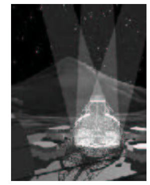
Hypertelescope architectures for direct imaging at high angular resolution

Venice 2001
Beyond Conventional Adaptive Optics



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ABSTRACT

Large hypertelescopes, i.e. "multi-aperture densified-pupil imaging interferometers", can be built in the form of "exploded" ELT's (EELT). An exploded OWL, spanning one-kilometer for example, has the same limiting magnitude and higher resolution. An Arecibo-type design, called CARLINA, is considered for implementation in a spherical crater or sink-hole. using balloon-borne focal optics. Its science includes deep-field imaging for cosmology. The possibility of having multiple, independently pointed, focal stations improves the science/cost efficiency with respect to the usual ELT designs having steerable mounts. With suitable adaptive optics, the CARLINA concept is seen as a strong contender for the next generation of large instruments.
For even larger sizes, reaching 10 or 20 kilometers, flat sites are more easily found on Earth, and can host hypertelescope versions of the Optical Very Large Array (OVLA) concept. Designs with either mobile or fixed telescopes are considered. These are more complex than the CARLINA, and not compatible with multiple focal stations.

1. INTRODUCTION

The principle of hypertelescopes, or "multi-aperture densified-pupil imaging interferometers", has been described elsewhere (Labeyrie 1996, 1998, Boccaletti et al. 2000), and their field limitations recently discussed in more detail (Labeyrie et al. 2001). The principle and properties are briefly summarized hereafter.

2. PRINCIPLE OF HYPERTELESCOPES

A multi-aperture Fizeau interferometer can provide direct images, the information content of which increases with the number of sub-apertures. Their luminosity however degrades catastrophically if the spacing of the sub-apertures becomes much larger than their size. The degradation is caused by the diffractive spreading of light from each small sub-aperture, generating a halo much broader than the main interference peak and taking most light away from it.

Michelson interferometers evade this degradation. The periscopic beam combiner can maintain image luminosity at arbitrary baseline sizes, and the combination scheme can be extended to include many apertures. If care is taken to configure the exit pupil so that sub-pupil centers be arranged like in the entrance aperture, a direct image is obtainable with full luminosity (Labeyrie 1996).

This is one way of achieving a hypertelescope architecture, and there are other equivalent arrangements using for example micro-lens arrays (Pedretti *et al*, 2000; Gillet *et al*, 2001) or fibers to densify the pupil. In all cases, full luminosity is achievable in the image at arbitrary baseline settings. The limited information content of the image, causes the same limits on field crowding as for a Fizeau arrangement having the same aperture pattern.

The image pattern in a phased hypertelescope having a highly densified pupil may be described as a "windowed convolution" of the object. There is a normal convolution of the object with a spread-function, the "interference" function, followed by "windowing", i.e. a multiplication by a "window" function. The interference function is the diffraction pattern from an array of Dirac points arranged like the centers of the sub-pupils in the exit pupil (or, with proper scaling, at the entrance since the hypertelescope architecture requires identical arrangements of centers in both planes). The window function is the diffraction pattern from a single exit sub-pupil.

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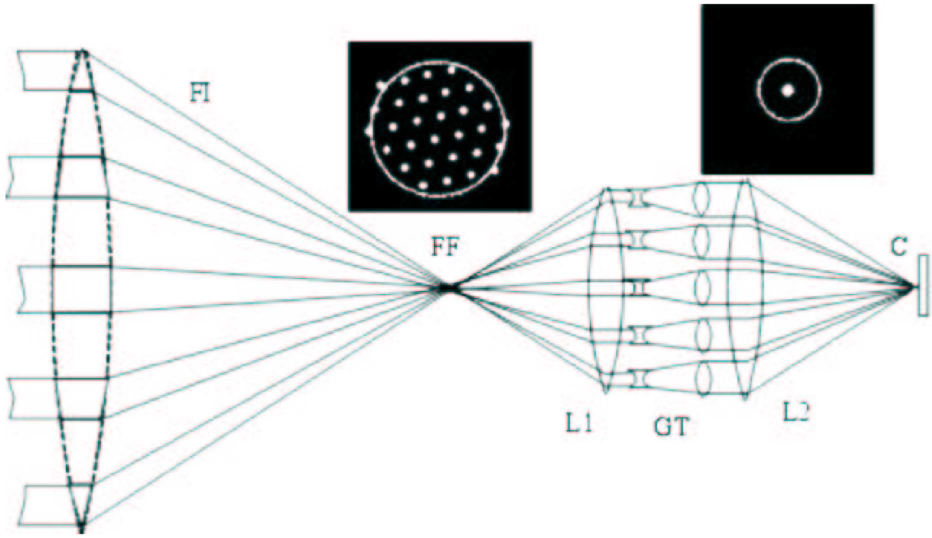

Figure 1. : Principle of the hypertelescope: the focal image FF provided by a Fizeau interferometer FI is re-imaged by lenses L1 and L2 on camera C, through an array of miniature and inverted galilean telescopes GT. They densify the exit beam, thus shrinking the diffractive envelope (dotted circle) of the focal pattern with respect to the interference peak. For an off-axis star, they also attenuate the local tilt of the flat wavefront transmitted from L1, while preserving its global tilt. The wavefront from an off-axis star thus acquires stair steps while becoming densified at L2. The interference peak is displaced more than the envelope, but remains within it if the step amplitude is below one wavelength. Beyond the "zero-order field" thus definable on the sky if the array is periodic, higher-order peaks move into the envelope. If non-periodic, a speckle pattern fills the envelope.

Like in radio interferometry, dynamic range can be traded against resel count by changing the aperture redundancy at given number of apertures N. The Exo-Earth Discoverer hypertelescope proposed to NASA for exo-planet detection in space (Boccaletti et al. 2000) has 37 hexagonal apertures arranged periodically, i.e. highly redundantly, across a few hundred meters. The exit pupil is fully densified , and seen as a quasi-monolithic aperture from the image plane. A coronagraphic attachment removes much of the star's Airy peak in the image (Riaud *et al*, 2000; Rouan *et al*, 2001).

The Exo-Earth Imager, also proposed as a subsequent step for obtaining resolved images of Earth-like planets (Labeyrie 1999a & 1999b), is similar but with larger sub-apertures (4 meter) and more of them (150) arranged non-redundantly across 150 kilometers. As mentioned below, simulations indicate that it can in principle show "green spots" on an Earth-like planet.

Such hypertelescopes can be designed in the form of a large "exploded" mosaïc mirror (figure 2) forming a Fizeau focal image. The image then enters a small "pupil densifier" camera (figure 1) which concentrates and intensifies it. Like in conventional ELT designs, the primary mosaic can be paraboloïdal or spherical. A corrector of spherical aberration is required in the latter case, and several can be installed in the wide primary field for independant observing with as many focal combiners, each equipped with one or several pupil densifiers (figure 3).

3. TESTS WITH MINIATURE HYPERTELESCOPES

Following the initial numerical simulations, the hypertelescope principle was verified and assessed through laboratory simulation. For sky testing, and approaching the diffraction-limited resolution without adaptive optics, a miniature hypertelescope, smaller in diameter than Fried's r_0 parameter, was used by Pedretti et al. (1999). It had 10x10 apertures and a single array of micro-lenses for pupil densification. This type of pupil densifier relies upon diffraction to spread the beams, a somewhat restrictive approach which reduces the design freedom.

A second miniature hypertelescope with a more elaborate and flexible "ray optics" pupil densifier, using a pair of confocal microlens arrays, has been built by some of us (SG, PR) and tested on a binary star (Gillet et al., 2001).

4. EXPLODED ELT'S (EELT'S)

On Earth, pending space implementations, exploded forms of ELT's provide attractive options for hypertelescopes having the same limiting magnitude, higher resolution, and higher science yield if implemented with multiple focal stations.

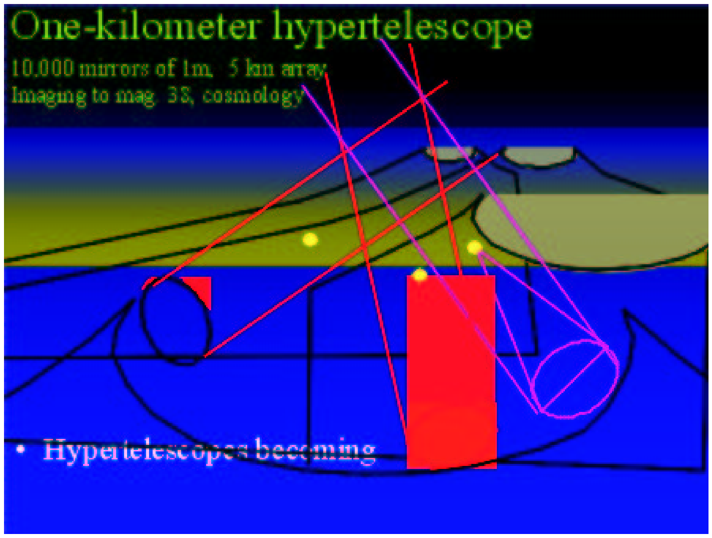

Figure 2. : Arecibo-type concept for a kilometer size hypertelescope. Segments of a diluted mosaïc mirror, spherical in shape, are carried by separate rigid supports in a crater or sink-hole. The focal surface is sampled by one or several stabilized balloons containing a corrector of spherical aberration, a pupil densifier, adaptive optics and the auxiliary instrument. The adaptive optics includes active correction for the slowly-varying piston errors of the primary mirror elements. In the absence of a large pointing mount, collecting areas larger than for ELT's are probably achievable at comparable cost. The multiplicity of focal balloons, which may carry different instruments, also increases the science efficiency.

4.1. The CARLINA concept for an EELT

As sketched in figure 2, the CARLINA approach is inspired from Arecibo's radio-telescope. It similarly uses a natural depression, volcano crater or karstic sink-hole, as a stable substrate carrying elements of a spherical mirror, in the form of an "exploded", i.e. diluted, mosaïc. A filled mosaïc is obviously better at equal diameter, but would be too costly at the scale of a square kilometer. Instead, mirror elements of 1 to 2 meter size, arrayed at 10 to 50 meters intervals and carried by stable fixed supports can be efficiently utilized according to the hypertelescope principle.

Arecibo's pylon-and-cable suspension, spanning 330 meters, for carrying the aberration corrector and detector is costly and can probably not be scaled to kilometric sizes. Neither is it suitable for carrying and tracking multiple focal stations, which could in principle multiply the science produced. A tempting alternative solution is the use of balloons, electrically motorized and stabilized. Following preliminary tests with a tethered wheather balloon, a prototype motorized balloon, 12 meters in length, is under construction by one us (HLC) and stabilisation testing is expected to begin in 2002.

A "polar" precursor of CARLINA hypertelescopes, dedicated to observations of the Polar star and which may eventually span 30 m, is under construction at Haute Provence. For flexibility the initial version uses flat rather than curved primary mirror elements.

4.2. Hypertelescope version of an Optical Very Large Array (HT-OVLA)

A different design for hypertelescopes involves the OVLA concept and variants investigated in our group since the 1970's, which may have influenced the VLTI and Keck interferometer schemes. These utilize flat ground as the platform, which increases the possible size range from perhaps a kilometer to 10 or even 20 kilometers. Coudé telescopes feed star light into a focal station, where beam combination is achievable in the hypertelescope mode. The telescopes can be mobile, to avoid delay lines, or fixed with mobile combiner elements serving as delay lines. In the former case, the aperture locus is an elliptical ring, which can be re-configured (Lardière, 1999) for matching to the type of object observed. In the latter, the apertures can be arrayed periodically in arbitrarily large numbers.

4.3. Science of CARLINA vs. HT-OVLA

Site availability probably limits the overall size of a CARLINA dish to 5 kilometers, providing a 1 km effective aperture, up to zenith distances approaching 45°. Within this operating range, the CARLINA should be preferable in most respects if the balloon technology can be developed. Its basic structure with fixed mirrors is much simplified with respect to the OVLA. The construction and operating costs are probably much lower.

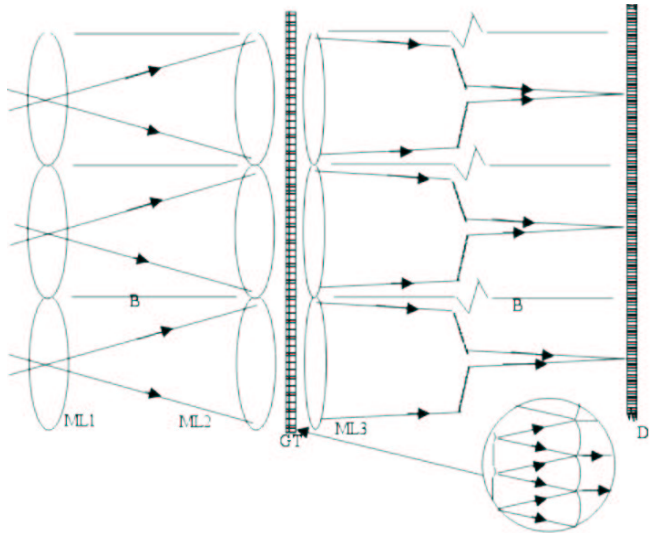

Figure 3. Integrated optics for multi-field imaging with pupil-densifiers in parallel. A pair of micro-lens arrays ML1 and ML2 are located respectively in the Fizeau focal plane and the pupil plane relayed by lenses ML1. The pitch is F l/d if F is the Fizeau focal length. Plate GT is an array of pupil densifiers, each being itself an array of micron-scale Galilean telescopes; in integrated optics form (inset). Another micro-lens array ML3 focuses the array of images on a single detector D. Baffles B prevent light leakage across image channels. The high-resolution images are not adjacent on the sky, but can be made adjacent on D for using efficiently the detector pixels.

Most critical regarding science is the number of collecting apertures, their combined area and the overall diameter. The collecting area of a CARLINA can potentially be as large as with the OWL for example, and probably even larger at identical cost, hence providing a similar or higher limiting magnitude of the order of 35 o 38 with adaptive optics.

The very narrow elementary field, or Zero Order Field (ZOF), of such a telescope would seem to affect observing modes such as those typically used for cosmology , where images of numerous deep-sky galaxies have to be obtained in a single exposure. However, within each focal station, thousands or millions of narrow ZOF images can in principle be exposed simultaneously (Labeyrie *et al*, 2001). They cannot be contiguous, the minimal sky pitch being of the order of λ/d (d is the sub-aperture's size) but a full image can be reconstructed from successive exposures.

HT-OVLA arrangements cannot easily reach a comparable collecting area since each elementary telescope is much more complicated and costly than CARLINA elements. Multiple ZOF areas can also be exposed in this case, but not as many and only within a single focal station.

In either case, adaptive optics must be available and be operable on faint sources, as is the case with the OWL and other ELT designs. As discussed in Labeyrie *et al* (this conference), the problem is of comparable difficulty with hypertelescope and ELT designs. Novel solutions are explored.

5. SPACE VERSIONS STUDIED

The perfect seeing and isoplanetism is obviously an enormous advantage of space. Pending access to space, the stratosphere would already improve things dramatically if hypertelescope structures could be operated there. Conceivably, large stratospheric balloons could carry a belt of small mirrors attached to their equator, and be pointed globally.

Alternately, solar aircraft such as NASA's Sunseeker, built by P.Mc Cready, could carry lightweight mirror elements. Several such large (currently 95 meter span) flying wings, each carrying a dozen mirrors for example, could be circling steadily around a stratospheric balloon, with their wings forming a nearly paraboloïdal corolla having its focus at an optical package carried by the balloon. This obviously raises formidable control problems, which may exceed in difficulty those expected in space for controlling formation flight.

In space, the formation flight of optical elements for interferometry has been considered since the TRIO proposal (Labeyrie et al., 1983), involving small rigid solar sails as weak actuators for driving the free-flyers. An "Exo-Earth Discoverer" concept, proposed by our group to NASA for its Terrestrial Planet Finder project, involves a hypertelescope with a spherical primary mosaïc spanning a few hundred meters (Labeyrie et al., 1999b & 1999c). One or several focal combiners are equipped with aberration correctors and auxiliary instruments such as a coronagraphic camera, spectro-imager, deep-field imager, etc...

For the longer term, the larger Exo-Earth Imager spanning 150 km, with 150 mirrors of 4 meters, has the potential capability of producing resolved images of Earth-like extra-solar planets. Simulations indicate that it can in principle form a 50x50 resels image of the planet where "green spots" like the Earth's Amazon basin will be detectable in 30 mn of exposure at 3 parsecs (Labeyrie 1999a).

Precursor systems are studied in our group (Lardière et al., 2001). A proposal to fly nano-satellites driven by small rigid sails in geo-stationary orbit has been submitted by Alcatel Space Systems and our group to the Centre National d'Etudes Spatiales. NASA has commissioned R. Angel and his group to further explore the use of small rigid sails for controlling spaceships.

6. CONCLUSION

The prospect of building Earth-based hypertelescopes much larger in size than the ELT's currently considered, and of comparable or larger collecting area, suggests the possibility of significant advances in the corresponding science. The physics of stars and their planetary systems will be better understood with images and spectro-images at higher resolution. Deep-sky objects such as the remote galaxy fields of interest for cosmology are also potentially observable, with the same limiting magnitude as an ELT of equal collecting area. This requires adaptive optics, a challenging problem also met by ELT projects, for which possible solutions are also being explored.

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