Feasibility of coupling Euro-50 interferometrically to a Carlina hypertelescope

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ABSTRACT

The interferometric coupling of an ELT with a large multi-aperture imaging interferometer can open new areas of science on compact objects. Numerical simulations indeed show that the combined image retains respectively the high luminosity and the high angular resolution of both instruments. The Canarian site envisaged for the Euro-50 is adjacent to the large Caldera de Taburiente crater, a favorable site for an optical and dilute form of the Arecibo radio-telescope. Our preliminary study indicates that the effective aperture size can exceed 1600m if a balloon or kite is used to carry the focal optics, also receiving a coudé beam from the Euro-50 if coupled. In spite of inherent limitations regarding field size and crowding, the 50 micro-arcsecond resolution thus achievable in visible snapshot images is of interest for stellar physics, active galactic nuclei and deep cosmological imaging of remote galaxies.

Interferometer, Carlina, multi-aperture, hypertelescope

1. INTRODUCTION

Forthcoming large multi-aperture interferometers may combine hundreds or thousands of aperture elements, providing a diluted aperture at the scale of one or several kilometers, for angular resolution reaching tens of micro-arcseconds at visible wavelengths[1,2]. Much larger sizes, approaching a million kilometer, are considered for space versions[3,6,7]. Direct snapshot images containing much information will be obtained according to the principle of "densified-pupil" imaging, also called hypertelescope imaging[1,4,5]. Whenever feasible, it will be of interest to couple such instruments interferometrically with Extremely Large Telescopes.
The prospect of a Euro-50 sited at Roque de las Muchachos (La Palma, Canarias), close to the rim of the large Caldera de Taburiente crater, raises the possibility of achieving such coupling with minimal hardware (figure 1). The concave crater can indeed serve as a nest for a "Carlina", a diluted optical form of the Arecibo radio-telescope[2]. This requires focal optics suspended 1.4km above the crater's rim, using a stabilized balloon or kite. Coupling with a Euro-50 located near the rim of the crater is then a matter of propagating a coudé beam from its mechanical node towards the focal optics of the interferometer (figure 1).
According to the principle of hypertelescope imaging, the densified pupil of the Carlina must be combined with the pupil of the Euro-50, not necessarily densified, in a way which preserves the pattern of pupil center's. The resulting image of a point source is a coherent sum of both images, i.e. a sum of the complex vibration amplitudes. The former typically has a much narrower central peak than the latter. The sum pattern moves globally if the star moves, its shape being invariant within the boundaries of the Direct Imaging Field.

2. CONCEPT OF A CARLINA INTERFEROMETER IN THE CALDERA DE TABURIENTE

The principle of hypertelescopes, and the sky testing of miniature versions, are described elsewhere[1,4]. Such instruments solve the luminosity problem arising in Fizeau-type multi-aperture imaging interferometers when the sub-aperture spacings are much larger than their size. They can be built in the form of a Fizeau interferometer, equipped with a small "pupil-densifier " attachment downstream from the Fizeau focus .
Hypertelescopes have a central Direct Imaging Field (DIF), the celestial size of which is ?/s , if s the average spacing between aperture elements. It is surrounded by a wider peripheral field, of diameter ?/d , if d is the sub-aperture diameter, where images can be reconstructed post-detection if the number of resolved sources, or "active resels", within it does not exceed the crowding limitation, of the order of N^2 if the apertures are arranged non-redundantly. Crowding and the ensuing loss of image contrast is a basic limitation of all interferometers, particularly those having few apertures. The limitation applies here within each sub-aperture lobe, but adjacent ?/d fields can be observed simultaneously in a multi-field mode with a mosaïc array of field lenses, each feeding

a miniature pupil densifier[1]. Aberrations in the Fizeau field limit the size of this mosaïc array, although separate corrections of off-axis aberrations can be introduced in each densifier.

Possible architectures for ground-based hypertelescopes can use flat sites, equipped with multiple telescopes feeding, through a coudé train of mirrors or through optical fibers[1], a common coudé laboratory where the beams are recombined. To accomodate the Earth rotation, flat arrays require either delay lines, like in ESO's VLTI, or mobile telescopes like in the early Optical Very Large Array[3,4] concept.

Such flat arrays can conceivably provide diluted apertures as large as 10 kilometers, but the cost of telescopes, delay lines, filed rotators, etc.. tends to restrict the number of such elements to tens rather than hundreds or thousands.

Another class of architectures is considered here[2]: it uses a concave site, such as an extinct volcano crater or a broad canyon, where fixed mirror elements can be arranged to fit a spherical locus. Unlike the Arecibo radio-telescope, having a full 330m spherical mirror made of aluminum plates, the mirror considered for the optical version is much diluted for reasons of cost, with elements of one or two meter size located hundreds of meters apart (figure 4). The focal combiner includes a corrector of spherical aberration (figure 3) and is suspended at the focal surface from a balloon or kite, depending on wind speed. Moving the combiner tracks the diurnal motion, thereby suppressing the need for delay lines. Several combiners, and possibly many of them, can be used at the same time with separate balloons for observing as many objects, and thus increasing the science efficiency of the instrument.

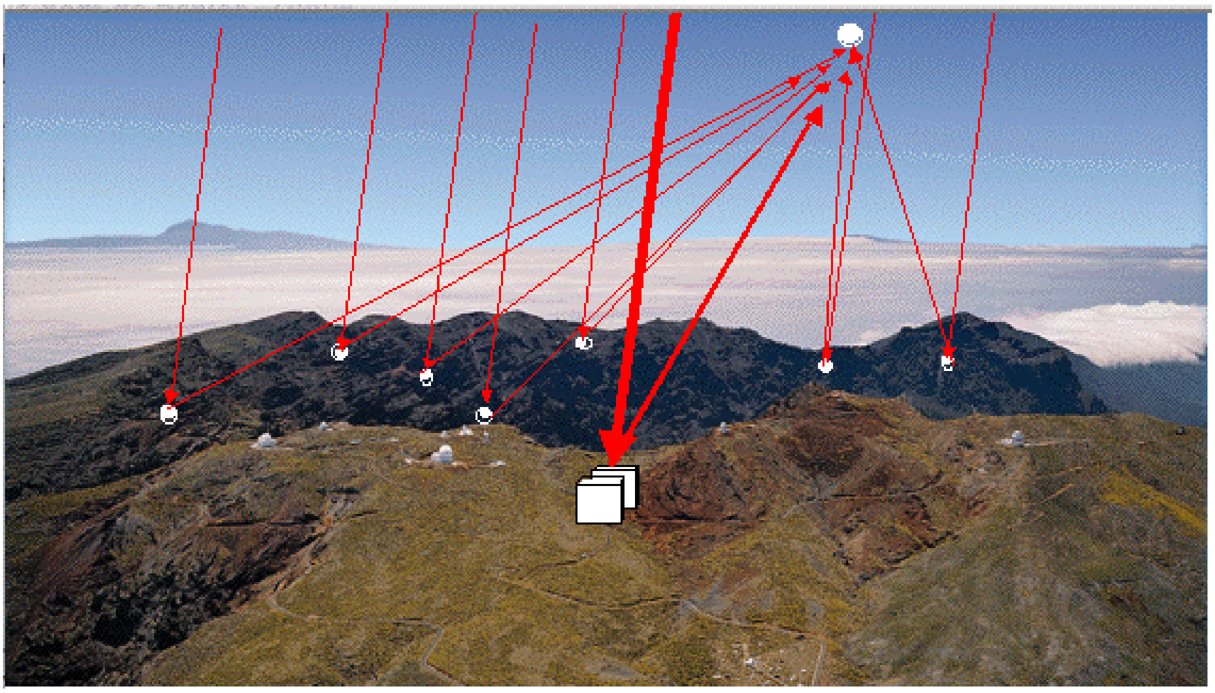
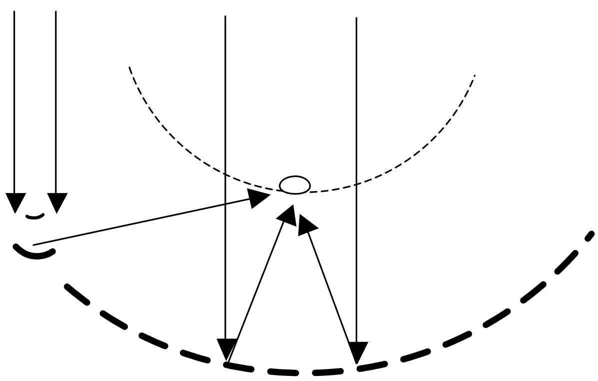


Figure 1: Interferometric coupling of a Euro-50 and a Carlina hypertelescope nested in the crater adjacent to Roque de las Muchachos. A coudé beam from the former reaches the balloon-borne focal combiner of the latter . It has many fixed mirrors of 1 to 1.5m size, positioned at co-spherical locations. A star's image formed at the focal sphere is corrected by a clam-shell corrector of spherical aberration and coma, followed by a pupil densifier which increases the image luminosity, et the expanse of field coverage The angular acceptance of the corrector limits the array size effectively usad on a given star to 1600-2500m.



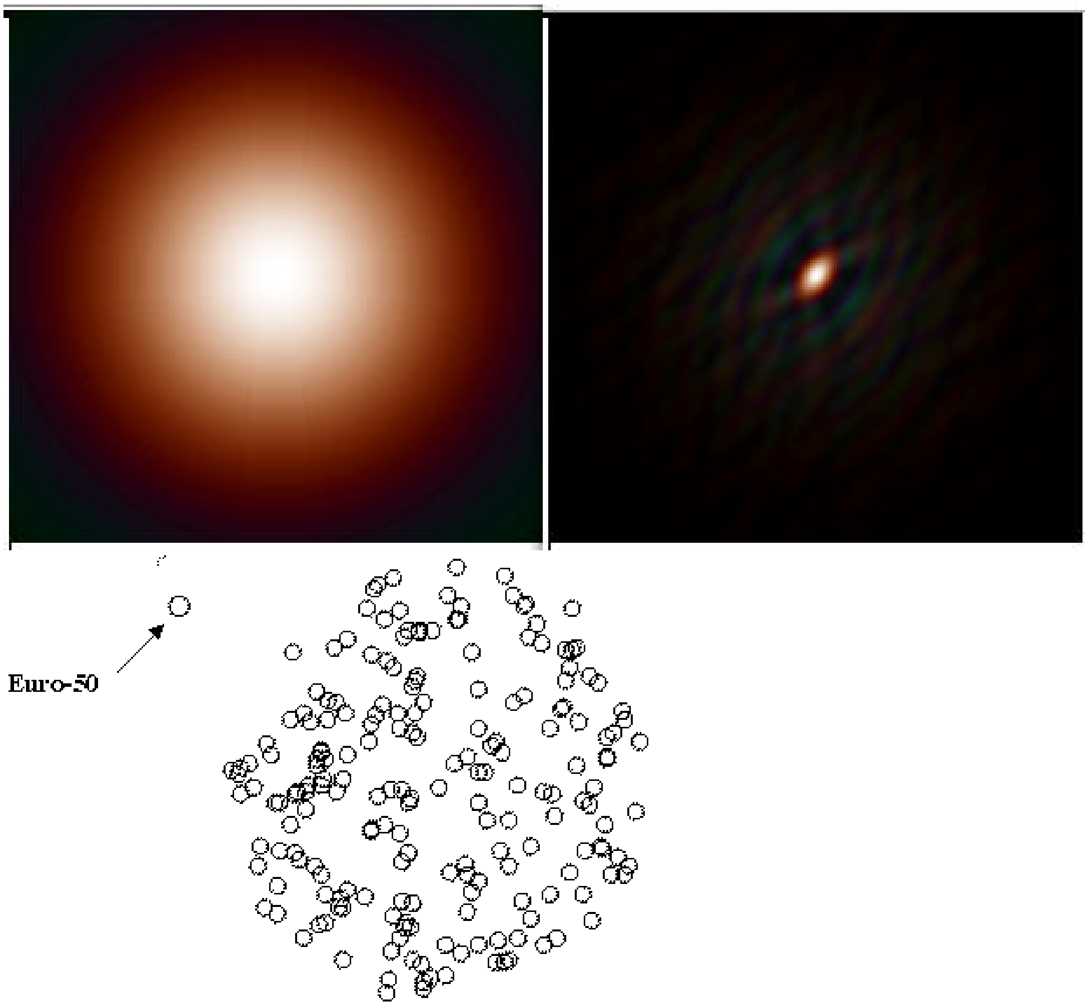


Figure 2: Top: Simulated example of combined image produced by coupling a Euro-50 and a hypertelescope having 200 sub-apertures of 1m, randomly located within a 1000 m diameter (perfect phasing is assumed). At left: 2 milli-arcsecond Airy peak of a Euro-50 alone. At right: combined image of a point source, shown at the same scale. The hypertelescope sub-pupils are densified 40 times, and the Euro-50 pupil is not densified. Most light is concentrated in the 50 micro-arcsecond wide peak. Its maximal intensity is 17.6 times higher than for the Euro-50 alone, in spite of its 12.5 larger collecting area. The pattern translates in response to star motion within the Direct Imaging Field,. of size 1 milli-arcsecond if the average spacing of the hypertelescope mirrors is 100m, and its peak vanishes beyond. Bottom: Densified pupil where the 40x densification factor of the 1m sub-apertures makes them nearly as large as the non-densified Euro-50 pupil seen. The random algorithm used to locate the small mirrors caused spurious superpositions of some densified pupils, but they do not affect much the diffraction pattern shown on top.

This class of hypertelescopes, called Carlina after a composite alpine flower, is restricted in the size of the effective aperture to two or perhaps three kilometers by the availability of large craters in good astronomical sites, and the feasibility of the spherical aberration corrector needed. The optical and mechanical structure can in principle accomodate hundreds or thousands of elements in the primary array. Their cost is low since each is a fixed mirror, very slightly concave and held in a passive support directly bolted to stable bed rock. Since the information content of images goes as the square of the aperture count, for non-redundant baselines, the information gain to be expected with respect to flat arrays may reach 10,000.

As apparent in figure 4, a Carlina array with effective aperture at least 1600m can probably be installed in the Caldera de Taburiente, the rim of which is a candidate site for the Euro-50. To assess its suitability, I went camping in the Caldera in November 2002, walking up along the exit canyon and climbing towards the upper slopes and cliffs. With a portable 12cm telescope I could visually assess the night time "seeing", which proved excellent even at the lower altitudes, with a high Strehl ratio and a slow motion of the speckled inner diffraction rings. Depending on the heigth of the inversion layer, however, a cloud layer invades the lower parts of the crater during a fraction of the nights.

The Caldera, said to be the deepest crater in the world, is far from hemispherical in shape, but the topography (figure 4) is compatible with the arraying of hundreds of mirrors arranged co-spherically with millimetric accuracy. Residues of tip-tilt and piston can be corrected with adaptive optics at the balloon-borne focal combiner, or in a coudé laboratory at ground level.

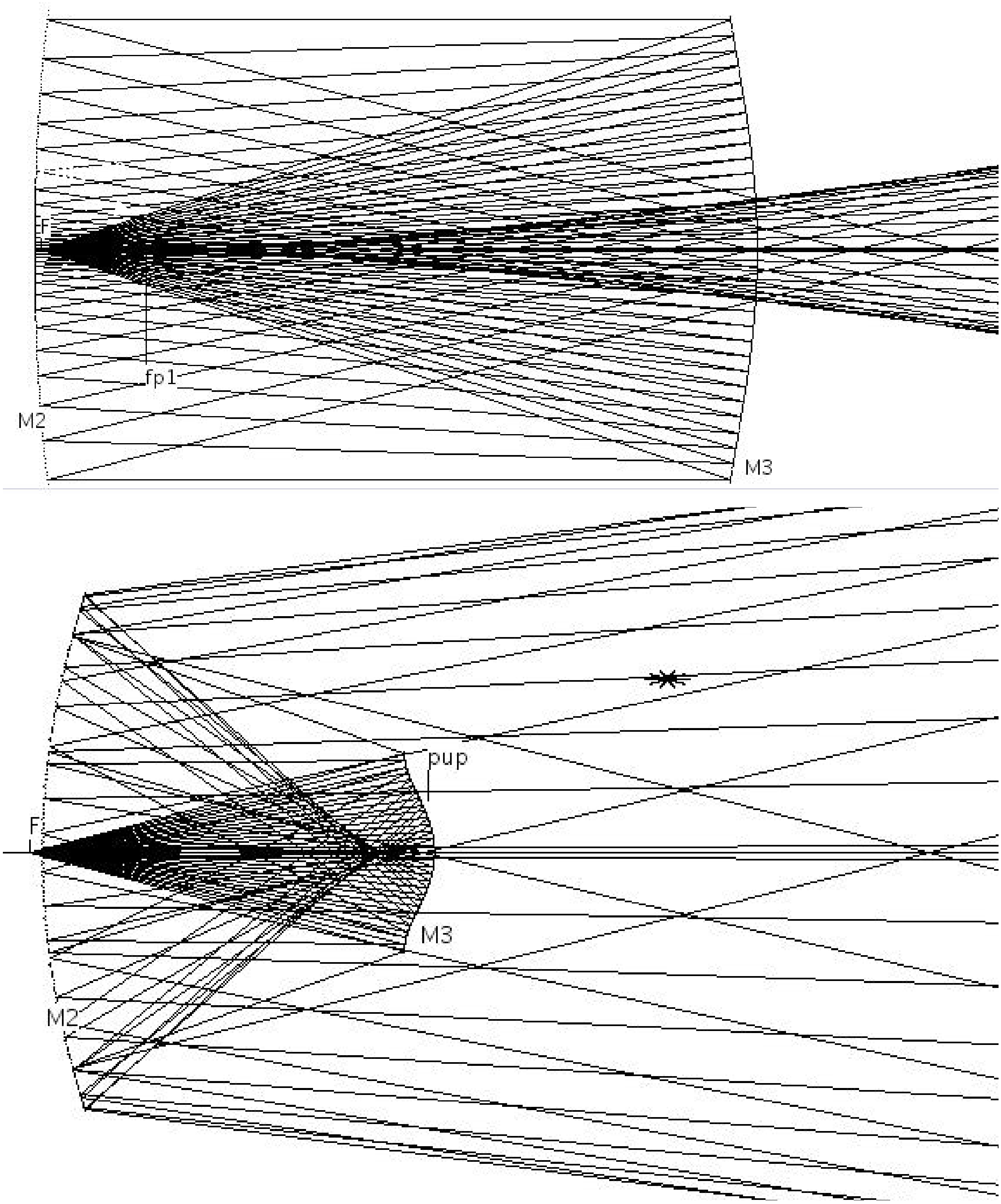


Figure 3: Types of clam-shell correctors located at the focal sphere of a Carlina hypertelescope to correct spherical aberration and coma, as designed with the RPLAN code of Mertz[5]. Top: a solution at F/2, requiring mirrors M2 and M3 of 14.7m size for a 1,625m effective aperture at M1, of curvature radius 6,500m. Bottom: a more compact solution where M2 is located at the best focus of M1 and folded nearly on itself. M3 is dilute,

with mirror elements smaller than 1mm for 1m sub-apertures at M1. The size of M2 is only 3.2m in this case, but a non-obscuring mechanism is needed to move the M3 array globally for tracking the sub-pupils, with also a triple micro-mechanical actuator carrying each M3 segment for adjusting the axial position and tilt.

The Caldera is a National Park, however, where the exceptional geological environment and ecosystem deserve utmost protection. For acceptability, a Carlina design must have very little impact. This appears achievable by doing without access tracks nor concrete piers for mirror supports. Being fixed and rather small , 1 to 1.5 m, the mirrors can have lightweight whiffle-tree supports. The mirrors and tripod supports can be brought by pedestrian porters, anchored in the basalt with three bolts, and adjusted in height and tip-tilt for co-sphericity. This adjustment is achievable with a laser theodolite or with a balloon-borne laser or retro-reflector temporarily held at the curvature center.

Mirror covers are probably unnecessary with modern protective overcoats on the aluminum or silver film, and this can avoid the complications of having radio-controlled covers, requiring motors and solar cells. Bird droppings are corrosive, but the bird density is very low in the Caldera and rain maintains mirror cleanliness, as demonstrated by the existing large mosaïc of unprotected mirrors in the Cerenkov detector of cosmic gamma-rays installed at the edge of the Caldera, close to the location considered for the Euro-50.

The mirrors, mostly located away from the few trails open to park visitors, will be essentially invisible to them. And they will be removable, with no residue, a few decades later if and when larger hypertelescopes become available in space. The balloon or kite is hardly visible 1450m above the crater rim and can probably be grounded during daytime for even less visibility.

The clam-shell corrector of spherical aberration, for which large and smaller versions are shown in figure 3, can utilize membrane[9] mirrors M2 and M3 having relaxed figuring tolerances since the light beams from the sub-apertures are very narrow. Both mirrors can be assembled in the form of a drum-shaped balloon where helium pressure contributes to the mirror rigidity. The Mertz parameters[8] corresponding to the solutions of figure 3 are respectively, in kilometer units : R=6.5; HM=-0.8125; SM=-0.32; XD=3.268849; fd =3.246749; PL=9.797773 and R=6.5; HM=-0.8125; SM=-0.26; XD=3.275349; fd =3.269249; PL=9.742773. Several colleagues (S.Gillet, P.Riaud) tried to ray-trace such systems with Zemax, but unsuccessfully, due to the strong asphericity of the surfaces. Another code, LASSO, has been extended by P.Rabou to load mirror profiles generated by Mertz's algorithm and to provide spot diagrams.

The small pupil-densifier stage needed after the corrected Fizeau focus, which uses a miniature array of inverted Galilean telescopes configured like the primary aperture has been tested[4] but not yet modelled in detail. Geometric ray-tracing is useless to assess the high-resolution image since it is formed by interference, and diffractive codes are therefore needed.

The atmospheric dispersion, producing star images elongated at the scale or arc-seconds at the Fizeau focus, must be compensated, and this is achievable with a strong prism or a diffraction grating located at the entrance pupil of the densifier. The strong dispersion becoming achievable in photonic crystal materials may be of interest to fabricate prisms of manageable size. Alternately, since single-mode optical fibers can replace the Galilean telescopes in the densifier[1], fibers having different lengths can be configured as a “fiber prism” having a large equivalent thickness. A series of interchangeable fiber prisms, having different angles, might however be needed to accomodate different zenith distances.

3. FEASIBILITY OF COUPLING WITH A EURO-50

If equipped with a small flat mirror located at the intersection of its azimuth and elevation axes, and bi-axially driven, the large telescope can in principle reflect a coudé beam towards the focal combiner of a Carlina (figure 1). It may require adequate openings in the dome structure, or a tri-axial mount with integrated enclosure like the boules of the GI2T[9] interferometer, variants of which appear of interest for Euro-50. At the focal combiner, the coudé beam should preferably by-pass the clam-shell corrector of the Carlina, and be directly combined with the interferometer beam downstream. No large delay line is needed if the Carlina’s mirror array is co-spherical with the mechanical node of the Euro-50. The first-order variation of the optical path difference is indeed corrected by the motion of the balloon along the focal sphere, and a rather small delay line suffices to compensate the higher order terms induced by the spherical aberration of the large spherical locus. This delay line can be installed, together with any bulky focal instruments, in a ground building if the combined image, once densified, is re-directed towards the ground. This coupling arrangement has possible variants which may repuire long delay lines. Coherencing and phasing of all beams is highly desirable, although speckle interferometric observations of simple sources remain possible in the absence of phasing. Phasing requires adaptive optics, using types of wave sensors suitable for diluted optics[10,11,12].

Figure 4: Altitude contours of a hemispheric dish fitting optimally in the Caldera, showing intersections (white dots) with ground contours which are possible locations for mirrors. The sphere's radius is 6500m and the altitude spacing of contours is100 m. The array can span about 7500 m in the North-South direction, but the effective aperture size usable on a given star will be smaller than 2400m (the white circle corresponds to 2,000m)., being limited in practice by the feasible size of the focal corrector. The location of the effective aperture varies with declination and the hour angle. The possible co-spherical site for the Euro-50 indicated at top left can be on the outer slope for invisibility from the Caldera. It extends the baselines lengths, especially when observing towards the North, and up to 6,600m when observing at 53° declination. The focus' altitude is 4,050m above sea level, i.e. 1,750 m above the crater's rim at 2,300m. The range of zenith distances accessible is 25°North and South of zenith, covering declinations from +3 to +53°.

3. CURRENT TESTING OF ELEMENTS FOR A SMALLER CARLINA

The positioning and stabilisation of balloon-borne beam combiners is currently under test in our group at Haute-Provence. J.Dejonghe and H.Le Coroller have begun testing tethered balloons positioned with computer-controlled winches, 130m above ground level. The passive stability is better than 10 mm with low winds at night, and the slow residual pendular motion appears correctible with a tri-axial voice-coil actuator carrying the

camera chip. 25 cm mirrors, having a closely identical curvature radius 70m, were figured by D.Vernet. One of them, and then several, will be arrayed co-spherically on ground supports. If interference fringes become obtainable, it will be possible to add tens or hundreds of mirrors. The adaptive optics system will use a "dispersed speckles" piston sensor[10,11,12] , a multi-aperture extension of the "dispersed fringe" sensors used since A.A.Michelson. A laboratory prototype has been built with V.Borkowski and code is being developed for on-line data processing and actuator control.
The instrument will be movable to Roque de las Muchachos near the Grantecan, and the coupling of both is considered, using the bi-axially driven M3 flat to extract a coudé beam from the dome. In the absence of a small crater near the Grantecan, a single ring of small mirrors can be used at the intersection of the ground with a sphere (a similarly small Carlina may also be of interest for the Euro-50 when a lower resolution is needed) . . Such testing, at the scale of a 100-300m aperture, can help assessing the difficulty and performance of the larger version considered in this article.

4. SCIENCE WITH A COUPLED EURO-50 AND CARLINA

The simulated images (figure 2), using aperture geometries typical of those achievable at Roque de las Muchachos, indicate the resolution and luminosity gains achievable, as well as the field extent usable for direct images. The limiting magnitude of the Euro-50 is increased in principle in the presence of sky background, if a non-resolved guide star is available in the multiple field of the CARLINA to activate its adaptive optics. No way of using laser guide stars for interferometers has yet been proposed.
Further simulations, using different types of objects and the optimal densification settings for each can provide more insight in the science performance . Coupling with an ELT indeed affects the field availability in a way which depends on the pupil densification setting, which is zoomable for trading luminosity against field. With the 1,625m effective Carlina aperture considered, images containing 20x20 resels, each sub-tending 50 micro-arcseconds, can be obtained if the average spacing of the sub-apertures is 160m. Hundreds of such images are obtainable simultaneously in the multi-field mode, which remains operable in principle when coupled to the ELT.
Such imaging characteristics have obvious uses for observing a broad diversity of bright and faint objects. Stellar physics, including the close environment of candidate black holes and neutron stars, is likely to benefit from such images. Active galactic nuclei and QSO's are also imageable. Deep fields of remote galaxies, of interest for cosmology, can also be observed if the Carlina has enough apertures to avoid crowding. Apertures can be added at any stage, as required by the observing programs, with little modification of the focal hardware.

5. CONCLUSION

At favorable sites such as the Roque de las Muchachos, a large ELT such as the Euro-50 can probably be coupled with a multi-element interferometric array having a smaller collecting area but angular resolution improved 30 to 120 times. The high-resolution snapshot images obtainable in principle can significantly amplify the range of science accessible to an ELT. The prototyping work currently initiated towards the development of a Carlina hypertelescope is expected to verify the operating performance of such instruments, and their cost, believed to be moderate.

REFERENCES

1. Labeyrie, A., "Resolved imaging of extra-solar planets with future 10-100 km optical interferometric arrays", , Astron. Astrophys.Supp.Ser., **118**, 517-524 (1996).
2. Labeyrie, A., "Current steps towards kilometric arrays of many telescopes: prospects for snapshot images with 10^{-4}" resolution", *Optical Telescopes of Today and Tomorrow*, Arne L. Ardeberg; Ed., SPIE Proc. Vol. **2871**, 787-794 (1997).
3. .Labeyrie, A. "Snapshots of Alien Worlds -- The Future of Interferometry'", Science, pp. 1864-1865, Sep 17, (1999)..
4. S. Gillet, P. Riaud, O. Lardière, J. Dejonghe, J. Schmitt, L. Arnold, A. Boccaletti, D. Horville, A. Labeyrie , "Imaging capabilities of hypertelescopes with a pair of micro-lens arrays" Astron. and Astroph., 400, 393-396, 2003.
5. "VIDA (Vlti Imaging with a Densified Array): a densified pupil combiner proposed for snapshot imaging with the VLTI" ,O. Lardière, A. Labeyrie, D. Mourard, P. Riaud, L. Arnold, J. Dejonghe, S. Gillet , Proc. SPIE 4838, Hawaii, 2002.

6. “Hypertelescopes and exo-Earth coronagraphy” ,Labeyrie,A. , "Earth-like planets and moons", ESLAB 36th Symp., p. 245, 3-8 June 2002, ESTEC, Noordwijk, The Netherlands, ESA SP-514, 2002.
7. Labeyrie,A., "Hypertelescopes and exo-Earth coronagraphy" proc. "Next Steps in Exploring Deep Space", ESTEC workshop, ESA 2003.
8. Mertz, L., in "Excursions in Astronomical Optics", Springer (1997) .
9. Chen,P.C. & Romeo,R.C," Advances in Composite Mirror and Telescope Technology" (this conference) 2003.
10. “A wavefront analysis algorithm for multi-aperture interferometers and hypertelescopes” , V. Borkowski, F. Martinache, D. Peterson, A. Labeyrie, "Earth-like planets and moons", ESLAB 36th Symp., p. 273, 3-8 June 2002, ESTEC, Noordwijk, The Netherlands, ESA SP-514, 2002.
11. Martinache, F., submitted (2003).
12. Borkowski,V. Labeyrie, A. Martinache,F. and Peterson,D. , in preparation (2003)