Hypertelescope imaging

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https://lise.oca.eu/
Hypertelescopes in space

- Many apertures:
- direct imaging with high resolution and sensitivity
- general observing on compact sources or clusters
- coronography, deep fields

hypertelescope version of TPF-I (Boeing/SVS study for NASA)
Artificial intelligence needed for modelling, driving and exploiting hypertelescopes

Initial optical modelling: Optical model needs adapted codes for mapping wavefront errors.

On Earth:
- Driving a complex robot:
  - Active co-parabolisation
  - Fine centering of sources in multi-field grid
- Adaptive co-phasing needed on Earth:
  - Piston sensing with 3D Fast Fourier transforms
  - Actuators driving
- Image processing:
  - De-convolving the pseudo-convolved image (Mary 2015)
  - Science interpretation

In space:
- Deployment and control of mirror flotilla
- Pointing
- Data compression and transmission
Interferometer: a poor man’s giant telescope

- Still works with only two elements: image is degraded, but resolution is not affected
Grand interféromètre à deux télescopes (GI2T)
Calern Observatory 1976-2007

γ Cass spectrum with interference fringes

precursor of VLTI in Chile
Steps toward hypertelescopes, on Earth and in space

- “Ubaye Hypertelescope” prototype partially built & tested
- proposed terrestrial “Extremely Large Hypertelescope” (ELHyT) with kilometric meta-aperture
- Space versions proposed to NASA & ESA, also lunar version
- [https://lise.oca.eu/IMG/file/WhitepaperProposalHypertelescope.pdf](https://lise.oca.eu/IMG/file/WhitepaperProposalHypertelescope.pdf)

Simulated imaging of an exo-Earth at 3pc, with a 100km hypertelescope flotilla in space.
The peak/halo ratio improves with more apertures but diffraction from each sub-aperture attenuates the interference peak. … a problem solved with "hypertelescopic imaging"
“Do it yourself” Fizeau imaging with a multiple aperture

Aluminum foil

- image improves with more apertures …
- … but remains drowned in a halo …
- … caused by diffraction through the small sub-apertures, and which takes energy away from the image…
- … a loss avoided with "hypertelescope" imaging
direct image of star cluster

310 apertures

750 stars

spread function

half-profile

interference peak

image without pupil rotation

image with pupil rotation
Simulated Fizeau images comparing 605 small apertures to 6 large ones, at equal collecting area & meta-aperture diameter.

- crowded image with the large apertures
Simulated Fizeau imaging:

30 apertures and 1000 stars

Image of a point source

uniform level subtracted

spiral aperture

1000 stars cluster

spread function

central interference peak

Log scale

Image of 1000 stars

Angular average

Half profile of spread function

Image of 1000 stars

without pupil rotation

with pupil rotation

Image of a point source
Extended Fizeau imaging with 36 subapertures, 450 stars

spread function

interference peak
Fizeau imaging simulation:
1000-element apodizing spiral aperture & 1000 stars

- Image profile
- Half profile
- Spread function & half profile
- Log scale
- Dark zone
- Interference peak
- Subaperture’s diffractive envelope
- Uniform level subtracted

Image without aperture rotation
Image with aperture rotation

Angular average
Spread function
Hypertelescope


- Directly-imaging interferometer, multi-aperture, with a pupil densifier
- Forms direct images....
- .... in a smaller field than a Fizeau interferometer, but intensified
Principle of the hypertelescope
or « multi-aperture imaging interferometer with pupil densifier »
Off-axis star

- Its image is shifted more than the envelope…
- … and eventually moves out of it => limitation of "direct imaging field"
Hypertelescope’s Direct Imaging Field

- On axis
- Off axis
- λ/D
- Dark zone
- 20 subapertures
- Fizeau spread function

Aperture

- D
- s
- Densified pupil
pupil densifier shrinks the image’s diffractive envelope
thus concentrating its light …
…and shrinking the field of view

Simulated hypertelescopc imaging

18 stars

200 subapertures
densified pupil

direct image

limit of « Direct Imaging Field »
Interferometer flotilla:

Why many apertures?

(Labeyrie et al., Experimental Astronomy, 2008)

- Image becomes crowded if number of point sources in Direct Imaging Field exceeds $N$
- Science vs. mirror size $d$, at given cost $C = N d$, where $\gamma = 2$ to 3
  $$\text{Sc} = C^{pa_d} \left\{ \frac{7}{4} \log_2 \frac{C}{pa_d} + (1 - 7\gamma/4) \log_2 d \right\}$$
- Strong science gain with decreasing $d$
- Many small mirrors better than few large ones, at given collecting area and meta-aperture diameter
  - same resolution and limiting magnitude
  - improved dynamic range, crowding limit, Direct Imaging Field
  - cost saving
- But how small? $d = 30\text{mm}$ diffracts a $1.5\text{m}$ lobe at $100\text{km}$
- $40,000$ mirrors of $30\text{mm}$ needed for the same collecting area as JWST: feasible with « Laser-trapped flotilla ».
Focal optics for multi-field and pupil densifier

- Field lens L1 and microlens array
- Beams from red and green stars focused by primary mirrors M1
- Optical bench tracks star by rotating about dome’s curvature center C_d
- Primary focus F_1
- Pupil densifier dome, with fixed attitude
- L5: Beam combiner lens
- L6: Multi-image magnifier
- Compressed image
- Fizeau image, segmented by microlens array
- \( \lambda/d \)
- \( \lambda/s \)
- \( \lambda/D \)
Testing of « Ubaye hypertelescope »

- following a smaller prototype at Haute-Provence (Le Coroller et al. 2014)
- under test with two 15cm mirrors, expandable to hundreds
- for a meta-aperture diameter up to 200m
« Ubaye Hypertelescope » concept

• 800m carrier cable (Kevlar 6mm) pendulating, and 6 oblique wires
• suspended focal gondola driven by 6 oblique wires and winches
spherical geometry
Suspended focal camera

2201m altitude

mirror element from star

camera

alignment camera
Cophasing hypertelescopes

- Wavefront control needed for:
  - coherencing,
  - interference
  - cophasing: Airy peak
  - easier in space!

- Tolerances:
  - $\lambda^2 / \Delta\lambda$ for coherence
  - $\lambda/4$ for cophasing
  - $\lambda/1000$ or $\lambda/5000$ for exoplanet coronography
Formalism of « dispersed speckle wave sensing »
(Martinache 2004, Borkowski et al. 2005)

The Fourier Transform of the dispersed image is the autocorrelation of \( \tau(u,v,\delta) \), tridimensional.

Inversible for calculating \( \delta(u,v) \) if aperture is non redundant.

If redundant: use Fienup’s algorithm (Martinache, 2004).

\[
I(x, y, k) = |TF|^2[\tau(u, v, \delta)]
\]
grism disperser with speckle-sampler microlens array

combined image, speckled if not cophased
Dispersed-speckle piston sensor
(Borkowski, et al., 2005)

- series of spectra from vertically adjacent speckles (red at right)
- … to build a spectro-image cube \((x, y, 1/\lambda)\)
- its Fourier Transform is calculated in 3 dimensions \(\Rightarrow\)
- laboratory simulated
Dispersed speckle: lab simulation with smaller piston errors
Extremely Large Hypertelescope (ELHyT) in Himalayan valley

- focal cameras carried by drones
- spherical or active paraboloidal meta-mirror
For space: « Laser-Trapped Hypertelescope Flotilla »:

Pellicle Beam Splitter produced by National Photocolor Corp.
"Laser-Trapped Hypertelescope Flotilla"

(Labeyrie et al., Experimental Astronomy, 2009)

- Meta-aperture size to 100,000km?
Laser-trapped mirror

- Interference of laser beams modulates the output intensities
- Radiation pressure $P/c$ reverses vs. position...
- ... at $\lambda/4$ intervals
- Cyclic blueward color shift for "pumping" toward central fringe
Pellicle beam-splitters for "Laser Trapped Hypertelescope"

- Pellicle
  - Semi-reflective for laser light
  - Reflective for star light
- Glass frame, prism profiled
- Self-centering in laser beam
Self-centering in laser beam through "laser tweezer" effect

Attitude also self-adjusting
Solution with only 2 or 3 herder spaceships

- Requires a delay line, or virtual delay line, attached to the laser
- Deployable from same satellite as camera
Beam fanning optics

To one trapped mirror

Returning beam from S2

Laser beam to S2 & S3

Lense array
Laser-trapped mirror element

- coarse alignment by laser radiation pressure on peripheral Fresnel lens
  - laser deviation translates
  - laser reflection by prismatic facets controls the coarse attitude
- fine alignment and cophasing by standing waves
- further modelling and lab testing needed
Laser-Trapped Hypertelescope Flotilla: Typical sizing

- Flotilla span: 1 kilometer
- Size of mirror elements: 30mm, mass 0.5 gram
- Laser power: 3mW per mirror
- Max. acceleration: 0.02 micron.s\(^{-2}\)
- Escape velocity of mirrors (axial): 30nm/s
- Collecting area of 6.5m JWST matched with 40,000 mirrors... requiring a 120 Watt laser.
- Delivery package for mirrors: volume < 0.2 m\(^3\)
- Deployment: with pair of directed laser beams
Operation at L2 in Earth penumbra

- Laser located in full sunlight, at edge of penumbra
- Full sky coverage in 6 months with continuous scan, transverse to Sun direction
Lab testing initiated in high vacuum, with torsion wire suspension (Bortolozzo & Residori)

- magnetic levitation also proposed by P.Riaud
Hypertelescopes in space: Searching for life on exoplanets

- global atmospheric spectroscopy is not conclusive
- multi-pixel spectro-imaging may detect seasonal changes analogous to the « indian summer »

simulated image of an exo-Earth at 3 pc 100km hypertelescope , with 150 apertures of 3m enhanced contrast by subtracting a uniform level
Signatures of exo-life

• Examples:
  – marine algal bloom
  – indian summer
• fast varying
Condition for multipixel imaging of exoplanet:

\[ N > F_{\text{star/planet}} \times R_{\text{planet}} \times C \]

- \( N \): number of subapertures
- \( F_{\text{star/planet}} \): planet to star ratio
- \( R_{\text{planet}} \): resels in area
- \( C \): coronographic gain

Example: 1000 mirrors for 30x30 resels on exo-Earth \( 10^{-10} \) at 3pc, if coro gain = \( 10^{10} \)
100,000km flotilla with hierarchical beam combiner for «Neutron Star Imager»

- reduces mirror sizes needed for primary array and beam combiners
Conclusions and future work

• space concepts for large hypertelescopes must be further validated…
  … through numerical simulation, together with dynamic behaviour of flotilla
  … and in the laboratory
• also testable in low Earth orbit (ISS?)

• laser-trapping concept may provide a low-cost route toward large interferometer flotillas
• **science:** a large gain is expected with the numerous mirrors and large meta-aperture flotillas in space
• … even on very faint sources
• … coronagraphy also needed for multi-pixel imaging of exoplanets