

SPACEBORNE HYPERTELESCOPE : A SPACECRAFT FORMATION FLYING CONTROLLED BY SOLAR SAILS

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ABSTRACT

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. Kilometric or megametric hypertelescopes are foreseen in space, formed from a vast formation flying of ultra-light optical elements. Solar sails are considered to control the attitude and the position of each free-flyer along the large primary sphere.

1. PRINCIPLE OF HYPERTELESCOPE

Astronomical interferometry has undergone a spectacular development during the last decades. Current trends announce generations of highly diluted instruments capable of producing direct high-resolution images. Hypertelescopes may be defined as multi-element interferometers using a densified exit pupil. As described elsewhere [1] [2] [3], 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 give a useless low-contrast image where the main peaks from each object point are buried in the non-uniform added halo contributed by the sidelobes of the spread function.

Densifying the exit pupil, which was already achieved in Michelson's historical 20-foot 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, but it does so at the cost of an important field reduction (figure 1). However, the field size of a hypertelescope increases with the number N of sub-apertures. Indeed, 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.

In practice this indicates the feasibility of large scale 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, and exo-planets will be imageable if coronagraphic attachments are used [4] (figure 2). Also, a million-kilometer scale hypertelescope will be able to observe and angularly resolve neutron stars [2]. These theoretical prospects have now been subject to verifications using numerical simulations, laboratory demonstrators, and actual observations with a miniature hypertelescope [5].

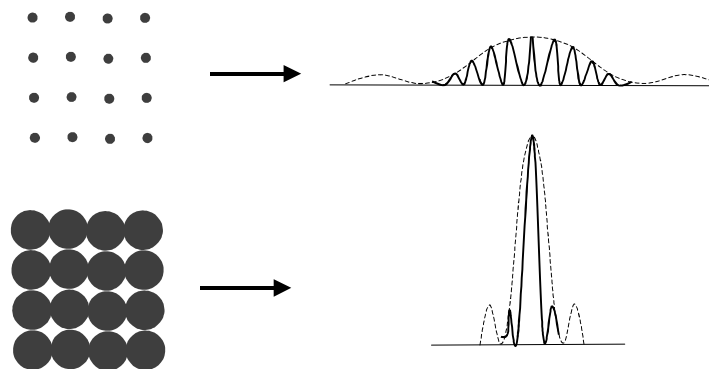


Figure 1 : Principle of snapshot imaging with a densified pupil. Top : pupil and image of a Fizeau interferometer. Bottom : densified exit pupil and corresponding image where the diffractive halo is shrunk. the central interference peak is intensified but the field of view is reduced.

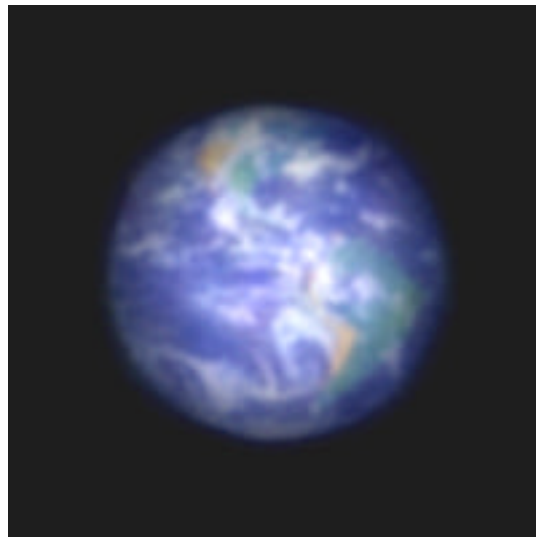


Figure 2 : Simulated image of the Earth, as observed from 3 pc with a 150 km hypertelescope having 150 apertures of 3 m. The visible green spots of vegetation suggest that such instruments will be able to search directly the presence of photosynthetic life on extra-solar planets.

2. HYPERTELESCOPE IN SPACE

Two versions of kilometric ground-based hypertelescope are under study : OVLA-type and CARLINA-type [2] [6]. The Optical Very Large Array involves mobile telescopes having a common Coudé focus at a central station. The slow motion of the telescopes during observation makes the concept compatible with a hypertelescope mode, using a hierarchical arrangement for the beam combiner [7]. A rather different concept for a large hypertelescope is CARLINA, which follows the same philosophy as the Arecibo radiotelescope, although with a sparsely paved primary mirror . It uses a natural depression as support for a large, fixed, diluted mosaic spherical mirror. High pylons, or a balloon, carry a focal combiner containing a corrector of spherical aberration, a pupil densifier and camera.

These ground-based hypertelescope versions both require a suitable site and rather complex mechanisms and adaptive optics to compensate the Earth rotation and the atmospheric turbulence.

The real future of hypertelescopes obviously lies in space where optical baselines approaching several hundreds or a million kilometres may become feasible. A first-generation 100m-baseline hypertelescope has been proposed to ESA [8] and to NASA for the Terrestrial Planet Finder mission. It can use a flotilla of dozens of small ultra-lightweight free-elements deployed in the form of a large diluted mosaic mirror. Reflected beams are recombined in a focal station. Many focal stations can be used independently. Being implemented as separate free-flyers, each can carry different specialized instruments. A polychromatic laser beacon located at the center of the primary sphere provides the full metrology of the mirror elements (figure 3).

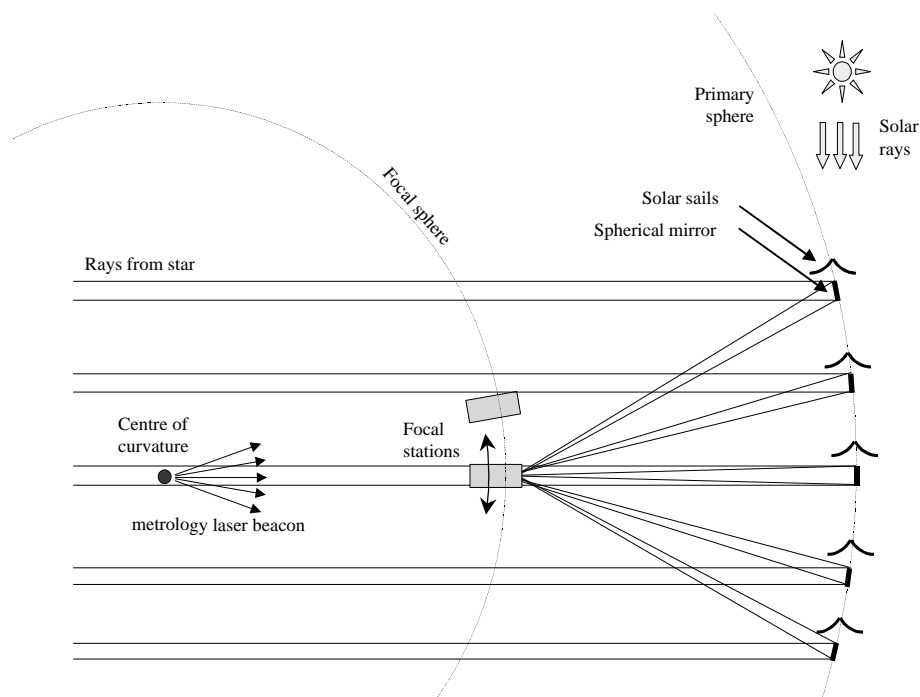


Figure 3: Optical layout concept for a space hypertelescope.

3. SPACECRAFT DESIGN AND CONTROL

Since the early TRIO proposal [9] of a large constellation of telescopes in space for interferometry, appreciable thinking was invested in exploring possible design solutions to define the simplest possible hardware configuration.

A first space hypertelescope configuration appears feasible with a 100-m sparse primary mirror made of 19 or 37 small segments held in a formation flight. A low-cost implementation appears feasible with small and light mirror element of about 30 to 90cm size, stabilized by solar radiation pressure.

Solar sails are well suited to provide the continuous force for sky scanning and the exquisitely delicate forces needed for maintaining the required co-sphericity at the sub-wavelength scale (60 nm is required for coronagraphy in N band). Stronger thrusters, such as ion thrusters, can perhaps be preferred for the faster, but less accurate and less frequent, positioning of the focal stations, as required to quickly acquire a new object after completing an exposure. It is however unclear whether the expected 30°K temperature of the mirrors is compatible with the contaminating exhaust from rockets.

Moreover, solar sails have an infinite autonomy and are not pollutant for mirror surfaces.

Table 1 shows the position accuracy and accelerations required for pointing and phasing a 100-m, f/3, hypertelescope in geo-stationary orbit, and the corresponding physical characteristics of the solar sails for 10-kg elements.

Tidal forces are strong at geo-stationary orbits and limit the size of the array to 200m. Lagrangian L2 orbits, or artificial L2 orbits, i.e. the modified Lagrangian equilibrium points achievable with radiation pressure [10] are preferable for larger hypertelescopes and for avoiding a slow drifts of the whole constellation.

Relative position accuracy	60 nm	Spacecraft total mass	10 kg
Required accelerations:		Inertia momentum	0.5 kg.m ²
- elements phasing	1. 10 ⁻⁷ m.s ⁻²	Solar sails surface	7.5 m ²
- sky scanning	2. 10 ⁻⁷ m.s ⁻²	Spherical mirror element diameter	0.3–0.9 m
- tidal forces	1. 10 ⁻⁶ m.s ⁻²		

Table 1: Position and acceleration requirements, and corresponding expected spacecraft characteristics.

Calculations show that 7.5 m² of solar reflective surface is sufficient to control the attitude and the position of an optical element having a mass of 10 kg. Recent advances micro-optoelectromechanical systems and ultra-light mirrors (SiC, composite, stretched membrane, etc.) seem compatible with this mass constraint. However, heavier free-flyers remain acceptable up to perhaps 20 kg, if their larger sail can fit in launchers such as Ariane 5 . Deployable solar sails are also possible, but presumably less reliable, and have not been considered here.

The solar sails are shaped (figure 4).like a hat, made of three off-axis paraboloids mirrors. Three small tiltable mirrors, located at each focus, give the force and torque required to control the position and attitude of the free-flyer, according to all six degrees of freedom with a 10 μN and 3 μN.m force range respectively [7]

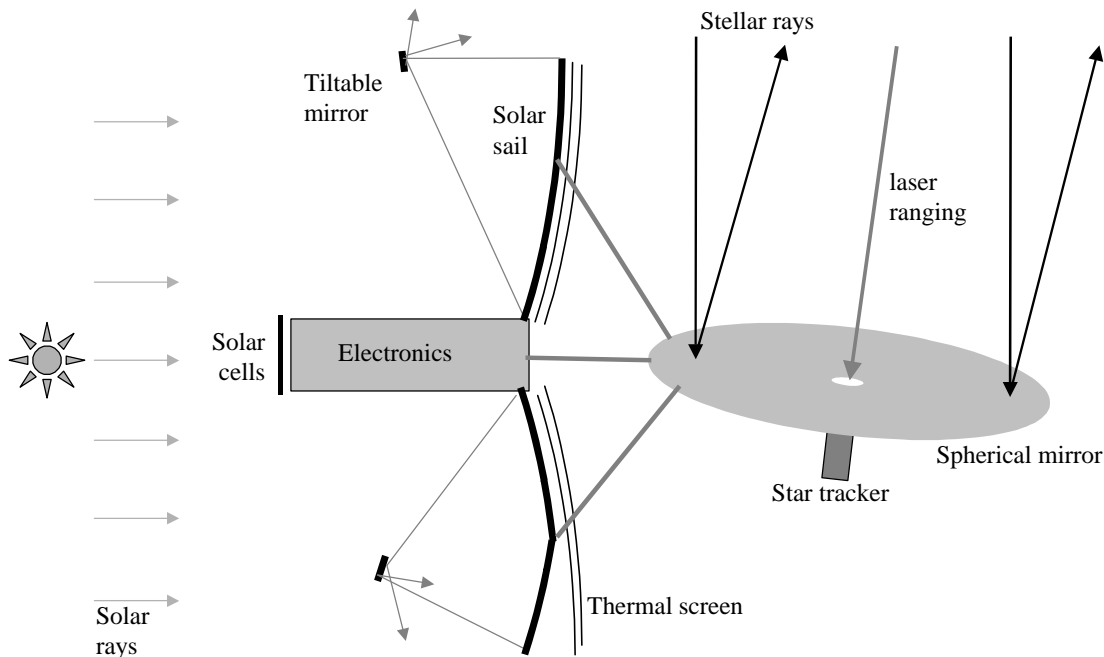


Figure 4 : Ultra lightweight free-flyer element of a space hypertelescope showing the solar sails and the spherical mirror attached to it by an angle bracket. Solar light incident on the sail is focused on small tilttable mirrors and reflected in different directions. A small array of solar cells fits at the apex of the sail structure. Pointing and phasing are ensured by a star tracker receiving light from a laser beacon in a separate free-flyer located at the curvature center of the mirror array.

The free-flyer control is ensured as long as the Sun's image remains on the three small tilttable mirrors. Simplicity demands that each solar sail be self-realigning to face the Sun, to recover the free-flyer control after the mission launch and deployment, and in case of accidental loss of the solar pointing. This appears possible with the basic solar sail design if the center of mass is located towards the apex. Oscillations are likely to arise, and they can be damped actively by the three small tilttable mirrors twice per period, when the Sun's image goes through these mirrors. Calculations show that the period of oscillations is about 2 hours, and that only one half-period suffices to damp oscillations [7].

4. CONCLUSIONS

From the mission point of view, the nano-satellite constellation philosophy is a recent approach which involves small, low-cost elements ensuring a high level of global reliability through their number and interchangeability.

Here, the 30cm mirror elements, spaced tens of meters apart, are of interest if they can be produced and controlled at low cost. Mass production techniques are of obvious interest. Molding techniques with composite materials, or sheet-metal forming techniques such as nickel electroforming, are obvious candidates for the small solar sail

"hat", the figure accuracy of which is arc-minutes. The small tiltable light deflectors can use electrostatic mini- or micro-mirror techniques such as developed by Texas, and Sandia. The attitude and position stabilisation loop can use coarse error signals from a local GPS-type system, to be tested in NASA's Nanosatellite Constellation Trailblazer mission.

These techniques can largely be tested in the laboratory by building, and vacuum testing, a few nano-satellite prototypes, complete with their solar sail and their tiltable reflectors. One here requires solar simulation, with wire suspensions and counterweights to cancel the Earth's gravity. Given the faintness of the radiation pressure force, less than a microNewton, care must be taken to avoid the confusing effect of radiometric forces, appearing at partial vacuum pressures, and electrostatic effects. Ways of avoiding the latter effects in space must be found.

Lastly, a set of 2 (or more) ultra-light geo-stationary satellites equipped of solar sails, laser ranging and star trackers, could be a low-cost test-bed to validate the control of a formation flying by solar radiation pressure, and to prepare future space hypertelescope missions.

5. REFERENCES

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