*A proposed observatory mission:*

# Hypertelescope Optical Observatory ( HOO)

## 1 to 100km flotilla for direct images at microarc-second resolution on stars, exo-planets and deep fields


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**Abstract**

Following earlier proposals of interferometric flotilla concepts for space, and hypertelescope versions for direct imaging and coronagraphy, an updated observatory-type instrument is now proposed in the form of a larger Hypertelescope Optical Observatory . Like a conventional telescope, but with the much higher resolution provided by its meta-aperture diameter expandable from 1km to 10km and perhaps 100km, it can provide rich direct images and spectro-images of varied sources. High limiting magnitudes, well beyond those of Keck, HST and JWST will be attainable if more collecting area is installed, in the form of thousands of flying mirrors which can be as small as 30mm.

The optical design can be similar to that of the ground-based hypertelescope prototypes currently tested [1] , and the kilometric version also studied [2] . Three options, previously described for the Luciola proposal [5], are again considered for the flotilla's drive and control system : 1- conventional micro-thrusters attached to each mirror; as recently tested in orbit by the pair of PRISMA micro-satellites; 2- small solar sails; 3- laser trapping in interference fields, providing passive stabilization at sub-wavelength accuracy .


## 1. Introduction

Interferometry at radio wavelengths has greatly improved its imaging performance and discovery potential when tens and hundreds of antennas became connected, pending the 100,000 considered in some current projects . Similar gains are expected at optical wavelengths, with the novel form of interferometer called “Hypertelescope” . Ground-based prototypes are being tested toward a dilute meta-aperture spanning a kilometer and combining hundreds of small mirrors. And space versions involving a flotilla of many small mirrors have also been studied since 1996. For a given collecting area and resolution , and likely also for a given cost, many small apertures provide a better imaging performance, in terms of dynamic range, than fewer large ones.

The HOO is intended to be an updated and larger version of the Luciola hypertelescope flotilla previously proposed to ESA . It incorporates new design concepts toward more flexibility , upgradability and expandability toward a 10 km or larger meta-aperture size.

Beyond conventional interferometric and coronagraphic techniques proposed for exoplanet detection in space, hypertelescope flotillas of many small mirrors can provide direct images with a high information content and dynamic range. With a meta-aperture size reaching 100km, not to mention the 100,000km also studied for a later generation of hypertelescopes in space, morphology details are in principle resolvable on some habitable exoplanets [17] . At exoplanet sites containing photosynthetic life, seasonal variations which may be observable spectroscopically may provide a robust signal for its detection.

The HOO, as a giant dilute telescope, is intended to be an observatory instrument with broad capabilities on many object types, including the faintest galaxies beyond the current magnitude and resolution limits of HST, JWST, and forthcoming large ground-based instruments equipped with a Laser Guide Star [1] , such as ELTs and the kilometric-sized "Extremely Large Hypertelescope" (ELHyT) [2] , currently tested with the 60-200m "Ubaye Hypertelescope" precursor [3] .
The HOO will thus not be restricted to exo-planet science, but usable like conventional telescopes on most celestial sources, for stellar physics, or observing neutron star and black hole environments, gravitational lensing, and deep-field imaging for cosmology, as discussed in the Luciola proposal previously submitted to ESA [5].

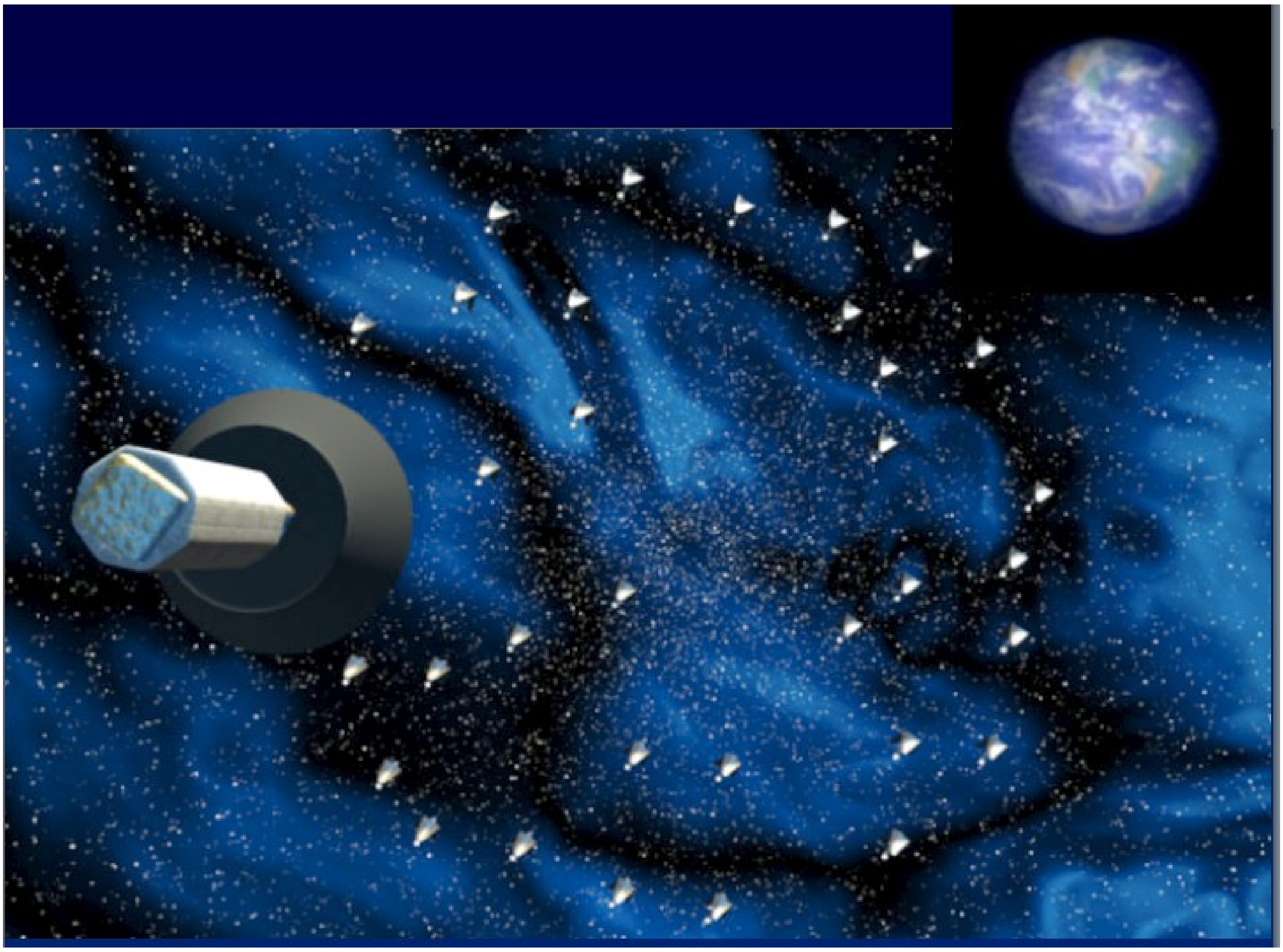

Figure 1: Artist view of the "Exo-Earth Discoverer" hypertelescope, ( courtesy NASA ). A flotilla of small mirrors, driven by similarly small solar sails, focuses star light toward one or more focal spaceships. Alternative driving options also considered are conventional micro-thrusters or laser trapping . Self-deploying versions, reversibly expandable between meta-aperture sizes in the range from 100m to 1, 10 or perhaps 100km , will be of interest for a broad diversity of science targets. The inset at top right is a numerical simulation of an Earth's direct image, recorded by a 100km hypertelescope at 3 parsecs. It has 100 sub-apertures of 3m.

Following the early TRIO proposal of an interferometer flotilla , the subsequent DARWIN version studied by ESA, and the initial hypertelescope proposals to NASA and ESA ( LOVLI, Exo-Earth Discoverer, Epicurus and Luciola ), the PRISMA test in orbit has supported the concept of a flotilla driven by micro-thrusters. As an effort to reduce the cost of Luciola, while using more mirrors of smaller size, the alternate concept of a "laser-trapped hypertelescope flotilla" was developed [6] and laboratory testing undertaken in high vacuum . If it becomes validated, it may drastically simplify the flotilla hardware, and its deployment across 100 km at the Lagrangian L3 point, as well as reduce the cost. It also favors smaller mirror elements, down to perhaps 30mm, with a million of them for a collecting area comparable to an ELT. The resulting theoretical dynamic range in the direct image would then also reach $10^6$, and in fact more since a form of apodization is achievable by decreasing the mirror density toward the edge of the flotilla, as achieved in radio arrays . Coronagraphic masking is also applicable.

The HOO concept which is proposed is flexible in terms of the flotilla size, expected to be adjustable from perhaps 100m to 10km or even 100km. The optimal size of the mirror elements and their number will have to be defined , as well as the feasibility of upgrades with subsequent deliveries of additional mirrors after some years of operation, as traditionally done for radio-interferometry arrays of antennas.

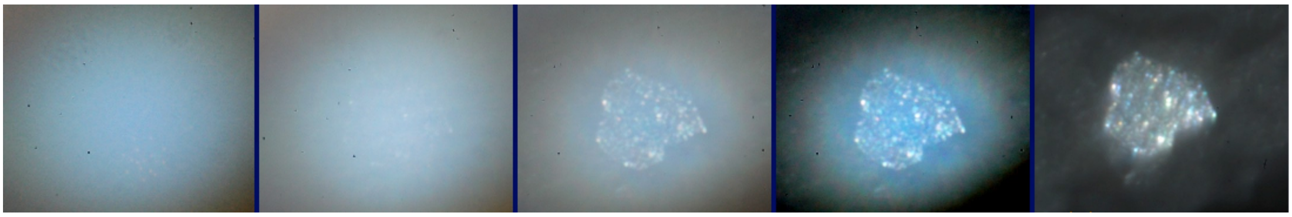

Figure 2: Laboratory images of an artificial star cluster, seen through Fizeau masks having various numbers of sub-apertures , randomly patterned. From left to right: 15, 50, 235, 600 and the full meta-aperture. The decreasing contamination by the sub-aperture's broad diffractive envelope is clearly evidenced. The Fizeau mask can be rotated during the exposure , for simulating aperture supersynthesis, which improves the image obtained with few apertures, but negligibly with many . Also, cases with large or small sub-apertures providing equal collecting area have been compared ( not shown here) to verify the theoretical gain of imaging performance in the latter case.

## 2. Science with milli- to microarcsecond resolution , direct imaging, and a high limiting magnitude

The history of discoveries in Astronomy, since telescopes began operating in the hands of Galileo, has been strongly influenced by the steadily increasing size of their aperture. As larger new telescopes became operated, they have often shown fainter sources or unexpected detail of major significance . The prospect of greatly improving both luminosity and angular resolution in future instruments such as interferometric flotillas of mirrors raises high hopes for abundant discoveries in many fields of astronomical research, including cosmology, astrobiology and perhaps SETI.

In the way of interferometry, the enhanced form called “hypertelescopes” was introduced for utilizing numerous sub-apertures and efficiently provide direct images . Its luminosity, identical to that of a monolithic telescope having equivalent collecting area, thus implies the same deep-field imaging capability as HST or the forthcoming ELTs when reaching a comparable collecting area, the cost of which should be less if the mirror elements are smaller .

### 2.1 Exoplanets

The spectacular recent progress of exoplanet observing is a strong stimulation toward further improving the instruments, especially for observing habitable exoplanets. Much of the rationale discussed for exoplanet science is relevant to the HOO, but its resolution, coronagraphic capabilities and the limiting magnitude reachable once upgraded bring further possibilities. Among these are:

**Resolved images of exoplanet transits, and spectroscopy of the refractive arc**

With a kilometric hypertelescope, transiting planets such as discovered photometrically by Kepler are opportunities for resolved images resembling those of the Sun-Venus transit events observed in the recent years . Briefly during immersion and emergence, these have shown spectacular crescent arcs likely resulting from grazing refraction of solar rays through Venus' high atmosphere.

Comparable images can be expected to become observable with the HOO on transiting exoplanets within a few parsecs. Because the crescent arc is little contaminated by direct starlight, this can in principle greatly increase the sensitivity of spectroscopy for probing the exoplanet's atmospheric absorption, and searching for bio-signature features. Instead, the coronagraphic observing of the same exoplanet at a different orbital phase, when it becomes well separated from its parent star, will likely be difficult for habitable exoplanets, even with a hypertelescope.

**Bio-signature signals observable at microarc-second resolution**

Beyond the 10km limit of meta-aperture size mainly proposed here, the 100km size previously discussed [17] for an " Exo-Earth Imager" can in principe provide much more detail on habitable exoplanets within a few parsecs. In particular the "Indian Summer signal" , i.e. the possible seasonal spectroscopic variation of photosynthetic life in some resolved zones at mid-latitudes, on exo-planets having a spin axis suitably tilted about their orbital plane, is of interest as a detection target since it can be a robust bio-signature [18].

Whether or not the necessary resolution and extreme coronagraphic camera can be planned as a possible upgrade of the HOO, or instead would require a separate mission at a later stage, will have to be studied.

**Supernovae and extragalactic Cepheids**

SNe are very rare events in our galaxy: typically a few per century. Conversely 2 or more SNe are discovered per year within the VIRGO cluster alone and in a 3 times larger volume, a hundred SNe could be detected at least, by an interferometer for an equivalent collecting area of a 10m telescope. Direct spatial information on the structure of the expanding ejecta, across different spectral lines would be obtained by a kilo to deca-kilometric imaging array. Thus enabling us to follow the details of the SN explosion and the complex mechanisms that govern the structural evolution within the local univers.

With 10 km baselines we will measure the individual members of star-burst HII regions in the Magellanic Clouds, the kinematics of compact clusters like in 30 Doradus by measuring the proper motion of member stars bringing news constrains on their IMF, multiplicity of stellar population and finally test the evolutionary scenarii of such clusters like star evaporation for instance.

## 2.2 Deep fields and cosmology

The modest limiting magnitude of existing interferometers, yet observing through the atmosphere in the absence of a laser guide star, has precluded work on deep sky sources. Hypertelescopes on Earth however may become capable of blind phasing with a Laser Guide Star, and thus reach high limiting magnitudes . In space, the wide isoplanatic patch, allows phasing hypertelescopes with a natural guide star , and reaching a high limiting magnitude, same on unresolved sources as with a monolithic telescope of equivalent collecting area.

This opens the way to a vast new realm of high-resolution imaging on:

- galaxy structures, including AGNs and the environment of central black holes,
- gravitational lensing bodies and background sources, including the predicted brief diffractive transients from " free floating planets" at sub-parsec distances [19].
- cosmologic sources, including little resolved galaxies fainter than those seen in the HST Ultra Deep Field, if the collecting area exceeds its $6m^2$ .
- optical counterparts of gamma ray bursts
- extragalactic supernovae and Cepheids

## 3. The HOO concept

Like Luciola [5], the HOO has a dilute flotilla of many small mirrors, belonging to a common spherical or paraboloïdal locus, and feeding light to one or more focal spaceships. For accurate positioning, it uses laser metrology systems such as discussed for Luciola, also studied by ESA, and possibly including the coarse positioning technique tested with the pair of PRISMA satellites. The new option , absent in the original Luciola proposal, of laser-trapped mirrors does not require a metrology system.

### 3.1 Basic specifications

The terrestrial hypertelescopes currently studied, such as the ELHyT , are unlikely to have a meta-aperture much larger than a kilometer, in the absence of large and deep enough craters or other concave sites on Earth. Larger flat sites are available and can conceivably carry hundreds of telescopes, but long delay lines would be needed and the cost would be prohibitive for hundreds of them.

A reasonable range of size for a first-generation HOO , the space version in flotilla form, may therefore be from 100m to 1km and 10km, with potential expandability toward 100km in the longer term . An adjustable size would be most useful if its feasibility is confirmed since different science questions need different amounts of resolution. As demonstrated by the PRISMA testing, even a rather modest investment during the coming decade can validate the basic technology and be strongly conclusive toward justifying ambitious upgrades. Much preliminary testing can be done in the laboratory, including for the Laser Trapped version. The ground-based prototype " Ubaye Hypertelescope", currently tested in a southern Alpine valley [1,3], can also serve as a test bench and provide useful experience for the alignment and cophasing techniques.

The number N of sub-apertures can be as small as nine initially if provisions are made for upgrading to many more, especially if the flotilla size is also expanded, once the basic operation and science potential are verified. Up to thousands of Luciola-type mirrors, or perhaps a million "laser-trapped" ones as small as 30mm, can in principle be incorporated in a large flotilla for a huge increase in imaging performance.

Among the possible sites in space the L2 Lagrange point of Sun-Earth is particularly attractive for the solar driven version, given its low and uniform level of microgravity . L3, being partially shadowed by the Earth , is of interest for the laser-trapped version, in which case the laser source should reside with its photovoltaic generator some distance away in full sunlight [6].

Closer to Earth, high orbits may offer sufficiently weak gravity gradients for stabilizing the flotilla with conventional micro-thrusters at the scale of several kilometers, as demonstrated at the smaller scale of their 100m spacing by the pair of PRISMA satellites.

### 3.2 Wavelength range and spectral imaging

The spectral range exploited covers much of the ultra-violet , visible and near to mid infra-red. The prospect of laser cooling for the laser-trapped version, if it becomes verified, may further extend the infra-red range.

Dedicated cameras and auxiliary instruments can be installed within the single or multiple focal spaceships. Arecibo-like optical designs, with a spherical but dilute primary mirror, indeed allow the simultaneous use of several such focal spaceships, independantly movable along the focal surface, and which can be specialized for various spectral ranges and auxiliary instruments. This has been successfully achieved at Arecibo and found most useful.

The narrow field of view which can be exploited within one focal spaceship is compatible with hyperspectral ( also called spatio-spectral) imaging, a highly desirable feature providing a spectrum of each resel .

### 3.3 Optical concept

For designing the optics of a hypertelescope, one typically begins by designing the "meta-telescope", i.e. a giant monolithic telescope having the same overall aperture size ( the meta-aperture size) . Best efforts are made to achieve the widest diffraction-limited field of view, using the usual design recipes.

One then virtually adds a multi-hole Fizeau mask in front of the aperture, with hole sizes d and distribution similar to the desired hypertelescope. The hole spacing is typically much wider than their size, and this greatly attenuates the image intensity. With hundreds of them, it however typically leaves the Airy peak in the point spread function ( PSF) little affected in terms of its width, thus preserving the angular resolution, but attenuated . The Airy rings become distorted into "speckle" sidelobes, and intensified relative to the peak . This degrades the dynamic range, thus affecting the detection of faint stellar companions such as exoplanets, and the contrast in images of extended or clustered sources.

Indeed, the Fizeau interferometer thus obtained, while retaining the angular resolution of the meta-telescope and its diffraction-limited field of view, is affected since the image-forming convolution degrades the image contrast when too many point sources are present within the diffractive envelope of the PSF. Also called "sub-aperture lobe", this envelope is generated by diffraction through individual sub-apertures of size d , and its angular size is $l/d$ , where $l$ is the wavelength.

This "image crowding" effect limits the number of point sources allowed within the lobe for images retaining some contrast. The direct image of a star cluster smaller than the $l/d$ sub-aperture lobe cannot be contrasted unless it contains fewer than $N^2$ stars , considered as point sources. The phenomenon affects all types of interferometers, as a consequence of their incomplete sampling of the incoming wavefronts.

Transforming the Fizeau interferometer into a hypertelescope with a multi-field camera then consists in adding small optical elements near the focal camera:

1 - a micro-lens array in the focal plane, with pitch matching the sub-aperture lobe. With an appropriate image scale, this can separate independant imaging channels for each sub-field thus selected.

2- a pupil densifier, typically an array of micro-scale Galilean refractors, is also inserted in each imaging channel . These provide in each channel a direct intensified image, but which covers only a fraction $l/s$ of the channel's sky coverage $l/d$, if the pupil is fully densified, where s is the sub-aperture spacing in the entrance aperture. The fractional sky coverage, in solid angle, is then $\{(l/s)/(l/d)\}^2 = (d/s)^2$ . This loss of sky coverage is the cost to be payed for the image intensification, which occurs in the same ratio. Fortunately, the central "Direct Imaging Field" , also called "Clean Field", thus created within each imaging channel can be offset toward any compact celestial source of interest located within the corresponding lobe, such as a resolvable star, exoplanet, or cosmological source.

The trade-off of intensification vs. sky coverage is adjustable, for fitting various types of sources, by varying the pupil densification. In addition, Aime ( 2012) and Mary ( 2012) have developed special deconvolution algorithms which can greatly extend the DIF coverage.

With respect to the full meta-telescope, the unavoidable loss of performance with the hypertelescope resides in the reduced sky coverage, the limiting magnitude, the dynamic range and the related image crowding. If upgrades prove feasible, following "early science" programs, by adding mirror elements through additional delivery missions, then all four performance aspects become improved.

Some design concepts allow "meta-aperture zooming", i.e. varying its size as may be needed to adapt the resolution for various object types.

Apart from gas or dust nebulae, most astronomical sources of interest for high-resolution imaging have compact components, often little resolved. The simulated direct-images of an Exo-Earth at 3pc ( figure 1, inset) , using a 100km hypertelescope with 100 apertures, illustrates the power achievable: continents are seen as well as oceans, cloud formations, and large forested areas such as the Amazon and Congo basins.

### 3.4 Sky coverage with the peculiar dilute and segmented field-of-view

When a Fizeau array is converted to a hypertelescope, by adding a multi-field separator with pupil densifiers, the dilute segmented aperture causes a comparable dilution and segmentation in the field of view captured by the direct-imaging camera in a focal spaceship. The image appearance effect resembles that of a printed image carrying a grid mask overlay with broad opaque lines, thus showing an array of narrow sub-fields. It does not prevent obtaining a full image, which requires stitching exposures made with slightly offset pointing.

### 3.5 The three driving options

Relevant hardware architectures and optical design concepts have been studied in much detail by different groups, mostly in Europe where a strong expertise has been acquired in the wake of its large terrestrial interferometers, the early TRIO proposal and the 1996 description of hypertelescopes .

For the HOO, three main options are considered for driving the hypertelescope flotilla:

**a- Propellant thrusters:** chemical micro-rockets, cold gas jets and ion thrusters are well known techniques . Their main limitation is the propellant volume which can be used, limiting the mission lifetime.

**b- Small solar sails**

Also proposed as an option for Luciola , according to the initial study for the TRIO proposal, small solar sails are of interest for driving the slow and accurate motions of the "flying mirrors". Sails not much larger than each mirror element can suffice at sites such as the L1 Lagrange point of Sun-Earth or an Earth-trailing solar orbit, where microgravity fluctuations are well below those in Earth orbit. In comparison with conventional thrusters, solar sails can potentially extend the operational lifetime and reduce the pollution of optical surfaces..

**c- Laser trapping** [6]

It uses a multitude of very small flying mirrors, typically 30 mm in diameter. Each is trapped by standing waves formed by a pair of laser beams propagating in nearly opposite directions . The scaling laws indeed indicate that the acceleration achievable for the small mirrors varies as their inverse size , at given total collecting area and laser power. This favors small mirrors for fast global repointing of the flotilla, but also for fighting gravity gradients, disturbances from micro-meteorite impacts, the competing solar radiation pressure, etc...

The more numerous smaller mirrors providing a given collecting area , at given flotilla size, also greatly benefit to the direct-imaging performance . Both the DIF extent and the dynamic range are improved. A practical minimal size, of the order of 30mm, is however imposed to keep the auxiliary optics, i.e. the focal optics , the laser beam launcher and associated diverging mirrors, within reasonable dimensions such as one meter.

A third benefit of smaller mirrors is to decrease the bulk and mass of the orbital delivery package, expected to be self-deploying with the laser beams. Typically, a delivery package smaller than a cubic meter can contain a million 30mm mirrors, 1mm thick, providing together a 1000m2 aperture area comparable to that of a 30m ELT, and providing a comparable limiting magnitude for the deployed hypertelescope.

### 3.6 Feasibility of adjustable flotilla size

Somewhat like the zooming of ordinary camera lenses, it would be desirable to have an adjustable flotilla size. Both the resolution and sub-field width would be influenced by such variation. Preliminary studies have indicated that this is likely feasible by expanding or contracting the flotilla. For the laser-trapped version, this appears feasible with active optical elements in the laser launcher package which modify the angular fan of the many laser beams.

## 4. Implementation steps

Like radio interferometers, optical hypertelescopes are highly modular and flexible in design, and they can grow or be up-graded, both in terms of meta-aperture diameter and of mirror density, by delivering additional elements. If the flotilla has a spherical geometry like the Arecibo radiotelescope, an additional upgrading possibility consists in adding focal spaceships for simultaneously and independantly observing different sky areas, as already demonstrated at Arecibo with its several detecors. This requires, on each focal spaceship, a corrector of spherical aberration in addition to the camera, spectrograph, coronagraph, etc... , which imposes a rather slow primary focal ratio if the corrector size is to remain manageable .

Since initially proposed, the concept of interferometric flotillas in space has been much studied, and tested in space with PRISMA for some of the basic control techniques needed. Only in 1996 did the "Hypertelescope" concept become proposed for efficient direct imaging. It became analyzed in theoretical detail, with different groups contributing theoretical analysis and numerical or laboratory simulations, confirmed by sky verifications at reduced scale [4,9,10]. Two ground-based prototypes are currently tested , with meta-aperture sizes expected to reach 200m, and a larger 1km version is under preliminary design . Like radio arrays of antennas, hypertelescopes have a flexible geometry which is upgradable. This is of interest on Earth for risk reduction and cost management, which may also be the case for a space flotilla if upgrades prove feasible at scheduled intervals , as achieved for HST.

### Technology readiness level

The TRD has been discussed in the original Luciola proposal to ESA, but this did not include the Laser Trapping option which appeared later. For all three driving options, testing steps in the laboratory and possibly in space are needed for a robust evaluation.

## 5. Hypertelescope prospects for the longer term

The following extrapolated concepts, mentioned for perspective, were explored in preliminary detail but raise significant technical issues, unlikely to become solved before several decades. They are not part of the present proposal.

### The "Dilute Bubble Hypertelescope"

Similar to the Arecibo radiotelescope, but in dilute form and with a complete dilute sphere for full-sky coverage, it features a static spherical array of hypertelescope "tiles" and a number of focal satellites, independantly moving along the half-sized focal sphere . The static mirrors save pointing time since the pointing of a source is achieved by moving one of the focal spaceships, which can be available near the new position .

**The 100,000 km "Neutron Star Imager" hypertelescope**

The 100,000km "Neutron Star Imager" appears feasible in principle, but at a later stage . It is sized for resolving highly compact sources such as the Crab Pulsar, the size of which is believed to be about 20km. Its very high intrinsic luminance, much beyond that of ordinary stars, provides enough photons per resel, unlike ordinary stars which would not be easily observed with the nanoarcsecond angular resolution. The science program would thus concentrate on sources such as supernovae, QSO's and other violent objects.

For an adequate focal ratio of the sub-apertures, limiting to a few meters the size of their focal Airy peak, the "Neutron Star Imager" needs large component mirrors of 8m, not necessarily many, but costly and requiring significant technical developments.

## Conclusion

The high science potential of a HOO and the concept flexibility appear to justify further testing and development in the laboratory and with ground-based hypertelescopes, toward defining a robust concept for a space instrument . Upgradability, if it proves feasible, can be most valuable.

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