Astronomy & Astrophysics manuscript no. coroller7
(DOI: will be inserted by hand later) 14 avril 2004

First light in a Carlina-type hypertelescope with balloon-suspended focal camera

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Received 15/04/04 / Accepted ...

Résumé Labeyrie (1996) established the feasibility of snapshot images with a multi-aperture interferometer having a densified exit pupil. The numerous widely spaced mirrors in these instruments, called hypertelescopes, amplify the usual difficulty of ajusting and phasing interferometers. A simplification is however possible, in the form of the optical and mechanical architectures called Carlina (Labeyrie et al. 2002). It is configured like a diluted version of the Arecibo radio-telescope. Above the diluted primary mirror, made of fixed co-spherical segments, a helium balloon carries a gondola containing the focal optics and detector. We describe in more detail the design of Carlina architectures, with versions having an equatorial drive and a coudé train. The optical design and the clam-shell corrector of spherical abberation is optimized with ray-tracing code. We built a Carlina prototype at the Observatoire de Haute Provence and verified the feasibility of tracking the diurnal motion of a star's image equatorially by pulling a cable with a computer-driven winch. This was achieved on the star "Psi Ursae Majoris", using a single segment of the primary mirror and a L3CCD camera in the gondola, 35 meters above. We expect to obtain usable high-resolution images in the presence of $5-10\,km/h$ winds affecting the balloon and focal optics. We also show that it is possible to co-spherize the primary mirror segments within one or a few microns, using wave sensing on the star or at the curvature center. No optical delay lines are needed, a significant simplification with respect to conventional interferometers such as the GI2T , the Keck , the VLTI, etc. These results demonstrate the short-term feasibility of large Carlina hypertelescopes. Such interferometers will provide snapshot images of star surfaces, and exo-planets if equipped with an adaptive coronagraph. Collecting areas comparable to those of ELT's appear feasible at a lower cost, while providing a higher resolution and similar limiting magnitude.

Key words. instrumentation : hypertelescope : interferometer : ELT : arecibo radio-telescope : Mertz clam-shell corrector — techniques : high angular resolution — star : visual — methods : observational

1. Introduction

Many-element apertures larger than 200 meters are required to obtain a usable number of resels in snapshot images of stellar surfaces, for a significant sample of the closest stars. A Similar size begin to resolve the diameter of a Jupiter-like planet at 2 pc. But the 8 meters size limitation for monolithic mirrors, and the 100 meters limitation foreseen for the mosaïc mirrors of the "Extremely Large Telescopes" currently studied, restrict their use for such science goals . The conventional interferometers using several telescopes have no such size limitation, and can therefore reach adequate resolution, but have a small number of apertures, affecting their ability to provide snap-shot images. Their cost and complexity are significantly increased by the delay lines (Mourard et al. 2003) which they incorporate.

In this article, we discuss various aspects of the hypertelescope architecture called Carlina (Labeyrie et al. 2002), which uses no delay-lines. We describe the construction and fisrt light of a prototype version using equatorial tracking. As explained elsewhere (Labeyrie 1996 ; Pedretti et al. 2000 ; Gillet et al. 2003) hypertelescopes provide snapshot images, using a densified pupil. The densified-pupil improves the image formation from a diluted aperture. At the combined Fizeau focus of a periodic diluted mirror, the image has a white central peak surrounded by many secondary dispersed peaks. The Fizeau architecture becomes inefficient for large interferometers where the spacing of the sub-apertures is typically much larger than their size. By densifying the exit pupil, the envelope of the combined image is shrunk and intensified while the secondary peaks are attenuated. Within a narrow field, the imaging properties of such

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instruments resemble those of ordinary telescopes.

In Sect. 2 we describe several architectures for a Carlina interferometer. In particular, we discuss ray-tracing results for a coudé version which relays a fixed image at ground level. We also discuss the optical design of a clam-shell corrector of spherical aberration used in the focal plane of Carlina. In Sect. 3 we describe a Carlina prototype which we build at Observatoire de Haute-Provence (OHP). We present initial results of star tracking in the presence of wind-induced oscillations at the balloon-borne camera. We conclude in Sect. 4, that Carlina hypertelescopes larger than 20 meters are feasible in the near future.

2. Architecture of a Carlina hypertelescope

Among the various possible hypertelescope architectures, the Carlina is analogous to the Arecibo radio telescope, although it uses a diluted primary mirror (Labeyrie et al. 2002). The primary mirror consists of many small mirrors, widely spaced with respect to their size, carried co-spherically by fixed supports inside a naturally concave site, canyon or crater (see Fig. 1). With stable bedrock and stiff, low-expansion, mirror supports anchored in it, the initial adjustment of the dilute optical surface can survive, within tens of microns, during long periods, months or years. Passive supports then suffice for the mirror elements if adaptive corrections are implemented in the focal optics. The following description is based on this philosophy, although motorized mirror supports can conceivably be utilized at a later stage if needed .

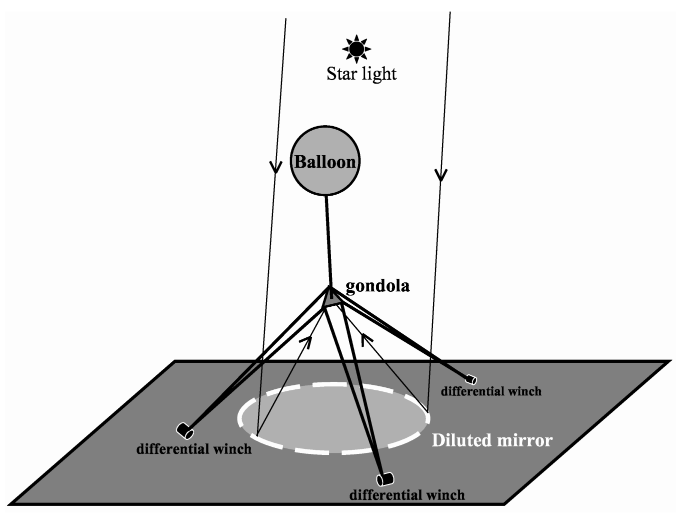

Fig. 1. Carlina version using six computer-controlled winches to define the position and attitude of the focal beam combiner. These can be combined as three differential winches

Above this diluted primary mirror, a gondola is suspended from a helium balloon and constrained by cables to move along the half-radius sphere. The gondola contains focal optics equipped with a clam-shell corrector of spherical aberration, a pupil densifier and a detector (see Fig. 2). Three pairs of cables tie the gondola to computerized winches at ground level. The balloon keeps the cable tripod tensioned, thus ensuring its rigidity within the limits defined by cable sag, in response to gravity and aerodynamic forces. The lengths of the six cables are determined by the three differential winches, thus defining the position of the gondola (see Fig. 1). The balloon typically oscillates in the wind while the tripod cables and the gondola remain little affected. Regarding the effect of the gondola's residual oscillations on the camera image, it may be remarked that they move globally the image without changing its shape. Unlike the jitter of component telescopes in conventional multi-telescope interferometers, which affects the relative positions and phases of component images in the beam combiner, the gondola's horizontal motion here produces a pure translation of the image. The vertical jitter produces pure defocus, and both can be corrected on-board with a simple x, y, z carriage. Unlike the case of a paraboloidal primary mirror, the spherical mirror allows continuous tracking, within its broad field, during hours by moving the gondola along the focal sphere. Conceivably, a deformable primary locus could be built to maintain a paraboloïdal shape remaining pointed towards the star being tracked. This would however require numerous actuators to drive the shape of deformable mirror segments, their rotation and their translation amounting to meters. In our current concept, the segments of the spherical primary mirror are carried by separate rigid tripods anchored in the bed rock built with low-expansion materials such as

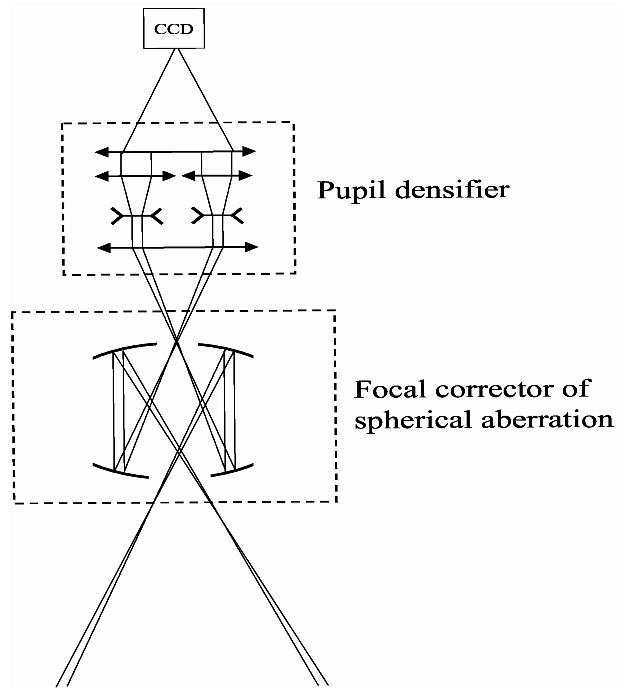

Fig. 2. The optics in the gondola will consist of a clam-shell corrector of spherical aberration, a pupil densifier and a CCD. Adaptive optics will also be needed to correct the positioning errors of the fixed primary mirrors, in tip-tilt and piston, as well as the atmospheric seeing.

carbon fiber. Unlike conventional interferometers (GI2T, VLTI, CHARA, etc.) no delay-lines are needed to maintain the balance of optical path lengths when the instrument follows the star's diurnal motion.

2.1. An equatorial version of Carlina

There are several ways of driving the gondola to track a star in the sky. In addition to the tri-axial scheme depicted in fig. 1, which requires six computer-controlled winches, the cable arrangement which drives the gondola can be configured for equatorial tracking as sketched in fig. 3. In this case, a single computer-driven winch suffices to track the diurnal motion. The cable arrangement can also carry a diode laser and metrology camera at the curvature center as described in Sect. 2.4, for monitoring the co-sphericity of the primary elements. The balloon must however be flown higher than in the triaxial mode (Fig. 1).

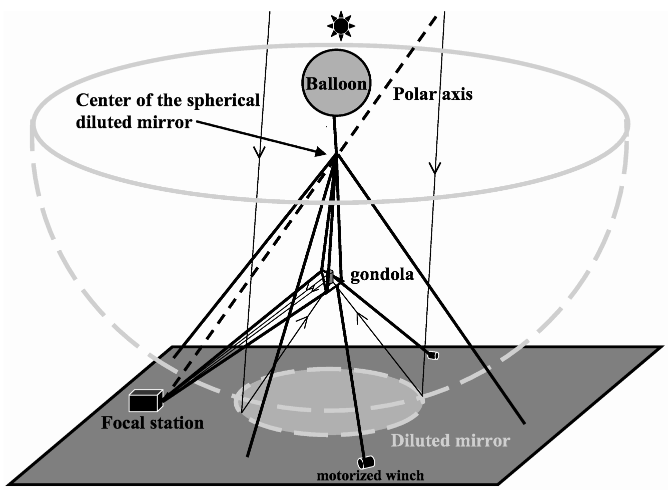

Fig. 3. Equatorial mode of star tracking with a Carlina. A single computer-controlled winch suffices to track the star.

In the equatorial tracking mode, the balloon is still tensioning a tripod of cables, but it is a fixed tripod of three cables rather than six, having its summit at the center of the primary mirror sphere (see Fig. 3). The gondola is suspended from this summit by three additional cables, at half the distance to the ground mirrors, which is the radius of the primary mirror. The gondola is thus constrained to moves along the focal sphere. A pair of additional cables connects the gondola to the intersection of the ground plane with the polar axis containing the mirror's curvature center. This constrains the gondola to rotate about this polar axis. The rotation is driven by one more cable connecting the gondola to a motorized winch at ground level. An antagonistic force is provided by a passive tensioning cable (see Fig. 3). With this architecture, the single computer-driven winch rotates the gondola about the polar axis, along the focal sphere, so as to track the star image with the gondola-borne camera. The length of the two cables from the gondola to the polar axis must be adjusted as a function of the star's declination.

2.2. The clam-shell corrector of spherical aberration

Spherical mirrors classically have a problem of spherical aberration. We correct it with a clam-shell corrector (see fig. 2, 6, 7), such as described by Mertz (Mertz 1996), which is located in the gondola close to the primary focal plane. This class of correctors, designed to meet Abbe's sine condition, corrects coma in addition to spherical aberration. The highly aspheric profiles of the two mirrors has become within the capabilities of diamond turning machines.

The mirror profiles of the corrector solution, found with the "RPLAN" code of Mertz are used as input for the Lasso code, developed by P. Rabou who further modified it for efficient interfacing with the Mertz routine. We also tried to use the Zemax code, but were unable to reach a comparable accuracy, owing to the limited order of the polynomial descriptions for the highly aspheric mirror profiles. Tolerances on gondola oscillations were also assessed by analysing the off-axis image degradation with Lasso.

A given size of the effective aperture, utilizing a given number of mirror segments, requires a curvature radius which decreases if the acceptance angle or focal ratio of the Mertz corrector increases. For a given maximal zenith distance of sky coverage, the total number of mirror segments needed therefore decreases when the acceptance angle of the clam-shell corrector increases. A larger angle is therefore better, but the size of clam-shell correctors increases as the third power of the focal ratio. As a reasonable compromise we have chosen F/2 as the focal ratio, a value for which the corrector diameter can be less than 1% of the effective beam diameter at the primary mirror.

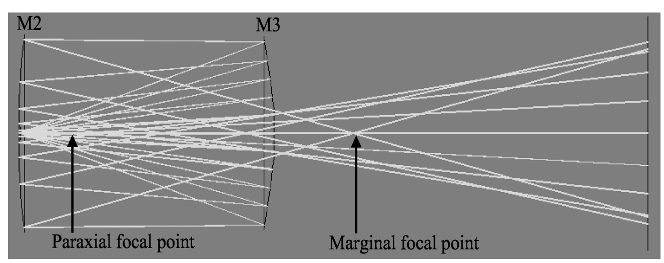

Fig. 4. Clam-shell corrector of spherical aberration and coma calculated with the Lasso code for F/2 acceptance. The paraxial and marginal foci of the primary mirror M1 (located far at right and not shown) are indicated. The corrected focus is at left, near the central hole of M2.

For the Carlina prototype described in Sect. 3, having a dilute spherical M1 mirror with 35.6 meter focal length and F/2 focal ratio, we designed a Mertz corrector having two highly aspheric mirrors M2 and M3, about 160 mm in diameter. The spacing of M2 and M3 is about 240 mm (fig.4). The seeing-limited field is apparent in the spot diagram of fig. 5. A star at 16.7" from the axis, produces

∼ 1" astigmatism on the image obtained with a primary spherical mirror at F/2, 17.8 m in diameter (see Fig. 5). This result is confirmed by a simple extension added to the Mertz routine to calculate optical paths for off-axis stars (Labeyrie, unpublished). This field angle, corresponds to ±3 mm on the camera and specifies a similar stability tolerance for the gondola. Such image jitter on the camera is acceptable, if the exposures are sufficiently short. No servo loop is needed in this case. The diffraction-limited half-field of the hypertelescope, with the 17.8 m aperture used around 600 nm wavelength, is similarly found to span about 3 arc-seconds. Like in the very similar design of OWL it can be increased by adding two small mirrors after M3.

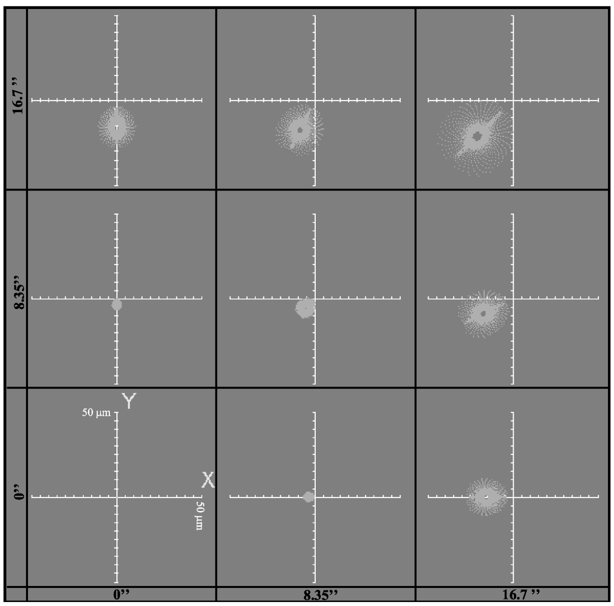

Fig. 5. Spot diagrams at the image plane of the clam-shell Mertz corrector for stars located up to 16.7" (top-right) from the optical axis, as calculated with the Lasso code. The smaller scale units on the X and Y axes correspond to 5 microns.

2.3. Coudé train feeding a ground laboratory

It is possible to reflect the star light from the gondola towards a fixed coudé focus in a focal station at ground level (see fig. 3). This is of interest for using bulky focal instruments, such as a spectrometer and adaptive optics, which do not fit easily in a small gondola and would require a larger balloon.
The coudé feed optics is located in the gondola after the focal corrector of spherical aberration and preferably also after the pupil densifier, typically containing a pair of lens arrays (fig. 6). Another solution involves a small flat mirror in the corrected focal plane, angularly driven to accommodate changes in stellar declination, and an off-axis paraboloidal mirror which refocuses the light to the ground (see Fig. 7). The pupil densifier and the CCD are in the focal station, thus requiring in the coudé beam a wider pupil and paraboloidal mirror if the image's angular size is kept identical.

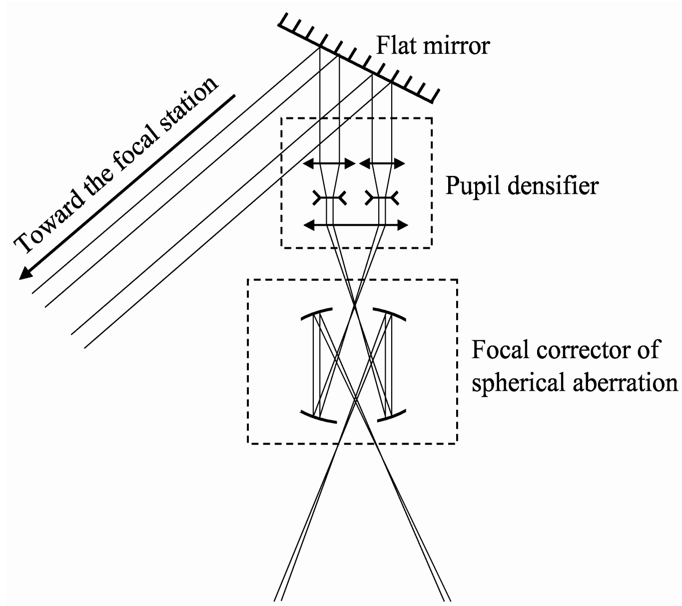

Fig. 6. Coudé feed in the gondola's focal optics. After the focal corrector of spherical aberration and the pupil densifier, using a pair of lens arrays, a flat mirror directs a coudé beam towards the focal station at ground level. The mirror must be rotated to accomodate different stellar declinations

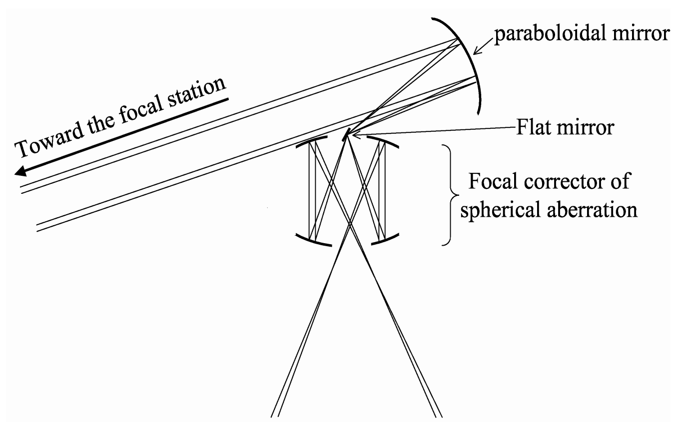

Fig. 7. Alternate scheme to fig. 6 for coudé optics, using a small tiltable flat mirror and a paraboloidal mirror. The pupil densifier and the CCD are in the coudé station at ground level.

The focal station is positioned on the polar axis (see Fig. 3) so as to receive a fixed image, only affected by field rotation and pupil drift, both correctible with a local rotating drive. In particular, the coudé beam can be collected by a classical telescope, which tracks the moving gondola. This telescope can be somewhat larger than strictly needed, to allow some tolerance of gondola tracking errors. The image can be stabilized with a tip-tilt corrector in the telescope.

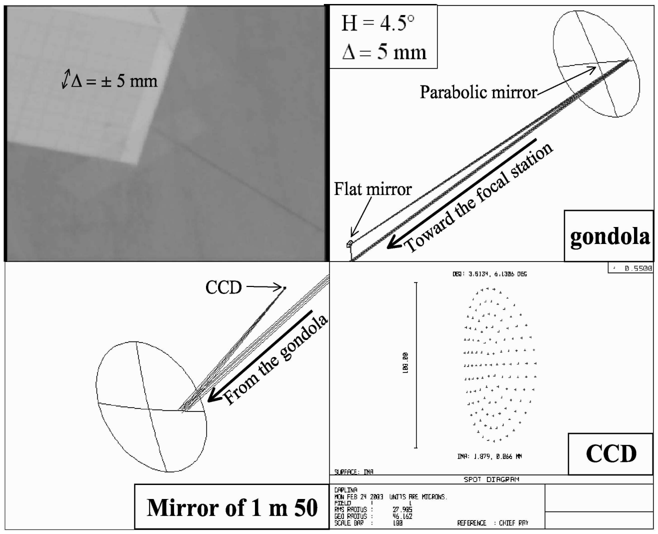

Fig. 8. The top-left of the figure shows a measurement at the Haute-Provence Observatory. A gondola without optics is placed under a balloon at 35.6 meters above ground. It oscillates by a few millimeters (rms) in the wind (Δ is the translation amplitude measured with a small telescope at ground level pointed at a sheet of millimetric paper glued on the gondola). The graph at top-right and bottom-left, shows a simple coudé train design, obtained with Zemax software. The corresponding spot diagram is at bottom right. At the top-right the gondola carries a small flat and a paraboloidal mirror (such as in Fig. 7 but without spherical aberration corrector). It is moved of 5 mm with the perfect position. On the bottom-left the light arrive on a focal station telescope focalized from the gondola. The light is translated of about one meter from the center of the mirror. The bottom-right picture show the image on the CCD (scale : 100 μm). The CCD is placed behind a lens that is in a pupil plan.

We assessed with Zemax ray-tracing the effect of field aberrations in this stabilisation procedure, in the context of the preliminary testing of our prototype described in sect. 3. At this stage there is a single 25 cm diameter primary mirror, of focal length 35.6 meters, and it is not yet equipped with the spherical aberration corrector. The ray-tracing results are shown in Fig. 8.

A flat mirror and a paraboloidal mirror are located in the gondola (as in fig. 7 but here without a clam-shell corrector) to re-focus star light on the large ground mirror of a 1.5 meter telescope serving as a coudé collector in the focal station. Its large mirror, serving as a field mirror, forms a gondola image above its focal plane, where a lens, too small to appear on the drawing (see picture at the bottom-left of Fig. 8), relays the star image on a CCD. The spot diagram (bottom-right of Fig. 8) is obtained for a 5 mm gondola guiding error and $H = 4.5$ degrees hour angle. At transit, the star is on the axis of the single 25 cm primary mirror. The image is slightly degraded, mainly due to astigmatism, in the absence of a spherical aberration corrector for this preliminary configuration. The contribution of the gondola displacement is weak and the diffraction pattern is only slightly degraded.

In this simulation we have optimized the focal length of the paraboloidal coudé mirror (mirror in fig. 7 and in top-right of fig. 8). If this focal length is large, the spot moves little on the ground telescope, in response to gondola oscilations but the coudé mirror has to be large and heavy to cover the full primary pupil. A 20 cm paraboloidal mirror with a focal length of 1 m is a good compromise for our prototype.

2.4. Coherencing and phasing the Carlina mirrors

In addition to the usual methods serving for acquiring stellar fringes with interferometers, a more direct procedure is usable in the case of Carlina architectures. It involves a light source at the curvature center (top of the tripod in fig.3) and a camera to observe the returning image produced by the primary mirror segments.

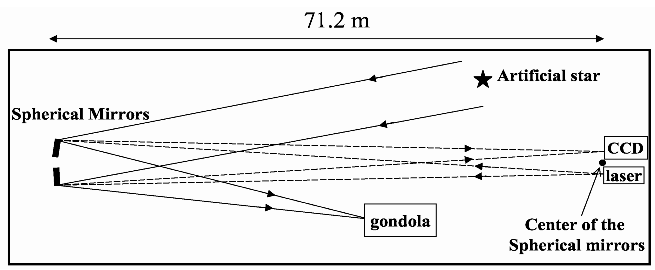

Fig. 9. Test optics arranged in the optical tunnel to develop phasing techniques. Two Carlina mirror segments spaced 35 cm apart produce fringes in the image of a point source located at their common center of curvature, 71.2 meter away. A camera records the fringes, found by using a laser with adjustable coherence length. With a white source, the piston balance can be adjusted within one micron.

This camera records the interference fringes that are used to co-phase the mirrors.

The laboratory experiment sketched in fig. 9 shows that the co-spherization of primary segments is conveniently achievable without a stellar input. In comparison with existing interferometers, this internal metrology procedure for Carlina architectures is a welcome simplification.

3. Description of a Carlina prototype built at the OHP and first results

At O.H.P we built a Carlina prototype system (Fig. 10), which is on flat ground, rather than in a crater, and therefore has a more limited celestial coverage. We have used the equatorial configuration described in Sect. 2.1 but not yet the coudé option, the gondola being equipped with a camera. The winches and other elements were positioned with a theodolite and a ranging laser, for a correct alignment of the virtual polar axis. The cables of the fixed higher tripod have a 45 degrees slope. In the rotating suspension the two cables which drive the gondola have a 22 degrees slope. The gondola stability is critically sensitive

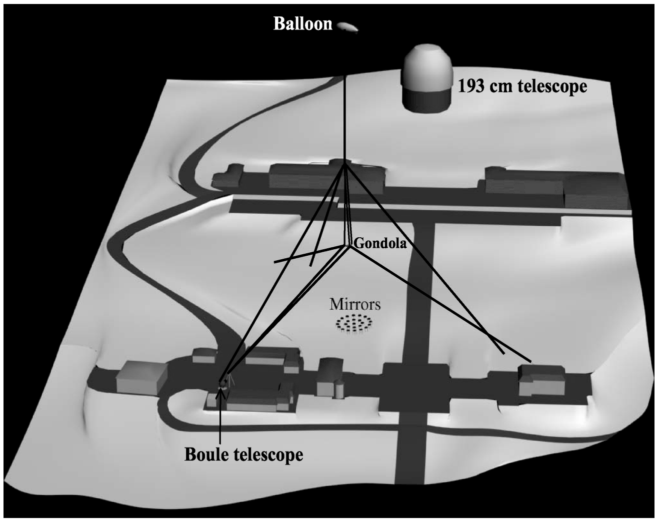

Fig. 10. Scale drawing of the Carlina prototype at the observatory. Pending crater sites, the flat ground is usable for limited declination coverage. The 4 mm Kevlar cables are thickened to make them visible. The 30-meter dome of the 193 cm telescope appears on top to indicate the scale. The 1.5 meter boule telescope at bottom-left, initially built as a prototype for the Optical Very Large Array (Arnold et al. 1999), is here potentially usable as coudé collector receiving light from the focal gondola (described in Sect. 2.3).

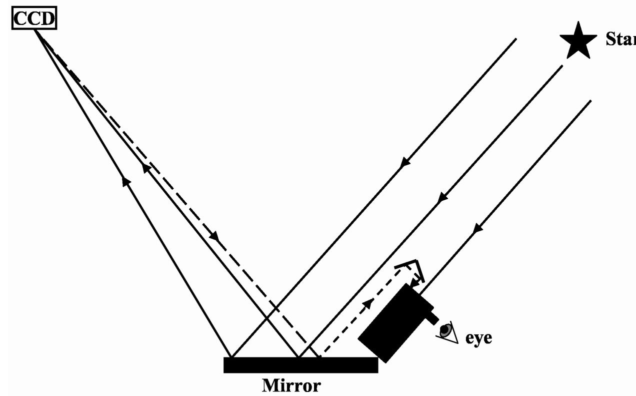

Fig. 11. Star acquisition system for Carlina. A small telescope is placed at the edge of the primary mirror segment and tracks the star. The light of a LED near the CCD in the gondola is reflected from the primary mirror segment towards a corner-cube reflector attached on top of the small telescope. The LED and the star appear in the telescope eye-piece and must be superposed by moving the gondola.

to the balance of cable tensions. We have developed a code and positioned the winches in order to optimize the cable tension.

The curvature radius of the diluted primary mirror is 71.2 m, the focal length is 35.6 m, and the altitude of the balloon is about 140 m. At F/2 the effective aperture is 17.8 m and the external mirrors will have to be supported 71 cm above ground to provide the curvature of the spherical primary mirror. We designed and built a balloon shaped like a water drop, 12 meter long, 4 meter wide and with 80 kg carrying capacity. Fig. 10 shows the architecture of Carlina with several mirrors at ground level. To verify the star tracking performance and oscillation behaviour, we began with a single 25 cm diameter element of the primary mirror, supported by a 1x1 meter concrete pier anchored in the bed rock. The mirror cell is carried by a carbon fiber frame through three manual micrometer screws. The Zerodur mirror was figured, together with several more having a matching figure within $\lambda/8$.

The initial observation used a single primary element and did not yet involve a clam-shell corrector since calculations had shown that the ensuing astigmatism is tolerable at moderate zenith distances (see fig. 8).

3.1. Star acquisition system

A small guiding telescope is placed at the edge of the primary mirror segment and tracks the star. It carries a corner-cube reflector covering part of its aperture (see fig. 11) to capture light from a LED source located near the CCD. This light is reflected from the primary mirror segment towards the star and part of it is retro-reflected into the guiding telescope (see fig. 11). The LED and the star appear in the telescope eye-piece and must be superposed by moving the gondola. This superposition ensures the correct centering of the star image on the CCD. The field of the guiding telescope is preferably large to help pointing the star.

3.2. first light in the Carlina prototype

The first light was obtained in March 2004 from the star "Psi Ursae Majoris" with an electron multiplier CCD (E2V type L3C65-06P CCD), of size 11.52 x 8.64 mm. The gondola was not yet equipped with a clam-shell corrector, nor coudé optics, having a CCD on board. We tracked the star during 30 minutes, before and after transit and the image remained on the CCD chip (see fig 12). In this first test, there was no focusing mechanism. The following night similar sequences on a magnitude 4 star proved overexposed, indicating that the instrument with its simple optical train may prove more sensitive than conventional interferometers having many reflections in their complicated coudé trains.

The response to manual guiding corrections, made with a guiding paddle acting on the right-ascension and declination winches, proved faster than one second, in spite of the Kevlar cable's intrinsic elasticity and that induced by their sag. This encouraging result was obtained without any servo loop, after the observer had centered the star on the CCD with the pointing system described in Sect. 3.1. The tolerable wind velocity is estimated to be 5-10 km/h. With stronger winds, the balloon tends to orient itself across the wind, and a larger tail appears required to avoid it. Tethered balloons having special lift-generating shapes are known to stand much stronger winds.

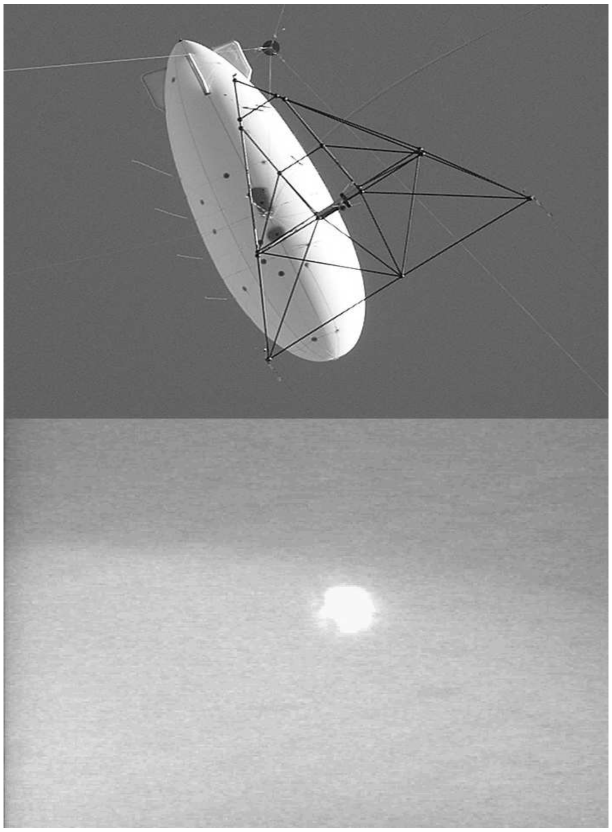

Fig. 12. top : tethered balloon, 140 meters above ground. The black disc seen near the tail of the balloon is at the curvature center of the primary mirror, 71.2 meters above it, and also at the top of the fixed cable tripod (see Fig. 3). The black triangle frame is the gondola, about 3 meters in size and made of 16 mm diameter carbon fiber tubes, which carries the CCD, 35.6 meters below this point. Bottom : first light for the Carlina prototype on star "Psi Ursae Majoris" obtained on March 02/03/2004. The field of the CCD Image shown is about one arc minute and the size of the star image is close to 7 arc-seconds due to astigmatism, focus error and seeing.

4. Conclusion and future work

In this paper, we have described several versions of the Carlina architecture for hypertelescopes. We have calculated optical designs having enough field of view to tolerate the oscillations of the gondola, up to a few millimetres. Their effect can be corrected with a servo guiding loop, acting as the first-order element of the adaptive optics which will be needed to correct the fixed piston errors, arising from the imperfect positioning of the primary mirror segments, and the atmospheric errors. Pending such adaptive corrections, the instrument is usable with full resolution in a speckle interferometry mode.

We describe the initial step of constructing a prototype version at OHP. We have tracked the star "Psi Ursae Majoris", with a single primary mirror element attached to the bed rock, and a CCD in the focal gondola 35.6 meters above. Steps are now taken to install additional mirror segments to obtain interference fringes. Mirrors can be coherenced with the arrangement described in Sect. 2.4. In the coming months, the gondola will be equipped with a clam-shell corrector of spherical aberration and a pupil densifier system (Labeyrie 1996). The design can in principle be extrapolated to large optical arrays spanning perhaps up to 1500 meters and incorporating hundreds or thousands of mirror segments, at sites such as the "Caldera de Taburiente" crater in the Canarian islands (Labeyrie 2003).

Given the encouraging initial results obtained with our prototype we consider for the shorter term an intermediate step at the scale of 50 to 200 meters. Once equipped with adaptive optics (Martinache 2004 ; Borkowski et al. 2004) it will in principle provide snapshot images of star surfaces. The brighter exo-planets, such as 51 Peg b or Tau Bootes, become angularly separated from their parent star with apertures larger than 30 meters at visible wavelengths and their relative luminosity of 10^{-4} to 10^{-5} is within the detectability range if a coronagraph is added, possibly with post-focus adaptive cleaning.

It will be of interest to compare large Carlina arrays with ELTs in terms of science/cost efficiency. In the same way that large ELT designs evolved from the Keck I telescope, large hypertelescopes can be expected to evolve, on Earth and in space, from the prototype described here.

Acknowledgements. This research has been funded by Collège de France. Some mechanical elements were fabricated by the OHP. The authors are grateful to P. Rabou from Grenoble Observatory, for his contribution to the optical ray-tracing with Lasso software. We are grateful to several students, F. Martinache, F. Ienna, A. Saglem and G. Le Marchand for their helpful contributions.

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