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Progress of the Ubaye hypertelescope project

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Abstract In this paper we present the principle of the prototype hypertelescope build in the valley of Ubaye in the Southern Alps. We detail the most representative results obtained during the last campaign of tests in August and September 2017. We conclude the paper by summarizing some of the other activities that we are developing toward the future implementation of an ambitious astronomical hypertelescope.

Keywords high angular resolution · hypertelescope

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1 Introduction

The discovery potential of classical telescopes is mostly influenced by their optical diameter D, determining their ultimate angular resolution λ/D, and their collecting area, determining their light collection capability. These improve as D and D^2 respectively in conventional monolithic telescopes. These quantities are not independent unless the optical aperture is dilutely segmented as an array of N many smaller mirrors, the size d of which can be small compared to their spacing s. A very much higher resolution is then obtainable, without affecting the light collecting area D^2, by spreading apart the small mirrors for a meta-aperture much larger than D, with a collecting area Nd^2 comparable to or exceeding D^2.

Such systems are interferometers. They can grow for improved resolution by spreading apart the small mirrors, and for luminosity either by enlarging them or increasing their number. The second method is preferable, as discussed in Labeyrie 1996 [3], since it also improves the dynamic range of the images due to the better sampling of the optical wavefront.

The system becomes a hypertelescope, defined as a direct-imaging multi-element interferometer using a densified pupil, if a pupil densifier is added near the eyepiece or the focal camera. This is a small element which is an array of miniature Galilean beam-expanders, inverted for magnifying each sub-pupil within the meta-pupil. As described in Labeyrie (1996) [3], Lardiére et al. 2007 [7], and Patru et al. 2007 [11], it intensifies the image as γ^2, where γ is the subpupil magnification achieved by each beam-expander. Most light collected from a point source can then be concentrated into the interference peak, thus improving the overall light efficiency. This blaze effect occurs at the expanse of sky coverage: the celestial field directly imaged at full resolution is then limited to a "Direct Imaging Field" (DIF) spanning $\lambda/(\gamma-1)d$ ideally reaching the "Clean Field" (CF) spanning λ/s when $s=(\gamma-1)d$, which corresponds to full densification, when the magnified sub-pupils become adjacent. It should be noted that this notion of "Clean Field" is not related to the hypertelescope principle, it is a general property of interferometers due to the sampling of the wavefront by the entrance pupil. The "Clean Field" matches the "dark zone" observable in the image of a point source, inside a wider and more intense annulus, containing speckles if the multi-aperture pattern is random or periodic peaks if it is periodic. However, separate imaging channels, spaced λ/d apart on the sky, and each covering the much smaller CF size, can be arranged for observing multiple sources such as a globular cluster, a remote galaxy, etc...

Most of the modern questions of Astrophysics can benefit or even directly depend from an improved spatial resolution. This is particularly true in one of the ASTRONET priority "What is the origin and evolution of stars and planets?". This theme is usually structured around six main questions: How do stars form? Do we understand stellar structure and evolution? What is the life-cycle of the Interstellar Medium and Stars? How do planetary systems form and evolve? What is the diversity of planetary systems in the Galaxy? Is there evidence for Life on exoplanets? The recent results obtained on the VLTI [2] or on the CHARA Array [12] demonstrate the importance of optical long baseline interferometry and the unique constraints this technique can bring on all these questions.

To achieve these science goals, the future construction of an ambitious hypertelescope is considered. We also intend to bring an answer to the current situation of optical interferometry. The conceptual solutions that have been used for the last four decades are indeed probably not correctly adapted to an array of hundreds of apertures. The complexity of the Coudé trains, the multiplication of mirrors, and delay lines will probably prevent the construction of an equivalent of ALMA in the optical domain. However, the construction of an hypertelescope will have to face other challenges. We can summarize them as: 1/ identification of a correctly adapted site on ground or decision for space deployment, 2/ management of the motion of the focal optics and of the field of view, and 3/ cophasing for enhanced performance in precision and sensitivity. In this paper we present in Sec. 2 the prototype hypertelescope that we have started to build in the Southern Alps and we discuss the recent progress and the future activities in Sec. 3. In Sec. 4 we briefly describe other important activities that are engaged for preparing the solutions to the main questions presented above.

2 Presentation of the Ubaye hypertelescope project

The optimal pattern of sub-aperture arrangements for hypertelescopes depends on the type of source observed. The VLTI[2], the CHARA[12] and other telescope arrays having a beam-combiner for interferometry can be equipped with a pupil densifier for operating in the hypertelescope mode, as proposed for the Very Large Telescope [6]. The optical delay lines, generally needed by such arrays for compensating the effect of Earth rotation in the absence of a global steerable mount, implies a high cost when 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 (also called Carlina), since they require no delay lines. They can therefore use hundreds of sub-apertures, thus allowing a far better imaging performance. The size limitation for steerable mounts is currently limiting the optical diameter of ELT's to about 40m, instead of the kilometric size considered for terrestrial hypertelescopes [5]. 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 metapupil seen from the focal receiver. This effect is not critical since the sub-pupil drift can be accommodated in the focal optics, and it causes a form of aperture supersynthesis during long exposures which can improve the imaging performance.

To verify the level of tracking accuracy achievable in actual conditions with a suspended focal gondola, the team has installed and tested since 2011

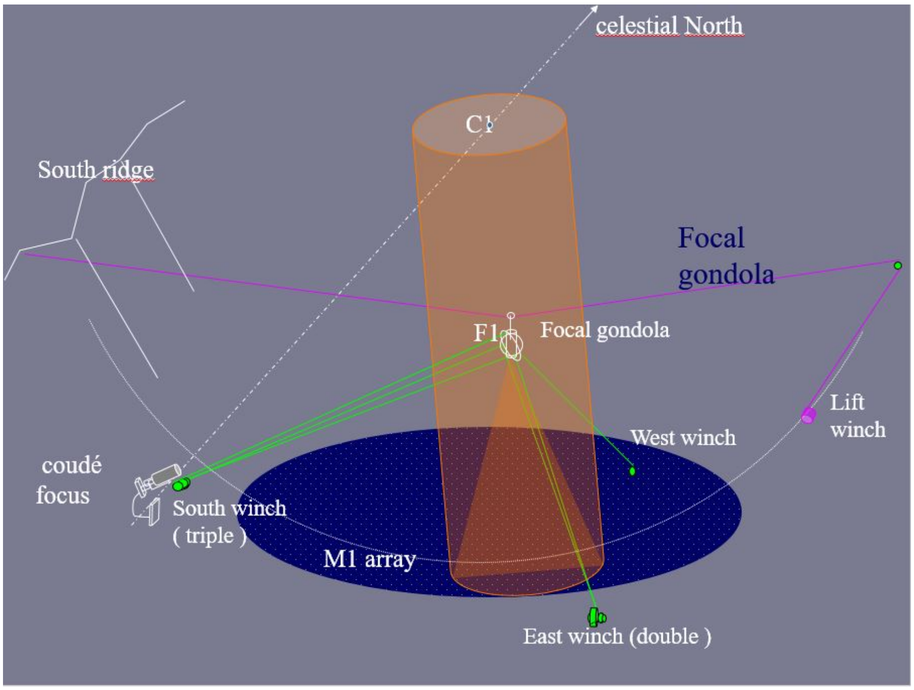

Fig. 1 Schematic representation of the driving system of the Ubaye hypertelescope prototype.

some elements of the "Ubaye Hypertelescope" prototype in a high valley of the southern Alps [4], after the initial encouraging results of Le Coroller et al. 2015 [8]. 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 metamirror 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 20kg range rather than hundreds of tons. A single suspension cable, 800m long across the Moutière valley, carries the focal gondola 101m above its floor (see Fig. 1). 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 [1]. Their coordinated action drives the gondola's all six degrees of freedom for adjusting its position and attitude. Servo-feedback is installed for automated tracking and focusing.

3 Recent progress and future activities

Four summers of construction and testing in the Moutière valley, at 2100-2300m altitude, with a North-South pair of 20 cm M1 mirrors spaced 15.8 m apart, and a simplified version of the gondola optics for initial testing with two-aperture fringes, have demonstrated the validity of the scheme. The focal gondola is equipped with two cameras. The first one permits to obtain an image of the two stars and the two pupils for the alignment and tracking control. The second one is used for the science purpose and is fed by a low dispersion grism also equipped with an anamorphotic optics for the correct adaptation of the spatial and spectral sampling. The optical scheme of the science beam is presented in Fig. 2.

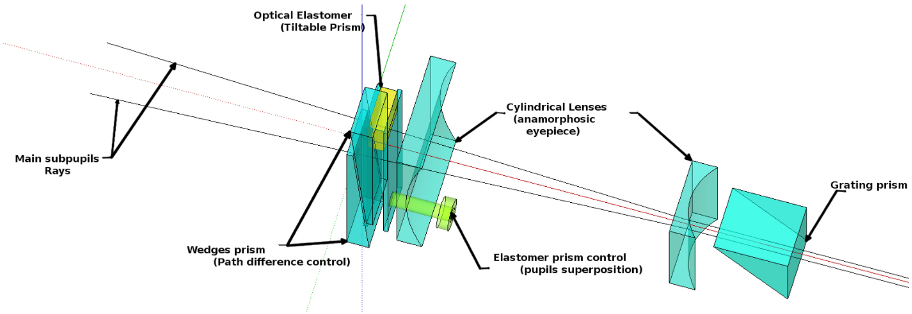

Fig. 2 Optical principle of the science beam in the 2-mirror special configuration. One of the beam goes through a tiltable prism allowing a fine tuning of the superposition of the two images. The optical path difference could be adjusted by translatable wedge prisms. An anamorphotic optic and a grism constitute the main optics of the dispersion system adapted to the correct sampling of dispersed fringes.

An electronic box controls the various systems installed on the gondola: wireless Internet and radio connection, laser diode, readout of the tension of the wires, control of the cameras, and radio transmission of their images. In the 2017-version of the optics, we also used additional motorized optics permitting to finely tune the superposition of the two images with a tiltable plate and to change the optical path difference between the two upcoming beams with a pair of counter-moving optical wedges (see Fig. 2). These systems were finally not used because of the redundancy with the possible tip/tilt and piston on the primary segments themselves. The required power is distributed by LiPo batteries that can go up and down from the ground thanks to a manual elevator and three electric contacts.

The automatic control software successfully achieved the gondola tracking with the specified millimetric accuracy required to stabilize the direct interferometric image on the sensitive area of the detector. In 2017 we have been able to achieve this performance for more than 40 minutes after the initial alignment. In the current configuration of the installation, the tracking is limited to ± 30 mn around the meridian transit by the balance of tensions on the driving wires. Real-time control of these tensions is performed and the readout of the values is remotely possible. The images of the cameras are remotely transmitted to the ground station to allow a real-time control of the images. Preliminary tests of a full autoguiding, with the cameras installed on the gondola have been performed but, for the moment, occasional fine corrections have to be typed on the computer's keyboard. They permit to correct the East-West, North-South positions of the gondola as well as its height above the array. They also control the triaxial orientation of the focal optics.

Although we were successful in 2015 in obtaining an image of the star Vega on the gondola, this step was not achieved in 2017 because of a shorter campaign and also of difficulties related to the first tests on sky of the new viewer system presented in Fig. 3.

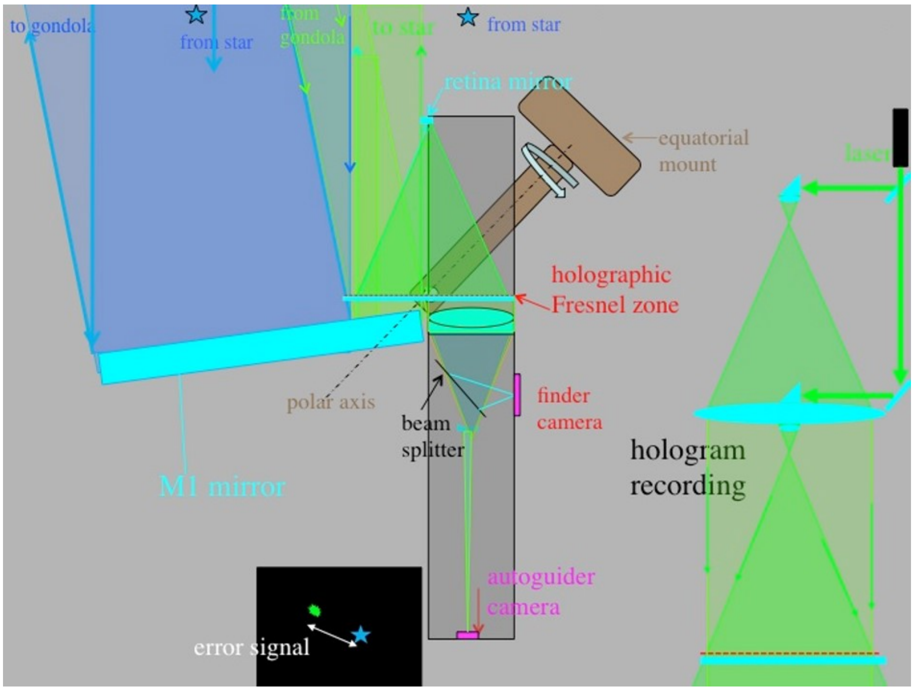

Fig. 3 Schematic drawing of the holographic viewer used at the Ubaye hypertelescope prototype. See text for detailed explanations.

The guider's camera or eyepiece sees the star image (in blue) through the hologram, with zero-order diffraction, and also the first-order diffracted image (in green) of a point source, in the form of a laser diode beacon located at the focal gondola's entrance. Its downgoing diverging light is collimated by the M1 mirror toward the star, when the mirror is correctly oriented. Part of the upgoing collimated laser light is focused by diffraction through the hologram onto the small "cat's retina" mirror, which reflects it back through the hologram, where it becomes re-collimated by first-order diffraction and co-propagating with the star's light, thanks to the specific properties of the hologram plate. The vector spacing of both spots on the camera is the error signal to be corrected for maintaining the star's image at the gondola's entrance. The correction is achievable either by tip-tilting the M1 mirror or by moving the gondola. If the M1 co-spherization has been previously adjusted, for example with similar guiders attached to each M1 mirror, the latter method is obviously preferable for preserving the co-spherization, and it is usable for auto-guiding the gondola. The hologram, patterned as a Fresnel zone, is fabricated with the recording arrangement shown at right, using the same laser, and which ensures zero spherical aberration. Together with the retina mirror, it is supposed to behave as a compact cat's eye reflector. This is in this last property that we have had difficulties during our last campaign. We have indeed identified an error of a few millimeters in the focus of the retina mirror, while the required precision should be of the order of $100\mu m$. That has generated an unknown difference between the correct superposition in the eyepiece and the actual superposition at the entrance of the gondola. This will be corrected in the future thanks to more in-depth testing in laboratory.

4 Other complementary studies toward the development of an ambitious hypertelescope

In parallel to the activities presented above, our team is also progressing on the study of the different aspects, critical for the implementation of an ambitious hypertelescope. The first one is related to the main science cases that a hypertelescope could address and is thus related to the field of view limitation. As a sub-product of this study, we also consider the possibility, as it is done on the FAST radio telescope [9], to go from a spherical shape to a deformable parabolic shape for the primary diluted mirror. And finally we shortly present the studies made to adapt the principle of a laser guide star for hypertelescope in order to reach much fainter magnitude in the future.

4.1 Overcoming the field of view limitation

The spherical shape of the primary diluted mirror in the Carlina/Ubaye design requires a corrector of spherical aberration, currently implemented in the form of a Mertz corrector. But the primary meta-mirror can be adaptively parabolized, like the FAST radio telescope [9], for an aberration-free image in the axis. Clustered compact sources can however be simultaneously imaged at high resolution by arranging an array of imaging channels, dissected by a matching array of field-lenses. The field aberrations appearing within the off-axis channels, mostly coma, are correctable separately in each of them, as discussed by Xie et al. (in preparation). The strategy is to sample the wide field into small individual fields of view by using a microlens array. Each small field can create a valid direct imaging field if equipped by independent phasing actuators properly controlled. The troublesome coma in the off-axis sub-fields caused by the primary mirror could indeed be considered in each small subfield as tilt and piston. Thanks to a Zemax simulation we demonstrate that it is possible to correct this by cophasing actuators and we show that a multi-field hypertelescope is feasible and can cover a dilute field of view spanning at least ± 10 seconds of arc on the sky.

4.2 Active primary segments for a deformable parabolic primary diluted mirror

As seen before, a large fraction of the aberration generated by the fixed spherical mirror could easily be reduced if one considers an adaptive parabolization. With the Ubaye configuration, a simple solution is to motorize each primary segment with three sub-micrometers actuators to allow slow tip/tilt and piston correction to position the segment on the instantaneous parabola. With 20 cm segments for a 200 m diameter of the meta-mirror, it can be shown that the required deformation of the small spherical segment is totally negligible. The difference between the sphere and the parabola could easily be established as $\Delta(x) = \frac{x^4}{8R^3}$, with R the radius of curvature and x the off-axis position of the considered segment. For a meta-mirror with a radius of curvature $R = 200\ m$, a variation of pointing of $\pm 15^{\circ}$ generates a difference of piston of $\pm 100\ mm$.

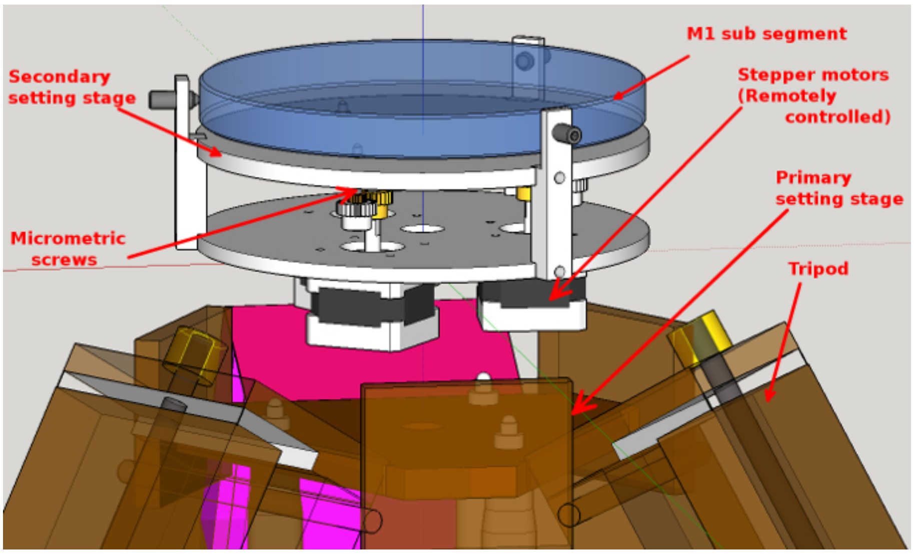

Fig. 4 Mechanical design of the new motorized tripod for realizing an active M1 meta mirror with segments adjustable in tip/tilt and piston.

As presented in Fig. 4, we have started the design and integration of motorized actuators on the main tripods and expect to test them in the coming months.

4.3 Laser guide star for hypertelescope

Nunez et al. [10] have investigated the feasibility of using a modified laser-guide-star technique that is suitable for large diluted apertures. The method consists of using subsets of apertures to form fringes in the sodium layer as a possible way to perform wavefront sensing with diluted apertures. This solves the problem of resolving the artificial star since the same subset of apertures is used to form the artificial star/fringes and to perform wavefront sensing by re-imaging the fringes, which contain optical path difference information. The use of several laser guide stars can in principle solve the classical cone effect problem due to the finite distance of the artificial star. Preliminary tests in the laboratory permitted to validate the technique in the case of a single laser guide star, and with signal to noise ratios comparable to those predicted by simulations. Aside from all the engineering feats that must be undertaken, the current main limitation of this technique is that the proposed phase-unwrapping method requires too many photons, and thus very powerful lasers.

5 Conclusion

In this paper we have given an overview of the most recent activities done in our team for the progress of the hypertelescope principle. The feasibility of a fixed diluted primary with a movable focal optics has been investigated. The main limitations of the current interferometers in terms of field of view and sensitivity are also discussed.

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