Hypertelescope imaging: from exo-planets to neutron stars

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ABSTRACT

"Densified-pupil multi-aperture imaging arrays" , also called hypertelescopes, provide a path towards rich images obtained directly at the focal plane. They typically involve a large Fizeau arrangement, with a small attached "pupil densifier" serving to gain luminosity at the expense of field . At scales ranging from kilometers to perhaps a million kilometers, such architectures appear of interest for stellar physics, galaxies, cosmology, and neutron star imaging with the larger sizes . Ground testing is initiated and space versions are proposed, particularly to NASA for its Terrestrial Planet Finder . The coronagraphic imaging achievable with this space version is expected to improve the detection sensitivity by attenuating the sky background contribution. Subsequent larger (150 km) versions can in principle resolve the "green spots" on an Earth seen at several parsecs . Current design work for a precursor array of "flying mirrors" driven by solar sails in geostationary orbit will be presented .

Keywords: Interferometric arrays , hypertelescope, stellar coronagraphy

1- INTRODUCTION

Forms of interferometric imaging through aperture synthesis, using multiple exposures to reconstruct images, have been highly successful at radio wavelengths and also demonstrated in simple cases at optical wavelengths. It however took a long time to realize that man -aperture optical arrays can provide snapshot images, with arbitrarily diluted apertures . This so-called "hypertelescope" approach to imaging may be viewed as a simple modification of the classical Fizeau interferometer. It has a vast potential, particularly in space where large arrays of relatively small apertures may become easy to implement with forthcoming techniques of formation flying .

2- PRINCIPLE OF HYPERTELESCOPES

2.1 THE LIMITS OF DILUTED FIZEAU INTERFEROMETERS

Fizeau considered telescopes equipped with a two -aperture mask at the entrance. The scheme can easily accommodate any number of apertures. It provides direct images in the focal plane, the information content of which increases quickly with the number of apertures. The spread function does not depend on the field location, within boundaries defined by the telescope's aberrations (coma, astigmatism, etc..). The imaging field is thus infinite in principle, although limited in practice by these aberrations . There is however a crowding problem when too many sources overlap their spread functions in the convolved image. The spread function indeed has a broad halo, caused by diffraction from the sub-apertures, which surrounds a central interference peak, appearing if there are more than 5 or 6 apertures, properly phased. Source crowding causes a loss of imag contrast since the image-forming peaks become contaminated by the superposed halos.

The halo also makes Fizeau architectures unsuitable for very large instruments where sub -aperture spacings are much larger than their size . In such cases, which include the Exo-Earth Discoverer, Exo-Earth Imager and Neutron Star Imager concepts mentioned below, the halo becomes much larger than the interference peak and leaves little energy in it .

If the aperture is a periodic lattice, the halo also contains a periodic lattice of side-peaks, also called "higher-order peaks" by analogy with those produced by diffraction gratings. A grid aperture indeed behaves like a crossed diffraction grating, and the higher-order focal peaks surrounding the zer -order peak are radially dispersed into spectra..

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If the aperture is non -redundant, there are no periodic peaks in the halo, but a background of color-dependant speckles surrounding the central white interference peak. If only for reasons of pixel economy and read-out noise , these halo patterns of Fizeau interferometers become difficult to exploit when observing with highly diluted arrays such as those of kilometric or megametric size considered hereafter.

2.2 DENSIFIED PUPIL FOR HYPERTELESCOPE IMAGING

A multi-aperture Fizeau interferometer can however be equipped with auxiliary optics (fig. 1) to "densify " the exit pupil[1]. This intensifies the image and makes it directly usable, with arbitrarily large and diluted primary optics . Most light from an on-axis star becomes concentrated in the central interference peak, if suitable phasing is achieved. This peak moves in response to star motion, within a limited field, without degradation if the pupil densification leaves the pattern of sub-pupil centers invariant. Within the narrow field , the imaging properties of such instruments thus resemble those of ordinary telescopes, hence the name "hypertelescope" adopted fo them . These properties were discussed elsewhere in some detail[2],[3],[4] and verified with numerical simulation, laboratory experiments, and also on the sky with miniature version [5], [6] .

To summarize them, it may be mentioned that there is in the sky a "Zero-Order Field", or ZOF, which i directly imaged . If the aperture is periodic, the celestial ZOF is surrounded by a "Highe -Order Field" (HOF), filling the sub-aperture's diffraction lobe , of angular size λ/d if d is the sub-aperture size. Its sources contaminate the direct image of the ZOF with higher -order peaks. Unfolding techniques, such as discussed below, can reconstruct post-detection a cleaned image of the HOF and ZOF if the number of resolved point sources ("active resels") within them does not exceed the number of apertures N . Such HOF reconstruction i also achievable to some extent with non -redundant apertures. With a non-redundant aperture, up to N^2 active resels can be directly imaged , thus relaxing the crowding limitation, but the dynamic range is degraded. On will therefore prefer non-redundant apertures to obtain direct resolved images and spectro-images of a star's disc. Instead, redundant and even periodic arrays may be preferred for obtaining coronagraphic images of a few un-resolved planets orbiting their parent star. When an exo-planet will itself become resolvable, with arrays larger than 10 or 100 km, non-redundant apertures will again be needed if the sub-apertures are large enough to feed separate coronagraphs up-stream of the beam combiner (Section 4) .

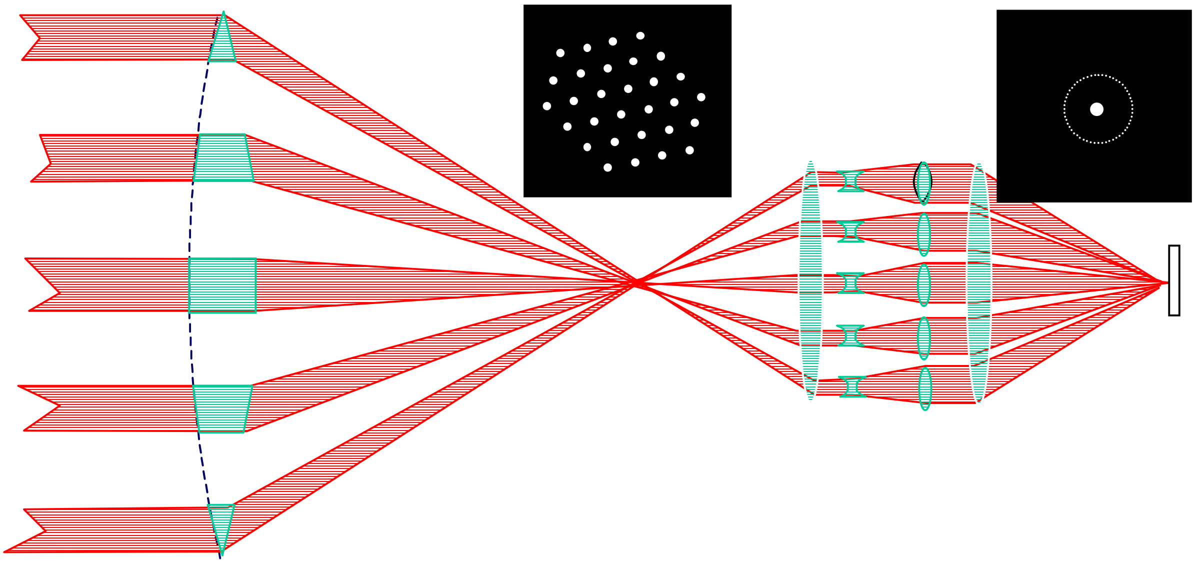

Figure 1: Hypertelescope principle. The Fizeau image at the prime focus of a phased optical array (left, sketched as a segmented lens) has numerous sidelobes if the aperture is highly diluted. With a pupil densifier (right), having an array of Galilean telescopes, light is concentrated into the central interference peak. Off-axis stars provide a displaced peak, up to a limit which defines the Zero Order Field (ZOF). Any source fitting within th celestial extent of the ZOF is thus directly imaged.

The angular diameter of the ZOF is of the order of λ/s where s is a typical spacing of the sub-apertures, between centers. For a given collecting area, increasing the number N of sub-apertures reduces their size *d* and their spacing *s*. It enlarges the ZOF without affecting the luminosity and limiting magnitude. In the N = infinity limit, the ZOF extent becomes infinite, and the instrument thus becomes equivalent to a telescope of same global size, but with luminosity reduced as the effective collecting area.

In hypertelescopes, the classical convolution relation describing the formation of images is replaced by a pseudo-convolution. There is a convolution of the object by a spread function which is the interference function, diffraction pattern from the exit pupil's pattern of centers (an array of Dirac peaks). This convolution is then multiplied (only approximately if the pupil densification is weak), by a fixed "diffraction function" , a windo -like envelope which is the diffraction pattern of a sub-pupil.

This reasoning shows that the field-crowding limitations are identical, for given residual contrast, with or without pupil densification. It also accounts for the echelle grating effect occurring with periodic apertures: like in Fizeau arrays, the interference function is then also a periodic lattice of peaks, spaced in proportion to wavelength. In white light, the peaks therefore become spectra, diverging from a central white peak of zero order. Among the spectra, the different orientations and dispersions may be considered as a form of encoding for each order. The convolution of field sources with this interference function adds spectra of different orders in the central windowed zone. The encoding allows an unambiguous reconstruction of the HOF image from the ZOF pattern.

One way of doing it involves a set of exposures made at adjacent wavelengths, using for example a spectro-imager arrangement. In the (x,y,lambda) data volume thus obtained, the dispersed orders become tilted rods. As proposed by one of us (LK), the volume can be Fourier transformed in 3 dimensions[7]. In the resulting output volume, the rods become tilted planes, intersecting at the origin. Each corresponds to a distinct encoded grating order. and thus contains information on a distinct piece of paving within the celestial HOF The celestial field contained in this piece of paving can be reconstructed by 2D Fourier transforming the relevant tilted plane.

A wider celestial field can be imaged in mosaic fashion, using an arrray of pupil densifiers in the Fizeau focal plane. Each covers a sky region λ/d matching the sub-aperture's lobe, and the crowding limitation applies separately in each of these imaging channels.

3- OPTICAL SCHEMES OF HYPERTELESCOPES

There are different possible optical schemes for hypertelescopes. Michelson's 20-feet beam interferometer is one of them, where pupil densification is achieved by the periscopic arrangement of four flat mirrors, and which can be extended to include many apertures[8]. Another scheme involves an array of telescopes with coudé foci feeding a beam combiner. Such combiners can be arranged to provide either Fizeau or hypertelescope modes of image formation. This is applicable to systems such as ESO's Very Large Telescope Interferometer and th proposed Optical Very Large Array[9], which may span perhaps 10 km in suitable flat sites.

Yet another hypertelescope scheme discussed below is analogous to the Arecibo radio telescope, although with a diluted primary mosaic mirror[10]. We call it CARLINA, name of a composite and ground-hugging alpine flower. On Earth, it requires a spherical site, possibly a volcano crater or a sink hole, up to 5 km in diameter. In space, it only requires formation-flying capabilities for a flotilla of free-flyers carrying mirror elements. Details of corresponding projects are given below.

Fiber-combined interferometers having multiple apertures can also benefit from hypertelescope imaging. Single-mode fibers, propagating light from each sub-aperture with appropriate delay lines, can indeed be bundled tightl at their exit opening, but in such a way as to reproduce the pattern of centers in the entrance aperture. A camera located downstream in the fa -field pattern of diffraction and interference receives a direct image, if adequate piston phasing is achieved. This remains to be verified experimentally with fibers, although a diffractive beam combiner using a micro-lens array, already tested on the sky[11], has somewhat comparabl properties.

4- CORONAGRAPHIC USES FOR IMAGING EXO-PLANETS

Since the solar coronagraph of Lyot, the technique has been extended to circumstellar observing with large telescopes and adaptive optics [12],[13]. New types of occulting masks, suitable for unresolved stars, were introduced in the recent years . Since the exit pupil of a hypertelescope can be filled, and shaped, like that of an ordinary telescope, such coronagraphs can be installed and utilized in a similar way . Recent calculations of signal and noise indicate that such coronagraphic hypertelescopes can in principle gain sensitivity, with respec to other known forms of nulling, for detecting exo-planets[14],[15]. This gain arises in the thermal infr -red, where the planet is bright but surrounded by zodiacal and exo-zodiacal emission and contaminated by thermal photons from the mirrors, etc… , as a consequence of a better rejection of these components in the image . Because part of this background emission is imaged together with the planet, only the fraction of it falling within the planet's resel affects its detection . Instead, the nulling approach using a beam splitter mixes the planet light with the background flux emitted by a comparatively large sky patch of angular diameter λ/d, where d is the sub-aperture size.

In the visible, it can be attempted to detect planets, as faint as 10^{10} relative to their star, with cascaded or multi-stage coronagraphy [16] (fig. 2). This requires that the star be unresolved at the visible wavelengths used, which implies sufficiently small apertures, such as an array's sub-apertures. Residual starlight in a coronagraphic sub-image (image from a single sub-aperture equipped with a coronagraph) of the planet-containing field is typicall speckled. The speckle phases can be measured and corrected by actuators to make them nearly uniform. This causes the formation of an interference peak in the far field . Focused by a lens, this peak appears within a wider pupil image and can be masked without much affecting the planet's light, spread across the full pupil . Another lens then relays the image plane, and the stellar background is much attenuated. The process can be repeated with similar additional stages, until too few stellar photons remain for measuring speckle phases . This residual starlight may then no longer affect the planet detection .

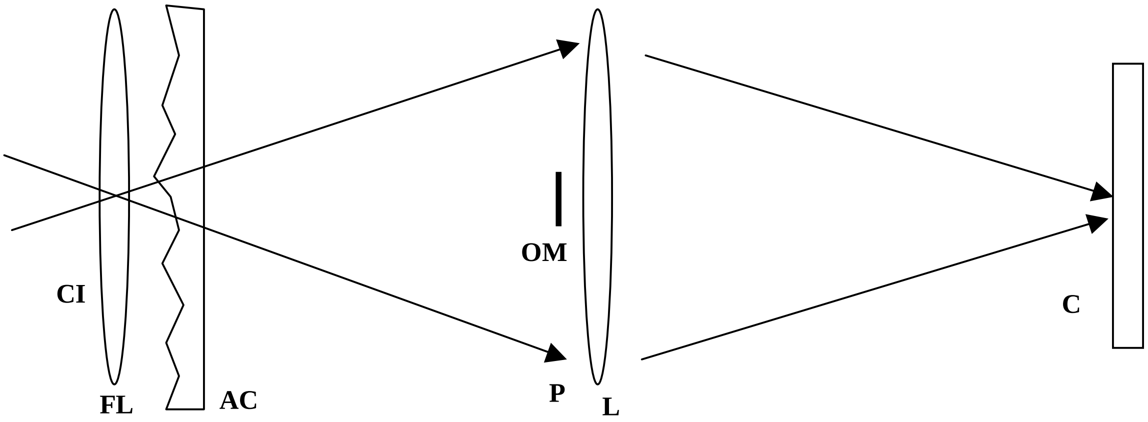

Figure 2 : Principle of multi-stage coronagraphy for telescopes and hypertelescopes . The cleaned image CI, output of a first coronagraph (not shown), is relayed by field lens FL and lens L to the camera C . The active corrector AC equalizes the phases of the star's residual speckles, so as to generate an interference peak or "ghost star" on the occulting mask OM, which therefore removes most of the stellar residue from the camera image . A wave analyzer, not shown, measures the stellar phase pattern in CI . Several such stages can be cascaded for deeper nulling, as long as the last one receives enough stellar photons to activate the active correction.

5- GROUND AND SPACE VERSIONS CONSIDERED

5.1 VLTI-HT: HYPERTELESCOPE IMAGING A THE VERY LARGE TELESCOPE INTERFEROMETER

The recent success of VLTI observations in Chile, with the prospect of coupling all four 8-meter telescopes and smaller ones , has encouraged us to consider a hypertelescope imaging mode, also providing coronagraphy. The initial proposal[17] for interferometry with several large telescopes, and the subsequent design of the VLTI by the European Southern Observatories, occurred well before the possibility of hypertelescope imaging was found. However, minor additions to the beam-combining optics can now provide this capability. The few apertures cannot provide much field, but there is a significant luminosity gain Also of interest is the coronagraphic performance attainable with accurate adaptive optics , using one or several cascaded stages of coronagraphy . A proposal for an instrument at the combined focus is currently considered .(Lardiere et al. , this conference).

5.2 OVLA-HT : HYPERTELESCOPE IMAGING WITH "OPTICAL VERY LARG ARRAY SCHEMES

The study of an Optical Very Large Array (OVLA) began in the late 1980's, a decade before the possibility of hypertelescope imaging was found. This possibility now provides a major enhancement of the science achievable with OVLA's. Several optical and mechanical schemes are considered, with either mobile telescopes, requiring no delay lines , or semi -fixed telescopes combined as a hierarchy of triplets with delay lines. Conceivably, tens or hundreds of telescopes can be combined in either way . The aperture pattern is preferably adjustable since the optimal redundancy is object -dependant: field coverage can be traded against dynamic range. Array sizes as large as 10 kilometers, or perhaps even 20 kilometers in the infra-red, appear feasible at flat sites such as the Salar d'Uyuni in Bolivia.[18]

5.3 THE CARLINA SCHEME FOR "EXPLODED" EXTREMELY LARGE TELESCOPES (E-ELT)

This dilute optical version (fig.3) of the Arecibo dish uses a concave site to carry a giant fixed spherical mirror , built in the form of a dilute mosaic. Its mirror elements are fixed and anchored to the bed rock by separate rigid tripods. They are slightly concave to match the global curvature, and pre-aligned to tolerances consistent with the thermal, tidal, microsismic, etc. geometry fluctuations of the crater, typically amounting to tens of microns. At Arecibo, the pylons and cables which carry the detector at the focal sphere, and drives it to track the source, are costly and cannot be extrapolated to much larger sizes. Ideally , a number of focal combiners should be driven independantly , each with a corrector of spherical aberration and pupil densifiers, to observe several sources across the very wide primary field of the instrument . Simultaneous science can indeed be achieved with many focal combiners if these are freely movable, and this obviously enhances the science/dollar efficiency of the instrument. Free-flyers in space offer ideal flexibility in this respect, with even the possibility of a fully spherical "bubble" array[19] . Pending space versions, a possible precursor on Earth involves tethered or dirigeable balloons, to carry the focal combiners above a crater-based array of mirrors . The fairly stable tilt and piston errors of the ground mirrors are corrected in the focal optics, together with turbulence, by adaptive optics[20].

We have begun some testing (fig.4) of the balloon option, using a 6–meter helium balloon, equipped and operated by one of us (HLC). Three high-modulus fiber cables are converging from ground anchors towards the balloon's gondola, itself suspended from the balloon by a length of cable to decouple the wind -induced roll motion. Residual translations of the gondola were monitored in various wind conditions, with a ground-based telescope and attached cam-corder . Preliminary results at low altitudes of 15 to 20 meters indicate a few millimeters RMS of gondola translation, at frequencies of 0.1 Hz . Active stabilization of the critical optical components appears feasible, using for example 3 laser range -finder beams for error signals . The continuous tracking of the star's image will require 3 compute -controlled winches. Corrections will be made by actuators, preferably located in the gondola to deal more efficiently with the cable's inertia, and their elasticity , mostly caused by sag.

. Dirigeable balloons also appear of interest for the higher altitudes needed fo a full scale CARLINA filling a 5 km crater, such as the E-OWL "exploded" version which we have proposed [21] to ESO for its Over Whelmingl Large Telescope .

Among the possible sites, a volcano crater south of Mexico city has been identified by S. Cuevas (private communication) . Before developing such sites, much initial testing and evaluation of CARLINA hardware can be achieved on a flat site with a single ring of ground mirrors, although the sky coverage is then reduced.

Pending the availability of stabilized balloons, some canyon sites can also support cables carrying focal optics above mirror segments at the bottom. The cliffs on both sides then replace the high pylons used at Arecibo. The Artuby canyon in the southern Alps also has a stable r einforced concrete bridge, 186m above the river bed, which is dry and about 50m wide between the vertical cliffs . Cables can be arranged for equatorial tracking with a single motor , and a fixed coudé image. This may allow simple testing in the sho rt term at lo -cost, and subsequent up-grades by adding mirror elements. We currently explore both the balloon and the canyon options for a hypertelescope capable of achieving useful science in the short term, and to grow if needed.

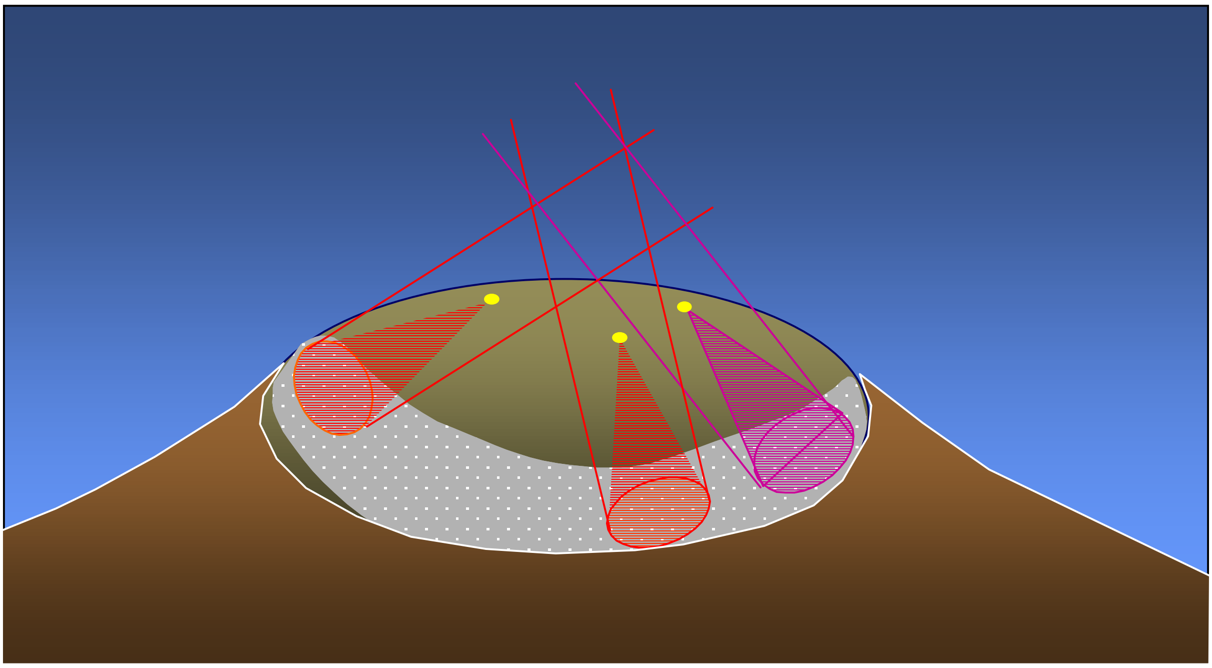

Figure 3: : CARLINA scheme for hypertelescopes. Like Arecibo's radio-telescope, it uses a spherical site to carry elements of a spherical mosaic mirror. The optical mirror is diluted, with many fixed segments carried by stiff tripods . Balloons, tethered or propelled, move along the focal sphere to track the images of observed stars. Each carries a Mertz corrector of spherical aberration and coma, a small pupil densifier (or several arrayed at λ/d pitch) and adaptive optics. Coronagraphic and other auxiliary instruments, as well as the detectors, are also carried by the balloons. Fixed coudé foci can also be directed towards ground locations . At suitable sites, array sizes as large as 5 kilometers may be achievable, but the effective aperture sizes are limited to 1 kilometer by the Mertz corrector. At F/2, its diameter is 1% of the effective aperture size.

We have also explored the feasibility of adding an optical hypertelescope at the 330m Arecibo radio-telescope. Some of the aluminum panels in the radio dish can be replaced by optical mirrors anchored directly to the bed-rock. A Mertz-type corrector of spherical aberration[22] can be installed on the focal structure. A small pupil densifier follows, and it must move to track the sub -pupil motion within the pupil image. Adaptive optics is also needed to correct the positioning errors of primary mirrors and the atmosphere, but it is unnecessary fo observing by speckle interferometry. The effective aperture size reachable is limited to about 60 to perhaps 100 meters by the Mertz- corrector. For initial assessment, a few optical mirrors, of 20 to 100 cm size can suffice fo the ground array, and their number can later be increased if justified .

Our study has however identified significant p oblems: 1 - it is difficult to install optical hardware .in th detector domes without disturbing the radio operation; 2- the oscillations of the suspended structure , of the order of 10 cm, require extra correction ; 3- the local climate and seeing are moderately adapted to visible observing; 4- safety rules during the frequent radar emissions at high power preclude human attendance in the focal area ; 5- very few nights are expected to be allotted yearly to optical observing, given the pressure fo radio observing . A serendipitous side-looking optical package attached to the main radio detector would suffer from fast image drift , which would make it little productive at the milli -arcsecond angular resolution considered. .

A smaller (50 m dish) radi -telescope of similar design exists in Armenia, and has a more rigid tripod support to carry the focal hardware. However, the aperture size which would be usable in optics would be limited to 10 or perhaps 20 meters with a Mertz corrector of manageable size.

The current studies of Extremely Large Telescopes (ELT's) pursued at ESO, in California, etc… consider Keck-like schemes with a large pointable mount carrying a man -element mosaic mirror. It is of interest to compare such concepts with "exploded" versions where a similar set of mirror elements is arranged as a larger diluted mosaic, arranged as a CARLINA. One gains resolution, if suitable adaptive optics is utilized. The limiting magnitude is unaffected.

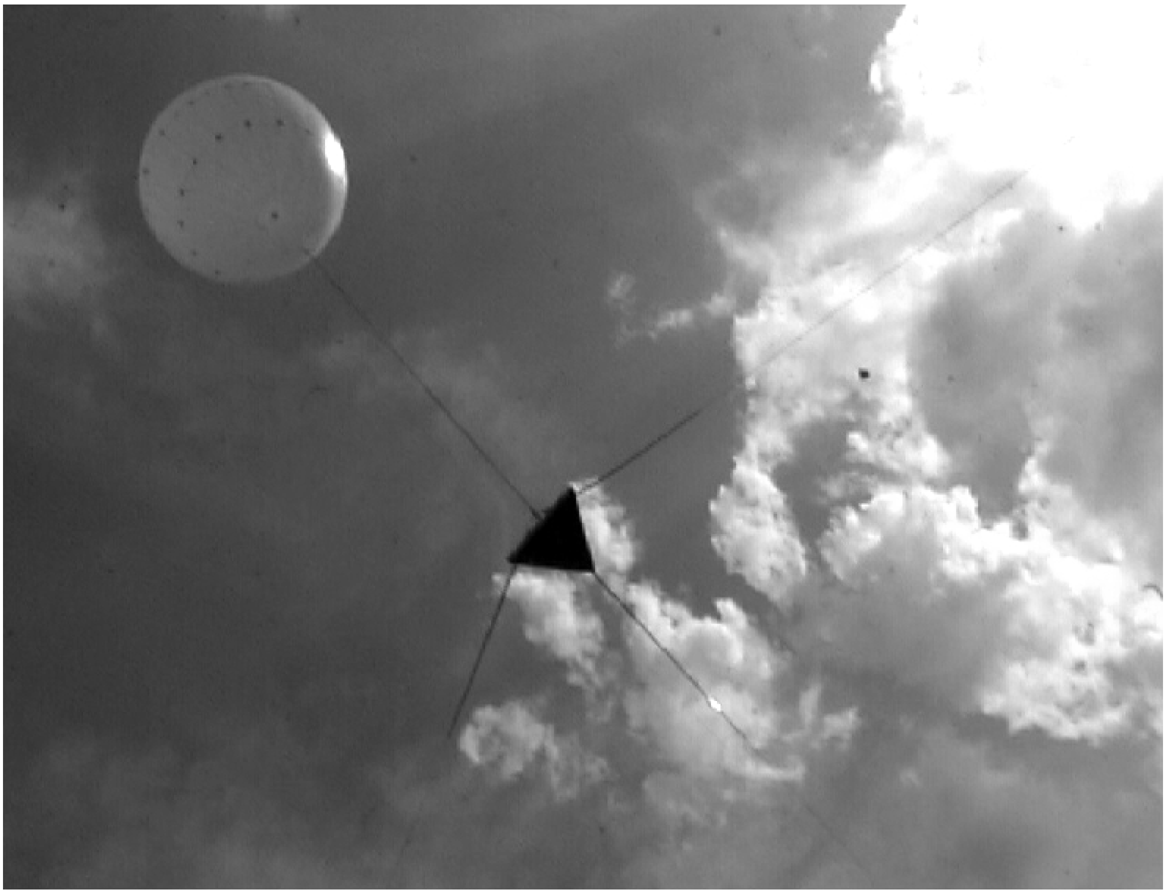

Figure 4: Stability test for the focal gondola of a CARLINA hypertelescope. A 6 -meter balloon lifts a gondola positioned by 3 high-modulus fiber cables. In the completed instrument, a diluted spherical mosaic of ground-supported mirror segments will focus a star image at the gondola -supported focal optics.. The image will be tracked by 3 winches pulling the cables. Fine guiding corrections, with microns of accuracy, will be achieved by on-board actuators. For designing the fine-tracking system, the passive jitter of the gondola is here being measured with a small ground telescope and camera.

A critical element in the comparison is the issue of field crowding: the limitation of N (or N^2 for a non-redundant array) active resels per lobe of the sub-apertures can affect the observation of very dense fields, and particularly the deep fields of remote galaxies which are a major cosmology target for such large instruments. It can however be shown that the crowding limitation remains invariant when exploding a mosaic mirror: before being exploded, a mosaic mirror with N elements of size d cannot provide information on more than 1 active resel per Airy disk, of celestial area $\{(\lambda / (d N^{1/2})\}^2 = \lambda^2 d^{-2} N^{-1}$. Once exploded, the image becomes uselessly smooth if the object has more than N active resels within $(\lambda d^{-1})^2$, which also amounts to 1 active resel per $\lambda^2 d^{-2} N^{-1}$. In the case of an exploded OWL (E -OWL) with 7,000 mirrors of 1 meter, the crowding limitation would be at 7, 000 active pixels in a sky patch of 0.1 ar -second, or 0.7 active pixels per square milliarcsecond . The comparison is however delicate since the non -exploded aperture still gives a usable image with more sources than resels, whereas the exploded version then gives a flat image with no usable contrast. More detailed assessments of the comparative performance and science impact will be needed before selecting concepts for such large instruments .

E-ELT's will also have a possible advantage over ELT's of similar collecting area when it will be attempted to search "lost planets" and other dark massive bodies located within a few parsecs, using "Diffractive Gravitational Lensing Events" [23] (DIGLEs) . A foreground lensing mass, if sufficiently symetrical, indeed projects "focus-less" images of background galaxies located at megaparsec distances. The aperture of an ELT or E-ELT can serve as a viewing screen, and can provide in its focal plane an image of the Einstein ring. The ring is typically 0.01 to 0.1 arc -second in size, in accordance with the metric size of the diffraction peak projected from the gravitational lens onto the ground aperture . The angular resolution is of the order 0. 01 nano-arc-second in the visible. The discs of stars in the background galaxy are usually resolved, since their projected geometrical image typically spans tens of meters. As these stellar images drift across the diluted aperture of an E-ELT, the star's dwell time on the sub-apertures varies as $N^{-1/2}$, as does the photon count detected during thi time, but the probability of detecting such events with all mirrors varies as $N^{1/2}$, if N is the number of apertures , at constant total aperture area. Exploded apertures are therefore preferable , but the sub-apertures must be large enough for collecting enough photons. Unlike the MACHO events produced by "geometric" gravitational lensing at much larger distances, DIGLEs are repeatedly observable on a given lensing mass as different stars of the background galaxy cross the line-of-sight. DIGLE surveys will be of interest to investigate the presence of cold dark matter They are becoming feasible with current advances in telescopes, adaptive optics, coronagraphy and the new photon-counting CCDs .

An E-OWL or other E-ELT can probably be made according to the CARLINA scheme with resolution reaching 100 micro-arcseconds if a suitable 5 km crater site is found . The crater depth needed is of the order of 1000 meters, for an effective aperture size of one kilometer, requiring an 8-meter corrector at F/2 . Thi obviously implies more site constraints than for ordinary ELT's . However, the dilute array of tripods carrying mirror elements in the crater may be easier to build than a huge pointable structure. The latter may however provide sky coverage beyond the maximal zenith distance (about 50°) observable from a crater . Another element of the comparison is the adaptive optics system , which is essential for both instruments . Wave analysis algorithms have been explored for measuring piston errors in hypertelescopes[24],[25] and the LIDA technique proposed by C.Townes [26] may become applicable, although perhaps only in the infra-red according t his calculations. The total number of actuators needed is the same for compact or exploded mosaics.

5.4 THE EXO-EARTH DISCOVERER (EED) PROPOSAL

In space, flotilllas of satellites are obviously needed for optical arrays in the size range from kilometers to hundreds and thousands of kilometers . Following the early proposals [27],[28] where small solar sails wer considered for accurate positioning, ESA explored the matter [29] and concluded in the feasibility of drivin elements with sufficient accuracy and reliability, using ion thrusters . This led to the DARWIN proposal [30] , followed by the TPF proposal [31] to NASA. Then arised the possibility of hypertelescope imaging. Its coronagraphic capability appeared promising for exo-planet detection, particularly with the efficient background rejection mentioned above in Section 4 .

Among the possible hypertelescope schemes, those with a concave primary array and focal combiner appeared well suited for space versions with multiple free-flyers . Either spherical (CARLINA scheme) or paraboloïdal shapes can be considered for the primary array: The sphere requires additional optics in the beam combiner (fig. 3) for correcting spherical aberration, but can feed images of many stars to as many combiners exploiting it large (tens of degrees, and fully panoramic with the "bubble" version[32]) primary field . The paraboloïd can reach a faster primary focal ratio, possibly reaching F/0.25 for a co-planar ring and focus, and the large Mertz corrector vanishes from th beam combiner, which however has to be single and located on-axis .

In either case, the corrected primary image, a Fizeau image, enters a pupil densifier, the simplest form of which has a pair of micro-lens arrays installed between a collimating and a focusing lens or mirror (fig.1). In the collimated beam, pairs of facing micro-lenses are arranged like tiny Galilean telescopes, oriented backwards. densified pupil can be obtained at the second micro-lens array . In the proposed EED version, this pupil resembles that of one Keck telescope, although the missing central element can here be retrieved, by pushing the focal combiner slightly off-axis, for minimal obscuration and optimal coronagraphic performance .

Visible and infra-red channels are separated by a dichroic beam splitter , before or after the densifier. In the infra-red channel, the stellar coronagraph is attached downstream from the densifier. In the visible channel , the planets of not-too-distant stars tend to be separated by the sub-apertures, while the star disks themselves tend to be resolved by the array. Pre-combiner coronagraphs, installed in each sub-image are thus of interest for visible observing. Each of these can have several cascaded coronagraphic stages containing wavefront analyzers and phasing actuators, as mentioned in section 4. This can in principle attenuate the star light residues down to a few photons per speckle and speckle lifetime. With the speckle lifetimes expected in space, hundreds or thousands of seconds, this residual count approaches the detectability level for the planet itself in a non-contaminated image .

An EPICURU [33] mission was proposed to ESA as a technical and science precursor for the "Exo -Earth Discoverer" (EED), itself previously proposed to ESA and NASA[34] as another possible version of their DARWIN and TPF instruments . The hypertelescope option was included among the industrial studies contracted by NASA. Among the contractors, Boeing/SVS and the associated Science Team explored several hypertelescope variants. The study confirmed the sensitivity gain achievable with hypertelescope imaging, relative to DARWIN's nulling technique using a beam-splitter. The exposure time for detecting an exo-Earth in the infra-red decreases 10 to 100 times, depending on the number of apertures, at given collecting area. Optimal array size , sub-aperture sizes and count have been explored through calculations and simulations. The added benefit of direct high-resolution images for general obs erving is also of obvious interest .

Since the primary array, with its spherical shape, has a broad field (tens of degrees), small rigid solar sails can have enough thrust to provide the slow global slewing and coarse pointing needed. Sails capable of dr iving ultra-low mass free-flyers are still studied in our group[35],[36] and elsewhere. The focal combiners, several of which can be used simultaneously for extra science, need to respond faster for fine image acquisition and tracking . Larger sails are thus needed there, but should be replaced by ion rockets if the size needed is so large as to cause pupil obscuration .

Early orbital tests are desirable for developing the techniques of formation flying. Our group investigates the design of nano-satellites driven by solar sails, and plans to test them in geostationary orbit . "Gossamer" free - flyers having a mass as low as 100 grams are considered. With a rigid sail of area 0.1 square meter, driving a membrane stellar mirror of comparable size, accelerations can reach 10 microns per square second, providing motions of 5 m in 1000 seconds. Passive stability, in terms of self-repointing towards the sun, is a desirable property of the sail system . The sail can be configured for such stability, but tends to have endless pendular oscillations unless the oscillation energy is removed by passive damping processes, currently being explored .

5.5 EXPANSION TOWARDS AN EXO-EARTH IMAGER (EEI)

Once control techniques for a flotilla of mirrors will be mastere d, it will perhaps not take many years to expand their size from hundreds of meters to hundreds of kilometers. This is the size needed to obtain well resolved visible images of an exo-Earth within a few parsecs . Simulation [37] have shown that visible "portraits" of such planets can be obtained in 30 mn of exposure, using a 150 km hypertelescope with 150 mirrors of 3 meters. . A non-redundant arrangement of the apertures, with three concentric rings , was found to provide an optimal trade-off between contrast and field .

Efficient coronagraphy is essential for removing the stellar stray light. The star being highly resolved by the array, at visible wavelengths, and also typically seen separated from the planet by the sub -apertures, it is again of interest to use separate coronagraphs in each beam before combining them. Again, these coronagraphs can have several cascaded stages, each containing adaptive optics, for a higher rejection[38] . The general design of the EEI can be very similar to the E ED., although a paraboloidal primary array may be preferred to avoid the need for a very large Mertz corrector at the beam combiner . The wide primary field of the spherical array , allowing many focal combiners to observe independantly , may howeve justify the development of focal correctors themselves segmented and carried by separate free-flyers . If the primary sphere is a full bubble [39], entirely but sparsely paved with mirror segments, then these do not have to move for accessing the whole sk y . Motion is needed only for the focal combiners .

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5.6 FEASIBILITY OF A NEUTRON STAR IMAGER (NSI)

For ever larger optical arrays, sizes will ultimately be limited by the number of photons received per resel. The, number decreases when exploding an array since it shrinks the celestial resels The Crab pulsar , believed to contain a compact neutron star of visual magnitude 18, requires huge baselines beyond 100,000 km to resolve the 20 km neutron star , but its extreme luminance can provide enough photons per resel through such a highly diluted aperture, with sub -apertures of a few meters . A "Neutron Star Imager" hypertelescope, spanning several hundred thousand kilometers.is therefore conceivable. It can be similar to the EED or EEI., but equires primary mirror elements as large as 8 meters to concentrate their focal Airy peaks within a comparable size, so that they be collectible with beam-combiner optics of manageable size.

The coherencing and phasing of such huge interferometers is d ifficult to achieve by external references alone, since ordinary reference stars do not provide enough photons per resel. The array can be accurately shaped, within Rayleigh's tolerance, with lase -based internal measurements, using for example a laser s ource at the curvature center of the primary sphere . Acquiring the high-resolution pulsar image within the ZOF or HOF is then a matter of scanning the beam combiner, itself internally phased, along the focal surface. External references are only needed to locate the scan window .

Alternately, the neutron star image can be acquired with the primary array shrunk to a small size , decameters or kilometers . If the image is kept centered in the ZOF while the instrument is enlarged to its nominal size, which causes a zooming effect, then no long-range metrology is needed to reach the full span and resolution.

Very few optically emitting neutron stars are yet known but it is tempting to clarify their physics with resolved images and spectro-images . At the nano-arcsecond resolution of 100,000 kilometer arrays , gravitational "seeing" generated by nearly static masses may require corrections by the adaptive optics system . Gravitational waves, emitted by binary stars, etc.. close to the line of sight, are not expected to generate "seeing", according to general relativit [40], in spite of interpretations by several authors (including one of us[41]) which proved incorrect. Scalar-tensor theories of gravity may however be compatible with such effects [42], and observations with th extreme sensitivity of a NSI are therefore of interest. Companions of neutron stars display strong relativistic effects, but their proximity to the star in principle attenuates any "seeing" effect which could be generated .

6- RADIO HYPERTELESCOPES IN SPACE

Hypertelescope imaging is in principle achievable at any wavelength, and particularly beneficial if detectors are multi-pixel and not photon-limited. In the radio range, heterodyning techniques have been highly successful for long-baseline and very-long-baseline interferometry, mostly Earth-based but now also including extra antennas in space. The hypertelescope mode with many apertures however intensifies the signal before detection, since it concentrates the halo energy, and therefore can improve the signal/noise ratio if the detector is not photon-limited. Multi-pixel detectors are then of interest to exploit the direct image. At radio wavelengths, diffraction by the sub-apertures can require rather large beam combiners, for example 300 meters for a 100,000 km array , assumed shaped as an F/1 paraboloïd, of 300m mirrors operating at 1 mm wavelength .

For future ground arrays such as the ALMA, the direct beam combination of a hypertelescope version howeve appears impractical, if only because huge delay lines or crater sites would be needed . It appears feasible in space however .

7- CONCLUSIONS

Once large optical arrays will become feasible with two or three apertures, adding many more will become a natural endeavor, considering the fast improving information content in direct snapshot images . On Earth and in space, new opportunities are arising for hypertelescope systems of increasing size and collecting area . They will initially be of interest for: 1 - stellar physics, by providing resolved spectro-images of stellar discs; 2 - exo-planet observation and the search for life, involving the detection of photosynthetic spots; 3 - active galactic nuclei and cosmology with deep-field images; 4- - neutron star physics and general relativity testing.

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