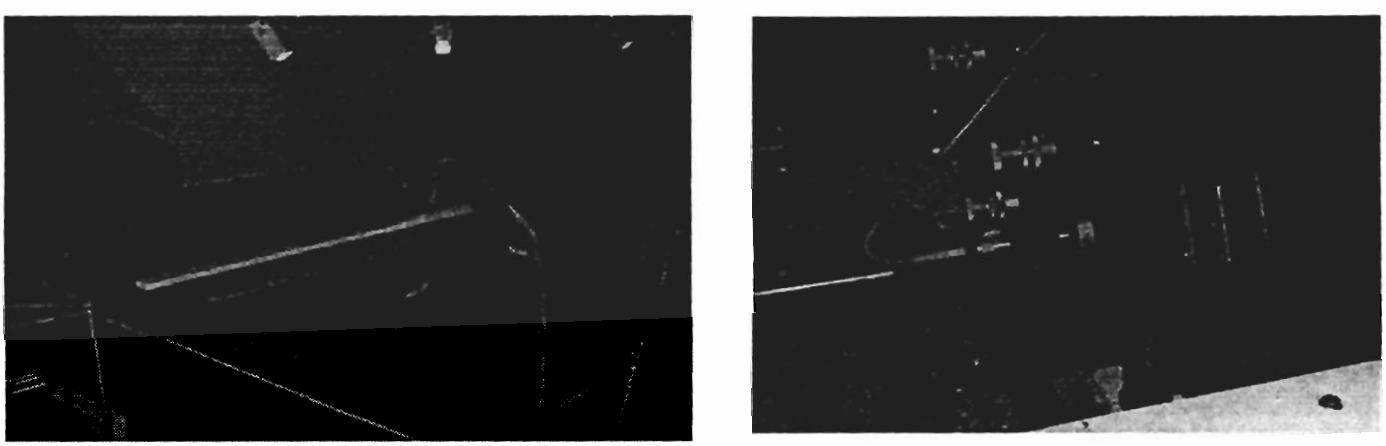

Figure 8: The LAROCA delay-line of the GI2T interferometer (left) and the VCM mounted as the secondary mirror of the newtonian cat's eye (right).

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