Concept study of an « Extremely Large Hyper Telescope » (ELHyT) with 1200m sparse aperture for direct imaging at 100 micro-arcsecond resolution

Antoine Labeyrie[a], Denis Mourard[b], Fatme Allouche[a], Rijuparna Charkraborthy[a], Julien Dejonghe[a], Arun Surya[c], Yves Bresson[b], Claude Aime[b], David Mary[b] and Alexis Carlotti[d]

[a] Collège de France, Observatoire de Calern, 06460 Caussols, France
[b] UNS, CNRS, OCA, Laboratoire Lagrange, B.P. 4229 06304 Nice - France.
[c] Indian Institute of Astrophysics, Bangalore - India.
[d] Dept. of Optics, Central Univ./City Branch, 9876 Light Ave., Philadelphia, PA USA 00555-9642

ABSTRACT

The hypertelescope construction initiated in the Southern Alps (Labeyrie et al., this conference) has provided some preliminary operating experience indicating that larger versions, up to perhaps 1200m, are probably feasible at suitable sites. The Arecibo-like architecture of such instruments does not require the large mount and dome which dominate the cost of a 40m ELT. For the same cost, an "Extremely Large Hyper Telescope" (ELHyT) may therefore have a larger collecting area. It may thus in principle reach higher limiting magnitudes, both for seeing-limited and, if equipped with a Laser Guide Star and adaptive phasing, for high-resolution imaging with gain as the size ratio, i.e. about 30 with respect to a 40m ELT. Like the radio arrays of antennas, such instruments can be grown progressively. Also, they can be up-graded with several focal gondolas, independently tracking different sources. Candidate sites have been identified in the Himalaya and the Andes. We describe several design options and compare the science achievable for both instruments, ELTs and ELHyTs. The broad science addressed by an ELHyT covers stellar chromospheres, transiting exo-planets and those requiring a high dynamic range, achieved by array apodization or coronagraphy. With a Laser Guide Star, it extends to faint compact sources beyond the limits of telescopes having a smaller collecting area, supernovae, active galactic nuclei, gamma ray bursts. The sparse content of remote galaxies seen in the Hubble Deep Field appears compatible with the crowding limitations of an ELHyT having 1000 apertures.

Keywords: Hypertelescope, long baseline interferometry

INTRODUCTION

In radio-astronomy, the number of antennas used in interferometric arrays has steadily been increased since the 1950's from a few units to tens and hundreds, pending the thousands now planned for some projects. Optical interferometers, however, have remained at the stage of a few sub-apertures, and this has drastically limited their imaging capability, despite the supersynthesis effect beginning to be exploited. Among the practical reasons for this limitation is the use of optical delay lines, the costly opto-mechanical components which are needed for coherently combining beams captured by separate telescopes at fixed positions. As described in Labeyrie, Lipson & Nisenson[1] and by Labeyrie et al.[2], such delay lines can be avoided by using a different architecture, inspired from the Arecibo radio telescope or its forthcoming larger and modified version FAST[3]. This allows in principle hundreds or thousands of sub-apertures to be used. Such designs for a giant dilute mirror, fixed but feeding a moving focal combiner, lend themselves to much larger sizes for the global aperture. Terrestrial versions will likely be limited to about 1000 or 1200m by the availability of suitably wide and deep craters or valleys, unless more shallow sites are used at different latitudes for declination coverage. We discuss the science outlook for such instruments and describe some design concepts.

Hypertelescopes are dilute optical interferometric arrays of many apertures, where the exit pupil is densified to efficiently provide direct images of complex sources[4,5]. Their theoretical imaging properties are greatly improved, in different aspects, with respect to conventional designs. Some of the direct-imaging properties will also potentially apply to multi-antenna arrays observing at radio and sub-millimeter wavelengths, when efficient multi-pixel detectors will become available. With the current trend towards thousands of antennas, hypertelescope architectures may also become of interest at these longer wavelengths, particularly in space where very large flotillas can be installed.

SCIENCE FROM AN ELT AND ELHYT SIZED FOR EQUAL COST

A coarse metric of science yield for hypertelescopes, vs. the number and size of sub-apertures, is derived for the case of space flotillas in Labeyrie et al. (2009). It does not include the multi-field and multi-gondola options nor the limitations from field aberrations, and would need refinements for reaching a meaningful comparison of the science achievable with an ELT and an ELHyt.

2.1 Stellar physics

Direct images, also providing spectra of each resel, at 80 micro-arcsecond resolution are highly relevant to stellar physics. This should greatly improve the physical modelling and thus our understanding of the mechanisms at work within stars.

2.2 Exoplanets: transits, coronagraphy

The “Direct Imaging Field”, also called “Clean Field” of an ELHyT with sub-aperture spacing of the order of 10m spans 10 milli-arcsecond in yellow light, and may thus cover any planets within the habitable zone of close stars. A coronagraphic attachment, with high-performance adaptive optics, is then needed to extract the very faint exoplanets from the star’s halo of scattered light. At shorter distances, planets and brown dwarf companions located one or several arcseconds from their star are also observable in field channels separated from the one serving for the star.

Those exo-planets which are transiting across their parent star’s resolved face are expected to provide spectacular displays, with enough contrast for viewing the transiting planet without coronagraphy. Among these, refractive arcs similar to that briefly seen at ingress or egress during the rare Sun transits of Venus, are particularly interesting since they provide appreciable information on the planet's atmosphere, especially with spectroscopy[6]. This, using an integral field spectrograph, is of interest for detecting spectral bio-markers such as O_3, O_2, etc..., with more sensitivity than during the star transit, and also than with coronagraphy at other orbital phases.

2.3 Deep field galaxies, cosmology

With a H-LGS Laser Guide Star and adaptive phasing, direct images of deep field sources will be obtainable in principle with the same sensitivity as an ELT at equal collecting area. The improved resolution is expected to increase the signal/noise ratio, and therefore further increase the limiting magnitude on point sources. And spectra will be obtainable for each resel in the images, at various spectral resolutions.

3. DESIGN OPTIONS FOR AN ELHYT

3.1 Array size, collecting area and cost

Major cost drivers in ELTs are the large pointing mount and dome, and these are necessarily absent from designs for an ELHyT since they would be prohibitively large. The latter can also have smaller mirror segments, providing more sub-apertures at given collecting area for a better sampling of the optical wavefront, improving the dynamic range in the direct image. These smaller mirrors can be made of thinner glass, and therefore at lower cost for a given collecting area, especially since their smaller size relaxes the requirement for a low coefficient of thermal expansion. A higher collecting area may therefore be expected for an "Extremely Large HyperTelescope" (ELHyT) matching the cost of an ELT, and it will be of interest to explore the trade-off in more detail for the various design options.

The array pattern should ideally be reconfigurable for suiting the type of source observed. This is probably feasible with a flotilla of mirrors in space, especially the laser-trapped version[7], but may be difficult on Earth. Low-redundancy patterns are generally preferred, except for extreme dynamic range with a coronagraph. Distorted square or triangular arrays, with a low-order pin-cushion or wavy distorsion for example, provide a reasonable trade-off among conflicting optical and mechanical requirements. Also, it is of interest to increase the mirror spacings toward the edge of the meta-aperture, as also seen on artist drawings of the Square Kilometer Array, since it provides an apodizing effect. Regarding the East-West distribution, this can be somewhat compatible with the drifting pupil behaviour if the observing time is limited to one or two hours near transit.

3.2 Imaging properties of an ELHyT

As discussed in Labeyrie 2007, the limiting magnitude for detecting a faint compact source against the sky background is identical for an ELT and a hypertelescope having the same collecting area. This is true both in the non-phased mode, assuming only that the hypertelescope sub-apertures are larger than r0, and with adaptive phasing, requiring in both cases a bright guide star or laser guide star. Unsurprisingly, both have a much higher limiting magnitude in the phased case, using a brighter guide star, whether natural or artificial.

The global extent of the ELHyT mirror array typically has to exceed that of its “effective” aperture, also called meta-aperture, exploited when tracking a star since the acceptance cone of the focal optics has a limited focal ratio such as f/1.75. The need for broad sky coverage typically requires array extensions, at least North and South for declination coverage if observing is restricted to near-meridian transits. For a highly cost-effective system, most mirror elements can be used simultaneously, if several focal gondolas are installed and independently movable (the Arecibo radiotelescope has several receivers, but they are not independently pointable, and the FAST variant is restricted to a single gondola by its paraboloidal figure).

3.3 The dilute field of view

Any type of conventional telescope optics has a diffraction-limited field of view, limited by off-axis or field aberrations such as coma and astigmatism, which inevitably shrinks the diffraction-limited sky coverage of a snapshot exposure if the instrument is scaled to a larger size.

For a paraboloïdal mirror, the low-order coma limits the diffraction-limited field angle to about $10N^2\lambda/D$, or $10\ N^2$ in units of the Airy size, thus providing $100\ N^4$ usable resels within the field area. For a 40m ELT at F/1.75 in yellow light, this amounts to a 84m” field, containing only about 32x32 resels.With its coma-corrected optics, the 57m Ubaye hypertelescope does better, despite its larger size at the same focal ratio. Its field limited by coma and matching diffraction spans 940m” and contains 522x522 resels. Scaling 20x for a 1140m ELHyT shrinks this field in the same ratio, thus giving 47m”, with the same resel content not depending on the scaling factor. These numbers match those for the corresponding metatelescopes, i.e. monolithic telescopes of identical size and optics, but without the pupil densifier.

Although quite narrow, and necessarily smaller than the 50 to 1000m” diffraction lobes from sub-apertures smaller than 2m, this field of the ELHyT is wider than the hypertelescopic “Direct Imaging Field” also called “Clean Field[5]” spanning λ/s , i.e. 10m” if the sub-aperture spacing s is 10m.

Also, additional field channels can be exploited if separated in the Fizeau focal plane where all beams become combined[2]. Each can include a separate corrector for its local field aberrations, thus usefully extending the sky coverage. A cluster of compact sources such as deep sky galaxies, a globular cluster, galaxy center, etc... can be efficiently imaged. Indeed, within each lobe channel of 50 to 1000m”, a compact source of interest can be centered into its central 10m” “Direct Imaging Field”.

Downstream from the Fizeau focal plane, the pupil densifier shrinks each of the sub-fields, down to a “Direct Imaging Field” spanning λ/s at full densification, if s is the sub-aperture spacing thus providing a sparse mosaic coverage. The densification trade-off can be adjustable while observing, by zooming the micro-optical array of Galilean or Cassegrainian telescopes which achieves the densification. The adjustement ranges from Fizeau, with its unlimited field (although limited by coma) to the full pupil densification.

Also, each sub-field can be separately centered on the star, galaxy, etc.. .to be observed. This is in principle feasible with arrayed micro-actuators and a mechanism resembling somewhat the systems for multi-slit spectrography. At much more widely spaced positions of the celestial sphere, degrees or tens of degrees apart , separate fields can also be observed simultaneously with separate independently-driven focal gondolas if the hypertelescope architecture is spherical rather than involving a FAST-type active paraboloidal meta-mirror .

The multiple gondolas, thus exploiting the focal sphere of the primary array, can be specialized for different wavelength ranges or observing modes such as coronagraphy, polarimetry, etc..., possibly including a Coudé feed to a ground laboratory as already tested at Ubaye. Some instruments can be supplied by users.

In this class of ELHyT, concepts are enlarged versions of the Ubaye Hypertelescope[2]. At the scale of a 1200m aperture , 20 times larger than Ubaye Hypertelescope and assumed to have the same focal ratio F/D = 1,75, it requires focal gondolas equipped with 3m mirrors for correcting the spherical aberration. Because they receive narrow light pencils from the sub-apertures, their optical quality can be relaxed and light-weight structures be considered. The figuring of the strongly aspheric M3 mirror is likely achievable with current aspheric polishing equipment such as the stressed-lap machine developped at University of Arizona.

3.4 Comparison of spherical and paraboloïdal architectures

The concept developed in China for the FAST telescope, with active mirror elements deforming its primary mirror as a paraboloïd which remains pointed toward the star observed, can be adopted in a modified form for an ELHyT. Since, in our case, the primary mirror is dilute rather than filled, for obvious reasons of cost, no attempt is made to build and actively shape a filled primary mirror, the cost of which would be prohibitive. Its relatively small segments (15 to 150cm) can be carried by separate active supports located at the nodes of the hammock-like carrier net. No large optics is then needed in the focal gondola, since it receives a correctly focused image which only needs conditioning with a pupil densifier, adaptive optics, etc..., all of which are small or even micro-sized optical elements.

However, the main advantages of the spherical concept reside in its fixed, possibly passive, primary array, and in the possibility of efficiently exploiting it with several focal gondolas. They can independently observe different parts of the sky, and some of them can be specialized for different spectral ranges and observing modes. Its main drawback is the complex gondola optics , with its M2 and M3 mirror(s) correcting the primary spherical aberration. Also, slots are needed in M3 to transmit most light rays from M1 to M2, and this restricts the freedom of patterning the M1 mirrors.

The paraboloïdal concept is simplified in this latter respect, but the large off-axis aberrations preclude using several gondolas. Also, the active primary array requires accurate actuators to generate the “tsunami wave” which reshapes the global paraboloïdal locus and maintains its axis directed toward the gondola, itself moving like in the spherical case to correct the first-order effect of Earth rotation.

The optical modeling of both concepts is under way with Zemax code (Rondi et al., Bresson et al.) for a detailed comparison of their performance, including the field coverage with a multi-field pupil densifier.

3.5 Gondola suspension

Pending space versions using a flotilla of mirrors, the Carlina class of terrestrial hypertelescopes which use no delay lines, whether spherical or paraboloïdal, requires a suspension system for the gondola(s). High pylons, perched at the rim of the large (330m) sink hole, are used at Arecibo and for FAST. A tethered balloon has been successfully experimented at Haute Provence (Coroller et al, 2004). A single traversing cable, 800m long and collapsible, is installed at Ubaye.

For the larger size of an ELHyT, to be nested in a deep valley or crater, a traversing cable, or several for multiple gondolas, also appears usable. Balloons require a large protective shed, implying appreciable daily handling, and the cost of helium maintenance is not negligible. Schemes using a pair of electric drones flying in a wide circle, could provide the needed lift without generating objectionable turbulence if the circle is larger than the collected stellar beam.

3.6 Mirror element supports

Stiff tripods have been installed at Ubaye, at selected positions where mirror segments have a moderate height above ground, less than 3m. This should probably not exceed 10m, unless guyed structures are used. The hammock-like netting of cables adopted at Arecibo and FAST is usable for higher altitudes above ground, up to 50m perhaps with active shaping controlled by grounded rods.

Some preliminary testing of such anchoring and its stabilizing effect, using a triplet of 6mm carbon rods in 6m length for “grounding” a suspended mirror, has been performed by one of us (AL), using laser fringes to monitor the mirror’s jitter. Its measured amplitude, a few microns in moderate wind conditions, proved comparable to the atmospheric piston . The scheme therefore appears of interest since windy nights will not be exploitable for reasons of fast “seeing” and of excessive gondola jitter, unless fast servo systems contribute to the adaptive stabilization, in which case they may also deal with the wind-induced jitter of the M1 segments.

3.7 Adaptive phasing

Both the ELHyT and the E-ELT must are expected to produce phased images on very faint sources, with diffraction-limited resolution, and therefore require adaptive optics together with a Laser Guide Star system. An important point in the comparison of ELTs and the ELHyT is the feasibility and *technology readiness level* of adaptive phasing on faint sources. Laser Guide Star systems[8] have established this feasibility at the Keck and other large telescopes, and extensions to ELT’s are also considered feasible. Preliminary laboratory simulations by one of us (AL) with a modified LGS version intended for hypertelescopes, called H-LGS, gave encouraging results, but more assessment is needed for a reliable conclusion.

Phased observing is highly desirable, although image reconstructions from sequences of seeing-degraded short exposures are also achievable by speckle interferometry and triple correlation on sufficiently simple sources, as simulated in the hypertelescope case (Surya et al. in preparation). These post-detection reconstruction techniques have been successfully used with large monolithic telescopes, thus also prove applicable to hypertelescopes but adaptive phasing is expected to reach a much higher imaging performance, and deconvolution techniques now developed by Mary et al.(2012, in preparation) now show promise of expanding the Direct Imaging Field.

Among the types of wave sensing methods suitable for hypertelescopes are:

A- the “dispersed speckle” sensor[9], and its version with discrete wavelengths extending the time-honored method of “dispersed fringes”[10] used since the late 19th century to balance the optical path difference in interferometers

B- a modified form of Shack-Hartmann sensor as presented in Figure 1. (Cuevas private communication).

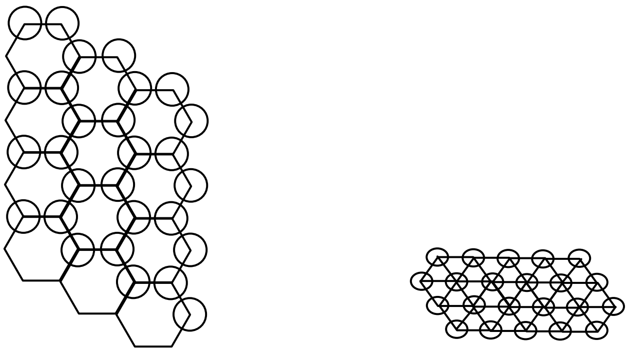

Figure 1: Triangular array of circular sub-apertures, as it appears at the exit of a pupil densifier (here providing 50% densification) concentrating the back-scattered laser light. Shack-Hartmann wave sensing is achievable with an array of triangular lenslets, each of which focuses light from a triplet of subapertures. Each focal spot is a 3-beam interference pattern, and the position of its central white spot is sensitive to OPD optical path errors among the three corresponding sub-apertures. The scheme is usable on bright stars, and also with a LGS if the large cone effect is tolerable, as can be the case in the mid infra-red.

3.8 Laser Guide Star

Like for conventional telescopes, adaptive phasing is achievable with a suitable wave sensor, and actuators, if a natural bright star is available near the observed source. If not, a Laser Guide Star (LGS) appears usable also in the hypertelescope case, if suitably modified to accommodate the large dilute aperture (Labeyrie et al. in preparation). On faint sources, a sodium Laser Guide Star (LGS)[8] appears usable for wave sensing across the dilute aperture, as achieved in some large monolithic telescopes, but the sparse wavefront pattern requires a modified LGS version, hereafter called “Hypertelescope LGS” or H-LGS.

3.9 Sites

The radio-astronomy sites at Arecibo and for FAST offer inadequate climate conditions for optical observing, and the coexistence of radio and optical hardware would raise significant problems. Few comparable crater-shaped natural features are located at good optical sites. The Caldera de Taburiente, at Canarias, with is 5km size and 2000m depth, has fairly good “seeing” but its shape is quite irregular, and its National Park status may preclude a major astronomical installation, although the elements may be nearly invisible to visitors (Labeyrie et al. Backaskog).

Major mountain ranges, in the Himalaya and the Andes, have a choice of valleys oriented East-West and having a suitably curved profile, which may be usable for observing sources near the time of their meridian transit, a tolerable restriction. With Google Earth, a quick preliminary selection of such valleys has been possible: just tilting the view toward the East or West horizon evidences those valleys which are oriented East-West and gives a coarse indication of their topographic merit. Among the candidate sites thus found in the Andean and Himalayan ranges, several have promising features. One example (see Figure 2) is the Spiti valley, at 4000-6000m altitudes in the indian Himayala Pradesh region, which is somewhat protected from monsoon precipitations and has road access.

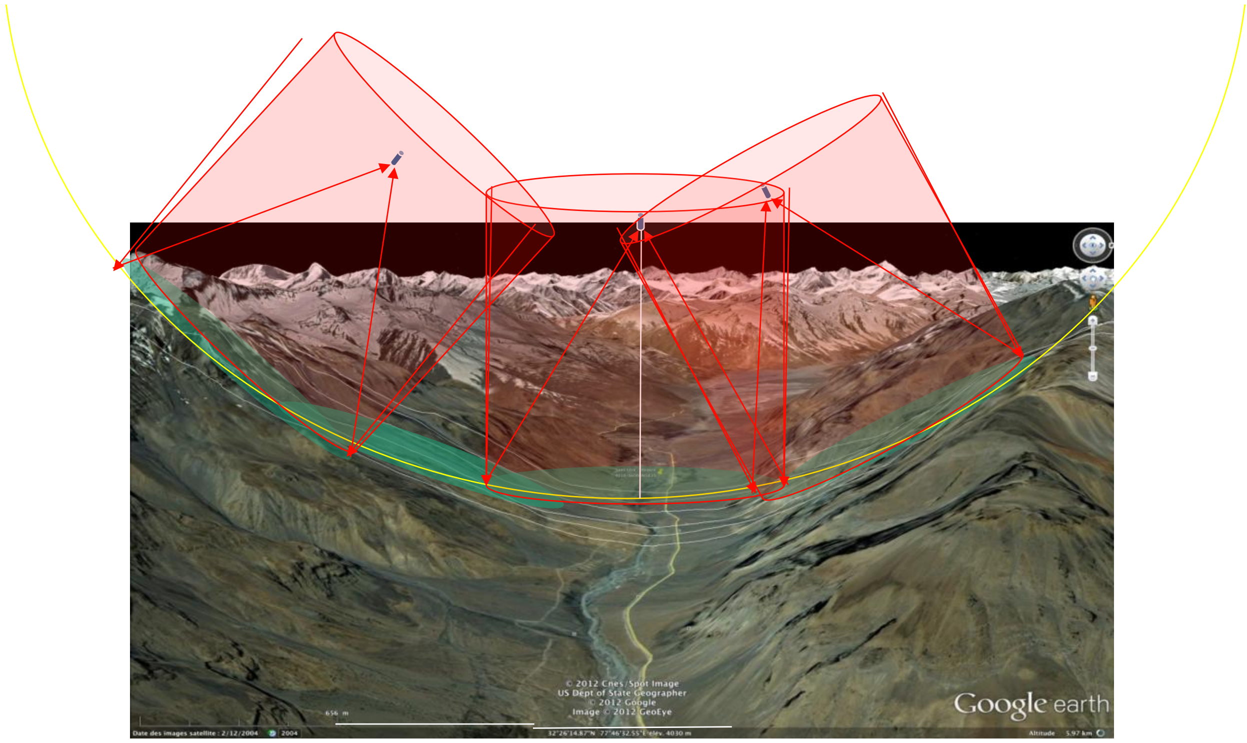

Figure 2: Representation of a possible implementation of a 1200m hypertelescope in the Indian Spiti Valley.

4 CONCLUSION

Extremely Large HyperTelescope can achieve a large gain in spatial resolution, direct-imaging performance and in interferometric limiting magnitude with Laser Guide Star. This will open broad science niches, including possibly deep fields and cosmology. Embryonic version can rapidly grow to full size but the design is highly site-dependent and thus an early selection will be needed

We have started a concept study to identify the main aspects requiring a detailed analysis. Based on the experience gain with "Ubaye Hypertelescope", we identify the possible trade-off between spherical and paraboloïdal design and thus the optical design of the combining optics, the possibility of accommodating a larger field of view, either a large one or a certain number of discrete ones and finally important studies are needed for the adaptive phasing including the possibility of a Laser Guide Star adapted to ELHyT.

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