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Optical design options for hypertelescopes and prototype testing

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ABSTRACT

Hypertelescopes are large optical interferometric arrays, employing many small mirrors and a miniature pupil-densifier before the focal camera, expected to produce direct images of celestial sources at high resolution. Their peculiar imaging properties, initially explored through analytical derivations, had been verified with simulations before testing a full-size testbed instrument. We describe several architectures and optical design solutions and present recent progress made on the Ubaye hypertelescope experiment. Arecibo-like versions with a fixed spherical primary meta-mirror, or an active aspheric one, have a suspended focal beam combiner equipped for pupil-drift accommodation, with a field-mosaic arrangement for observing multiple sources such as exoplanetary systems, globular clusters or active galactic nuclei. We have developed a cable suspension and drive system with tracking accuracy reaching a millimeter at 100m above ground.

Keywords: hypertelescope, interferometer, stellar,

1. INTRODUCTION

Extremely Large Telescopes (ELT), with mosaic mirrors as large as 39m for the E-ELT, will not reach the current angular resolution of optical interferometers such as the VLTI and the CHARA, having much longer baselines. But these cannot produce direct images, rich in information content, owing to the modest sampling of the optical wave with the few sub-apertures used. Many sub apertures would be required, as planned for the proposed hypertelescopes. Their principle (Labeyrie 1996) extends the classical Fizeau interferometer, not only by using many sub-apertures instead of just two, but also by using pupil densification for improving the light concentration in the interference peak.

The principle can be materialized on Earth with arrays of telescopes, connected by coudé trains through optical delay lines. But these, being costly, then restrict the number of sub-apertures. Because hypertelescope theory predicts a better imaging performance and science output for many small apertures rather than few large ones, for a given collecting area and meta-aperture size, we designed and tested a different opto-mechanical architecture. This is a dilute version of the Arecibo radio telescope, with a large fixed concave meta-mirror, and a movable camera on its focal surface.

In space, similar architectures can be considered for much larger meta-apertures, in the immaterial form of many small mirrors virtually assembled as a "meta-mirror flotilla". Several versions have been proposed to NASA and the European Agency, including a "Laser Trapped Hypertelescope Flotilla» (Labeyrie et al., 2013).

Following two decades of calculations, simulations and prototype testing at increasing scales, we discuss optical designs for Earth and space versions. We also report on the testing, in a south Alpine valley, of the Ubaye Hypertelescope expected to reach a 200m meta-aperture size. The principle can be materialized with different optical architectures and opto-mechanical designs. One of them, a dilute optical form of the Arecibo radio telescope, has been tested during the last four years in the upper Moutière valley of the Southern Alps. It demonstrated the feasibility and operability of the concept with its cable-suspended focal camera, driven with millimetric accuracy for tracking the motion of a star's image.

2. DIRECT-IMAGING INTERFEROMETERS: FROM FIZEAU'S MASK TO THE HYPERTELESCOPE

Fizeau's early 1875 suggestion of masking a telescope's aperture with a pair of smaller sub-apertures, subsequently tested by Stephan, stimulated the subsequent work of Anderson, Michelson, and others who pioneered the modern development of optical stellar interferometry. At radio wavelengths, a similar breakthrough occurred in the 1950's, but more quickly reached a stage of using many antennas. They did not provide direct images, in the absence of multi-pixel detectors, but indirect ones through heterodyning and aperture-synthesis reconstructions. With many antennas and Earth-rotation synthesis, however, these images quickly became better than those obtained with optical interferometers, then limited by the small number of sub-apertures which could be used. Even in Fizeau's days, multiple sub-apertures could easily have been operated on a masked telescope, but turbulence would have caused the formation of speckles rather than a peaked spread function providing direct images, a problem now solvable with adaptive optics. A more basic limitation of many-aperture Fizeau imaging, not avoidable with adaptive optics, is the spreading of light among the many side-lobes of the spread function, with little remaining in its central peak if the aperture is highly dilute.

The hypertelescope can be described as a large multi-aperture Fizeau interferometer, equipped with a small pupil-densifier array of miniature Galilean telescopes which is inserted in a relayed pupil plane after the Fizeau focal plane. This concentrates most of the collected energy in the interference peak, thus greatly increasing its intensity but reducing the size of the directly imageable field.

As previously described, hypertelescopes are multi-aperture interferometers providing a direct image of compact sources. The meta-beam, containing beams from all sub-apertures which converge on their way toward the image plane where they are co-focused, is then densified before reaching it. As previously described in more detail, such densification does not destroy the direct image, but shrinks the diffractive envelope of the interference function. The notion of a point spread function then vanishes since the image of a point source becomes position-dependent. The image of an extended source may then be described by a pseudo-convolution with the source function. It restricts the field size which can be directly imaged down to a "Direct Imaging Field" (DIF) (Labeyrie, 2007, Lardière et al., 2007). And it intensifies the image, approximately as $\gamma_{\square}^2$ if $\gamma_{\square}$ is the pupil densification factor, by concentrating into the interference peak the light diffracted across the sub aperture lobe. Sources smaller than the DIF's size ϕ_{DIF} are directly imaged. Larger ones can to some extent be reconstructed post-detection with the algorithm of Mary, exploiting the known off-axis evolution of the interference function. The maximal DIF size ϕ_{DIF} is on the order of 0.1 arc-second in visible light if the primary sub apertures are spaced s= 1m apart, but only 0.01 arc-second if s= 10m

. Hence the advantage of using, for a given meta-aperture size and total collecting area, more mirrors of smaller size, which also improve the contrast of the interference peak, and thus the dynamic range of the direct images.

3. ARCHITECTURE OPTIONS FOR HYPERTELESCOPES

3.1 Choice of aperture pattern

The optimal pattern of sub-aperture arrangements for hypertelescopes depends on the type of source observed. Any aperture pattern is usable, even with unequal sub aperture sizes if they are equalized by the pupil densifier. Various aperture patterns have been proposed, with different amounts of redundancy. A low redundancy is often preferred, except for the coronagraphic imaging of highly contrasted sources, where a periodic grid can provide a nearly filled densified pupil. With low-redundancy patterns, their geometry does not much affect the performance for direct imaging if the sub-aperture count N is large, or if the aperture can be varied or rotated during the exposure, using Earth rotation for example. In space, with a flotilla of mirrors, variable aperture patterns will likely be possible.

3.2 Arrayed telescopes

The VLTI, the CHARA and other telescope arrays having a beam-combiner for interferometry, such as the "Optical Very Large Array" proposed by AL before exploring hypertelescope imaging and recognizing the advantage of small sub apertures, can be equipped with a pupil densifier for operating in the hypertelescope mode, as proposed for the Very Large Telescope (Lardiere et al., 2003). The optical delay lines, generally needed by such arrays for compensating the effect of Earth rotation in the absence of a global steerable mount, however implies a high cost of adding more telescopes, and thus restricts the number of apertures, thereby limiting the imaging performance. This performance can be much improved with the numerous apertures usable in the case of Arecibo-like architectures, since they require no delay lines. They can therefore use hundreds of sub-apertures, thus allowing a far better imaging performance. The following sections concentrate on these architectures.

3.3 Dilute versions of the Arecibo and FAST radiotelescopes for a static mirror array: the Carlina architecture

In the recent years, J. Dejonghe, H. Le Coroller, S. Gillet, R. Chakraborthy, and some of us (AR, PR,YB, PR) have explored with AL several candidate optical designs for Earth-based hypertelescope architectures inspired from Arecibo's radio telescope and the larger FAST version now built in China. Like these instruments, the broad concept (fig. 1) has a giant mirror, but here in dilute form, being made of segments which have to be small compared to their spacing, for saving weight and cost. They are anchored, through stiff tripods, to the bedrock of the concave site, or possibly carried by a "spider's web" of crossed cables like at Arecibo but with added vertical tensioning ties for a more accurate and stable figure at the scale of optical wavelengths.

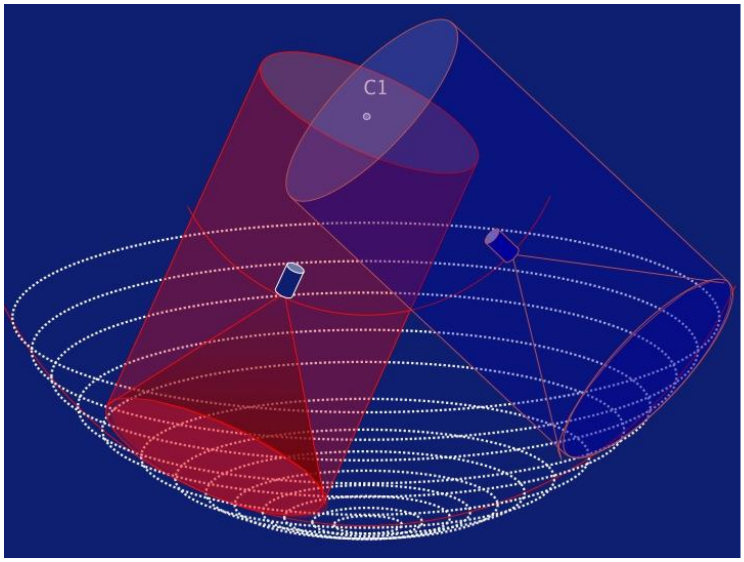

Figure 1: schematic representation of the general hypertelescope concept

A focal camera, with auxiliary optics including a pupil-densifier, a multi-field separator, cophasing actuators with a wave sensor, and a spectro-imager, is suspended above the M_1 meta-mirror for capturing the focal image of the observed star. It is movable, in an accurately controlled way, for tracking the diurnal motion of the stellar image. This is currently performed with a computer-driven system of six oblique cables, plus a passive carrier cable, but may later utilize a laser-stabilized drone, possibly assisted by a small lenticular balloon for reducing the propeller-induced turbulence. A prototype drone is built by F. Taillandier in our group for developing accurate stabilization techniques.

As the observed star follows its celestial path, the focal optical train is kept aligned with it while tracking the moving focal image, thus being rotated about the center C_1 of the meta-sphere M_1 and its polar axis, along its half-size and concentric focal sphere (fig.1) . One component of the focal optics, its dome-shaped pupil densifier (fig. 2), is prevented from rotating, being swiveled about its center and kept at a fixed attitude relative to the fixed M_1 for accommodating the pupil's drift. As discussed in Section 3.3.1, this is indeed a specific requirement with respect to conventional telescopes, arising from the varying direction of the star relative to the primary array. Another requirement is the need for a focal optical package which is compact for suspension from a long cable traversing the valley, or being carried by a flying gondola.

The detailed optical concept, with design variants, has been modeled by some of us (AR, PR, TL, TH) with ray-tracing and interference calculations of the direct image in Zemax (Houllier et al., in preparation).

3.3.1 Pupil drift accommodation for Carlina architectures

With terrestrial Carlina architectures, the absence of a giant steerable mount for globally pointing the hypertelescope as a solid system causes an apparent drift of the sub-pupils pattern with respect to the meta-pupil observed by an eye located at the focal image of a moving star. The size limitation for such mounts is currently limiting the optical diameter of ELT's to about 40m, instead of the kilometric size considered for terrestrial hypertelescopes (Labeyrie et al., 2012). In space, no mount will be needed for supporting or steering a flotilla of mirrors together with its focal spaceships, using thrusters such as ion jets, small solar sails, or "laser trapping" beams. Meta-apertures as large as 100,000km may then become feasible.

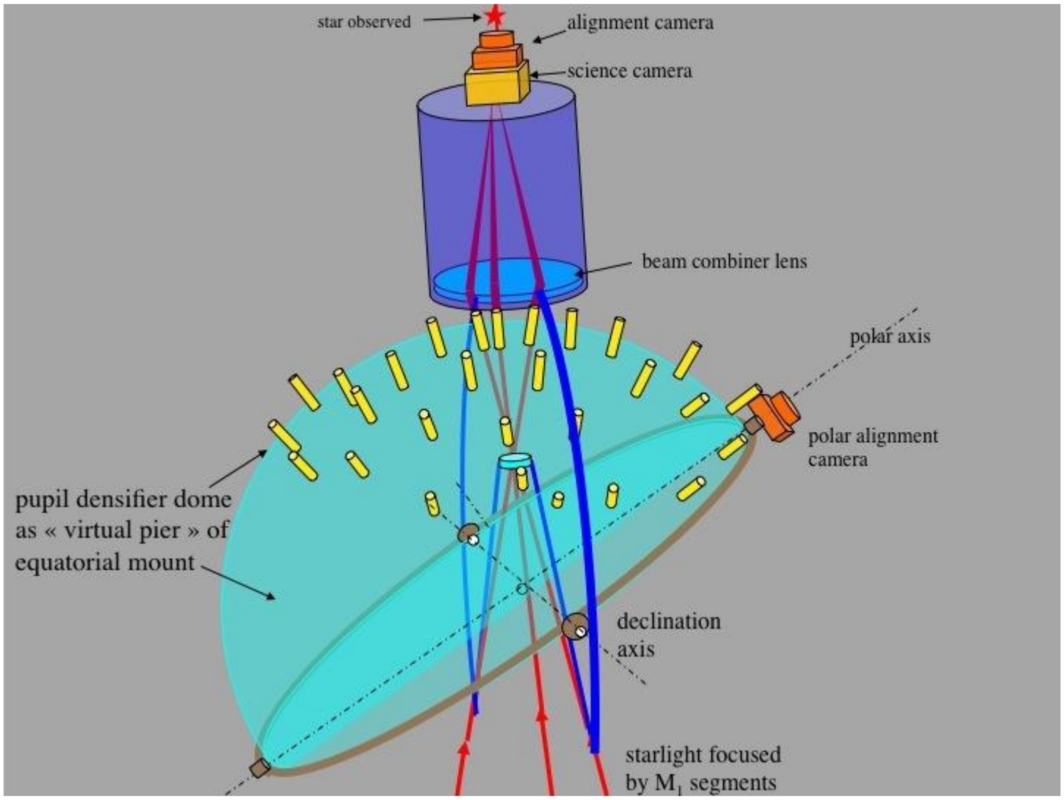

Figure 2: Dome-shaped pupil densifier for pupil drift accommodation. It is kept fixed in attitude, while tracking the star's image, and carries a small fork-type equatorial drive which keeps the focal field lens and downstream optics aligned together and with the star's celestial direction. The dome behaves as the virtual pier of the equatorial drive. The polar alignment camera provides error signals for maintaining its polar alignment and driving the hour angle.

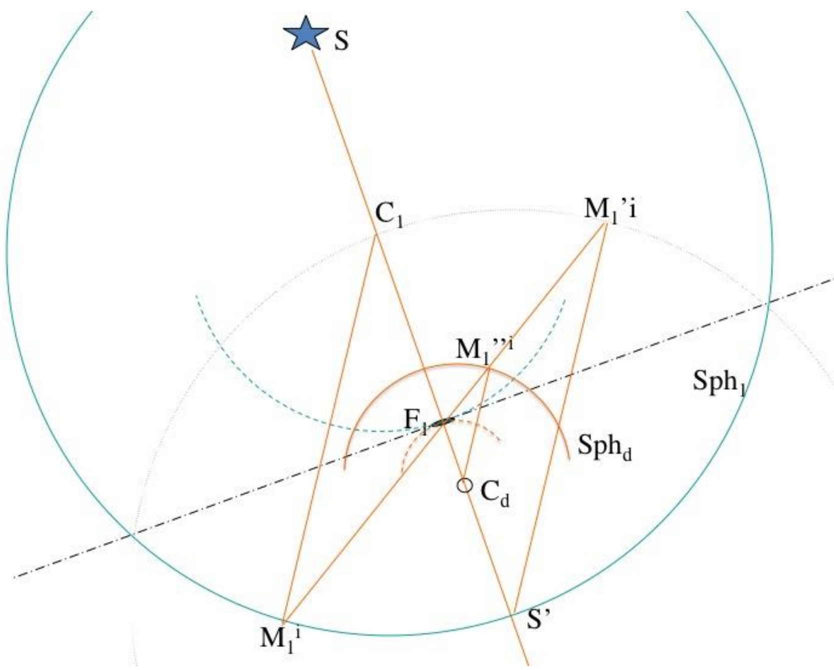

Figure 3: Accommodation of pupil drift relative to a static and spherical primary meta-mirror. A dome-shaped pupil densifier carries a homothetic projection of all primary segments such as M_1^i. The dome center C_d is kept aligned with C_1 and the star observed, while its attitude is kept invariant with respect to the fixed M_1. The projection center, located halfway between the dome and its center C_d, is at the primary image F_1 of the star, where a field lens achieves the pupil projection onto the dome. Pupil densifier elements are attached to the dome at the projected points $M_1^{''i}$ corresponding to each M_1^i mirror segment. This projection remains invariant while the dome undergoes a curvilinear translation for tracking the star's focused image, thus accommodating the pupil drift by maintaining each pupil densifier element centered on its assigned sub-pupil. While a star is tracked, sub-pupils leave the active zone on the West side, and others reach it on the East side.

In these various cases where focal optics is moving, with respect to the primary mirror elements M_1, for tracking the source observed, the Fizeau focus F_1 is at the tip of a "ray acceptance meta-cone», converging from part of the M_1 array. It defines the effective primary focal ratio, currently F/1.75 with the Mertz corrector, and the contributing zone of the meta-mirror, i.e. the meta-aperture, which is actually exploited for the star observed. This meta-aperture is typically smaller than the full array of mirrors, as needed for a broad sky coverage (fig. 1). And it drifts, relative to the array of sub-apertures, while the gondola tracks the focal image of the observed star. This relative drift thus causes some M_1 mirrors to become blinded on the West side while others become contributing on the East side. A corresponding drift arises in the pupil image projected by the focal field lens L_1 onto the pupil densifier. It can be accommodated by transversely moving the densifier elements with respect to the focal optical train. Such translation was arranged in the early prototype tested at Haute-Provence (Le Coroller et al., 2015) but the geometric solution was not exact and residual distortions occurred. Now, an exact geometric solution has been found by one of us (AL).

As shown in fig. 2 and 3, it uses a dome-shaped pupil densifier, maintained at a fixed attitude with respect to the fixed M_1 meta-mirror, while the remaining focal optical train rotates to maintain its alignment with the star's celestial position. Triangles $F_1 C_1 M_1$ and $F_1 C_d M_1'$ are homothetic, in the ratio R_1/R_d of the meta-mirror's and the dome's radii R_1 and R_d , since their angles F1 are equal , and two of their sides have the same length ratio: $F_1 C_1 / F_1 C_d = C_1 M_1^i / C_d M_1^{''i} = R_1 / R_d$.

Their sides $C_1 M_1^i$ and Cd $M_1^{''i}$ are therefore parallel, with equal zenith angles. This ensures a homothetic projection of all mirror segments through F1 onto the dome, and its fixity on it when the star moves while the dome maintains its attitude. Figure 2 sketches a mechanical linkage, including a small equatorial drive, which meets the geometry conditions.

4. ALIGNMENT TOOLS AND TECHNIQUES

4.1 Cospherization or co-aspherization of the primary meta-mirror

With rigid supporting structures anchored in stable bedrock, hundreds of mirrors can be expected to remain stable during months, at accuracy levels of the order of arc-seconds for tip-tilt and tens of microns for piston. The coarse shaping achieved with such tolerance suffices if a finer and active stage of adjustment is at work in the focal gondola, together with an adaptive stage for cophasing the wavefront segments.

4.1.1 Reference beacon at M1's curvature center

Methods related to those traditionally used for mapping the bumpiness of large concave mirrors, were used in the initial hypertelescope prototype at Haute-Provence, where C_1 could be accessed by a gondola suspended from the same tethered balloon which carried the focal package half-way down. Forms of Optical Coherence Tomography will likely also become applicable, possibly with optics flown at C_1 by a drone.

4.1.2 Measurements from ground toward a star and focal gondola.

If C_1 is not easily accessible, the following types of alignment devices can map M_1's piston and tip-tilt errors:

1- A commercial theodolite for coarsely positioning the mirror elements;

2- A modified sextant scope for coarse piston sensing among the primary mirror segments
3- A cat's eye scope for sensing tip-tilt errors among the mirrors, also serving for autoguiding the gondola.

2- and 3- can be equipped for real-time sensing, later needed for active feedback . And the tip-tilt sensor can also serve for auto-guiding the focal gondola.

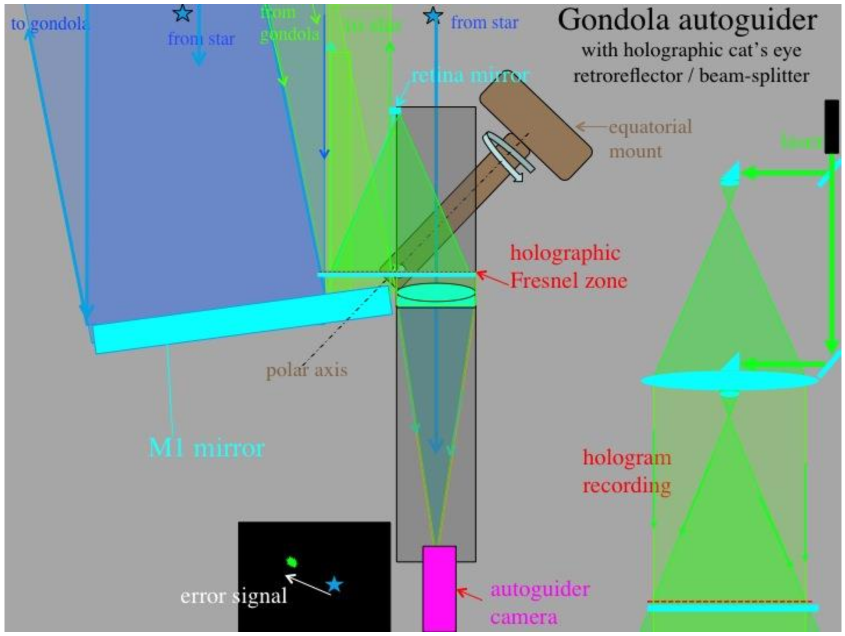

Figure 4: Sensor of tip-tilt error, or gondola position error, attached to one segment of the primary mirror M1. Light from the observed star and from a green laser beacon aboard the gondola provides a pair of spots in the scope's eyepiece or camera. Their spacing vector indicates the tip-tilt error. Since the star's light is expected to be focused by the mirror segment at the gondola's field aperture, the reversely propagating laser light must be collimated by the mirror toward the star. The retro-reflective cat's eye arrangement, using a holographic Fresnel zone as its large focusing element, reverses the propagation of the emerging laser light, toward the same autoguider camera which receives star light, transmitted through the hologram in its 0^{th} diffracted order.

The tip-tilt sensor sketched in fig. 4 is a more compact and holographic version of those previously described, which used a corner cube-reflector or a two-mirror cat's eye. Like these, it is oriented toward the West-moving star by a small equatorial mount. For measuring the gondola's distance, a laser telemeter tracks its East-ward motion. It is attached to a second small equatorial scope (not shown) having a virtual polar axis symmetrized by reflection through M_1.

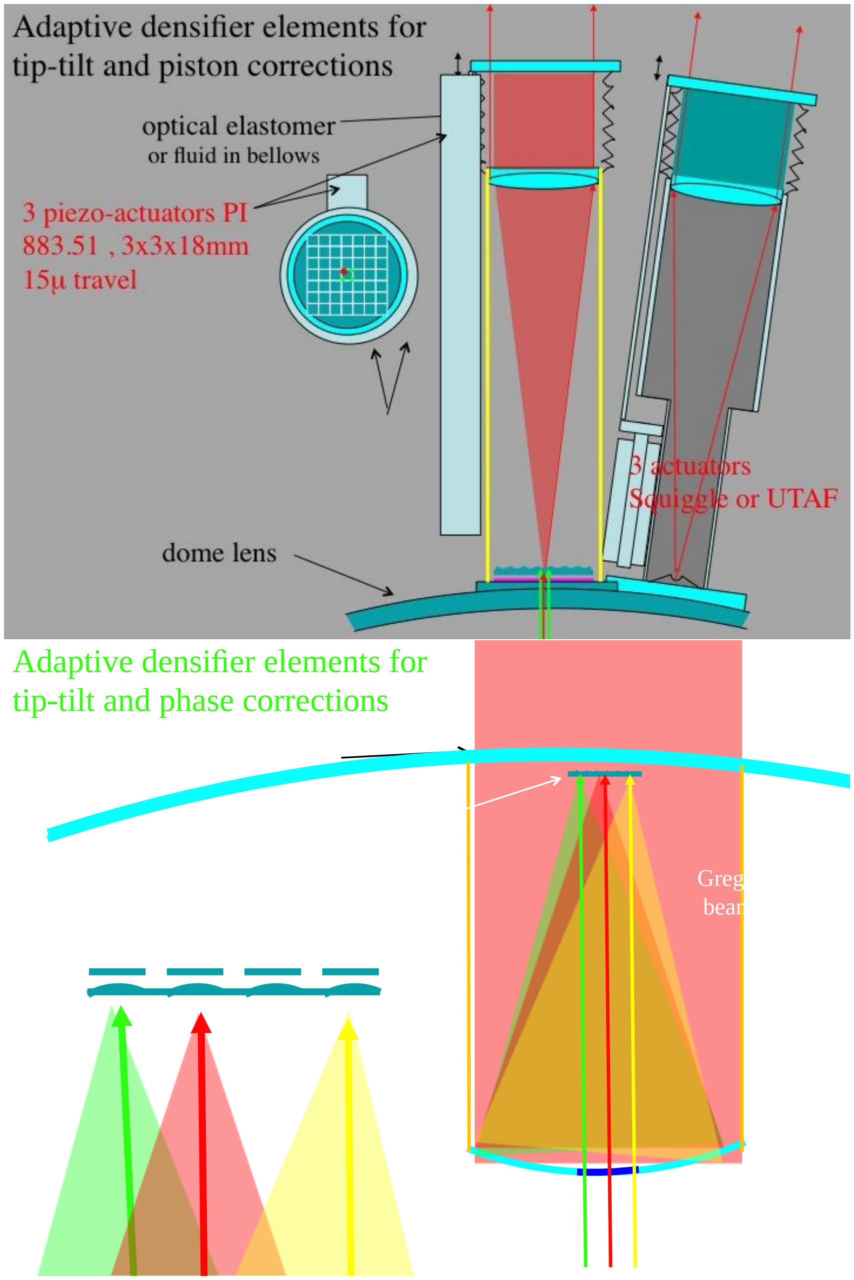

Fig 5: Cophasing actuators considered: A- liquid or elastomer actuators, transmissive, can be attached to each L_4 lens of the Galilean beam expanders in the pupil densifier. A triplet of actuators allows corrections of piston, tip and tilt: B- alternately, micro-mirrors, electrostatically actuated, can be inserted inside Gregorian beam expanders serving as pupil densifier elements. For applying differential corrections of tip-tilt and phase to each of the multiple sub-fields, as may be needed in conditions of poor isoplanetism, the L_3 micro-lens arrays can instead be made adaptive. Atmospheric phase cells are here assumed larger than the primary sub-apertures, but intra-subpupil turbulence can also be corrected with additional actuators and suitable wave sensing.

4.2 Positioning and guiding the focal optics

In addition to these ground scopes, a field acquisition and guiding camera is being installed in the focal gondola, at the field aperture of its optical train. Its 30arc-second guiding field is expected to provide the primary error signal for controlling the gondola's tracking.

4.3 Adaptive tip-tilt and cophasing

It is highly desirable to install adaptive cophasing, although initial observations can be made without it, using image reconstruction techniques such as Speckle Imaging. On monolithic telescopes, its limiting magnitude has been higher than that of adaptive optics, in the absence of a Laser Guide Star. And its applicability to hypertelescopes has been verified by (Surya et al. 2014).

The wave sensor needed for adaptive cophasing has to be modified with respect to the Shack-Hartmann sensors usually serving on monolithic telescopes, since they map the wave's phase by integrating the local slope errors which they measure across the bumpy but continuous wavefront. It is unsuitable with the discrete wavefront segments in the hypertelescope. Instead, the hierarchical sensor (Pedretti et al., 1999), the dispersed-speckle sensor (Borkowski et al., 2005; Labeyrie et al., 2002; Martinache 2004) and the Chromatic Phase Diversity sensor (Mourard et al., 2014) , were developed for hypertelescopes.

If the isoplanatic patch, also called "isopistonic angle", of the atmosphere, determined by the minimal altitude of its turbulent layers above the instrument, is larger than the field covered by the multi-field arrangement, then all field channels can be corrected together by a single set of tip-tilt-piston actuators.

4.4 Modified Laser Guide Star for cophasing faint sources

Pending hypertelescopes in space, where the reference star for wave sensing can be degrees away from that observed, terrestrial versions would much benefit from using an artificial reference star for adaptive cophased observing on faint sources, a mode which interferometers have not yet been able to attempt. The modified "Hypertelescope Laser Guide Star" (H-LGS) version (Nunez et al., 2014) of the Laser Guide Star (LGS) systems (Foy and Labeyrie, 1985) which became used at the largest telescopes is a candidate approach which requires further assessment, particularly regarding the laser power needed.

5. DEVELOPING AND TESTING A FULL-SCALE CARLINA PROTOTYPE

5.1 Description

To verify the level of tracking accuracy achievable in real conditions with a suspended focal gondola, the team has installed and tested since 2011 some elements of a "Ubaye Hypertelescope" prototype in a high valley of the southern Alps. Selected for its smooth curvature and East-West orientation, its topography favors near-meridian observing with a meta-aperture diameter potentially reaching 200m, and a larger meta-mirror size for annual coverage of the Northern celestial hemisphere. Unlike the massive suspended focal structure of the Arecibo radio-telescope, with its alt-azimuthal support for the large focal corrector and receiver, it has a much smaller focal package, with mass in the 10kg range rather than hundreds of tons.

A single suspension cable, 800m long across the Moutière valley, carries the focal gondola 101m above its floor. The cable, oriented North-South, can pendulate East-West to allow during an hour the diurnal tracking of a star by the gondola, which can also roll along it for declination adjustments. This is driven with millimeter accuracy by six thin cables, $1mm^2$ in section and made of high-modulus aramid fiber, attached to the gondola and actuated by small winches under computer control (Enmark, et al., 2011). Their coordinated action drives the gondola's all six degrees of freedom for adjusting its position and attitude. Servo-feedback is being installed for automated tracking and focusing.

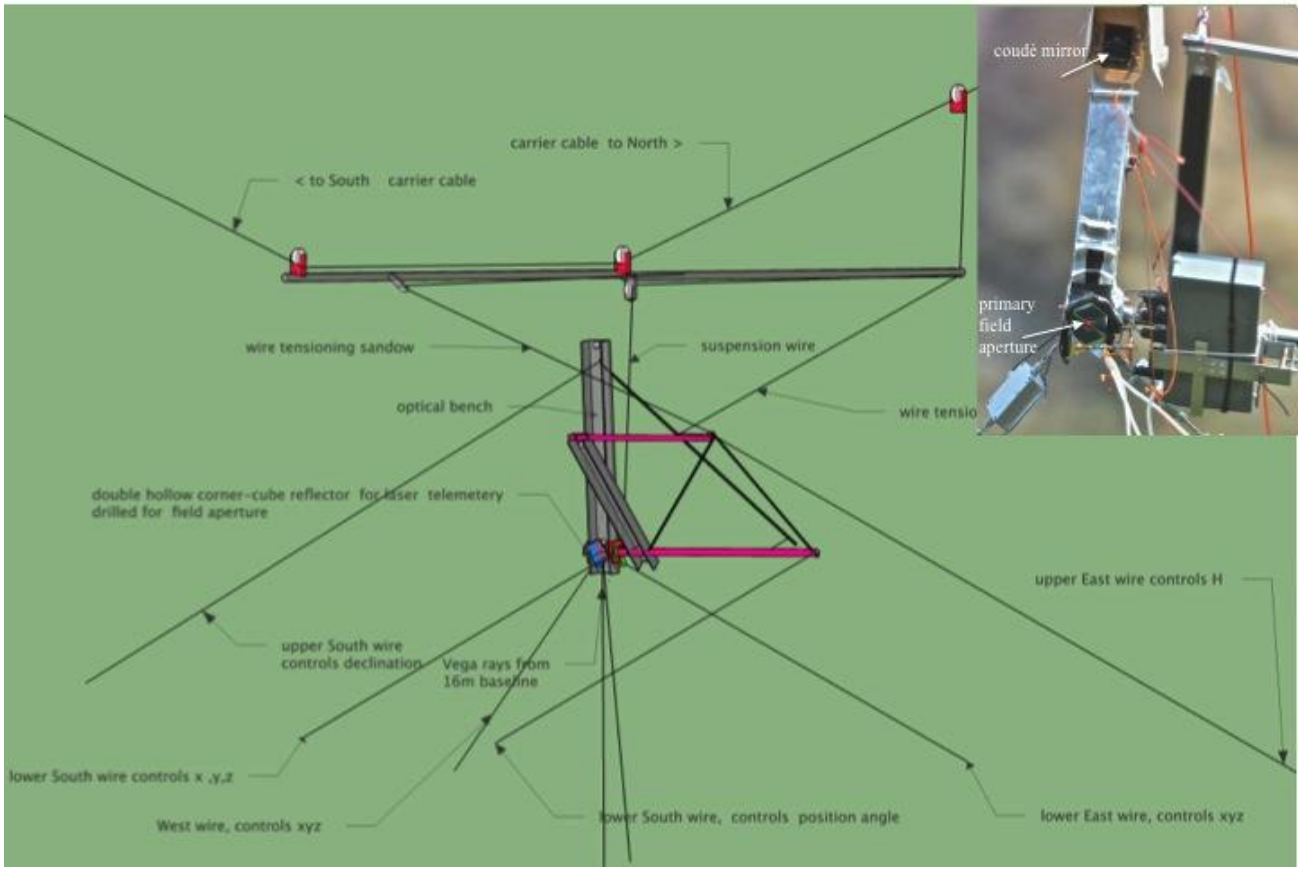

Figure 6: Simplified focal gondola used for testing the guiding stability and tracking with the initial pair of M1 mirrors. The suspension cable and six active oblique wires which control the position and attitude of the focal optics are represented. Right: view through the coudé collecting telescope, positioned 186m to the South at the polar projection of C_1 where the three South winches are also located, showing the red beacon LED at the entrance of the focal optics.

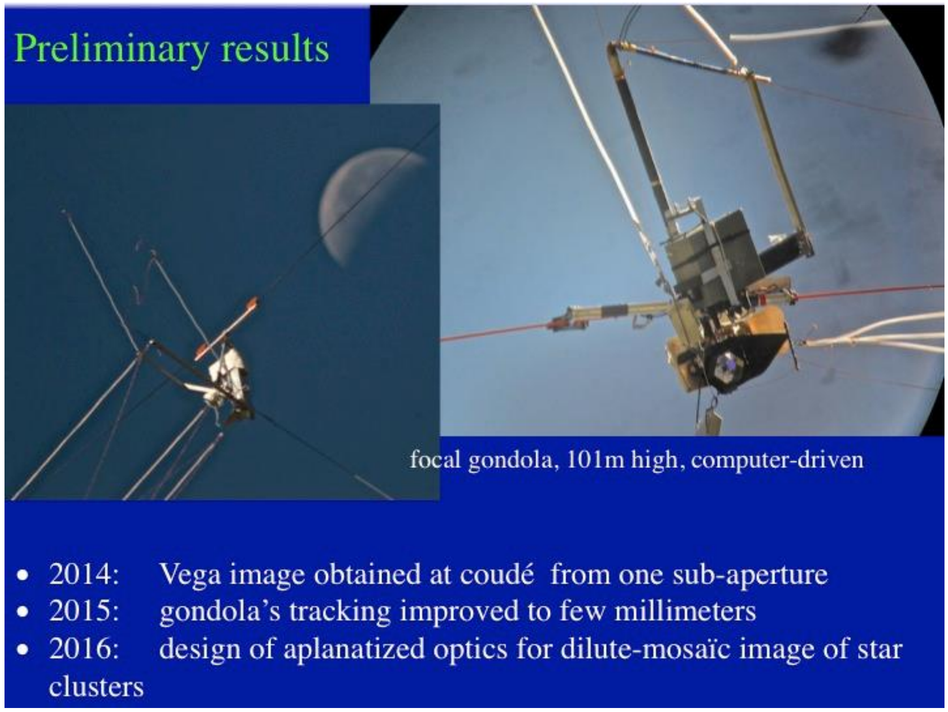

Figure 7 : Views of the gondola from below and testing steps achieved

5.2 Testing results

Four summers of construction and testing in the Moutière valley, at 2100-2300m altitude, with a North-South pair of M_1 mirrors spaced 15.8m apart, pending hundreds, and a simplified version of the gondola optics for initial testing with two-aperture fringes, have demonstrated the validity of the scheme. Software developed by DM and RP successfully achieved gondola tracking with the specified millimetric accuracy. Pending full autoguiding, yet to be implemented as cameras are becoming installed on the gondola, occasional fine corrections for the programmed coarse tracking motion had to be typed on the computer's keyboard. The focal gondola, then not yet equipped with cameras for alignment control and science, instead carried a small flat mirror, driven biaxially for a coudé feed of the focused starlight toward a 20cm collecting telescope at ground level . Its location, at the polar projection of C_1, the curvature center of M_1, allowed the telescope's equatorial drive to track the gondola's star-like apparent motion.

The video[1], recorded through the telescope, shows the gondola's tracking behavior (see Fig. 7). Its operation was further demonstrated as Vega's coudé image could be observed in the eyepiece, although not yet with autoguiding. In addition to the autoguider camera being installed at the gondola's entrance port, a redundant error signal is provided by a small "star and gondola" equatorial scope at ground level (fig.4), using additional code developed by PN. It also serves for the tip-tilt adjustments of the M_1 mirrors. A second equatorial scope, mechanically coupled but inverted for tracking the gondola's apparent motion as reflected from the M_1 mirror, directs a laser telemeter beam for measuring its distance with millimetric accuracy.

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Vidéo suivi de la nacelle depuis le télescope C8

5.3 Flat hypertelescope testbed at Calern Observatory

A "flat" and static testbed has also been installed in 2016 at Observatoire de Calern, where previous generations of interferometers had been built since the 1980's, for preparing the observations at Moutière. It has an artificial star, consisting of a cat's eye reflector, located 1.2km away toward the local summit, vertically flipped supports for the "real" M_1 mirrors aiming the artificial star, installed along the track of the historic I2T interferometer, on carriages for adjustable spacing mobile, and a focal station 108m away, where the artificial star image is co-focused onto the tested gondola, suspended against the GI2T laboratory's building , with its six winches for realistic control testing and software development.

Close to the focal gondola, a laser beam launching assembly has a bi-prism for illuminating both M_1 mirrors which focus its light onto the cat's eye reflector, and a beam-splitter which separates the returning light and feeds it to the focal gondola under test, suspended from a short cable and driven by its six computer-controlled winches. The system has quickly produced laser fringes and serves for developing improved optics, electronics, software code, etc ... and also for training observers toward the real observing at Moutière. Other simplified testbeds, fitting in the laboratory, are also used for testing some parts of the system, such as the holographic aligner.

CONCLUSIONS AND FUTURE WORK

As the peculiar imaging properties of hypertelescopes became understood, and their potential relevance for astronomy realized, we worked out detailed optical designs for several concepts. They encouraged the partial construction and testing of a full-size prototype, expandable for initiating a science program. It demonstrated the feasibility of a compact focal gondola for tracking and recording the focal image of a star.
Following steps now considered include: 1- Further refining the optical modelling and comparing different designs, 2- testing a drone platform carrying the focal optics, and possibly several for observing different sources in parallel. 3- "Early science" observing in a Speckle Imaging mode; 4- adaptive cophasing for direct imaging; 5- the testing of a modified Laser Guide Star system for extending the direct imaging to faint sources.
The "early science" observing should help deciding whether a full science program can usefully be initiated at the Moutière site, while progressively upgrading the instrument toward hundreds of sub-apertures. Or if it should be moved to a different site, among the candidate ones found in Chili and the Himalaya. Indeed, the growth capability of Carlina hypertelescopes, from a modest testbed to a rich aperture with powerful imaging performance, also allows moving it to different sites. More of them may become interesting candidates if and when stabilized focal drones become developed for flexible observing, possibly in parallel on different sources.

We also consider some preliminary testing at the E-ELT site, using a few small mirror elements and a focal drone, to assess the operability of a coupled E-ELT and hypertelescope (Labeyrie, 2004).

In space, the proposals for hypertelescope versions (Labeyrie et al., 2013), potentially using a laser-trapped flotilla of tiny mirrors, may greatly influence the evolution toward " better, faster, cheaper " optical arrays spanning 100 to perhaps 100,000 kilometers.

AKNOWLEDGMENTS:

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