The first diluted telescope ever built in the world

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ABSTRACT

We have built at the Haute-Provence observatory (France) the first diluted telescope in the world. We describe this prototype called Carlina, made of three 25 cm mirrors separated by a maximum baseline of 10.5 m. The three mirrors in place are already coherenced and first light is scheduled for September-November 2012. In this article, we will mainly describe the focal gondola. We propose to build in the near future a 50-100 m aperture Large Diluted Telescope. This diluted telescope will be more sensitive than regular interferometers (Keck, VLTI, etc.), with higher imaging capabilities. A LDT will open new fields of research in astrophysics thanks to very high angular resolution imaging of the surface of supergiant stars, AGN, gravitational micro-lens systems, exo-planets, etc.

Keywords: Instrumentation, interferometers, baseline, interferometry, telescopes, high angular resolution, balloons, adaptive optics, hypertelescope

1. INTRODUCTION

The number of astrophysical publications, using interferometers has increased a lot during the past twenty years. Nevertheless, many astrophysical objects are not observable with the current interferometers because of their lack of sensitivity (generally the limiting magnitude is $m_v < 10$). For example, Active Galactic Nuclei are difficult to observe using regular interferometers even if some progress has been done during the last years.[1] This is also the case for a direct detection of microlensing effects which should be resolved with $100\,m$ baseline interferometers. The displacement of the photocenter of the multiple lensed images with respect to a reference star can in principle be detected with the VLTI/PRIMA. Nevertheless, a more sensitive interferometer, with higher imaging capability, will be able to obtain direct resolved imaging of gravitational microlensing. Thus, the number of targets that we will be able to observe in interferometry, in particular to provide direct snapshot images, will increase with the sensitivity and number of mirrors.[2]

In this context, studies are under way to propose a new generation of interferometers. Their imaging capabilities, and sensitivities will have to be largely improved compared to regular interferometers (VLTI, Keck, CHARA). To reach these goals, they will have to provide a good coverage of the uv plane (large number of mirrors), a simple optical train in order to minimize the number of reflexions on the mirrors. In the future, they will have to be equipped with adaptive optics (adapted to diluted pupils) and they should accommodate various focal instruments, such as spectrographs or coronagraphs. A diluted telescope (Paper I, II[3,4]) like Carlina could meet all these criteria. It consists in an optical interferometer configured like a diluted version of the Arecibo radio telescope: above the diluted primary mirror made of fixed cospherical segments, a helium balloon (or cables suspended between two mountains), carries a gondola containing the focal optics (Fig. 1). We have built at the Haute-Provence observatory a prototype of this new type of interferometer (Paper I, II).

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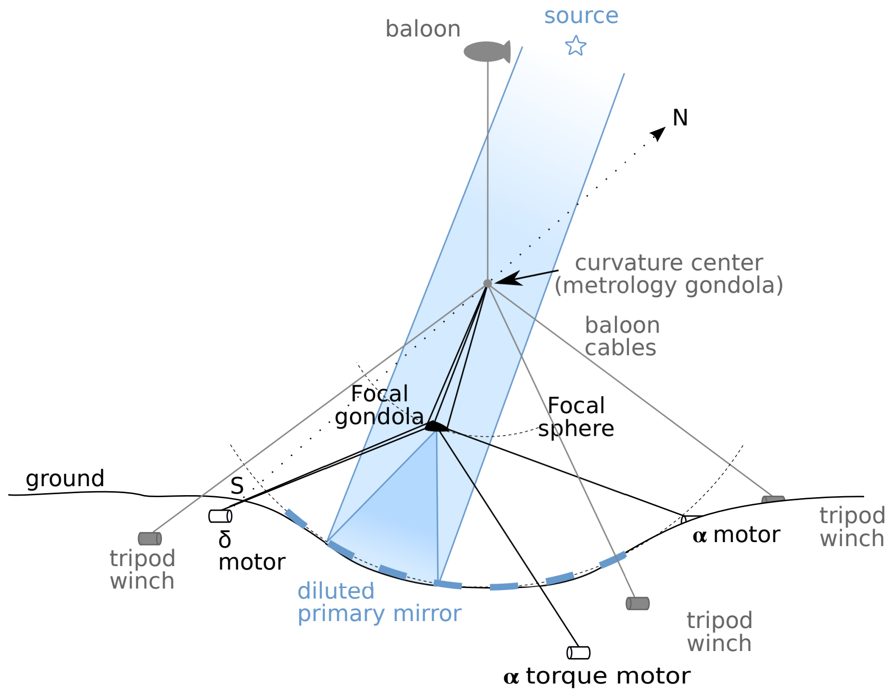

Figure 1. Principle of the diluted telescope. In order to show the whole experiment, we did not respect real scales on this drawing. The diluted primary mirror and the positions of the metrology and focal gondolas are indicated. The latters are attached under a tripod of cables that stabilize the experiment. This tripod has its summit at the curvature center of the primary mirror (paper II). For the sake of clarity, the metrology gondola at the curvature center is not represented (in reality, there are two tripods attached to the metrology gondola at the curvature center).

Note that, a diluted telescope can also be viewed as a masked Extremly Large Telescope.[5] Aperture-masking increases the dynamic range at very small separations. In the speckle dominated regime (Photon noise is negligible) the real power of sparse aperture masking is manifest.[6] Thus, the aperture masking community is getting wider, and the number of observations using NACO and SAM (Sparse Aperture Masking) has significantly increased.[6] This mode will probably be interesting with the surface of the E-ELT for observations that will require high dynamic, and angular resolution. From this point of view, the OHP prototype is also a preliminary study in order to propose a new generation of Post-ELT telescopes (aperture $> 50 - 100\,m$). A diluted telescope with a 100 m aperture, working with hundreds of mirrors could also complement ELTs[5] and very long baseline interferometers.[7]

One goal of the 10 m baseline OHP prototype is to test the whole optical train of a diluted telescope. In particular, we checked that we are able to stabilize the gondolas with enough accuracy to record metrology, and stellar fringes (see specifications in Table A1 of Paper II). In paper I, we obtained fringes on Vega with a pair of adjacent mirrors stopped down to about 5 cm and providing a 40 cm baseline. It has been an encouraging result but mainly a demonstration that we can track a star with a camera attached under a helium balloon. For larger baselines (5-10 m in the second stage of this experiment), it has been necessary to develop a metrology (stabilized by a servo loop) attached at the curvature center of the primary mirror (under the helium balloon) in order to align the primary mirrors with a one micron accuracy. This metrology has been developed with success (Paper II). Here, we mainly focus on the recently built focal gondola .

2. GENERAL PRINCIPLES

The general architecture of a diluted telescope has been detailed in Papers I, II. The primary mirror is spherical (like for Arecibo) and diluted: it is made of fixed co-spherical mirrors. Above this diluted mirror, a metrology gondola is positioned at the curvature center of the primary sphere. It is used for the alignment of the primary

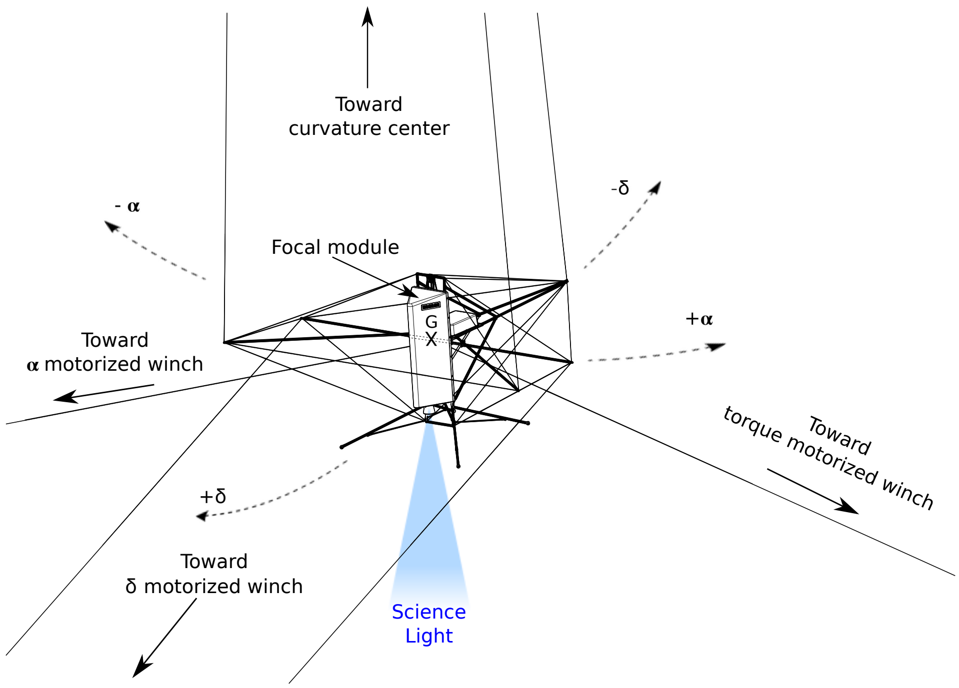

Figure 2. The focal gondola. It is made of carbon fiber tubes (bold lines), about 2-3 m in size, which carry a focal module of triangular shape. The stiffness of the gondola is insured by small PBO wires between the carbon tubes. The cross at the back of the focal module is the gravity center of the gondola. The cables (α, δ and toward the curvature center) are attached in such a way that all the rotations are blocked, and the resultant forces apply only to the gravitational center.

segments with one micron accuracy. Under the metrology gondola, a focal gondola is constrained by cables to move along the half radius focal sphere (Fig. 1). Schematically, the stability of the gondolas is insured by a motorized tripod of cables strained by a helium balloon or cables suspended between two mountains and/or Pylons. The servo loop, and the metrology device at the curvature center of the primary mirror has been largely discussed in Paper II.

The main advantages of such a design are the absence of delay lines, the simplicity of the optical train, and the possibility of using an internal metrology at the curvature center (metrology gondola) to align the mirrors on the primary sphere (Paper II). Compared with ELTs, a diluted telescope is much more lighter. It doesn't need a mount to carry the primary mirror, and it is not protected by a huge dome: each small primary mirror (25 cm at OHP) has its own cover.

3. MECHANICAL DESIGN OF THE FOCAL GONDOLA

We have built a new gondola to carry the focal module that did not exist in the first version of the prototype (paper I). The focal gondola is a lightened structure made of guyed 16 mm carbon fiber tubes that carry a focal module (Figs. 2, 3). The size of the gondola is about 3 m on one side; it is a good compromise between lightness and stiffness. This gondola is suspended by three cables below the curvature center at half the radius of the spherical primary mirror (Figs. 1, 2). The cable arrangement which drives the gondola is configured for equatorial tracking as sketched in Fig. 1, and described in Paper I. A single computer-driven winch (α torque motor in Fig. 1) suffices to track the diurnal motion while a torque motor maintains a constant strength. The cables (α, δ and toward the curvature center) are attached in such a way that the gondola can rotate only around the equatorial axis passing through the curvature center of the diluted primary mirrors (35.5 m above). The other rotations are all blocked within the limits defined by cables sag, and the resulting forces applied only to

the gravitational center of the focal gondola (G on Fig. 2). The azimuth of the gondola can be adjusted and blocked with δ cables (see Fig. 2).
The mechanics that carries the focal optics has been designed with the CATIA software (Fig. 3). The focus can be adjusted with a motorized screw that moves the whole focal module (See focus motor in Fig. 3).

The optics in the focal module (Figs. 3, 4) has been optimized to be as sensitive as possible by using a densifier optics[8,9] and a photon counting camera.[10]

3.1 The densifier

In the reference frame of the star, and the focal gondola, the pupil turns around the polar axis. During the tracking, the image of the pupil, created by L1 (see Figs. 3, 4 and Sect. 4.2), drifts at the entrance of the densifier. To track the pupil, the densifier is mounted on a gravitational pendulum. The densifier stays always vertical, and it follows the pupil by turning both around a declination axis, and an equatorial axis (Fig. 3). The oscillations of the pendulum are damped by highly viscous silicone oil. A more detailed study, of this complex optomechanical device, will be provided in a forthcoming paper. For a future project, it could be of interest to study a motorized version of this densifier.

4. OPTICAL DESIGN OF THE FOCAL MODULE

The spherical aberration of the primary mirror is corrected close to the primary focal plane by two highly aspheric mirrors (M2 and M3 on Fig. 3) . This class of correctors proposed by Mertz,[11] designed to meet Abbes sine condition, corrects coma in addition to spherical aberration. The main characteristics of the Mertz corrector (Fig. 4) were presented in Paper I. The highly aspherical figures of the two mirrors have been fabricated by the compagny Savimex (located at Grasse, France) using a diamond-turning machine. The fizeau focus (F1 on Fig. 3) is in the hole of the M2 mirror. The Lens L1 (Figs. 3, 4) creates an image of F1 in F2 that is also the densified focus. A dichroic reflects the red part of the light on the guiding camera ($\lambda > 700nm$) and leaves the blue light pass toward the scientific camera ($\lambda < 700\,nm$). The lenses L3, and L4 create an image of the densified focus (F2) respectively on the guiding camera, and the photon counting camera (scientific camera). The scientific camera can be equipped with different filters (ex : $\lambda_c = 562\,nm$, $\Delta\lambda = 40\,nm$).

4.1 Fields of view and displacement tolerances

The optical design has been optimized with the Zemax software (Fig. 4). The field of view of ± 24 arcsecond at the fizeau focal plane (F1 in Fig. 3), and on the guiding camera, is limited by the hole in the M2 mirror. The axial displacement tolerance before separating the three spots (tolerance on the vertical position of the focal module before losing the fringes) at the focal plane is $\pm 0.2\,mm$ (about $\pm 0.6\,mm$ with a turbulence having a fried parameter of about $8\,cm$).
The field of view to see the fringes in the narrow densified envelope is $\pm\,0.15$ arcsec (Fig. 5). Taking into account the atmospheric turbulence (it magnifies the envelope of light where we can detect the fringes) and the number of fringes in the coherence length of the filter (14 fringes for the filter : $\lambda_c = 562\,nm$, $\Delta\lambda = 40\,nm$), we should be able to detect the fringes in about 0.5 arcsec. We expect about the same amplitude of oscillations for both the focal, and metrology gondolas. Thus, the drift during the tracking should be smaller than one fringe per exposure time of one millisecond as it was the case for the metrology fringes (Paper II).
Note that an integrated model of the carlina telescope has been done independently by a Sweden team.[12] Although, the geometry and the length of the cables used in their simulations are not the same as in our experiment, the oscillation amplitudes of the metrology gondola that we have measured (Paper II) are consistent with their computations. They found that the standard deviation of the image motion is 0.19 arcsec, while we have measured oscillation amplitudes of ≈ 10 metrology fringes in closed loop (Fig. 12 in Paper II), equivalent to about 0.1 arcsec on the sky.

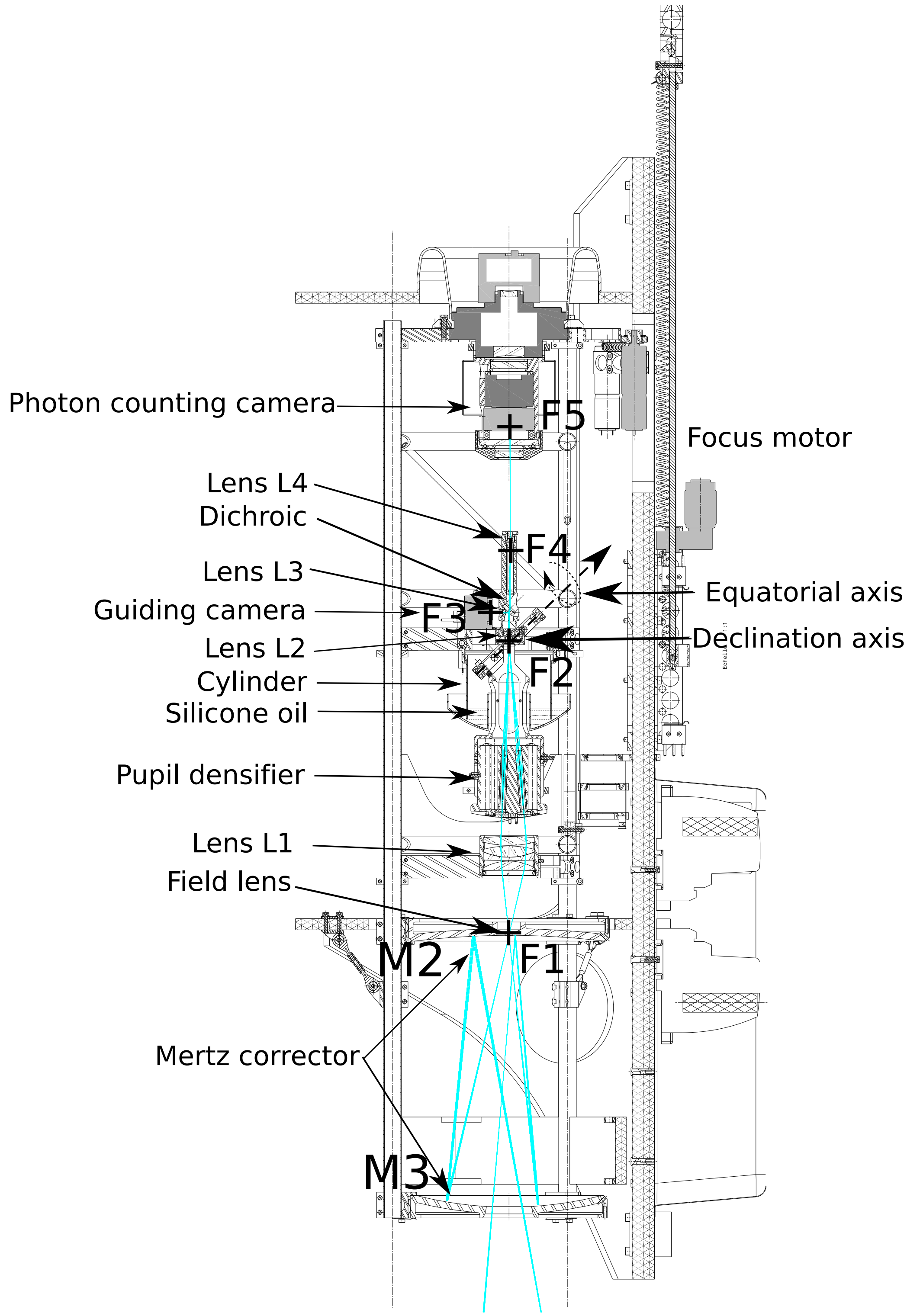

Figure 3. The focal module, attached to the carbon fiber tubes gondola presented Fig. 2, designed with the CATIA software. In blue, we have superimposed the optical rays computed with the Zemax software (see Fig. 4). F1 and F2 are respectively the Fizeau, and densified Focus. F3 and F5 are the densified foci magnified respectively for the guiding camera, and the photon counting camera.

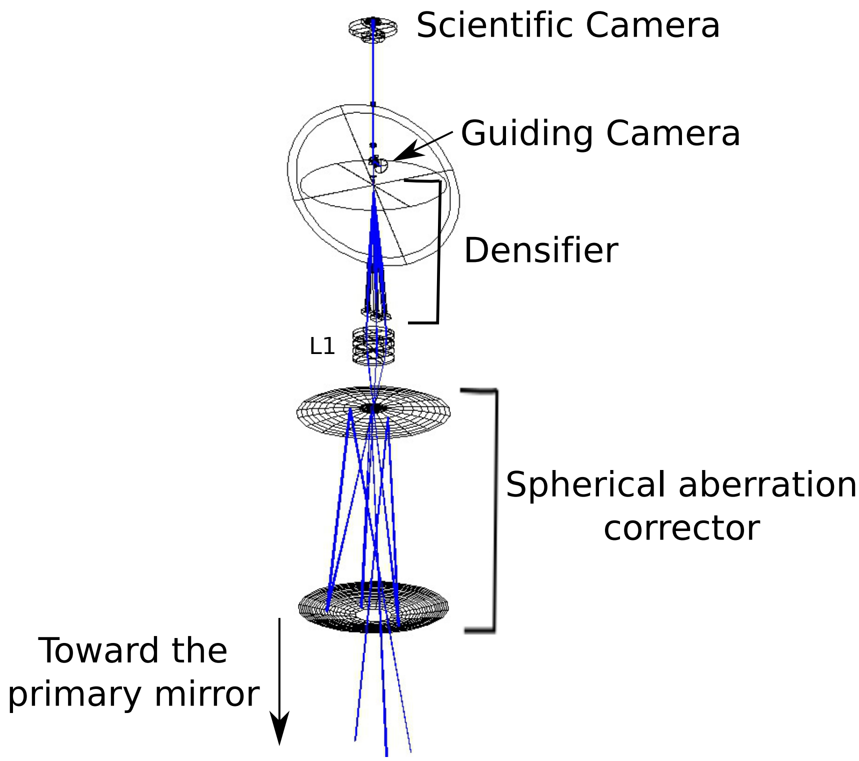

Figure 4. Optical design of the focal module computed with the Zemax software. On this view, we see the three beams coming from the three primary mirrors.

4.2 Tolerance on the densifier position

In Fig. 6, we show that the lenses of the densifier have to be positioned in the gondola with an accuracy better than $78\mu m$! During the alignment procedure, we have tested in real conditions that the gravitational pendulum is positioned with the required accuracy: the scientific camera has been replaced by a red laser. We have checked that the image of the pupil projected on the ground (three red spots of about 25 cm) falls on the primary mirrors. During the tracking, the red spots have stayed centred on the mirrors, proving that the densifier is correctly positionned in the gondola.

5. POSSIBLE IMPROVEMENTS

In the future, the performances of such a diluted telescope will be improved with a tip-tilt correction. This correction has to be made before the densifier in order to stabilize the fringes in the center of their envelope. In our focal gondola this correction can be done by controlling the position of the lens L1 (Figs. 3, 4) with a servo loop locked on the fringes.

It would be also interesting to study, if it is possible to control at 100-1000 Hz the piston and tip-tilt of the primary mirrors for an adaptive correction. The solutions using lightweight mirrors, and piezzo actuators have to be studied. A "shack-hartmann" in the gondola will provide the tip-tilt of each mirror while the piston error can be deduced from the position of the fringes. We are studying an algorithm based on an inverse-problem approach. This approach has been succesfully tested for the detection and localization of particles in digital

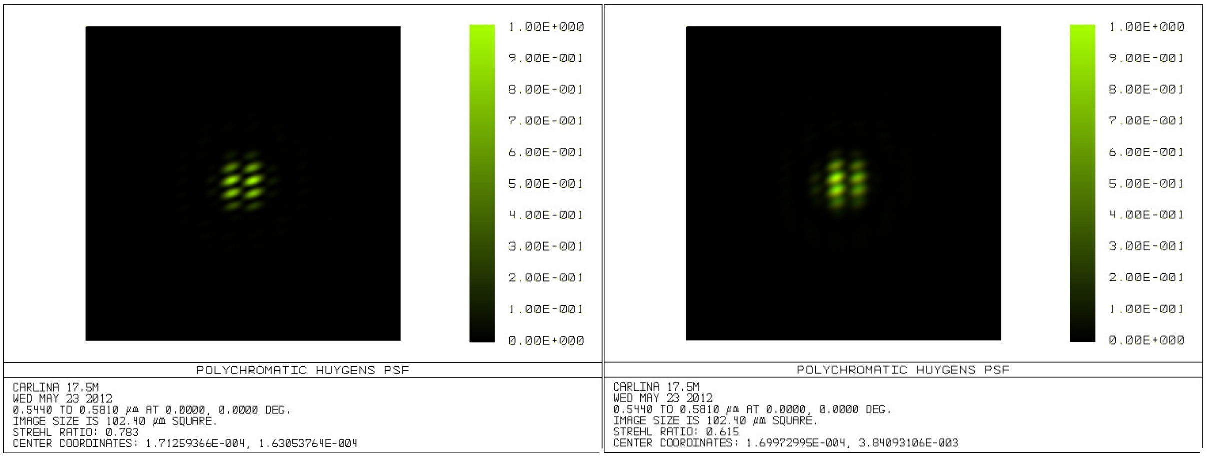

Figure 5. PSF (for the three mirrors of the OHP prototype), on axis (left) and off-axis by 0.15 arcsec (right) in the densified focal plane (F5 on Fig. 3) computed with the Zemax software.

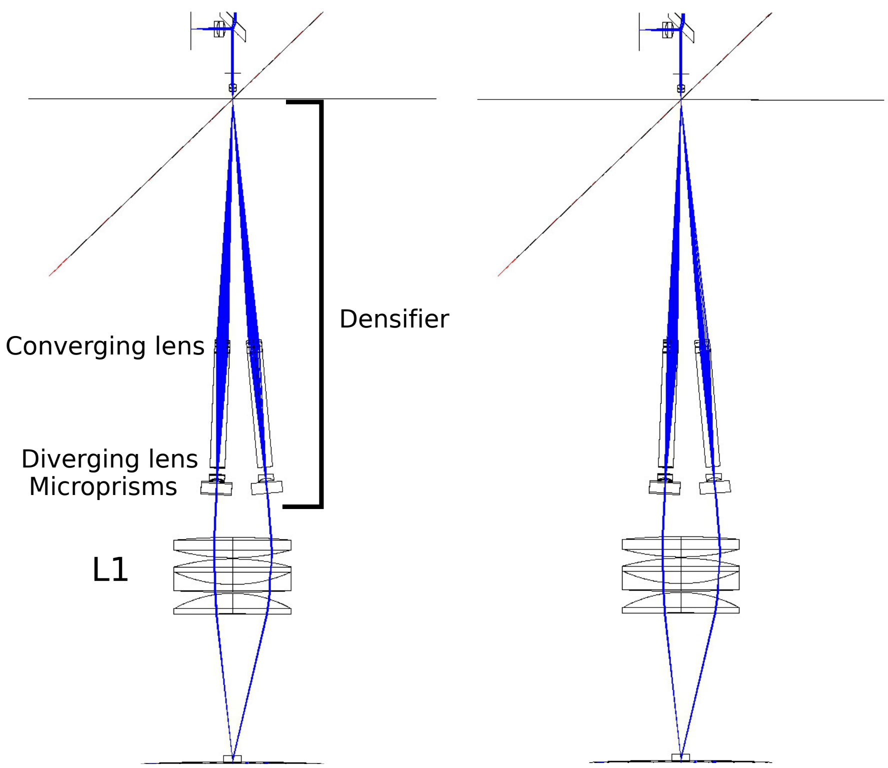

Figure 6. Optical rays in the densifier computed with the Zemax software. The pairs of microprisms (positioned head to tail) at the entrance of the densifier have been adjusted in order to equalize the optical paths between the three optical channels. Left: the densifier is perfectly vertical and aligned with the optical axis. Right: The densifier is rotated by 0.03 deg from the vertical. It corresponds to a shift of 0.078 mm of the diverging lenses. The beams are at the limit from vignetting at the level of the converging lenses.

holography[13] . In this field of research (fluid mechanics), fast algorithms are required to analyse high-speed phenomena. More computations are required, to test this idea in the case of fringe detection.

6. CONCLUSION

We have presented the optomechanical study of the focal gondola. It is a lightened structure made of guyed carbon fiber tubes that carry a focal module containing the optics. This structure of about 3 m on a side is attached in order to track the stars in an equatorial mode.
The main result presented in this paper has been to show experimentally that the densifier tracks the pupil with enough good accuracy (lenses of the densifier positioned with an accuracy better than $78\mu m$).
After eight years of development, the prototype is now completed (metrology, servo loop, focal gondola, etc.), and we should obtain the first fringes on stars in the coming months (June-July 2012). We will characterize the performances of such an interferometer (limiting magnitude, contrast of the fringes on an unresolved star, etc.).
The OHP prototype is the first diluted telescope that has been built in the world. We propose to build during the coming 10 years a scientific demonstrator with an aperture of $\approx 50\,m$ that we will call the LDT (Paper II).
A sinkhole at Calern observatory (south of france) could be a good place to build such a scientific demonstrator.
Such a diluted telescope should push the limits of sensitivity, and imaging capabilities of the interferometers.

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