SPACEBORNE HYPERTELESCOPE CONTROLLED BY SOLAR SAILS

O. Lardière, A. Labeyrie

LISE CNRS 04870 Saint-Michel-l'Observatoire, France, Email: lardiere@obs-hp.fr, labeyrie@obs-hp.fr

ABSTRACT/RESUME

Snapshot imaging of exoplanets seems feasible with muti-apertures interferometric arrays according the hypertelescope principle. A space hypertelescope can be formed from a vast constellation of ultra-light optical elements positioned by small solar sails along the large primary sphere. Our calculations show that 1m^2 of solar reflective surface is sufficient to control a mass of 1.3 kg in geo-stationary orbit. However, L2 orbits are preferable for hypertelescopes larger than 200m, in order to avoid tidal forces between elements and slow drifts of the whole constellation. A 10kg-spacecraft is the heavier limit to have a reasonable solar sail size, but 1kg would be preferable. This mass constraint seems compatible with recent advances in MOEMS and ultra-light mirrors.

1. INTRODUCTION

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 which provide an interesting contrast gain for coronagraphy and exoplanet searching [1] [2].

2. HYPERTELECOPE IN SPACE

Two versions of kilometric ground-based hypertelescope are under study : CARLINA-type [3] and OVLA-type [4]. 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 large hypertelescopes certainly lies in space where optical baselines approaching several hundreds kilometres may become feasible. A first-generation 100m-baseline hypertelescope has been proposed to ESA [5] 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 spherical mirror (Fig. 1). Reflected beams are recombined in a focal station carried by another free-element. Many focal stations can be used independently. A polychromatic laser beacon located at the centre of the primary sphere provides the fine metrology of the mirror elements.

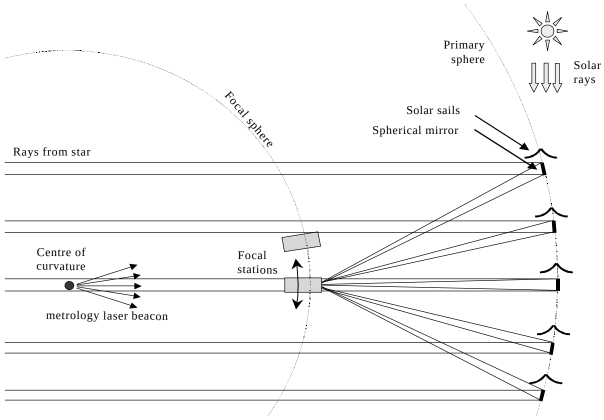

Fig. 1. Optical layout concept for a space hypertelescope.

3. SPACECRAFT DESIGN AND CONTROL

Since the early TRIO proposal [6] of a large formation flying of telescopes in space for interferometry, solar sails seems well suited to provide the continuous force for sky scanning and the exquisitely delicate forces needed for maintaining the element position 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 ion rockets.

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

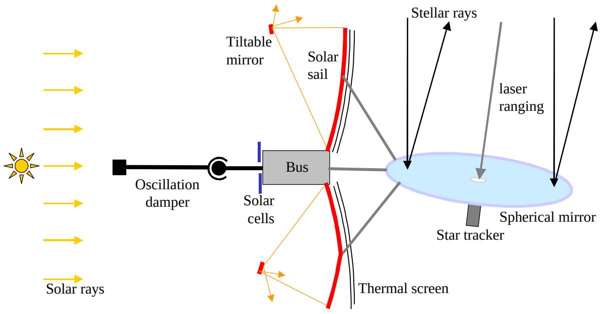

Fig. 2. Ultra lightweight free-flyer element of a space hypertelescope with its solar sails and the spherical mirror attached to it by an angle bracket.

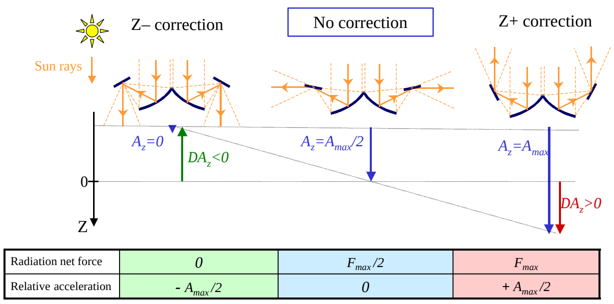

Fig. 3. Example of positioning control along the sunward axis (Z). In absence of correction, only the half of the radiation net force is compensated in order to be able to generate relative acceleration between different elements in the both directions.

The solar sails can be shaped like a hat made of three off-axis paraboloïdal mirrors (Fig. 2). 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. An example of relative positioning along the sunward axis is shown on Fig. 3.

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 solar sails face the sun. Self-realigning is possible if the center of mass is located towards the apex. Slow oscillations (T=2hrs) arise, but they can be damped passively with mechanical, electrostatic (variable capacitor), or electromagnetic (galvanometer) dissipater.

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 a 1.3-kg element.

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

Relative position accuracy	60 nm	Spacecraft total mass (goal)	1.3 kg
Required accelerations for: elements phasing sky scanning tidal forces	$1.\ 10^{-7}$ m.s^{-2} $2.\ 10^{-7}$ m.s^{-2} $1.\ 10^{-6}$ m.s^{-2}	Inertia momentum	0.05 kg.m^2
		Solar sails surface	1 m^2
		Spherical mirror element diameter	0.2–0.6 m

A full sky scanning can be achieved in 6 months by a slow and continuous rotation of the whole satellite constellation around the curvature centre and the solar anti-solar axis.

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 [7] are preferable for larger hypertelescopes and for avoiding a slow drifts of the whole constellation.

Our calculations show that 7.5m^2 of solar reflective surface is sufficient to control the attitude and the position of an optical element having a mass of 10 kg [8]. 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.

To increase the solar sail efficiency we can collimate the reflected solar beams using an afocal "solar telescope". A "Fresnel" flat sail is interesting for compactness (Fig. 4). Omni directional (+/-90°) tiltable deflectors using thin plan double sided mirror or µ-shutters with reflective coating seems also possible to increase the angular beam deflection range (Fig. 5).

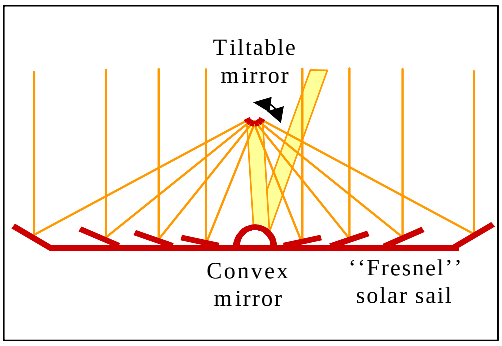

Fig 4. Compact and efficient collimator using a "Fresnel" solar sail.

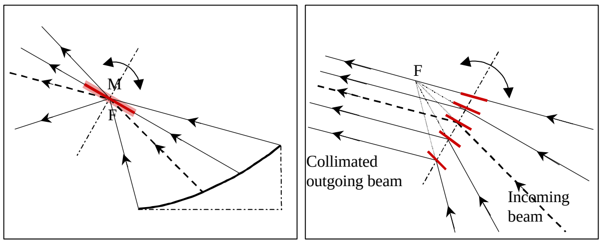

Fig. 5. Possible omni-directional tiltable beam deflectors: thin plan double sided mirror (on left), micro-mirror array (on right).

4. CONCLUSION

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. Ultra lightweight hardware components are needed.

Spaceborne hypertelescope concept gives a unique application for small non-deployable solar sails which are now technically feasible [9]. Molding techniques with composite materials, or sheet-metal forming techniques such as nickel electroforming, are obvious candidates for the small solar sail, the figure accuracy of which is arc-minutes. The small tiltable light deflectors can use electrostatic mini- or micro-mirror techniques. The attitude and position stabilisation loop can use coarse error signals from a radio-telemeter or local GPS-type system, to be tested in NASA's Nanosatellite Constellation Trailblazer mission.

Lastly, to complement the ESA SMART-2 mission, we propose a set of 2 ultra-light geo-stationary satellites equipped of solar sails, laser ranging and star trackers 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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