Alignment-invariant mirror holder for cryogenic environment and its application to GIANO-TNG

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ABSTRACT

There are many ways to achieve the positioning accuracy established from tolerance in a cryogenic environment. One method is an opto-mechanical design which stays aligned at room temperature and at liquid nitrogen temperature without modifications. This could be achieved using aluminium mirrors with thermally matched aluminium holders and optical bench, that isotropically contract at cryogenic temperatures.

The design of holders should allow some adjustment of the optics positions to correct possible errors in manufacturing of the optical bench and/or optical holders themselves, without precluding the isotropic contraction during the cooling to the working temperature.

This work illustrates the last prototype of cryogenic mirror-holder developed in our laboratory. The mirror mounting is based on a set of six forces which pull the mirror against the tree orthogonal faces of a reference corner. Adjustments to the mirror alignment can be achieved by means of six aluminium micrometers. Here we describe the device and illustrate the test results.

Keywords: Criogeny, mechanics, mirror holder

1. INTRODUCTION

GIANO is an optimized near infrared spectrograph which can yield, in one shot, 0.9-2.5 micron spectra either at low ($R = 200$ and/or $R = 500$ with a 1" slit) or high (up to $R = 50000$ with a 0.5" slit) resolutions maintaining, in both modes, a very high throughput throughout the whole spectral range. This project is part of the Second Generation Instrumentation Plan of the Telescopio Nazionale Galileo (TNG) located at Roque de Los Muchachos Observatory (ORM), La Palma, Spain. GIANO will be installed at Nasmyth B focus of TNG.

The optical bench is machined by a single block of the same material as the the mirrors. The mirror support and the alignment system are an evolution of those built by our group for AMBER@VLT and takes into account the much larger size and mass of the mirror. Compared to the former projects, where the mirrors were directly interfaced with the bench through suitable supports, the GIANO mirrors have the advantage of being rigidly mounted onto separate brackets manufactured by the same company which make the mirrors. Each bracket can be therefore worked to the most convenient shape for the alignment system.

The spectrometer of GIANO is designed to work at cryogenic temperature, this implies that the optical system will be aligned at room temperature and successively cooled undergoing a temperature change of about 200 K in the process. The optical bench, the mirrors and their holders will all be manufactured in aluminium so that in the cooling process the unavoidable contraction of the material will be homogeneous and isotropic and the alignment of the optical system will be preserved to the maximum possible degree.[1] This is a well established technique that has been employed in the development of other infrared instruments such as the spectrometer of AMBER.

Unlike other IR instruments, the optical system of GIANO needs a very careful and complicated alignment.[2] This led to the necessity to develop an holder that allows micrometric movements during the alignment process and does not induce deformations that can compromise the performance of the system after the cooling.

2. HOLDER PROTOTYPE

The structure of the holder prototype consists of a mounting plate suspended within an encasing obtained in the external frame. Both the mounting plate and the external frame are made of aluminium 6082.

The mounting plate position has to be adjusted to obtain the best possible alignment of the optics, for this reason it is necessary to control all of the six freedom degrees of the plate. The plate is therefore suspended by means of twelve iron springs pulling towards the external frame; six micrometers, one for each pair of springs, push the plate in the opposite direction and allow for the regulation of all the freedom degrees.

Two micrometers placed on the upper side allow to control the vertical position and the z-axis tilt, one micrometer placed on a lateral side controls the horizontal position. Three micrometers positioned on the back side control the position along z-axis and the tilts in the horizontal and vertical directions (see figure 4). Each micrometer is equipped with a blocking ring to block the screw in place once the system is aligned.

The mirrors of GIANO that will be installed on this kind of holder will have masses up to 30 kg for this reason each of the springs must be able to provide a force of about 25 N in order to guarantee a stable alignment. The micrometers are manufactured of aluminum 7075 which is an harder aluminium alloy, to prevent the force of the springs from damaging the threads.

As already said the optical bench, the holder and the mirrors are all manufactured in aluminium to ensure that, after the cooling, the system will have undergone an homogeneous and isotropic contraction; on the other side there is no means to control the deformation during the cooling process. This is because the cooling does not occur concurrently in every part of the system (see figure 4). In particular the mounting plate is likely to cool slower than the fixed frame since the latter is in contact with the optical bench and the nitrogen tank and the former has but few contact points with the fixed frame only. During the cooling process thus the fixed frame is expected to contract before the mounting plate.

The micrometers are solidal to the fixed frame and press on the mounting plate; during the cooling process they could bring about the mounting plate since the friction coefficient increases in the vacuum and at low temperature. To prevent this, particular care was taken in the design of the contact system between the micrometers' heads and the mounting plate

The contact between each micrometer and the mounting plate is realized with a steel sphere. The sphere is placed between the micrometer's head and a hollow cylinder loosely fitted in a hole on the mounting plate (see figure 4). Both the micrometer head and the hollow cylinder are made of steel to resist the pressure generated by the springs. This contact system reduces the radent friction allowing the mounting plate to slide freely back and forth remaining aligned.

The holder prototype developed for the tests measures 145 × 145 × 32 *mm*. In the spectrometer up to six holders will be employed, each scaled according to the size of the mirror mounted.

3. MISALIGNMENT MEASUREMENT

The tolerances on the mirror alignment were determined with ray-tracing simulation[3] of the whole system. To test the performances of the holder prototype, in terms of alignment stability of the mounting plate's plane and the fixed frame's plane, we needed to devise a measurement with a sensitivity that would allow the detection of the misalignment within the tolerances. The best way to achieve the desired sensitivity was an interferometric measurement. The measurement was carried out with two different test configurations.

The first and more simple configuration is shown in figure 4. We used two plane aluminum mirror fixed on the mounting plate and on the fixed frame of the mirror holder. The mirror holder was mounted in a cryostat. The beam of a commercial Fizeau interferometer was aligned with the mirror mounted on the fixed frame by means of two 45-degrees adjustable mirrors. The mirror secured on the mounting plate was aligned using the micrometers of the holder. The wavefront coming from the aluminium mirrors was then measured at room temperature. Air was pumped out from the cryostat by means of a turbo-molecular pump and the system was cooled down to the temperature of liquid nitrogen. During the cooling process the temperatures of the two mirrors and the inner pressure were monitored constantly. After the cooling process some adjustments to the position of the two 45-degrees mirrors was necessary to re-align the aluminium mirrors with the interferometer beam. This does not affect the final results where only the relative alignment of the fixed frame and the mounting plate is taken into account. The wavefront was measured again at $T \simeq 100$ K and finally the system was heated up to room temperature and a last measurement was taken as a test for hysteresis of the system.

This kind of measurement is pretty straightforward and the acquired data are easily interpreted since they consist in straight fringe patterns. In terms of wavefront what we get, as expected, are two director cosine pairs describing the orientation of the two mirrors. The measurement yields information on the tilt along the X (horizontal) and Y (vertical) axes that are only two of the six freedom degrees we are interested in.

The second test configuration involves the use of two paraboloidal off-axis mirrors. Their intrinsic asymmetry allows to retain all the information on the six freedom degree of the mounting plate and the fixed frame. The paraboloidal mirrors, made of aluminium with diamond turning technique, are produced by Edmund Optics. They have a focal length of 101.6 mm, a diameter of 50.8 mm and an off-axis parameter of 54.5 mm. As in the previous configuration, the mirrors were positioned on the fixed frame and on the mounting plate, with the same optical axis and forming an angle of $\pi/2$ between each other. A glass sphere with a 4% reflectivity was positioned with its center in the focus of the paraboloidal mirrors. The collimated beam coming from the interferometer was focused in the center of the sphere so that each ray was reflected back on the mirrors and reentered the interferometer. In this case the preliminary alignment of the system was carried out in two different steps. First the two mirrors and the sphere were aligned at room temperature. After closing the cryostat a further repositioning of the sphere was necessary to correct the effect of the dewar window. As in the previous case the measurements were carried out at room temperature, at about 77 K after an adjustment of the reflecting sphere position, and again at room temperature.

This measurement allowed to obtain the information on the six freedom degrees of the surfaces. In addition the test mirrors are used in double pass thus increasing the sensitivity of the measurement. The catch was that the interpretation of the acquired fringes patterns proved to be rather tricky. We employed a raytracing software to retrieve tip and tilt data from the wavefronts relative to the two mirrors. Basically we modeled the test optical layout in the two different configurations with $ZEMAX^{®}$ raytracing software then we optimized the tips and tilts of the aluminium mirrors to reproduce the measured wavefronts.

To pass the wavefront data to the raytracing software we fitted a set of Zernike polynomials to the measured wavefront surface. Although Zernike polynomials might not be the best choice to work with off-axis diamond turning mirrors,[4] they proved to be the simplest method to handle the measured wavefront data in the raytracing program.

4. RESULTS AND CONCLUSIONS

In both the test configurations several measurements were carried out at room temperature, after the cooling and after the system was heated to room temperature again. Every dataset is composed by the wavefront corresponding to the mounting plate mirror and the wavefront corresponding to the fixed frame mirror. In table 1 the tilt difference between the the working temperature status and the room temperature status are shown for the plane mirror configuration.

The absolute values of the relative tilts for the fixed frame mirror are three times the corresponding value for the mounting plate mirror. This is because of the high radiative input from the dewar window that induced a temperature difference between the front and rear faces of the mirror holder at the equilibrium of about 5 K. This temperature difference induced a slight bending of the holder structure which caused the fixed frame mirror, positioned on a corner of the holder to tilt in the negative outward along the X and Y axis. A rough estimate of the induced tilt leads to about $5 \cdot 10^{-4}$ Deg. However, even without this correction, the resulting differences between the tilts of the two surfaces remain within the tolerances.

In table 2 the tip and tilt differences between the the working temperature status and the room temperature status are shown for the paraboloidal mirror configuration.

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Table 1. Tabulated result of the measurements carried out with the plane mirrors configuration. The tilt variation between working temperature and room temperature expressed in degrees is shown in the first two columns for the mounting plate and the fixed frame. In the third column the difference between the mounting plate and the fixed frame expressed in degrees is reported.

	Fixed frame	Mounting plate	Difference	(radians)
Tilt X	-0.00170	0.00056	0.00227	0.00004
Tilt Y	-0.00176	-0.00044	0.00132	0.00002

Table 2. Tabulated result of the measurements carried out with the paraboloidal mirrors configuration. The first two columns report the value of tips and tilts differences between working temperature and room temperature. Tilts are expressed in degrees and tips are expressed in millimeters. In the third column the differences between the mounting plate and the fixed frame are reported.

	Fixed frame	Mounting plate	Difference	(radians)
Tip X	-0.00642	-0.00270	0.00227	
Tip Y	0.00279	0.01742	0.00132	
Tip Z	-0.00565	-0.01334	0.00132	
Tilt X	-0.00138	-0.00905	-0.00768	-0.00013
Tilt Y	-0.00286	-0.00239	0.00047	0.00001
Tilt Z	0.00469	-0.01737	-0.02206	-0.00039

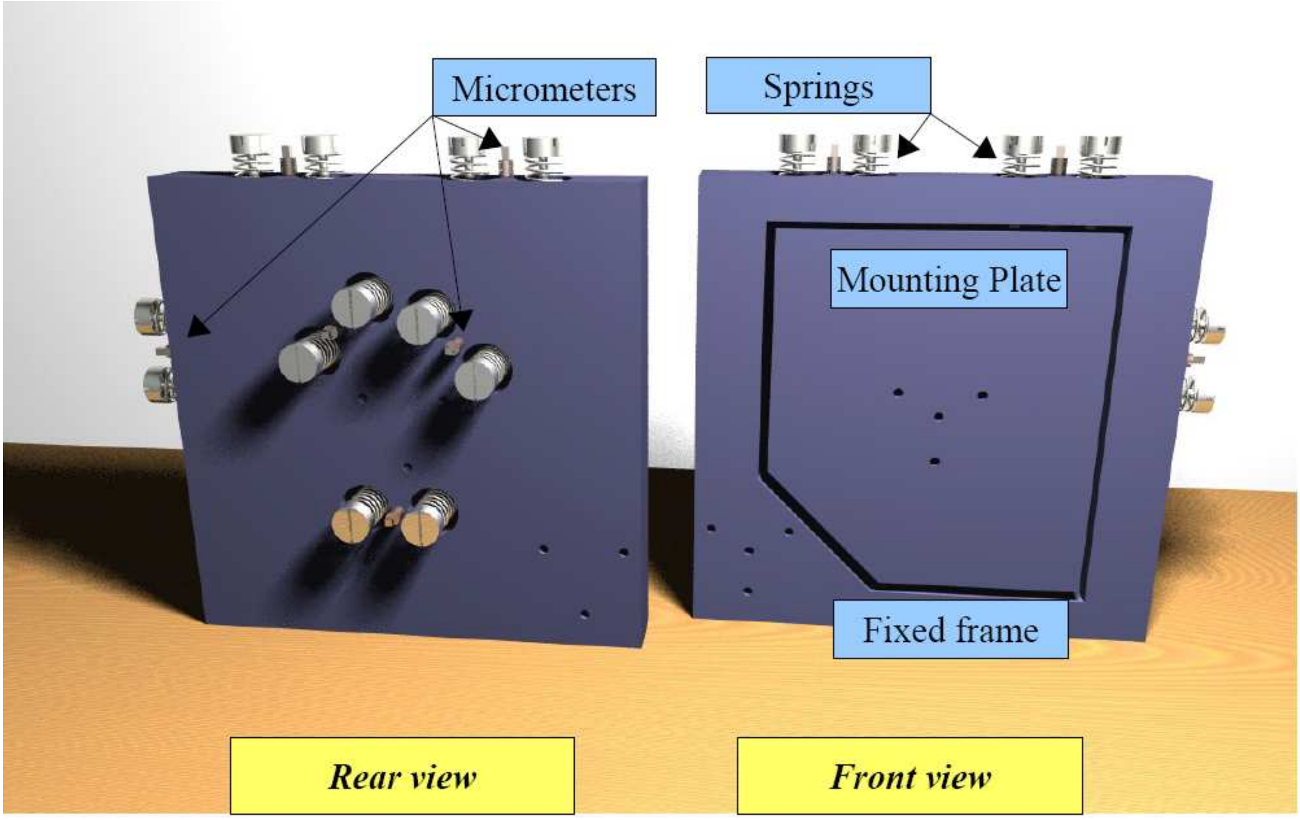

Figure 1. The drawing shows the rear and front views of the mirror holder. On the front side of the holder the holes for the screws of the test mirrors are visible.

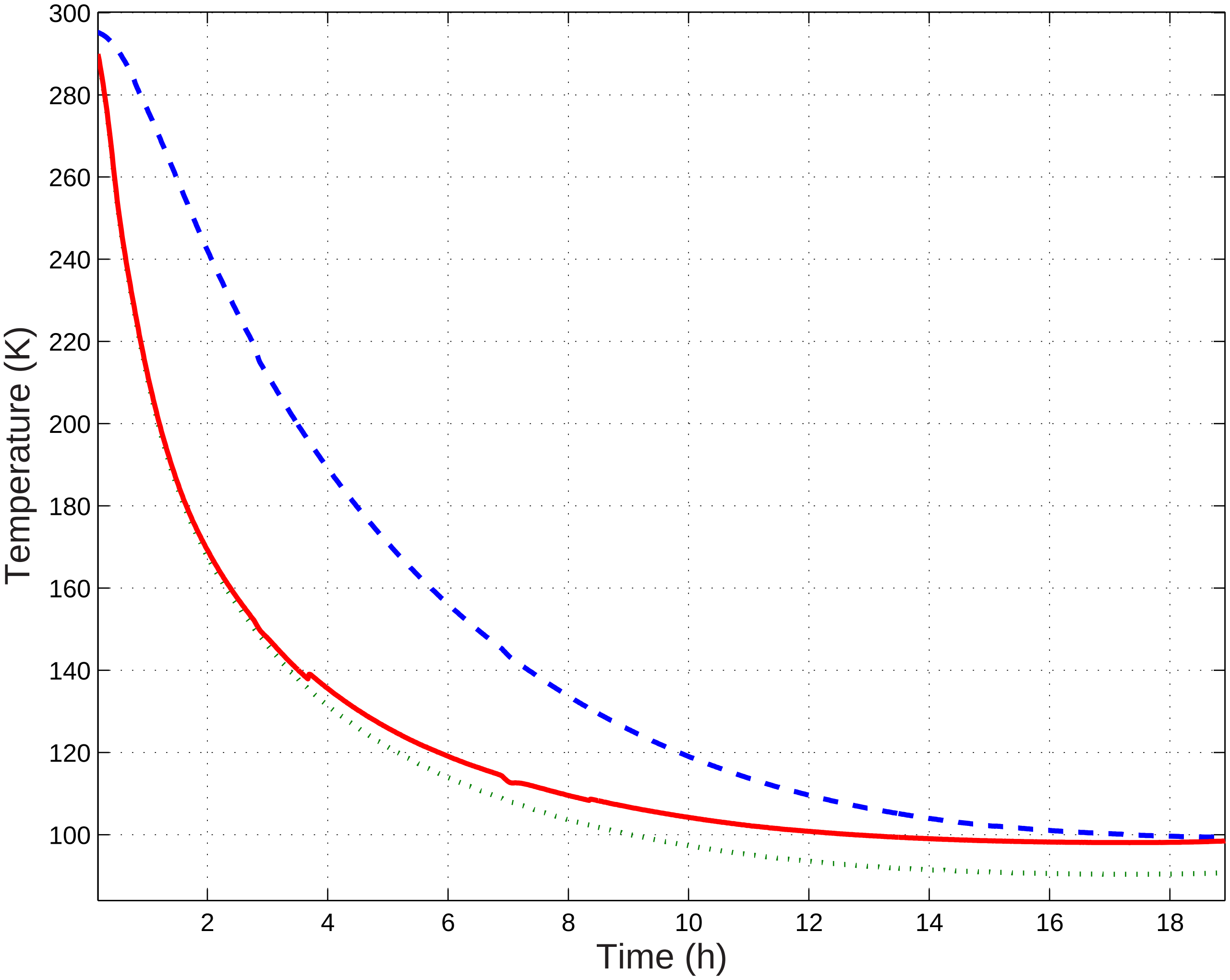

Figure 2. Temperature evolution during the cooling process. The dashed line is the temperature of the mounting plate, the solid line is the temperature of the fixed frame and the dotted line is the temperature of the external surface of the nitrogen tank. The thermal equilibrium between the fixed frame and the mounting plate was reached in about 20 hours at 100 K. This was due mainly to the high radiative input from the dewar window.

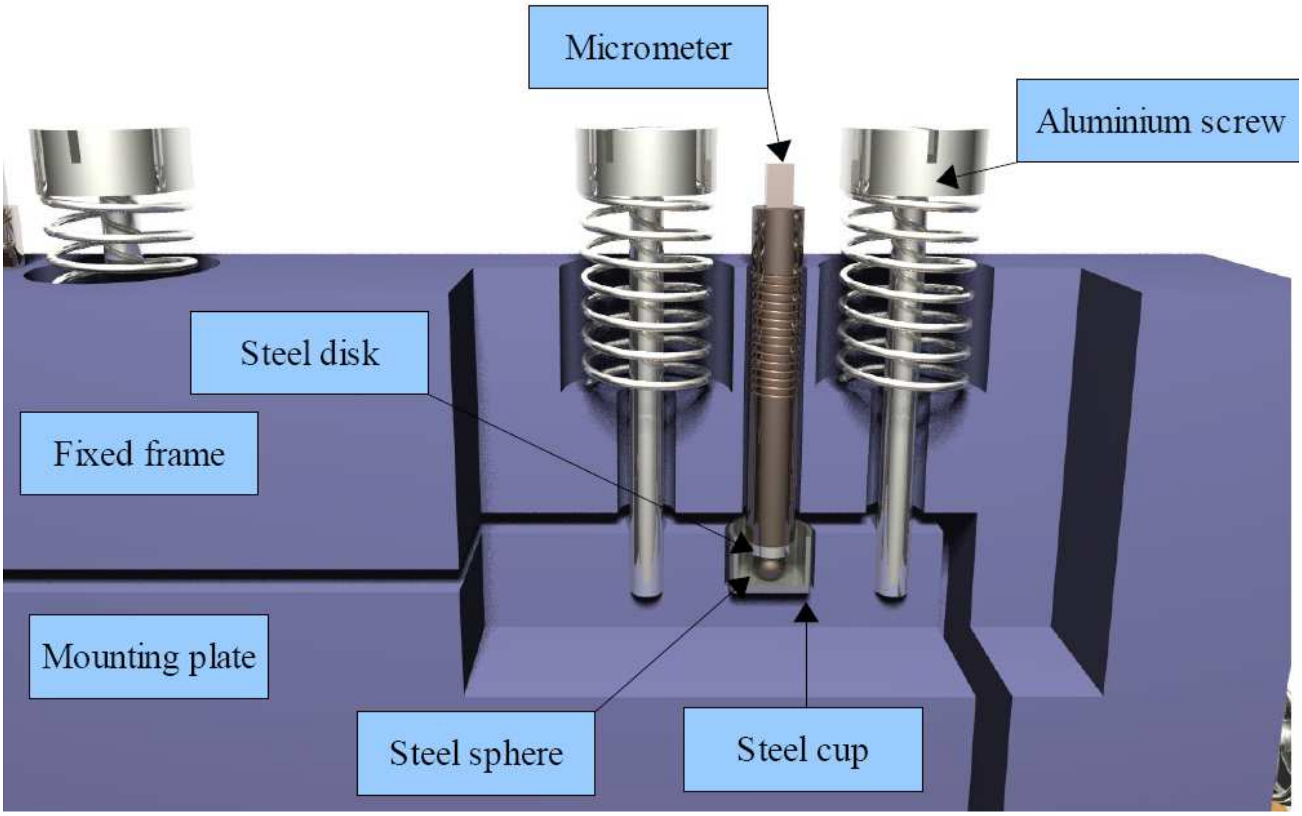

Figure 3. The drawing shows the inner details of the micrometers. The micrometric screw, manufactured in aluminium 7075, is equipped with a blocking ring and is terminated with a steel disk. The disk press on a steel sphere placed in a steel cup. The cup is slightly smaller than the hole in the mounting plate to account for the higher termal expansion coefficient of aluminium.

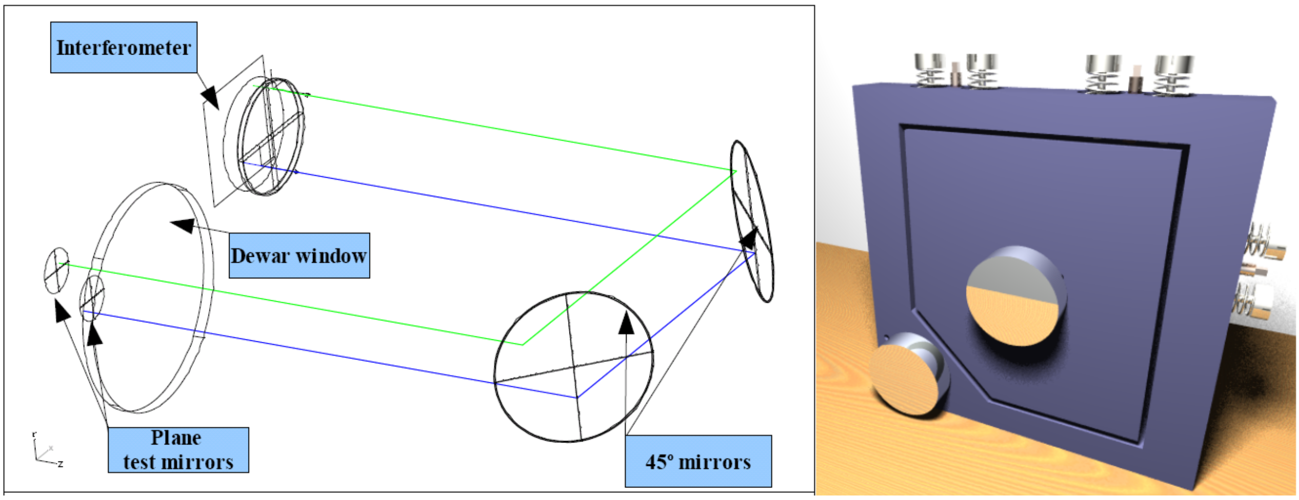

Figure 4. The drawing on the left shows the optical layout of the test carried out with the plane mirrors. The beam coming from the interferometer is folded by the two 45^o mirrors and directed on the two aluminium mirrors through the dewar window. The drawing on the right shows the plane mirror mounted on the fixed frame and on the mounting plate of the holder.

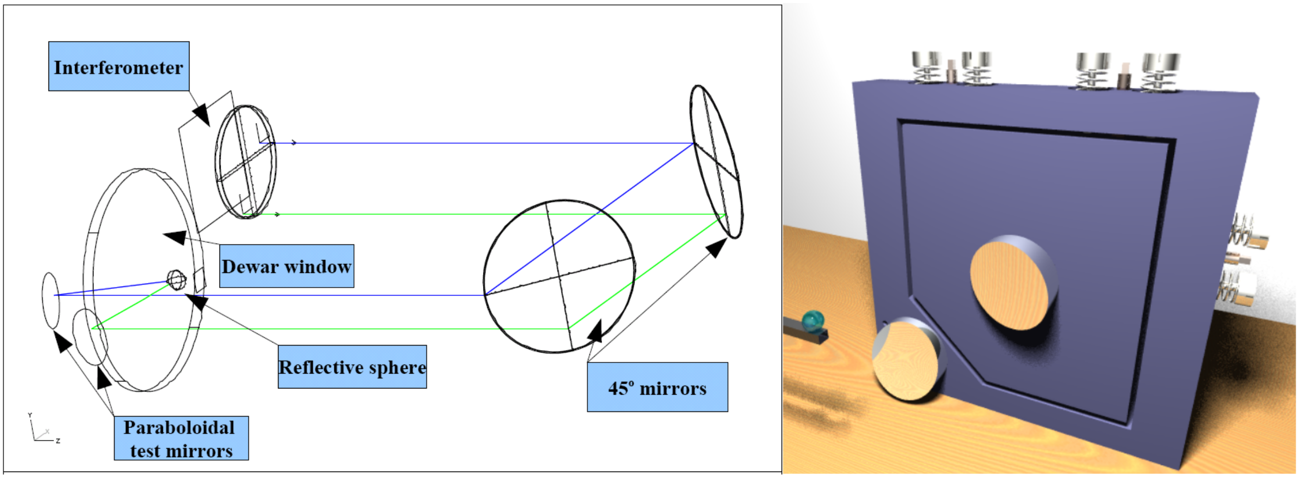

Figure 5. The drawing on the left shows the optical layout of the test carried out with the paraboloidal mirrors. The beam coming from the interferometer is folded by the two 45^o mirrors and directed on the two aluminium mirrors through the dewar window. The light striking the mirrors is focused in the center of the sphere and reflected back on its path. The drawing on the right shows the reflecting sphere and the paraboloidal mirrors mounted on the fixed frame and on the mounting plate of the holder.