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The CARLINA diluted telescope, a new class of interferometer: Opto-mechanical design and results of the OHP experiment

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Abstract. Today, a significant number of optical interferometers are in operation around the world. Baselines longer than 300 meters are reached, and these facilities produce unique high angular resolution data. Nevertheless, the number of telescopes constituting these interferometric arrays is still limited (maximum 6). The Carlina diluted telescope concept represents a novel architecture, similar to that of the Arecibo radio-telescope, except that it works in the optical, and uses a sparse aperture. This particular design allows having a large number of sub-apertures, without significant technical complications, and should provide novel scientific data with rich u-v coverage. In 2003 began at Haute-Provence Observatory (OHP) the construction of a Carlina prototype to explore feasibility and technical solutions necessary to the implementation of this concept. This article summarizes the main technical characteristics of this prototype, and the observations conducted with the full experiment.

1. Introduction

After ten years of development, we have just completed the construction of a Carlina prototype at Haute-Provence Observatory. Carlina is a peculiar type of optical interferometer that works without delay-lines, and has a high potential for imaging. An important effort has been put into the development of original solutions required by the peculiar design of Carlina: new mechanical solutions, servo-loops and laser metrology to stabilize the optics borne by a tethered helium balloon. We will mainly describe the general architecture of the prototype, the metrology destined to align the primary mirrors with micrometric precision, and the focal gondola, which is the last module developed and built at OHP. We will present the first observations, and the main results obtained with this prototype.

2. Principle of the Carlina architecture

Carlina is a new kind of interferometer: a giant diluted telescope (Le Coroller et al. 2004; Le Coroller et al. 2012) whose primary mirror is constituted of a large number of small segments, distributed on the surface of a large virtual sphere (Fig. 1). This array of fixed subapertures produces an image of the sky on the half-radius sphere (focal sphere). A gondola carrying the focal optics is placed on that sphere, where the image of the observed object forms. As explained above, the giant diluted primary mirror is fixed and anchored to the ground. The only moving part is the focal gondola. It is suspended under a cable tripod, whose summit is located at the curvature center of the primary sphere. This cable tripod is kept taut by a pulling force, provided either by a helium balloon, or by a solid structure (pylons, cable attached between two mountains, etc.). Computer controlled winches ensure the guiding of the focal gondola.

3. The OHP prototype

The prototype built at Haute-Provence Observatory is a scale Carlina implementation. We assembled this prototype to develop and experiment the new and original technical solutions required by this concept. The OHP experiment has been largely described in previous papers (Le Coroller et al. 2012). The primary mirror is made of three segments positioned on a 70-meter radius sphere, forming three baselines of respectively 5, 9 and 10 meters. These mirrors are accurately positioned in Tip-tilt and piston within one micron accuracy thanks to a laser metrology system. The cable tripod, kept taut by the upward pulling

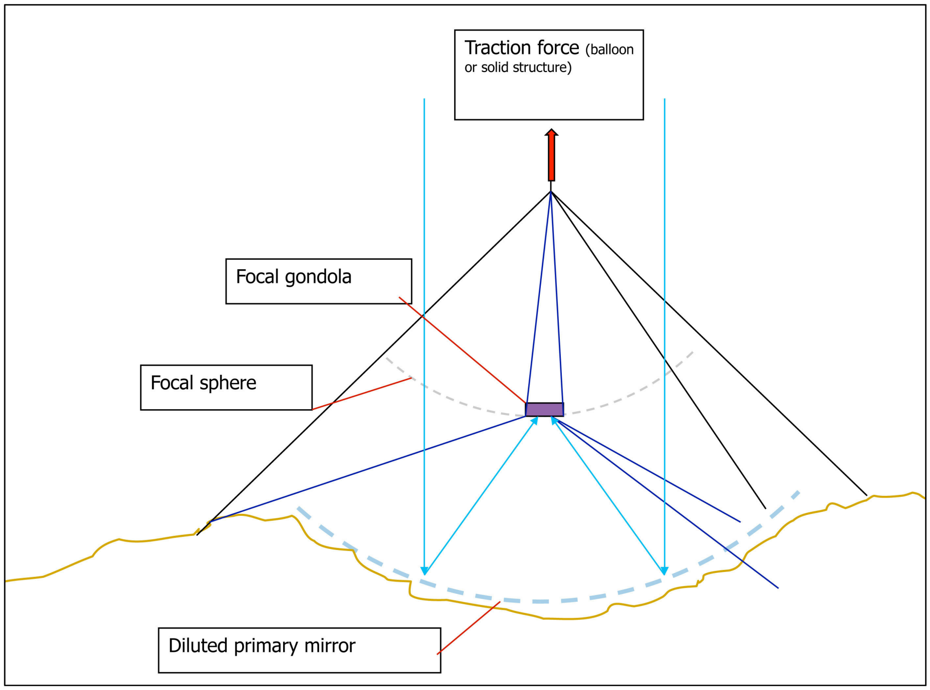

Figure 1.: *Diagram of the Carlina diluted telescope: a spherical diluted primary mirror forms a high resolution of the sky on its focal sphere. A focal optics catches the images of the object. All the system is suspended from cables.*

force provided by a helium balloon, is stabilized with servo winches. The light (carbon-fiber) focal gondola, carrying an optical corrector and two detectors, tracks the observed object thanks to some motorized winches.

3.1 A diluted primary mirror

The primary is made of three 250 mm zerodur segments, anchored to the ground and manually adjustable in tip-tilt and piston. Their support is a rigid carbon-fiber hexapod, topped by a fine adjustment mechanism. To adjust the position of the mirrors and make them fit the 70 m virtual sphere, a two-step method is used: First, a "total station", or tachometer (instrument combining a high-precision theodolite and a laser distance-meter), allows to position a target disposed in three

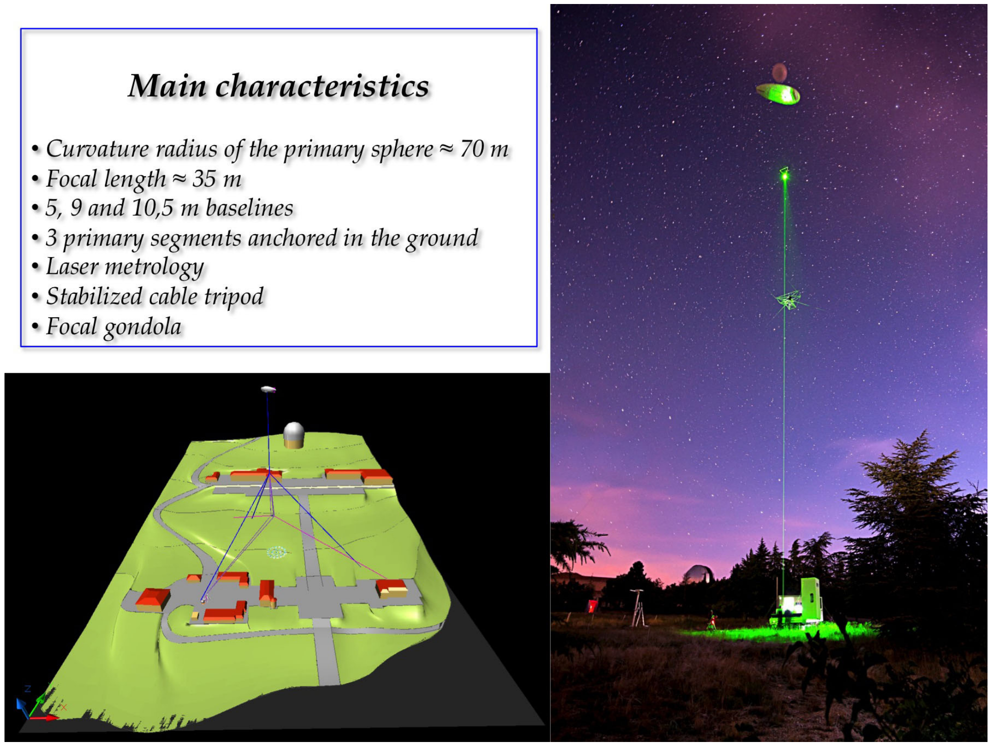

Figure 2.: *Views of the OHP Prototype*

points on the mirror within 100 microns accuracy. Then, a few microns accuracy is reached with the laser metrology system described below. The mechanical mounts that carry the primary mirrors are supposed to ensure high stability, and gives good results on short periods (1 or 2 hours). Nevertheless, some slow drifts in tip-tilt and piston have been observed over longer durations. It was not possible to determine whether this was due to mechanical drifts or ground movements. For a larger project, a permanent servo-loop, using metrology fringes information, would be probably required to automatically adjust the position of the primary segments over long periods.

3.2 The laser metrology

As explained above, a metrology system is necessary to measure the position of the three primary mirrors. This metrology has been described in detail in Le Coroller et al. 2012. Here, we quickly recall the main

Figure 3.: *View of the three primary segments: the mirrors are disposed on rigid carbon legs, and manually adjustable in tip-tilt and piston (This pictures has already been published in Le Coroller et al. 2012)*

lines. The principle implemented here is to light with a white source the three mirrors from the curvature center of the primary sphere and to get the white fringe in the formed image. A super-continuum laser from Leukos Company is used. The basic way to proceed would be to put the laser near the center of curvature, 70 m above the ground, and to get the image back directly on the side of the source. For weight considerations and for accessibility, a convex mirror (called metrology mirror), placed 1 m below the curvature center, is used to project the source and the image at ground level (Fig. 4). We will describe further more in detail the way to attach and stabilize this optics. As we will see after, the metrology mirror is affected by residual oscillations of a few tens of mm amplitude. This produces some sideway motion of the return beam of about 10 to 30 cm. In order to be able to send the beam

to the detector despite these motions, a 600 mm field mirror is placed at the focal plane. This mirror forms an image of the pupil near his own focal plane. This image is very stable, and at this level, the three beams coming from the three mirrors are obviously separated. But a few centimeters after this plane, due to the very important diffraction, the beams are again partly superimposed. We choose to put the detector in this "pseudo pupil plane" where the residual motions of the white fringe are drastically reduced (Le Coroller et al. 2012).
The adjustment procedure of the primary mirrors begins by activating the manual tip-tilt screws on their supports, until the three spots are superimposed on the metrology CCD camera. Since the coarse adjustment has previously been done with the "total station", the white fringes can then be found relatively easily and centered in the image (fig. 5) using the piston adjustment. The resolution of this manual procedure may be of order of one fringe or less, but since there are only three mirrors forming a 3-fringe pattern always secant in one point, there is no precise reference for piston adjustment. The fringes are centered in the seeing limited diffraction pattern with an accuracy of a few fringes i.e. few microns. With more than three mirrors, additional fringe patterns should be more precisely positioned in order to have only one cross-point. The metrology to co-spherize the segments of the primary is an active-optic, and does not require an accuracy better than the atmospheric piston.
Nevertheless, in the focal gondola, this method could be used as a fringe tracker sensor (a kind of AO for diluted telescope). For this method, we propose to test a new algorithm: the idea is to find an analytic solution that describes the white fringes pattern. Then, we can fit this equation on the stellar fringes to track the fringes position. This method should be faster than using a Fourier transform to track the fringes phase. Note that a similar method has been used for micro-particle detection in digital holography (Soulez et al. 2007).

3.3 A cable giant telescope

Like for the Arecibo radio telescope, the structure of Carlina is made of long cables. The material chosen for all the cables of the experiment is Zylon PBO HM, from Toyobo Company. Its tensile modulus is nearly 3 times higher than the one of high modulus aramid fiber (270 GPa and 109 GPa, respectively), for a similar density. The first part of the structure is the "cable tripod", which provides the support for the entire experiment. The location of the summit of this tripod coincides with curvature center of the primary mirror (Fig. 1 & Fig. 2). An upward force is needed to tauten the cable tripod. The OHP prototype initially used a helium balloon, providing approximately 70 kg of force. With this geometry, the motion of the tripod's summit is kept under a few

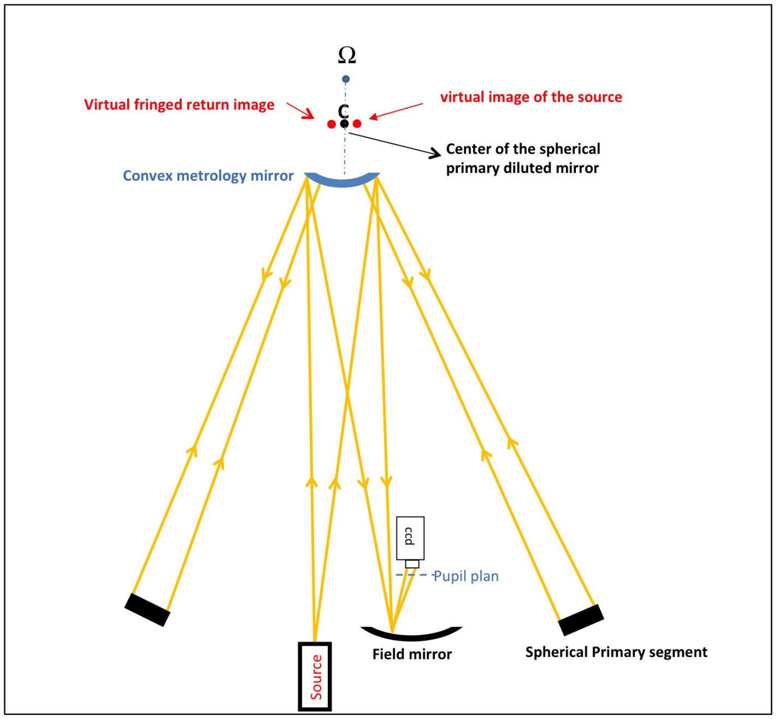

Figure 4.: *Diagram of the laser metrology system: a white source illuminates the primary mirrors from the curvature center of the primary sphere. White fringes are observed in return. For more convenience, the source and the detector are projected at the ground by the convex metrology mirror (Drawing extract from Le Coroller et al. 2012)*

tens of centimeters while the balloon oscillations in the wind reach 3 to 5 meters. The metrology mirror is placed at the summit of the tripod, where the cables suspending the focal gondola are attached. These two functions don't tolerate large displacements. As the convex metrology mirror is nearly spherical, it is not the oscillations of the mirror itself that must be reduced, but those of its curvature center. Five degrees of freedom of the mirror have to be blocked by the cable tripod (rotation around the vertical axis has no impact). For this reason, the cable tripod is in reality made of six cables, forming a more rigid double tripod structure, attached to a "girder gondola", or metrology gondola: the upper tripod is attached at the summit of the girder and matches the

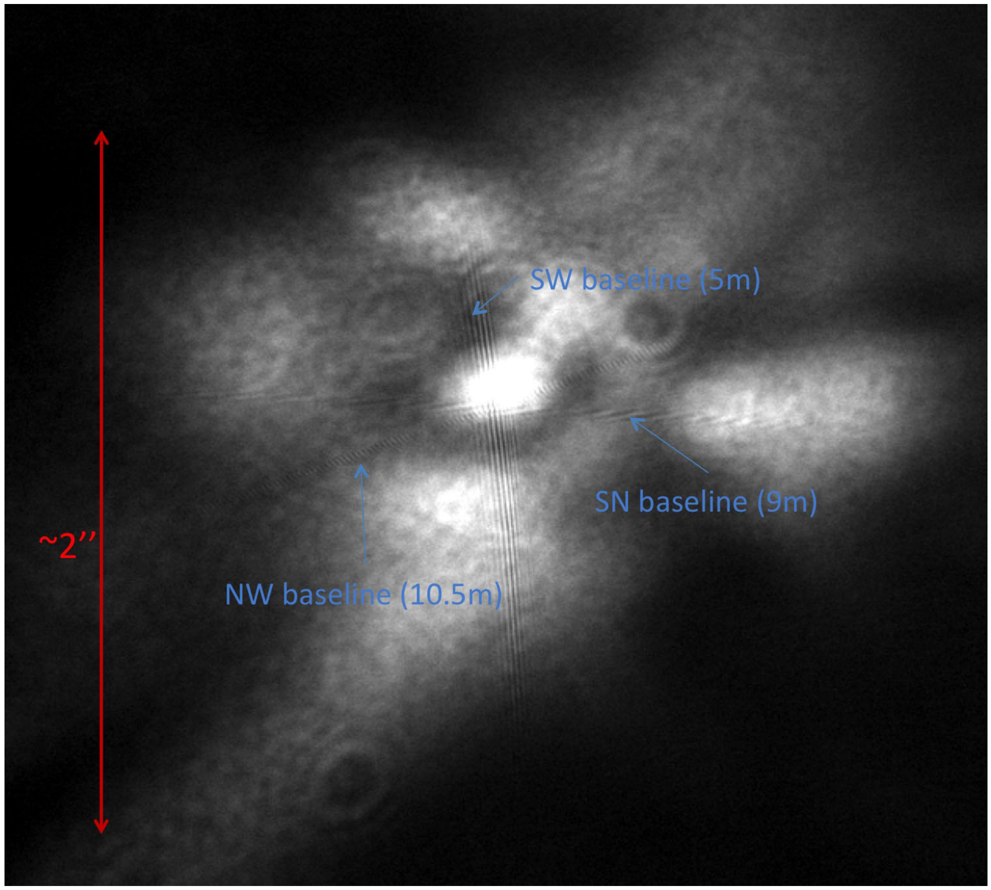

Figure 5.: *Metrology fringes: when the mirrors are correctly adjusted in piston, the 3 fringe patterns are centered in the turbulence spot (picture from Le Coroller et al. 2012).*

curvature center Ω of the metrology mirror (see Fig. 6), while the lower tripod is attached at the bottom of the girder, where the metrology mirror is situated. The curvature center of the primary sphere is at the focus of the convex mirror, at the middle of the girder (the girder length is equal to the metrology mirror curvature radius). At the bottom of the girder are also attached the cables of the focal gondola and those of the helium balloon. Thus, the main perturbation forces are applied at the same point. Special motorized winches and a servo-loop system are used to stabilize the lower tripod. This architecture further reduces the oscillations of the summit of the lower tripod down to a few millimeters. The stability of the summit of the upper tripod (curvature center of the metrology mirror) then reaches a few tens of millimeters, while the cables are not motorized. Of course, a fine servo-control system could further improve these performances (Le Coroller et al. 2012).

3.4 **Absolute positioning of the metrology gondola**

To position the metrology gondola in the 3-dimensional space, a vertical laser beam is used, to materialize the vertical axis of the entire installation. This laser beam must pass through the curvature center of the primary sphere. The verticality of the laser is obtained thanks to a reflection on a horizontal liquid mirror. The accuracy of this adjustment is ± 2 arcsec.

3.5 Actively stabilizing the lower tripod

At ground level, three custom motorized winches allow to control the cables length. To monitor the position of the summit of the lower tripod, a stereoscopic vision system has been developed (Fig. 6). At the summit, two retro-reflectors are placed. Two lasers light these retro-reflectors from two different locations on the ground. The return light from the reflectors is recorded by two small telescopes, fitted with position sensitive devices (PSD) at their focus. The two PSD gives four coordinates (P_{x1}, P_{y1}, P_{x2}, P_{y2}). Using a singular value decomposition, we can find a linear equation: $\Delta L = M.P_{XY}$, where L is the lengh of the cables, M is the matrix of the system, and P_{xy} are the coordinates given by the PSD (Le Coroller et al. 2012).

3.6 **The tracking system**

As we saw earlier, the only moving part of a Carlina diluted telescope is the focal gondola. It is placed on the focal sphere, which is the half-radius sphere concentric to the focal sphere. The observed object, the curvature center (C) and the focal gondola are aligned during the observation. To perform this alignment, the focal gondola is attached in (C), and at the intersection between the polar axis through (C) and the ground, so it can turn around this polar axis, describing an equatorial movement (Fig. 7). The "delta" motorized winch allows changing the declination and apply corrections. The "alpha" motor is used for tracking. The system is kept taut by a torque motor. Indeed, since the "alpha" winch is controlled in velocity and unrolls its cable while tracking, a tension cable is required on the opposite side to provide the appropriate force while rolling. This cable is controlled in force and not in velocity, to avoid hyperstatism and hyperdynamism problems. To achieve this force-controlled rolling, a torque motor was used at first,

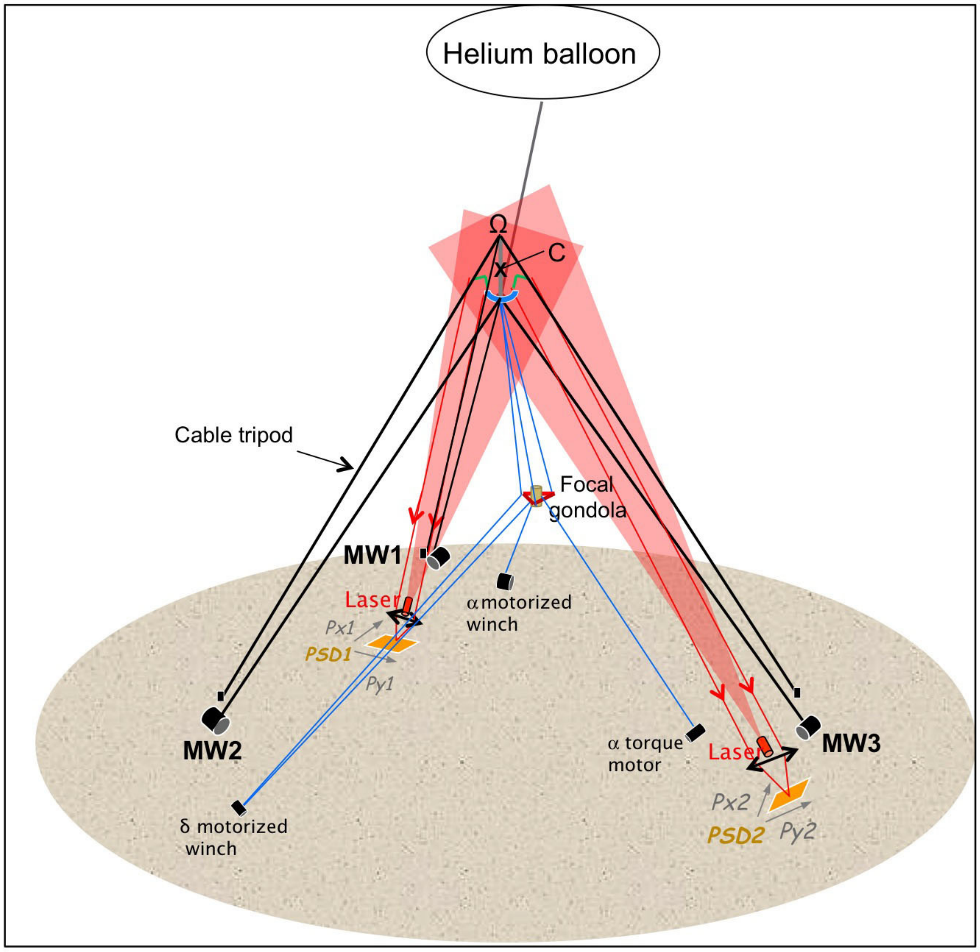

Figure 6.: *The cable structure: a double cable tripod, which summit coincides with the curvature center (C) of the primary sphere, constitutes the support of the experiment. It is tensioned by a traction force, here provided by a helium balloon. The focal gondola is suspended below. The system is stabilized thanks to laser measurements and motorized winches.*

but we obtained better performance with a long elastic that provided a smoother motion. In a future project, a torque-motor compatible with very low speed, and giving no jolts when the rotor turns from one coil to another, would have to be studied carefully.

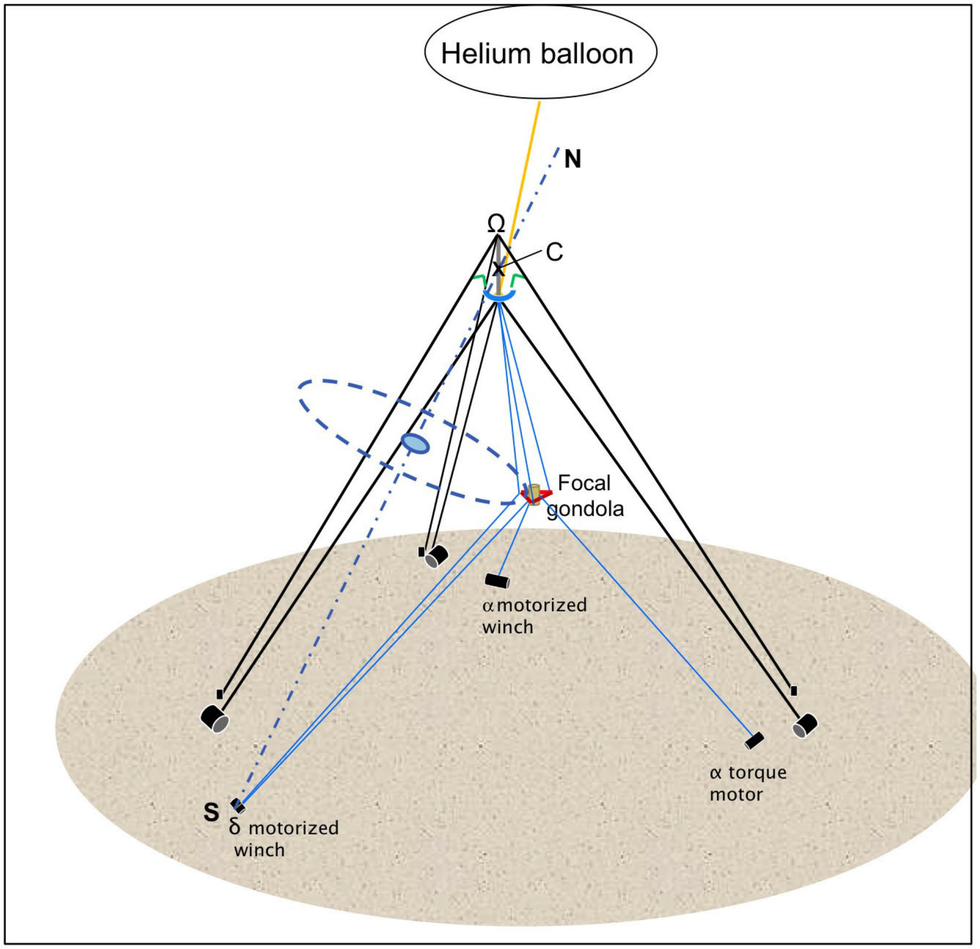

Figure 7.: *The tracking system: The (S-N) axis represents the equatorial axis. As the focal gondola is suspended and attached to the (S) and (C) points, it describes an equatorial movement.*

3.7 **The focal gondola**

The focal gondola is a carbon fiber truss structure carrying the "focal module" that contains all focal optics. The geometry of the structure and that of the attachments points is optimized to minimize angular oscillations: yaw, pitch and roll (Le Coroller et al. 2012, SPIE). The frame, made of 16 mm diameter carbon tubes and PBO guy-wires, has

the shape of a 3 m wide equilateral triangle. The barycenter of this triangle is also the center of gravity of the focal gondola (Fig.8). Three vertical cables coming from the metrology gondola situated 35 m above are attached at the three corners of the triangle (Fig. 7). Tensions in these cables are naturally equal. They sustain the weight of the gondola, and block the rotations around horizontal axis (pitch and roll). With these three cables, the gondola can only rotate around the center of curvature of the primary sphere, and around the optical axis. In order to block the rotation around the optical axis, two "delta" cables, coming from the intersection between the polar axis through (C) and the ground, are attached at both extremities of a carbon tube which passes through the center of gravity of the gondola. It follows that the latter can only rotates around the equatorial axis. Any acceleration of the "delta" cables will produce a real movement along the declination axis, with no parasitic tilt. Finally, to produce the equatorial tracking, the "alpha cable", coming from the alpha winch, is attached at the center of gravity, as well as the "torque cable", which ensure the tension of all the system. Just like for the "delta" cable, any acceleration of the alpha or torque cables will produce a pure equatorial movement, with no undesired tilt, since the cables are attached at the center of gravity of the focal gondola.
The focal gondola is the only moving part of the Carlina diluted telescope. A conventional N-aperture interferometer will require N-1 delay lines, accurately driven during the observation. A real advantage of the Carlina concept is that whatever the number of sub-apertures, there is only one moving part. Nevertheless, as shown in the table below, the challenge in term of control is comparable.

Table 1.: *Focal Gondola versus Delay line. R is the curvature radius of the diluted telescope's primary mirror; F is the focal length of the primary mirror; B is the maximum baseline; λ is the wavelength*

	Focal Gondola	Delay Line
Max speed (m/s)	$7.3 \times 10^{-5} \times \frac{R}{2}$ ($7.3 \times 10^{-5} \times 2B$ at F/2)	$7.3 \times 10^{-5} \times \frac{B}{2}$
Max drift	$\lambda F/B$ per exposure time (2λ at F/2)	$\frac{\lambda}{2}$ per exposure time

We can see that if the F-ratio chosen for Carlina is F/2, the max speed of the focal gondola is 4 times higher than the one of the delay

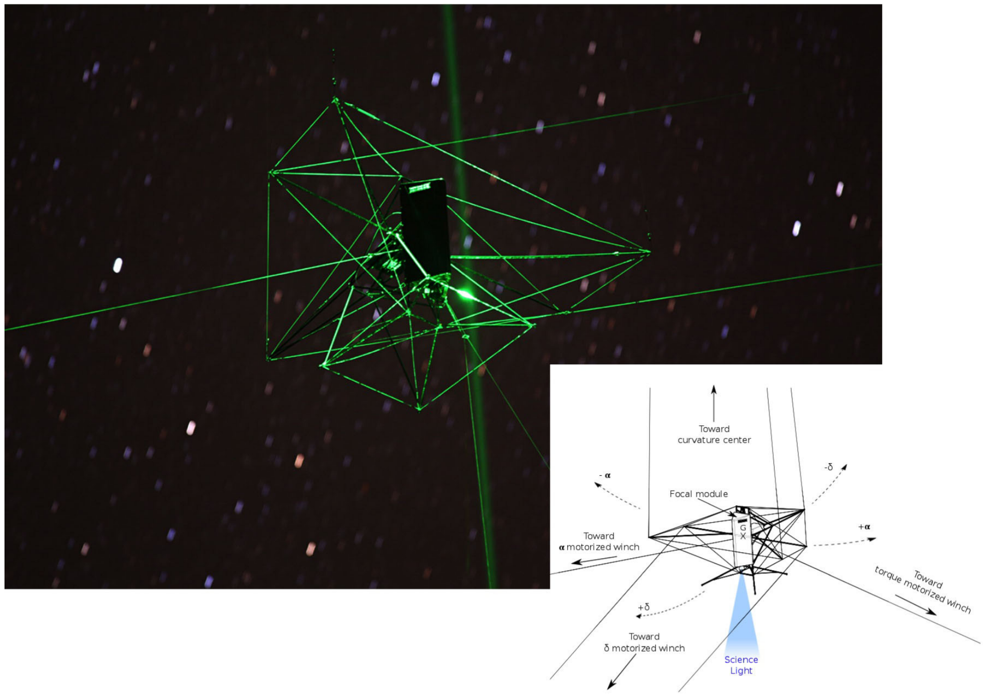

Figure 8.: *The focal gondola: a focal module (containing focal optics and detectors) is inserted into a 3 m triangular carbon structure. The geometry and the attachments positions are optimized to reduce adverse inclinations.*

lines, as well as the maximum "acceptable" drift (beyond, the fringes are totally blurred). Of course, the maximum drift to get good data must be drastically lower, which is a challenge for a cable-suspended focal gondola.

3.8 The focal optics

The focal optics carried by the focal gondola mainly comprises a spherical aberration corrector (because the giant primary is spherical), called Mertz corrector, a pupil densifier, a photon-counting camera, and a guiding camera (Fig. 9).
The Mertz corrector is made of two highly aspherical mirrors, obtained by precision diamond machining. It gives a 40 arcsec guidance field.

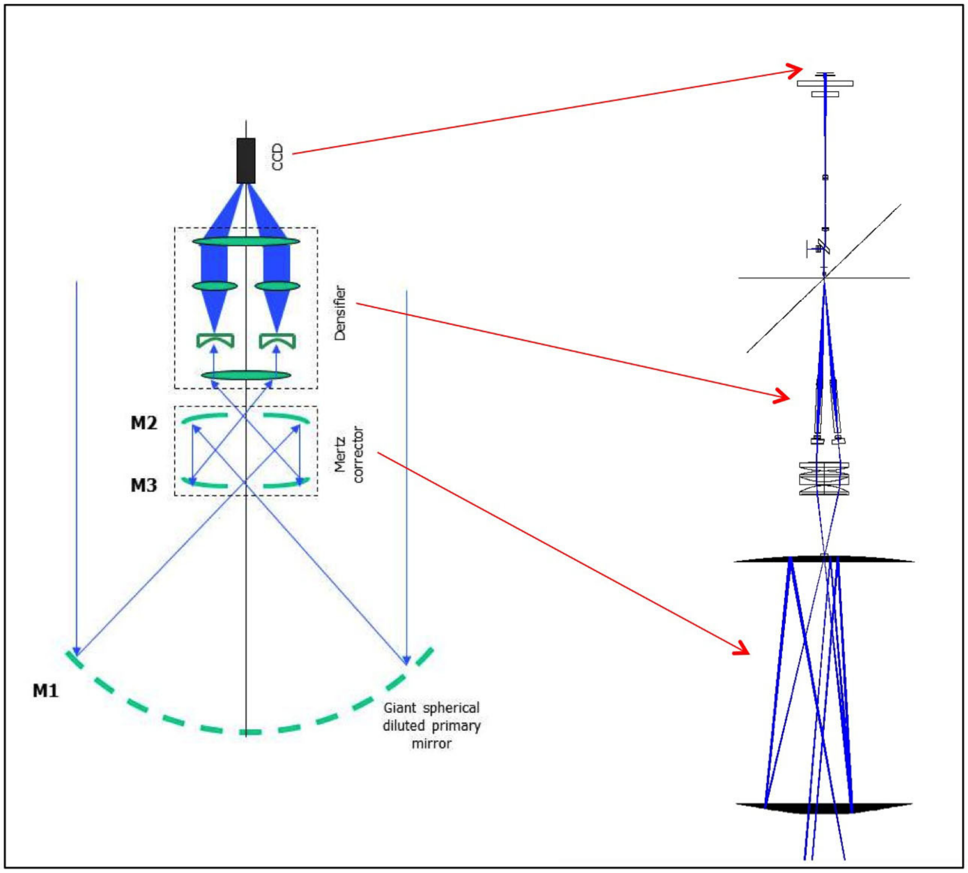

Figure 9.: *The focal optics: a Mertz corrector corrects spherical aberration on the axis. A pupil densifier (device destined to reduce the envelope size versus the fringes size) is disposed into the beam, before the light is directed toward a guiding camera and a photon counting camera.*

Over approximately 10 arcsec, the three spots provided by the three primary segments begin to separate.

This corrector gives a focus where the three spots are correctly superimposed, and where the diffraction envelope is about 40 times larger than the fringes. A pupil densifier is an optical device composed of one diverging lens and one converging lens on each beam, destined to reduce the envelope size with regard to the fringes size (Fig. 11). This device is placed in a pupil plan, and must follow the pupil movement during

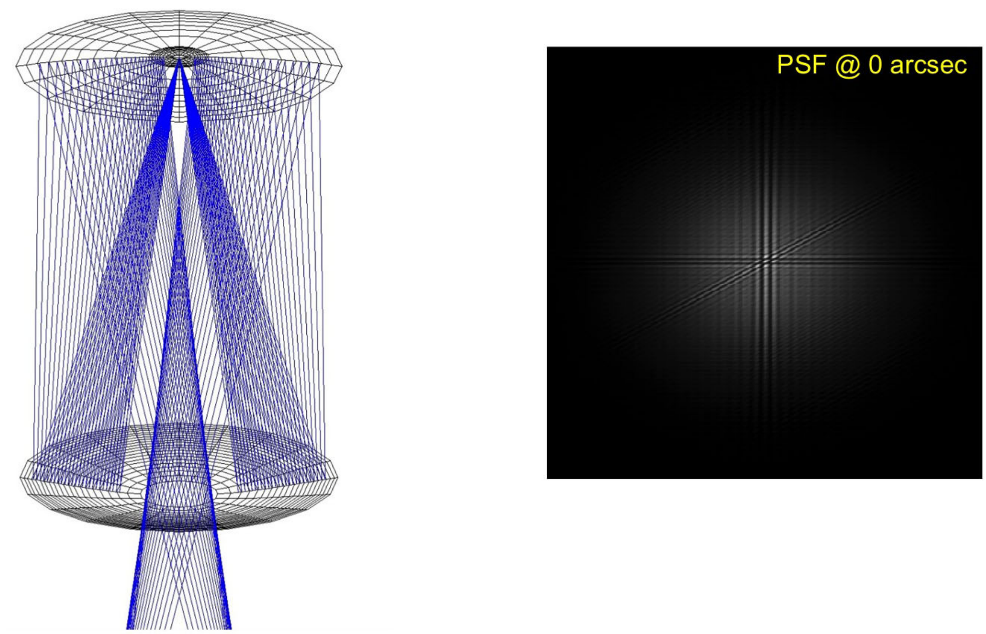

Figure 10.: *The Mertz Corrector, and the resulting PSF, on-axis.*

tracking within about 0.1 mm. On the OHP prototype, the densifier is passively positioned, using an equatorial mount oriented by gravity: while the focal gondola tilts during tracking, describing it's equatorial movement, the densifier has to remain always vertical, describing the reverse tilt movement relative to the gondola. This system is mechanically damped, using high viscosity oil.
Successful lab tests and laser sky tests showed the densifier was correctly positioning itself, but the required guidance accuracy (0.1 arcsec) for the focal gondola was impossible to reach without embedded fine motorized guiding system. This severe requirement is due to the fact that in a densified image, two different scales are present: The scale of the fringes is larger than the scale of the envelope. When a tracking error occurs, the fringes rapidly exit the envelope.

For this reason, a simplified Fizeau version of the focal optics was developed, by removing the pupil densifier, and modifying the optical design to adapt the size of the images on the science detector and on the guiding detector (Fig. 12). The guidance tolerance was then released to ±1 arcsec. We obtained good tracking results with very low

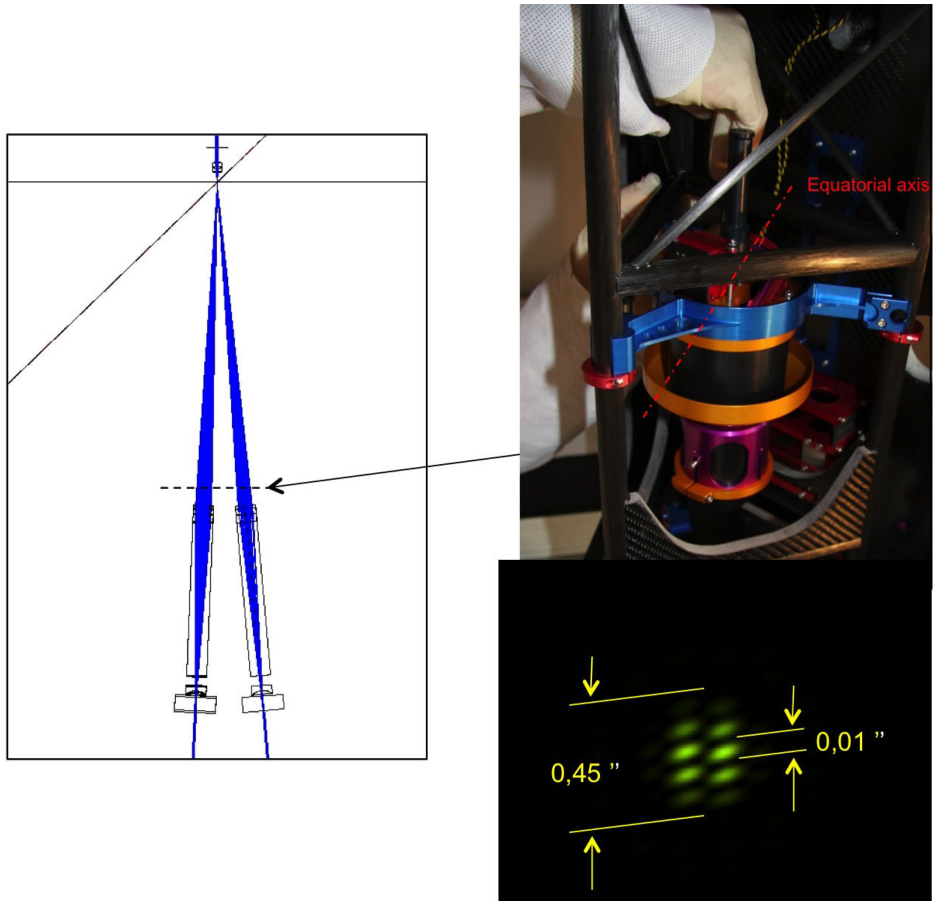

Figure 11.: *The pupil densifier: a pair of diverging/converging lenses are placed into each beam, near a pupil plan. Thos produce a reduction of the envelope sizen abd has no effect on the fringes size. To follow the pupil movement, this device is passively positioned on an "equatorial pendulum".*

wind. Nevertheless, better performance could be expectable with fine motorized guiding system in the gondola.

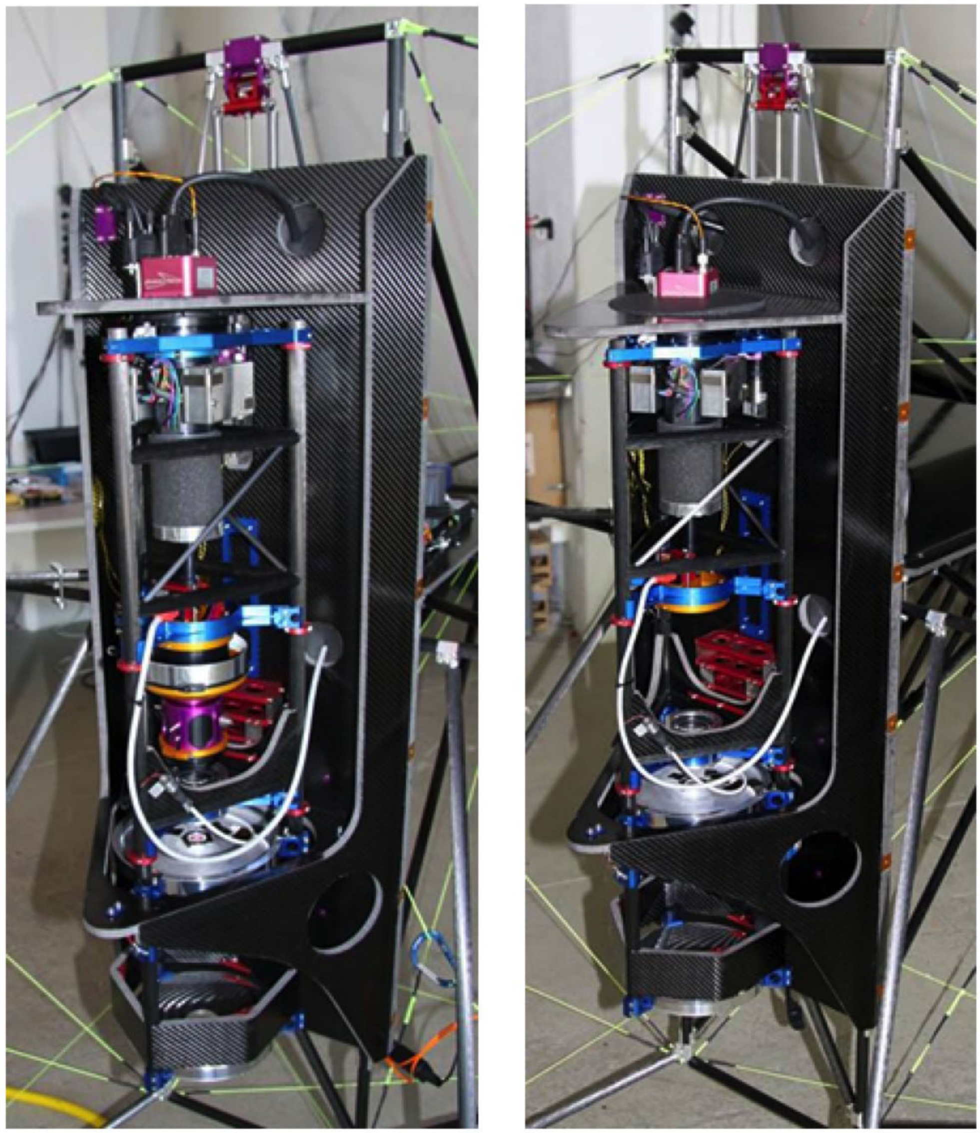

Figure 12.: *Views of the focal module: on the left, initial version with the pupil densifier; on the right, the simplified Fizeau version.*

4. Observations and results

The construction of the prototype began in 2003 and followed a progressive development, with a certain number of milestones. In May 2004, the first observations with a simplified installation (only two adjacent mirrors, no servo-loop, no metrology, no focal optics in front of the detector) were conducted, and showed a reasonable quality of the tracking, allowing to keep the image of the star on the detector during a few tens of minutes (Le Coroller et al. 2004). In 2007, the Merz corrector was manufactured and tested on the sky with three mirrors regardless of coherence. In 2010, the servo-loop and the laser metrology system were assembled (Le Coroller et al. 2012). Then the complete focal gondola was constructed, and first stellar observations with the entire prototype of a Carlina diluted telescope began in 2012. Experience proved the use of a helium balloon to exhibit some serious drawbacks: not only because of its intrinsic sensitivity to wind, but also because it imposed a complete disassembly of the installation every morning and re-assembly every evening: the balloon cannot stay in flight during the day when the wind speed overcomes 15 km/h. The balloon was eventually replaced by a lifting crane for the last observation run, in September 2013 (Fig. 13).

Over the course of a four night run, the prototype was deployed using the crane. After several adjustments, the prototype reached nominal operating performance, each sub-system working as designed: The installation was first positioned using the vertical laser reference. Then, the servo-loop system of the cable tripod was turned on, and the tip-tilt and piston of the primary segments were accurately adjusted, thanks to the metrology system. The white metrology fringes could be kept during the night, with some small adjustments every one or two hours. Several stars could be pointed and tracked correctly, with a variable performance of the tracking, depending on wind conditions.

A preliminary data analysis in September 2013 didn't show the fringes. Recently (February 2014) we improved the analysis procedure, for example by taking into account the rotation of the baselines due to the earth-rotation to add more data. Fringes are detected. The analysis method and results will be presented in a forthcoming paper.

Several hypotheses were formulated to explain the difficulty to detect the fringes, although the presence of the white metrology fringes a few minutes before and after each star tracking:

- Bad geometry of the Mertz corrector: the spherical aberration corrector, made of two high aspheric mirrors, is difficult to test optically in lab. Nevertheless, some measurements had been done on each mirror in 2007, and showed a good shape, with a 5 microns incertitude. Moreover, sky tests (in 2006 and 2013) with three spaced-out mirrors showed that the three spots remained well superimposed during all the tracking.

Figure 13.: *The Carlina-OHP experiment in September 2013: the helium balloon was replaced by a crane.*

- The relative ease with which the metrology fringes were obtained could have given too much confidence regarding the possibility to get stellar fringes. Indeed, as explained before, in the laser metrology system, the fringes are formed in a pseudo pupil plan, where the fringe velocity due to residual oscillations of the metrology gondola is drastically reduced, compared with fringes velocity in a focal plane. Even if the oscillations of the focal gondola should be comparable to those of the metrology gondola, the velocity of the focal fringes is 64 times higher (as it has been verified recently with Zemax). It is then possible that the stellar fringes were present, but undetectable because totally scrambled during a 5 ms exposure time. More data taken using a short exposure time (1ms) will be soon reduced.

It therefore appears that a big effort on the gondola stabilization (fine embedded motorized tracking system), much more massive structures and cables with high pre-load, use of inertia wheels, as suggested in T. Andersen's paper (2014), would be necessary for a Carlina diluted telescope to work properly.

5. Conclusion

After ten years of development and efforts, the prototype is completed. Original opto-mechanical solutions have been proposed, constructed and tested, to stabilize optical devices attached under cables. For example, the metrology mirror is stabilized within 200 microns accuracy, at 70 meters height! The primary mirrors are adjusted within one micron, thanks to a specific white-laser metrology. We were able to track the stars with 2 arcsec accuracy in very low wind.

Recently (February 2014) we improved the analysis procedure and fringes are detected. The analysis method and results will be presented in more details in a forthcoming paper.

Nevertheless, some solutions to stabilize the focal optics could be studied for a further project.

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References

Andersen, T., Le Coroller, H., O.-Petersen, M., Dejonghe, J. 2014, Linearized Model of an Actively Controlled Cable for a Carlina Diluted Telescope, in *Improving the performances of current optical interferometers & future designs*, Proceedings of Haute Provence Observatory Colloquium (23-27 September 2013) Edited by L. Arnold, H. Le Coroller & J. Surdej

Le Coroller, H., Dejonghe, J., Arpesella, C., Vernet, D., Labeyrie, A. 2004, Tests with a Carlina-type hypertelescope prototype, A & A, 426, 721

Le Coroller, H., Dejonghe, J., Regal, X., Sottile, R., Guillaume, C., Meunier, J.P., Clausse, J.M., Blazit, A., Berio, P., Deram, P., Ricci, D., Le Vansuu, A. 2012, The first diluted telescope ever built in the world, Optical and Infrared Interferometry III. Proceedings of the SPIE, Volume 8445, article id. 844514, 8 pp. (2012).

Le Coroller, H., Dejonghe, J., Regal, X. , Sottile, R. , Mourard, D., Ricci, D., Lardière, O., Le Vansuu, A., Boer, M., De Becker, M., Clausse, J.M.,Guillaume, C., Meunier, J.P., 2012, Tests with a Carlina-type diluted telescope. Primary coherencing, A & A, 539, 59

McAlister, H. A., ten Brummelaar, T. A., Gies, D. R., Huang, W., Bagnuolo, W. G., Shure, M. A.,Sturmann, J., Sturmann, L., Turner, N. H., Taylor, S. F., Berger, D. H., Baines, E. K., Grundstrom, E. and Ogden, C., 2005, APJ, 628, 439

Soulez, F., Denis, L., Thiébaut, E., Fournier, C., Goepfert, C. J., 2007, Opt. Soc. Am., Vol. 24, No. 12, 3708