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Sites and adaptive phasing for 1-10 km hypertelescopes

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Abstract. Densified-pupil interferometers, also called hypertelescopes, can provide direct images usable for general imaging and coronagraphy. Kilometric hypertelescopes are much easier to operate in space, but the time scale and cost involved may justify ground-based versions. Some terrestrial sites are considered to host a 10 km planar telescopes arrays or a 5 km spherical arrays comparable to the Arecibo radio-telescope.Lastly, we propose two wavefront analysis methods to phasing a kilometric ground-based hypertelescope.

interferometry / hypertelescope / pupil densification/ snapshot imagery / adaptive optics

1. Introduction

Long-baseline optical interferometry raises high expectations for a large gain in angular resolution from Earth or space. Among the current developments is a recent concept for snapshot imaging with multiple apertures. The instruments are called hypertelescopes since they behave like a giant telescope having a sparse aperture.

2. Principle of hypertelescopes

Hypertelescopes may be defined as multi-element interferometers using a densified exit pupil to provide snapshot images. As described elsewhere (Labeyrie A. 1996, Labeyrie A. 1999, Boccaletti et al. 2000) hypertelescopes are related to multi-aperture Fizeau interferometers, i.e. systems equivalent to a large telescope carrying an aperture mask with multiple holes. When the holes are small with respect to their spacing, which obviously happens when considering kilometer or megameter scale arrays, Fizeau systems suffer from the inefficient light concentration in the main interference peak of the spread function. Their imaging field is in principle infinite in extent, neglecting geometric and other limitations, but the number of active resels (resolution elements) which can be imaged in a snapshot exposure is limited to about πN or N(N-1)/2 depending on the aperture redundancy.

Exceeding this limit gives a useless low-contrast image where the central peaks from each object point are buried in the non-uniform added halo con-

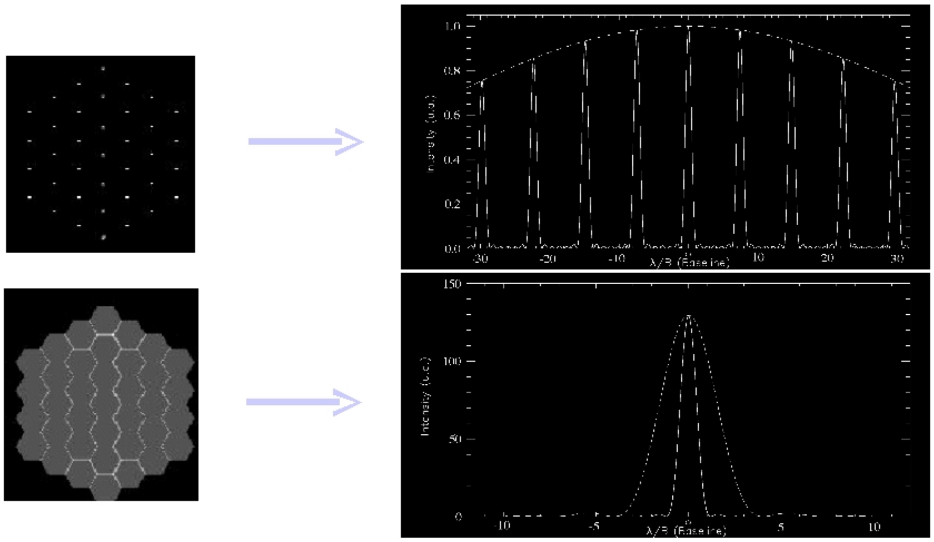

Figure 1. Principle of the pupil densification. In the densified case (bottom), the interference peak is shrinked : the relative intensity of the central peak is higher but this is done at the cost of the field which is considerably reduced.

tributed by the sidelobes of the spread function. This is a classical limitation of radio-interferometers, which is avoidable by using multiple exposures with different aperture patterns, according to the methods of aperture synthesis. Densifying the exit pupil, which was already achieved in Michelson's historical 20-feet interferometer beam, and is feasible in other ways, tends to shrink the diffracted halo with respect to the size of the central peak, and it simultaneously intensifies the peak since energy is conserved. According to a "golden rule" worded by (Traub 1986), saying that only Fizeau interferometers could produce a direct image, it was long believed that such pupil densification precluded the formation of a direct image. Labeyrie (1996) has however shown that this is not so if the densification conserves the pattern of sub-aperture centers. Both authors now agree to propose an "extended golden rule" thus formulated : "Any multi-aperture imaging interferometer must have an exit pupil where the pattern of centers is identical to that in the entrance aperture. The relative sizes of the sub-pupils may be modified, and in particular, they may be uniformly enlarged, which will concentrate the energy in the central interference peak" (Traub and Labeyrie, private communication).

In practice this indicates the feasibility of large scale (as large as a million kilometers appear feasible for observing the details of the Crab pulsar), interferometers having multiple small apertures for producing snapshot images of compact objects. With hundreds of apertures as small as a few decimeters, the apparent disk of stars will be resolvable in thousands of resels. Also, circum-stellar planets will be imageable if coronagraphic attachments are used

(Boccaletti et al. 2000) These theoretrical prospects have now been subject to verifications using numerical simulations, laboratory demonstrators (Gillet S. et al. 2001, in preparation), and actual observations with a miniature hypertelescope (Pedretti et al. 2000). Ground and space versions are under study, and steps are taken for limited testing at the Arecibo radio-telescope, using small (25cm) optical mirrrors in gaps of the radio dish .

3. Forms of Earth-based hypertelescopes

In many respects, hypertelescopes are much easier to operate in space than on Earth, but the time scale and cost involved in developing even simple hardware for controlled arrays of free-flying optical elements in space may justify terrestrial versions. In space, a flotilla of dozens or hundreds small elements can be deployed in the form of a large mosaic mirror, although a much diluted mosaic. Whether paraboloidal or spherical (with a focal corrector), the global shape can provide a Fizeau image in the focal plane. A small attachment can densify the pupil and provide directly usable snapshot images. Pointing is achievable by globally rotating the array, which is slowly steerable with small solar sails attached to each element. A "moth-eye" version allows full sky coverage with fixed elements, using moving focal stations (Labeyrie 1999) .

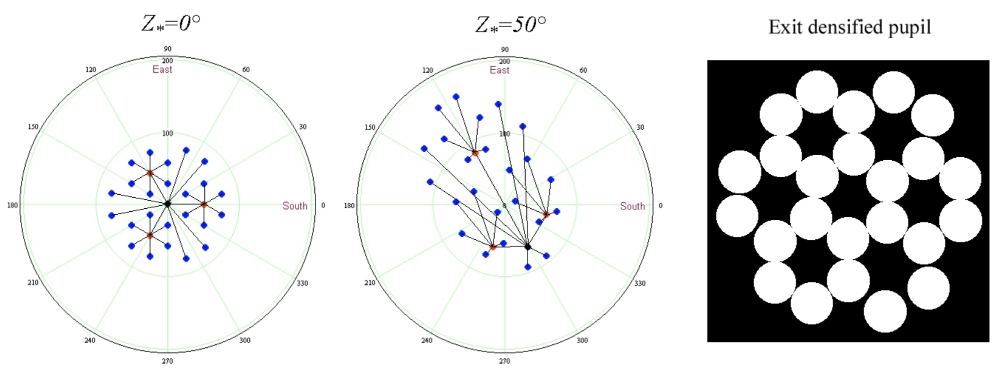

Figure 2. A possible version of an OVLA-type hypertelescope consists in a hierarchy of several rings of mobile telescopes and combiners. This 24-telescope array is represented for two different zenital distances. The shape and the orientation of the densified exit pupil can be stabilized during the observation.

On Earth, site issues have a dominant importance for interferometers. In addition to the usual astronomical criteria, large interferometers require a suitable terrain geometry at the scale of one to ten kilometers. Both flat and spherical sites are of interest, respectively for OVLA-type or CARLINA type concepts. As described elsewhere (Labeyrie et al. 1999) the Optical Very Large Array concept involves mobile telescopes having a common Coudé focus at a central station. The slow motion of the telescopes during observing makes the concept compatible with a hypertelescope mode, using suitable optics in the beam combiner. Ways of arraying the telescopes more freely than along a single ring have been studied (Lardière, thesis 2000). A prototype telescope element, containing a 1.5 m active mirror, is undergoing tests and is expected to join the GI2T interferometer for further testing. With these design options, the OVLA concept may, in the coming years, become ready for a full scale implementation. In terms of site it will require a rather flat expanse of 10 km size. Deviations from flatness are tolerable since the telescope translation mechanism, using wheels or a hexapod, can tolerate moderate slopes, and the beam combiner optics can also self-adjust to accept tilted Coudé beams.

A rather different concept for a large hypertelescope is the CARLINA, which owes it's name to a composite alpine flower. Following the same philosophy as the Arecibo radiotelescope, it uses a natural depression as support for a large, fixed, spherical mirror, albeit in diluted mosac form (fig. 3). Rigid tripods anchored into the bedrock each carry one mirror element. A focal combiner, hovering above the large array, carries a corrector of spherical aberration, a pupil densifier and camera. Several such combiners can be used independantly for parallel observing of several objects. Balloons, either tethered or motorized, are considered for carrying the focal packages.

4. Comparison of OVLA and CARLINA

CARLINA designs can perhaps reach aperture sizes of the order of a kilometer, using a crater, a valley, or a sink hole of 5 km width and 800m depth. Potential sites are considered in the Reunion island, which had a candidate site for the VLT, and in other volcanic or karst areas. The High Atlas range of Morocco may also have steep valleys approximating the required spherical curvature over part of their surface : a brief observation made by one of us at Oukaimdem (A.L.) with a 20cm telescope during the conference has shown encouraging characteristics of sub-arc second and slow seeing.

The size limitation comes from the sites and from the size of the spherical aberration corrector. OVLA arrays may prove expandable beyond 10 km , and flat sites are more abundant than spherical ones. Salt lakes in the Chilean or Bolivian Andes may prove adequate, although there is some concern about flooding and corrosion. In addition to the usual requirements for visible and infra-red sites, large interferometers require microsismic quietness.

5. Wavefront analysis and adaptive phasing

Terrestrial versions of hypertelescopes require adaptive optics for high-resolution snapshot imaging. On bright stars, this is achievable with the techniques developed for ordinary telescopes, although the wave analysis system must be modified to measure the inter-aperture piston errors. Several methods are considered (Pedretti E. & Labeyrie A. 1999, Cuevas S. 2000 (this conference), including the dispersed-speckle method briefly outlined hereafter. Like in the case of Extremely Large Telescope projects (ELT), a major issue is the adaptive phasing of faint objects, and whether refined adaptive techniques will achieve a sufficient sky coverage. Hypertelescope arrays may be considered as "exploded" versions

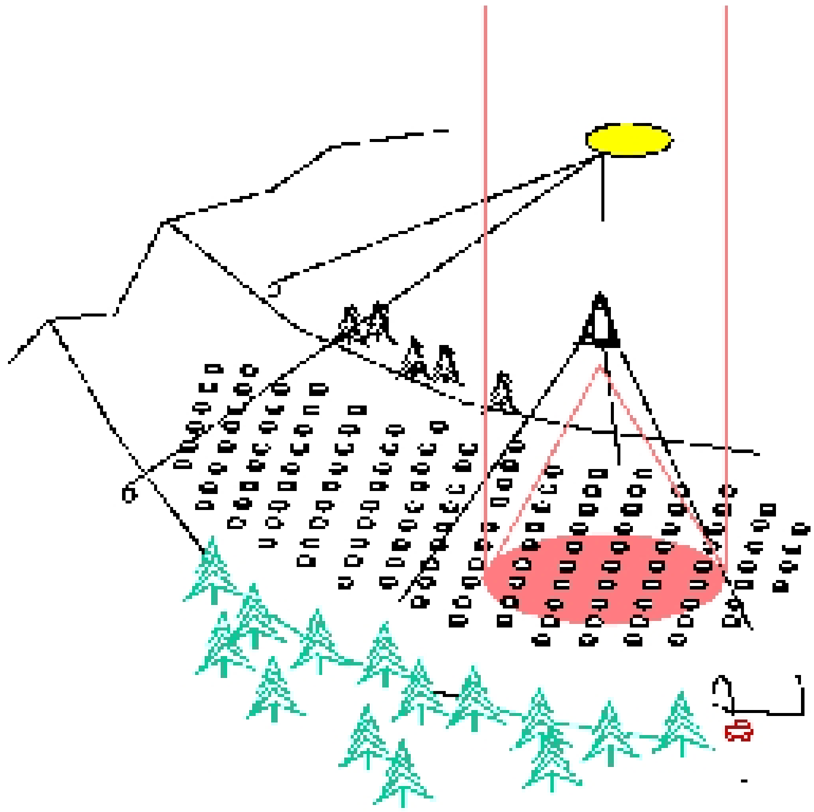

Figure 3. The Carlina project uses a natural depression as support for a large, spherical, diluted mosaic of mirrors. Rigid tripods anchored into the bedrock each carry one mirror element. A focal combiner carries a corrector of spherical aberration, a pupil densifier and camera. Several such combiners can be used independantly for parallel observing of several objects. Balloons, either tethered or motorized, are considered for carrying the focal packages. a diluated mozaic of small mirrors

of ELT's dense mosaic apertures, and the problem of building a tri-dimensional model of the atmosphere's refractive index, using tomographic techniques, is obviously aggravated by the sparse aperture. Figure indicates a possible approach using a number of reference stars suitably located, up to tens of degrees apart.

The case of only two turbulent layers, a ground layer and a rather high altitude layer, is worth discussing as it may lead to more general solutions. In this case one uses two guide stars in addition to the faint science source. Both guide stars are selected in such a way that the three sets of beams intersect at the high turbulent layer, albeit with a permitted lateral shift amounting to one or several periods of the mirror array spacing (the array is assumed periodic with square or hexagonal pitch). Wavefront maps, including piston errors, are obtainable for both guide stars. Subtracting them, after an appropriate shift to compensate the lateral displacement, removes the contribution of the high layer, which is identical in both maps. The translation however leaves an edge residue. The subtracted map is a convolution of the ground turbulence map, including mirror errors, with a pair of points having opposite signs, representing the separation of both star projections on the mirror array. It can be deconvolved to calculate the ground turbulence map, including mirror errors. The relevant part of this map is then subtracted from one of the initial turbulence maps to obtain the high turbulence map. Adding the ground and high turbulence maps thus calculated, with appropriate shifts, then provides the wavefront map for the faint source, and therefore the actuator signals needs to correct it.

Edge effects, and the adverse effect of zeros in the Fourier transform of the pair of points, which create gaps in the deconvolved map, can probably be mitigated if one more star is used. Whether this approach can be generalized for turbulent structures including more than two layers, using more guide stars, remains to be explored. A single high-altitude turbulent layer can in principle be analyzed with a reference star, in a CARLINA array, but the technique does not easily generalize for multiple seeing layers.

6. A wave analyzer using dispersed speckles

An efficient way of acquiring the fringes and balancing the optical paths in a two-aperture interferometer involves dispersed fringes. Already utilized visually by Michelson and Pease at Mt Wilson, and adapted to photon-counting cameras by (Koechlin & Rabbia Y. 1985), the method can perhaps be extented for use in multi-aperture interferometers. Snapshot images recorded with a Fizeau or a hypertelescope interferometer, if spectrally filtered to achieve temporal coherence in the presence of wavefront distortions, feature speckles if the exposure time is shorter than the atmospheric life-time. Simultaneous images can be obtained at many wavelengths by using a mutli-spectral imaging scheme such as developed by Courtès or a Superconductive Tunnel Junction camera (STJ). The set of monochromatic speckle patterns thus obtained can be stacked to form a x, y, λ data cube, which can be subjected to a tri-dimensional Fourier transformation. In the x, y, λ data cube, the contribution from a triplet of sub-apertures, each having a uniform phase, is generally a honeycomb pattern. Its tubular cells are conical, owing to the usual proportional dependance of interference pattern size with respect to wavelength.

To obtain cylindrical and parallel tubular cells, the x, y, λ data cube can be distorted according to a trapezoïdal law. Phase differences ("piston errors") among the three apertures then induce tilt and translation in the parallelized honeycomb. This is conveniently analyzed in the Fourier space, using a tri-dimensional Fourier transformation. The 3-D Fourier pattern is a sextuplet of points, arranged as a flat hexagon, the plane of which is tilted according to the two independant phase errors among the aperture triplet. Many triplets can be defined in the entrance aperture, and the corresponding sextuplets in the Fourier volume have varied orientations and overlap. The legacy of phase-closure methods in radio-astronomy indicates that all phases can be calculated from this Fourier pattern if the aperture has enough redundancy. Optimal algorithms for extracting this information yet have to be developped, and their efficiency to be assessed, in comparison with the above-mentioned other known methods applicable to the coherencing and phasing of multi-aperture interferometers.

7. Conclusion

Results on the ground are expected in the coming years, and should help to define successors for the VLT and Keck interferometers. "Exploded" forms of an OWL-type telescope are expected to reach the same limiting magnitude, while improving the resolution 10 times (in the CARLINA case) or 100 times (in the OVLA case). The exciting possibilities of hypertelescopes for high resolution snapshot imaging on Earth justify efforts for finding adequate sites and developing phasing methods suitable for large diluted apertures.

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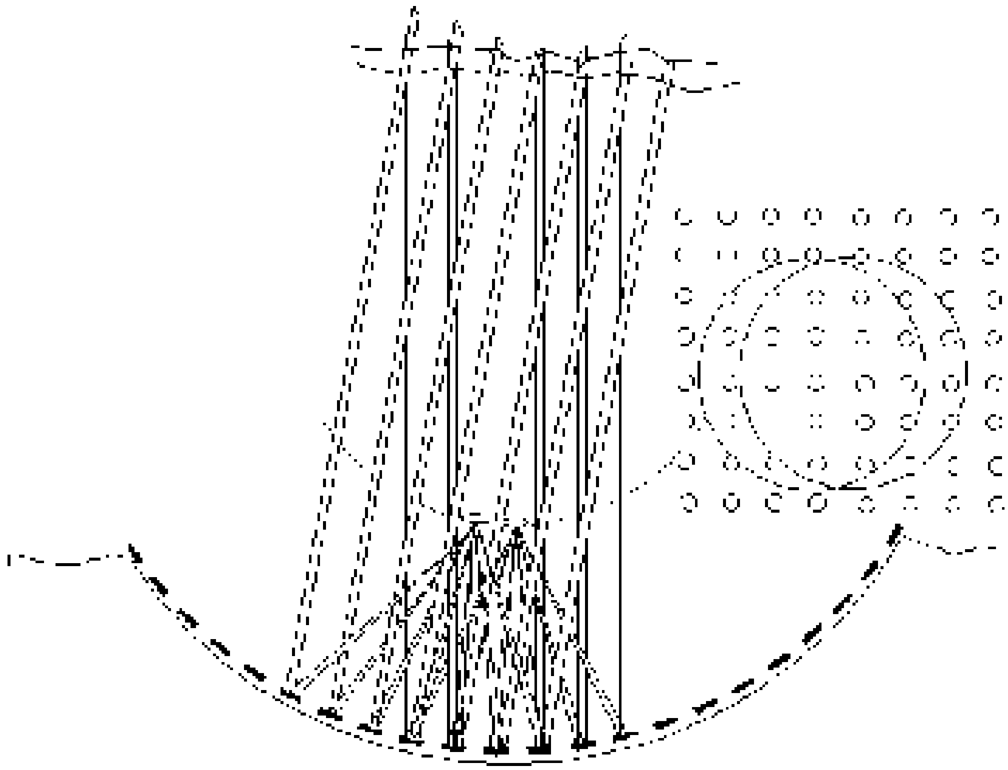

Figure 4. Prospects for adaptive seeing correction, using natural guide stars, in a spherical optical array. For a single turbulent layer L, a bright guide star is selected, up to 15 away from the faint science source, in such a way that both arrays of collected beams intersect at L. If the array of mirrors is perfectly spherical and phased, the layer L induces identical phase errors in both images. These can therefore be measured with a wave analyzer at the brigtht focus, and the error signals be fed to a deformable mirrror near the faint focus. Observing one more bright star can in addition provide a map of the ground turbulence, including mirror errors. Additional layers of turbulence can probably be mapped with more guide stars, selected in such a way that arrays of beams intersect at each layer. The low layers affecting the converging beams, between the mirror array and the foci, can presumably be probed and mapped with weak laser beams propagating between these elements.