FRESNEL FORMATION FLYING:
HIGH RESOLUTION IMAGER FOR OPTICAL ASTROPHYSICS

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SUMMARY

The scope of this paper is to present the capabilities of a very innovative concept: a distributed spatial imager for astrophysics, and the potential technical solutions.
The instrument uses a binary Fresnel zone plate, based on the diffraction focusing principle. This implies long focal lengths, hence a formation flying approach on the basis of some tens of kilometers.
The major interest of this particular approach to diffractive focusing is that is has the same resolution as a classical lens or mirror of equivalent size, but there is no optical material involved in the focusing process: just vacuum, holes punched into a thin opaque membrane, and a very light supporting structure. Another interesting feature, specific to the particular grid-like pattern of the primary focusing zone plate, is the high dynamic range achieved in the images. These two elements make it possible to launch a very large Fresnel array allowing resolutions and dynamic ranges never reached before, leading to new science objectives.
Of course a lot of technical challenges have to be overcome. This is the reason why critical domains have been identified, then addressed by R&T activities and, moreover, the performance limits explored with astrophysicists, in order to define the science needs that could be fulfilled with such capabilities.
This paper presents some technical responses, and how a lot of domains in astrophysics can take advantage of such missions.

1- INTRODUCTION

To propose such a type of instrument concept for space application is not totally new.
Since 1993, ideas circulate among people like Y.M. Chesnokov (1993), R.A. Hyde (1999), J.T. Early (2002) or more recently D. Massonnet (2003).
Since 2004, the Centre National d'Etudes Spatiales (CNES) and Laboratoire d'Astroophysique de Toulouse – Tarbes have been pursuing R&T actions on the instrument concept.
In 2007, a very performing concept with good achromatisation and very high dynamic range has been demonstrated on a test bench.
A more performing model will be built this year and tested on real astrophysics sources.
Following these studies, a proposal was presented to the ESA Cosmic Vision board.
In parallel, an important and large frame study, lead by CNES, evaluates the technical challenges and assesses the scientific potential of this instrument concept, compared to other future astrophysics missions.
Section 2 of this paper presents the principle of a Fresnel imager and the history of its evolution for space applications. Section 3: how Astrophysics can take advantage of this new concept to climb an important step in observation performance, then in the science involved.
The fourth section proposes and justifies the space segment architecture possibilities, while the fifth section presents the formation flying particularities in term of GNC of such a mission. This last section also some give practical examples of distributed instrument sizing for particular missions.
The conclusion gives the status and perspectives.

2- THE INSTRUMENT

2.1- Description of the optical concept

In the Fresnel array, focusing is achieved with no optical element: the shape and positioning of a high number of subapertures in a large foil being responsible for beam combining by diffraction for a fraction (5 to 10%) of the incident light. The consequence of this high number of subapertures is high dynamic range imaging capabilities.

This interferometric array can be seen either as an aperture synthesis array or as a particular case of diffractive zone plate. Beams from the individual subapertures are recombined by diffraction and interference. The subapertures are positioned so that a 2π phase shift occurs at the first order of diffraction between neighbouring zones. As a consequence the emerging waves are in phase and interfere constructively to form an image at the focal plan.

Due to this subaperture positioning law, an incoming plane-wave is turned into a spherical outgoing wavefront. An image is directly formed by the array, the dense sub aperture pattern leading to a compact and highly contrasted Point Spread Function (PSF).

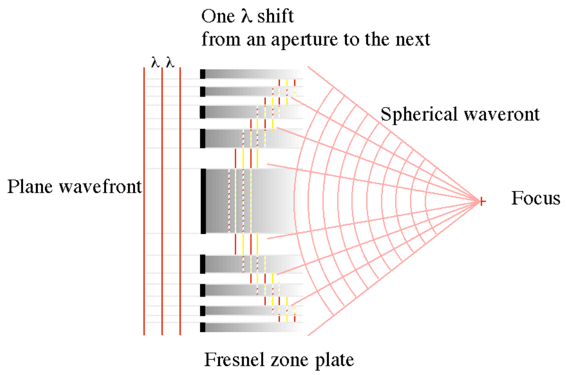

Fig.1: an incoming plane wave is partially turned into a spherical converging wavefront by the action of a diffractive Fresnel array. A fraction of the light, not represented on the figure, remains a plane wave, another fraction becomes divergent.

The figure above presents the diffractive focusing. This simplified sketch shows the behavior of a plane wavefront passing through a Fresnel zone plate, and how it is affected by the subapertures layout.

The emerging wavefront is cut into segments by the subapertures layout; a given segment can be connected to the neighboring one with a one-wavelength shift, resulting into a local tilt of the average wavefront. A proper positioning law of the subapertures' positions connects these local tilts to create a spherical wavefront. This spherical wave then converges into a focal point. Only a fraction of the light applies to a one-wavelength shift (Order +1). The other possible shifts cause other types of emerging wavefronts (Order zero, -1, +3, -3, etc.). Order 0 corresponds to light unfocussed by the Fresnel lens and is used for guiding purposes, as explained later.

Fresnel zone plates are related to the concept of Fresnel Zones, defined as follows: consider a point in space (call it f as in focus) and a plane away from that point (call it aperture plane). Now take concentric spheres centered on F with increasing radii, the increment step being constant and called "wavelength".

The spheres larger than a minimal radius will intersect the aperture plane, forming concentric rings in it. A Fresnel zone is the corona delimited by two neighboring rings. Although the spheres are equally spaced, the intersection rings in the aperture plane are not; the centermost Fresnel zones are the largest. However, they all have the same area.

An optical element (e.g. lens) of diameter D placed in the aperture plane and centred on the Fresnel zones defined above, will contain a certain number of them. This number N of Fresnel zones in the lens depends on the diameter D of the lens, on the wavelength λ and the distance F between the aperture plane and the focus.

$$N = D^2/(8.F.\lambda) \qquad (1)$$

The Fresnel interferometric arrays proposed here differ on several aspects from zone plates, which are usually made of concentric rings. Our pattern is more elaborate (see figures) and makes the opaque zones connected throughout the array, allowing the use of vacuum for the transmissive zones (subapertures) while preserving mechanical cohesion of the whole frame.

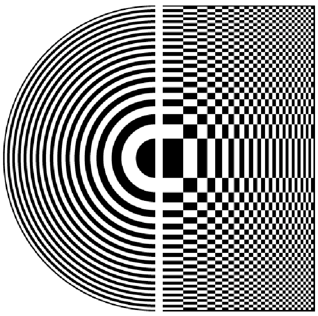

Fig. 2. Circular (Soret) zone plate & example of orthogonal Fresnel array, 15 Fresnel zones (half sides).

2.2- Historical context

Proposals for using Fresnel zone plates in formation-flying conditions in space have been made since 1993: Y.M. Chesnokov [05], R.A. Hyde [02], J.T. Early [06], and D. Massonnet [07].

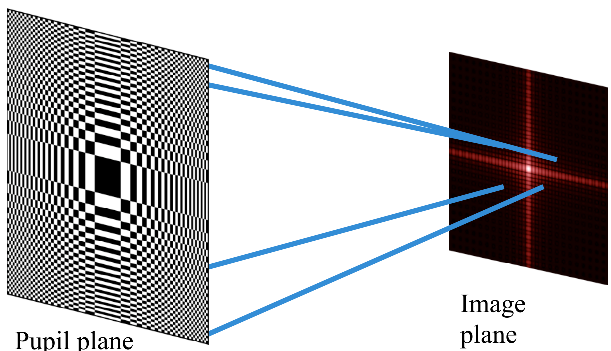

Fig. 3. Image of a point source (Point Spread Function computed by Fresnel Transform).

Normally, diffractive optics are very chromatic, and allow observations only in a narrow band pass. The chromaticity issue has been addressed by Hyde [02], Chesnokov [05], Faklis & Morris [08], and solved using an optical principle by Schupmann [01]. Broadband, chromatically corrected observations are now possible with diffractive optics.

Our proposal differs from the previous ones in several aspects. In 2004, we have proposed an interferometric approach, an orthogonal geometry, the use of vacuum instead of an optical active medium, and the high dynamic range applications. The dynamic range is defined here as the ratio of the average intensity in the image field outside the central lobe of the Point Spread Function (PSF) and its spikes, over the maximum intensity in central lobe of the PSF.

3- SCIENTIFIC APPLICATIONS

Due to the fact that no optical element other that opaque material and vacuum are used in the primary array, a large spectral domain is observable. The proposed scientific goals will be astrophysical observations in the UV, visible and close IR domains, each using different spectral channels in the receiver spacecraft optics.
We study possible configurations in the range from 3 meter to 30 m primary optics. For each configuration, we investigate different spectral domains, leading to different angular resolutions, and of course different physical phenomena observed.

The main interest of Fresnel arrays is the possibility opened to high angular resolution (directly related to the aperture size) and high dynamic range (related to the sub aperture layout of the Fresnel array).

A first study concerning the usability of Fresnel array has been carried in 2005 for exoplanet detection (Koechlin, Serre, Duchon 2005), it showed the feasibility of terrestrial planet spectroscopy at 10 parseccs in the UV, visible and close IR, using 30m Fresnel arrays. Other types of exoplanets, such as “Hot Jupiters” should be much easier to detect and require 10m or smaller apertures, but exoplanets are far from being the only possible target of a Fresnel mission.

An international scientific group is being formed to explore the stellar physics with a Fresnel array: mapping a supergiant for example, and mapping its close vicinity as well, thanks to the high dynamic range. Star formation regions. The domain investigated is more towards the U.V., as there lies the highest possibilities in terms of angular resolution.
Galactic physics are also explored, such as dense molecular clouds. Large Fresnel arrays will yield enough luminosity in the U.V. to gather spectral and image data further inwards these interesting regions, rich in spectral lines.
An additional target consists of the small bodies of the solar system, which could be imaged with unprecedented resolution, giving data complementarily to probes sent in the solar system.
Deep sky observation of galaxies at Z=6 or higher may also bring new science, as large Fresnel arrays may bring in more light than smaller but more expensive apertures in space.

4- DESCRIPTION OF THE SPACE SEGMENT AND EXAMPLES:

4.1 Frame of this paper

Because the concept of a Fresnel imager is very large, it is necessary to keep border lines here.
Spectral bandwidth
We propose to limit the bandwidth from around 120nm (Lyman alpha) up the near IR around 5 to 10µm. This upper limit depends mainly on the cooling capability of the Fresnel lens. For example, a simple sun shield allows cooling the lens down between 100K and 130K allowing observations up to 5 µm, while a more sophisticated passive system, like V-groove technology, allows cooling below 100K and observations to 10 µm.
The UV limit of 120 nm is the limit of major optical difficulties, and the Lyman alpha wavelength is very important for astrophysics.
Due to the optical design of the primary array (i.e. a mechanical limit to the number of Fresnel zones)
this bandwidth implies focal lengths in the range 500m to 50km, which is new but reasonable for GNC considerations for a two-satellite formation flying system.
This UV to IR bandwidth covers a very important field of the astrophysics domain.

Main aperture size
The second important parameter is the Fresnel lens size.
The range from 3m up to 30m is considered in this paper.
A 3m lens allows interesting science and can be launched “as is” avoiding further deployment in space. In the major launcher fairings, a 3.5m Fresnel lens can be directly accommodated.
A 30m lens allows a totally new astrophysics science but needs of course an important deployment system. This value is considered at present time as a limit for reasonable technology developments.
Moreover, for such a lens size, the needed sun shield is very important itself meaning huge constraints on the GNC problematic.

Other parameters
Over these two first evident parameters, two other flexible ones have to be considered.
The first one is the lens diameter of the receiver optics. Because this last is a classical one, its size impacts directly on cost and mass. Absolute higher values are not given here but it is reasonable to limit this last between 0.5m and 2m depending of the Fresnel lens diameter range.

The second flexible parameter is the cost of such a mission because it has to be considered in terms of science return to cost ratio in the frame of the future missions' landscape.
At last, it can be noticed that, in the frame of this paper, only the Earth-Sun L2 positioning is considered (gravity gradient, thermal stability and field of view) because it appears as the only option allowing conciliating all constraints.

4.2- Fresnel lens satellite

The only important need is to guarantee a very good precision of the Fresnel pattern projection over the aperture plane. This issue can be split into different topics. The two main ones being:
- the deployment and stability, which is mainly a mechanical problem including membrane, folding, deployment mechanisms and structures,
- the radiance and radiations from the filled parts of the lens pattern toward the receiver optics, due to reflected light and lens temperature.

This last item is linked to the lens membrane thermo-optic coatings performances, and to the sun shield efficiency. As described later, these are also linked to orientation limits with respect to the stray light and shield dimensions with respect to the sun heating.
Of course, the sun shield size impacts deeply on the structure and mechanisms problematics and, as already noticed, on the GNC problematics.

<u>Deployment and stability</u>

Basically, the goal is to unfold a large membrane and to guarantee its shape and positioning stability with respect to a given referential. The stability is also a thermo elastic problem related to the structure and satellite links, but mainly with the sun light heating. This last point will be developed in the "radiance and radiations" section. Nevertheless, only thermal gradients and inhomogeneous tensions in the membrane can induce image degradation, because a homothetic deformation of the focusing pattern acts only on its focal length, which can be controlled by the GNC.
On one hand, different technologies are validated or under study concerning the folding issue and, on the other hand, different spreading supporting structures offer interesting capabilities as inflatable or ultra lightweight structures.
The choice of the Fresnel pattern can be an important driver for the structure type approach, particularly if the lens is square or circular and if the centre pattern is full or void.
However, it can be noticed that structures based on the gossamer principles are intrinsically interesting for this purpose.
Finally, structures and patterns have to be optimized to master there respective interferences.
At present, the very high dynamic range need can be managed through two different main ways:
A square pattern with its particular constraints on the supporting structure but allowing a specific management at strategic imaging level,
Or a circular pattern using a PIAAC, at scientific channel level if FUV is not required.

<u>Radiance and radiations</u>

As introduced above, these aspects are directly linked to the image quality on the instrument part of the receiver satellite. All back stray light reflected on the back side of the Fresnel lens toward the receiver degrades the image. In the same manner for IR observations, the heat radiations coming from the membrane material contribute to noise.
Finally, for very high dynamic ranges, the only solution is to maintain the Fresnel lens in the shadow of all bodies with a shield and an appropriate orbit.
For instance, an L2 position allows having the Sun, the Earth and the Moon on the same side of the formation and a small Lissajous orbit allows maintaining these three bodies in a small sector, thus limiting the required shield size and allowing a consequent observation sector.
The size of this shield is an important concern for GNC because it induces an important unbalance between the ballistic coefficients of the two satellites. The solar pressure flux thus imposes important means to maintain the pointing, hugely reducing the lifetime.
Finally, a compromise has to be found between the shield size to limit the propulsion and GNC impact, and on the other hand the sky sector observable at each instant.
The best solution consists in the addition of a solar sail on the receiver satellite to have it balanced again.
In fact, the field of view problematics here is the same as that of Planck and Gaïa.
The receiver satellite can itself reflect light towards the Fresnel array, which would send it back to the optics.
A global optimization has to be done on the different surface thermo-optic coatings of the Fresnel lens, the shield, and the front side of the reflector satellite, to limit the light reflections and thermal radiation.

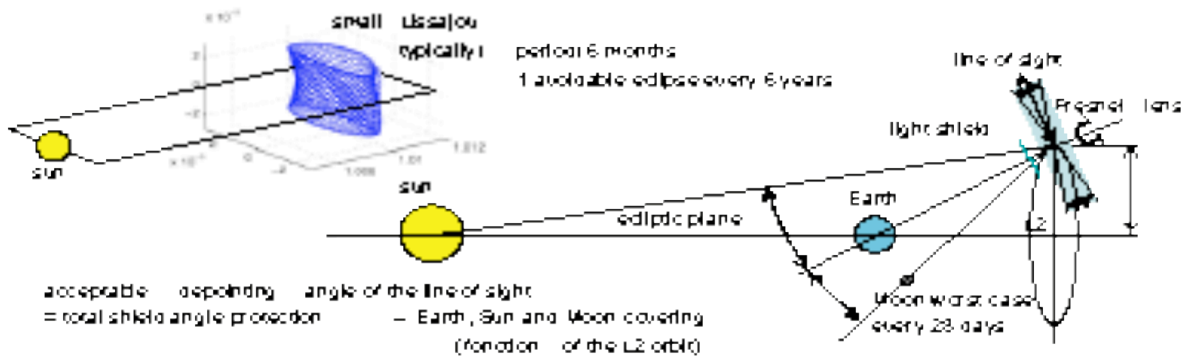

Fig. 4 Pointing strategy at L2.

4.3- receiver satellite for a possible mission

The principle of this formation flying control is to consider the lens satellite as the free flyer and the receiver as the follower spacecraft. The main particularities of this follower are:
- to guarantee target pointing, attitude stability and separation distance, then to support control actuators, system and sensors, one of which being coupled with the science instrument, as explained further.
- to support the receiver instrument which can be more or less complicated depending of the mission.

The "focal instrumentation" in the receiver spacecraft will feature several channels, each dedicated to a particular waveband, and further specialized in high resolution imaging, high resolution spectroscopy, or high dynamic range coronagraphy.

In the proposal we submitted to the ESA Cosmic Vision call for 2015-2025, we proposed six channels, four in the U.V. covering continuously from Lyman α to 350nm, one in the visible and one in the close IR at 900nm.
The coronagraphic mode will be used for small field observations of the vicinity of bright sources, including, but not limited to, exoplanets.

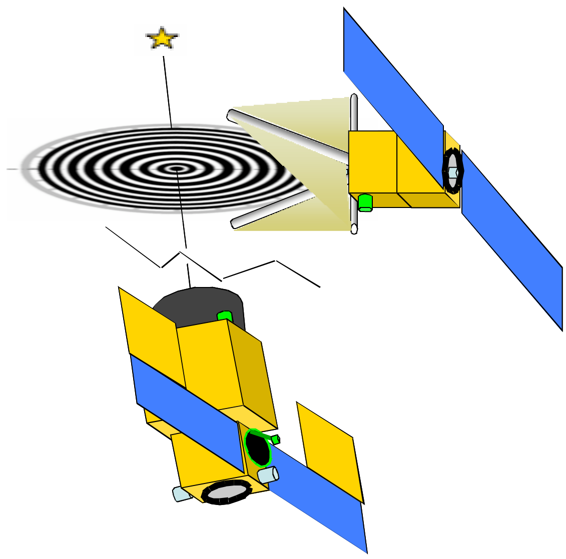

Fig. 5 Configuration principle :one spacecraft (top) holds the Fresnel lens, the other (bottom) is placed at focus and holds the chromatic correction and focal instrumentation. It features additional "solar sails" to equalize cross section for solar radiation pressure between the two satellites.

4.4- Competing instruments

The competing instruments, at the time the mission could be launched, are JWST, GALEX, FUSE and PLATO.

To be competitive in terms of resolution with JWST, 3 metres apertures are needed: Although JWST will have a 6.5 m mirror, the U.V. capability of a 3 m Fresnel array makes it more resolving. 15 to 20 meters apertures have to be envisioned to be competitive in terms of luminosity.

4.5- Space segment architecture example

5 –FORMATION FLYING GUIDANCE NAVIGATION & CONTROL (FF-GNC)

5.1- In-orbit life of Fresnel Formation Flying

The in-orbit life of Fresnel Formation Flying can be split into three main phases, as seen from the GNC point of view:
- Transfer trajectory & Station-keeping,
- Changes of astrophysical target & focal length,
- Coarse, Acquisition & Fine "Pointing".
We describe briefly the first and second phases, with numerical examples. We describe in more detail the third phases, namely the coarse and fine pointing, including fine pointing acquisition.

Transfer trajectory & Station-keeping

It is foreseen that both spacecraft will be launched by the same launcher.
They will be injected by the launcher into a transfer trajectory from Low Earth Orbit to a "Large Lissajous" L2-orbit. Each spacecraft will travel separately during this transfer phase. The total velocity increment needed for trajectory correction during this phase is less than 100m/s.
For the transfer between "Large Lissajous" (>230000km x 690000km) and the final orbit ("Small Lissajous": typically~100000km x 300000km) both spacecraft need a velocity increment of ~200m/s.
For a 10 years formation life-time on "Small Lissajous", the total velocity increment for station keeping is less than 100m/s.

Astrophysical target change and (or) "main focal" length modification

1) The "Main focal" length needs to be changed to observe a given target at different wavelengths: in this mode, the Receiver or the Lens Spacecraft should adapt their relative distance F (Main focal length) in accordance with the wavelength λ. For a lens of diameter D with N Fresnel zones, we have:

$$F = D^2/(8.N.\ \lambda) = Constant \qquad (2)$$

The Main focal length F of a 10 m diameter Fresnel imager is given in table 1 for various wavelengths λ and number N of Fresnel zones:

Table1. Great Focal Length : F= f(N,λ)

λ(micron)	0.397μ	0.600μ	0.918μ	1.400μ
N=1000	31.5km	20.8km	13.6km	8929m
N=2000	15.7km	10.4km	9078m	4464m
N=3000	10.5km	6944m	4539m	2976m

We see, *Table 1*, that inter-spacecraft distances are kilometres, even tens of kilometres. Consequently a Main focal length modification represents a several kilometres travel.
If the mass of the spacecraft achieving the relative position correction (Receiver or Lens S/C) is 1000kg, and if we limit the velocity increment (ΔV_T) dedicated to the focal length modification to for instance to 0.5 m/s, the manoeuvre duration is 2000 s/km, plus the duration of the thrusts (250s for 4x1N thrusters).
With chemical propulsion (hydrazine), a focal distance modification consumes 0.5kg of mono-propellant.

2) Change of astrophysical target (repointing): The Fresnel Imager "pointing" is determined by the orientation of the Main optical axis linking both spacecrafts, and by the orientation of the secondary optical axis, internal to the receiving optics (Fig. 6. § 5.1 and Fig 7. § 5.2).

So, pointing is modified by a translation of one spacecraft with respect to the other (in a direction perpendicular to focal change) and an attitude correction for both spececraft. A "pointing slew" is a process similar to a Main focal change. For example, a Pointing slew of 2.3° (0.04rd) when spacecraft are separated by a 25 km Main focal corresponds a 1 km travel.
Focal change and slew manoeuvres can be combined to minimize the fuel consumption.

Coarse, Acquisition & Fine "Pointing" for astrophysical observations

1) Principle of Fresnel Imager "Pointing": (*see Fig.6.*)

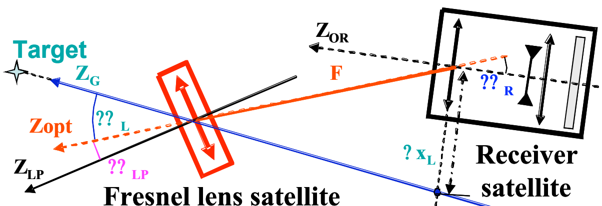

Fig. 6.Principle of Fresnel Imager "Pointing"

Fig.6 shows the main parameters of the Fresnel "Pointing" principle:
$\Delta\theta_L$: Angle between the main optical axis Z_{OPT} and the target direction Z_G (*The main focal length F being oriented along Z_{OPT})*
Δx_L : Lateral shift between the centre of the receiving optics and the target line (*passing through the centre of the main Fresnel lens*) (*Δx_L # $F.\Delta\theta_L$)*
$\Delta\theta_R$: Angle between the main optical axis Z_{OPT} and the axis Z_{OR} of the receiver optics.
$\Delta\theta_{LP}$: Angle between the main optical axis Z_{OPT} and the axis (*perp. to the plane*) of the Fresnel lens Z_{LP}

We get a correct Fresnel imager pointing with the three following actions:
1st : Align Z_{OPT} with the target direction ($\Delta\theta_L$ # 0)
2nd : Align Z_{OR} with the target direction ($\Delta\theta_R$ # 0)
3rd : Align Z_{LP} with the target direction ($\Delta\theta_{LP}$ # 0)
Action 1 corresponds to fine control of the relative lateral position Δx_L between both spacecrafts (Typical accuracy required: *Δx_L* < 0.5mm to 2mm).
Action 2 corresponds to fine pointing of the receiving optical axis towards the target (Typical accuracy required: 200nrd to 2000nrd).
Action 3 corresponds to pointing the primary Fresnel lens towards the target (Typical accuracy required: 0.1° to 0.3°).

2) Coarse pointing and acquisition of the fine pointing:
The best level of " fine pointing" accuracy for this kind of Formation Flying is very constraining (~1mm in lateral position corresponding to ~30nrd for the

main optical axis orientation (in the worst case) and ~200nrd for the receiver axis pointing. We have to provide a coarse navigation system for pointing, with a field of acquisition about 100 times as big as the field of view for the fine system navigation *(Coarse field of view : ~200mrd or ~12° and fine "pointing" field of view : ~2mrd or ~0.12°- See §5.2 : Fine navigation & acquisition of fine navigation)*

5.2- Fresnel Formation Flying Navigation

We describe first, the Navigation principle, second, the Navigation means and modes, and third, the "Navigation implementation and performances".

Navigation principle

The Navigation system of this formation flying measures nine degrees of freedom (d.o.f): 2x3 d.o.f for the attitudes of the two spacecraft and three d.o.f for the satellites relative position: two being the relative lateral position vector Δx_L and one the longitudinal position along the main optical axis.
Out of these nine independent parameters, three are the attitude control of the lens satellite, controlled with star trackers on 3 axes (Accuracy ~ 0.1°).
A similar accuracy is sufficient for the d.o.f corresponding to the rotation of the receivier spacecraft around its optical axis Z_{OR}.
The focal distance F is measured by a specific laser telemeter. (*detailed in section "Navigation means"*)
Four d.o.f remain, two corresponding to $\Delta\,\theta_R$ (*orientation of the receiving optical axis*) and two to $\Delta\theta_L$ (*orientation of the main optical axis*). *(see Fig.7)*

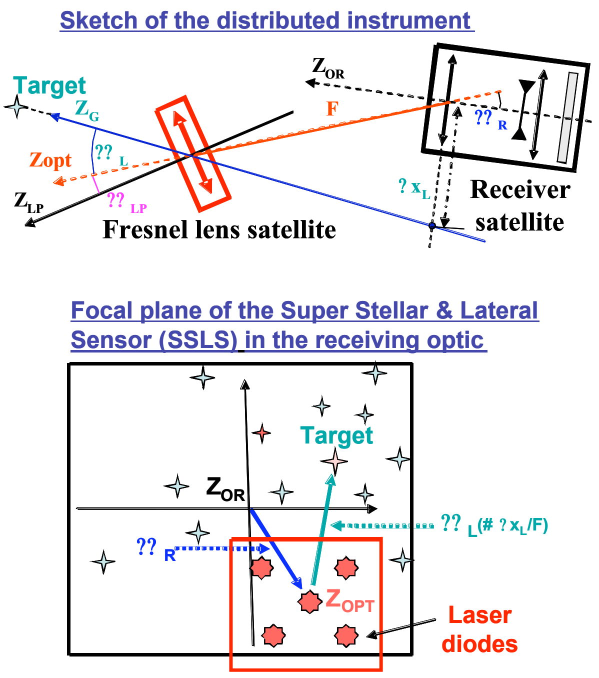

Fig. 7. Fresnel navigation principle

These four d.o.f must be controlled with accuracy (see "Coarse pointing and acquisition of the fine pointing" at section 5.1), which is solved by:
1st The same optics for the lateral sensor and the stellar sensor, to limit misalignment.
2nd A sensor of sufficient angular resolution, i.e. optics of sufficient diameter. <u>This "Super Stellar & Lateral Sensor" (SSLS), should be integrated into the scientific receiving optics.</u>
Fig. 8 shows the principle of the SSLS, displaying two options (a and b) according to the spectral band used (UV and Vis+IR).

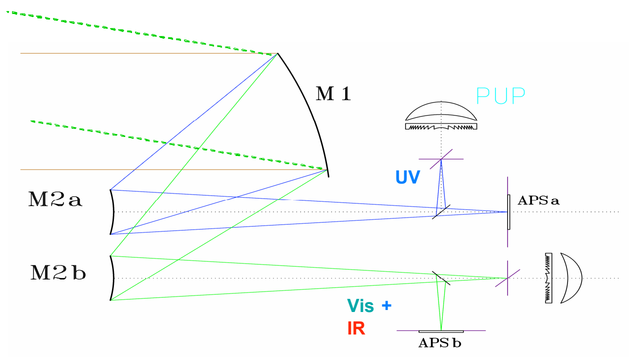

Fig. 8. SSLS principle.
The focal plane detector of the SSLS is named APSa or APSb, depending on the spectral band used. APS stands for Active Pixel Sensor. It could be the detector technology in the SSLS.

Navigation means and modes

Two classes of navigation subsystems will be used according to the three phases described at the beginning of paragraph 5.1:

1 For navigation on transfer trajectory, station-keeping, change of astrophysical target or focal distance, the formation will use:
-One RF sensing navigation (4πstrd) mainly for safe mode and formation acquisition (on each spacecraft),
-One digital sun sensor with a field of view (f.o.v) of +/-30° (two-axis) for safe mode and formation acquisition (on each Spacecraft),
-One coarse 3-axis gyro (+/-10°/s) for safe mode and formation acquisition (on each Spacecraft),
-One star & relative navigation sensor (f.o.v : +/- 10° two-axis). This sensor will be an adaptation of a standard star tracker (an APS detector is well adapted for the relative navigation function). This sensor is implemented for the coarse "pointing" function (Measurement of $\Delta\theta_R$ and $\Delta\theta_L$ with an accuracy of +/-20 arc sec). This coarse navigation sensor is only on the receiver spacecraft, and there is a standard star tracker on the lens spacecraft.
Remark : A redundant equipment is provided with each nominal equipment (excepted for the SSLS)

2) Navigation for "fine pointing" and acquisition of "fine pointing":

The navigation accuracy for "fine pointing" is such that the f.o.v of the SSLS will be limited (See "Navigation principle" and Fig.7). For instance, a lateral control of 1.25mm (40nrd for the angular control of the main optical axis and about 16nrd in terms of navigation accuracy for a main focal length of 31500m), we show below that the minimum SSLS f.o.v is larger than 1mrd. Hence, the coarse navigation should have an accuracy better than 1/4 of the SSLS f.o.v (~250µrd or ~50 arc sec) including alignment uncertainties between coarse and fine sensors.

A laser telemeter is essential for the measure of the main focal distance in fine navigation mode (Typical absolute accuracy ~10cm and in stability ~1cm).

Navigation implementation and performances

1) Fine navigation & acquisition of fine navigation:

The basis of the SSLS is to superpose on the same detector at its focal plane: the optical centre of the lens spacecraft, marked by reference lights, and the sky target unfocussed by the main array, directly seen through it from order 0 (see introduction). The superposition of these two will ensure proper alignment of the target direction axis Z_g with the main optical axis.

To obtain the required specs, from the value of the main focal length F in eq.(1), we express the required SSLS field of view (f.o.v):

$$SSLS\ f.o.v = 4\ D_{LENS} / F \quad (3)$$

Then we compute the SSLS required focal length, assuming a 0.04 m size for a 4000 pixels detector matrix on the SSLS focal plane (10µ pixel size):

$$SSLS\ focal = 0.04 / SSLS\ f.o.v \quad (4)$$

The angular accuracy $\Delta\theta_{L(Navig.)}$ will be driven by the precision of the detector reading. Supposing it corresponds to 1/20 of the pixel size in the SSLS focal plane, i.e. 0.5µ, we have:

$$\Delta\theta_{L(Navig.)} = 5.10^{-7} . SSLS\ focal \quad (5)$$

Consequently, the lateral control obtained by the SSLS on the Fresnel Formation is equal to $F.\ \Delta\theta_{L(Navig.)}$.

This will have to meet the lateral control needed for the Fresnel Formation, which is expressed by:

$$\Delta x_{L(Control)} = D_{LENS} / 8N = 1.25mm \quad (6)$$

This drives the focal length of the SSLS optics, shown in table 2.

Remark : In this example of SSLS detector we suggest to use Active Pixel Sensor (CMOS technology).

<u>Table2</u>: Fine Navigation performances (D_{LENS} = 10m)

D_{LENS} = 10m ; N= 1000 ; $D_{REC.}$ = 1.5m				
λc	0.397µ	0.600µ	0.918µ	1.400µ
F	31.5km	20.8km	13.6km	8.93km
SSLS f.o.v	1.27mrd	1.92mrd	2.94mrd	4.48mrd
SSLS focal	31.5m	20.8m	13.6m	8.93m
$\Delta\theta_{L(Navig.)}$	16nrd	24nrd	36nrd	56nrd
$F.\Delta\theta_{L(Navig.)}$	0.5mm	0.50mm	0.50mm	0.50mm
$\Delta x_{L(Control)}$	1.25mm	1.25mm	1.25mm	1.25mm
$\Delta x_{L(Command)}$	0.75mm	0.75mm	0.75mm	0.75mm

This table summarises the performance specs of the fine navigation system for a Fresnel formation flying with a primary lens diameter of 10 m, N=1000 Fresnel zones, and observations at four wavebands, centred on four central wavelength λc.

F *is the "main focal distance"*

SSLS f.o.v *is the Super Stellar Lateral Sensor field of view*

$\Delta\theta_{L(Navig.)}$*:SSLS angular accuracy (Navigation for lateral control)*

$F.\Delta\theta_L$: SSLS linear accuracy (relative lateral position)

Δx_L : relative position accuracy (Requirement)

The last line specifies, without margin, the required accuracy of the lateral position command & actuation ($\Delta x_{L(Command)}$ # 0.75mm)

2) RF & Optical Coarse Navigation:

Coarse sun sensors (or cell current intensity of the Solar Generator) and coarse 3-axis gyros allow attitude control of both spacecraft for safe mode and collision avoidance :

-Accuracy in attitude: ~1°

-Accuracy in attitude rate : ~0.001°/s

The RF sensing system, the optical coarse navigation sensor (digital sun sensor + "star & relative navigation sensor" (see § 5.2) and laser telemeter allow formation acquisition, orbit correction and control, focal change and target change :

-Accuracy in attitude for both spacecraft : ~1/100°

-Accuracy in relative position: ~10m (lateral and longitudinal position)

At last, optical coarse navigation sensors and laser telemeters allow acquisition of the fine formation navigation with the following performances:

-Accuracy in attitude for the receiver: ~1/1000°

-Accuracy in attitude for the lens spacecraft: ~1/100°

-Accuracy in relative position: ~1/1000° (~20µrd) equivalent to ~1m for lateral and longitudinal relative position.

5.3- Fresnel Formation Flying Control & Actuation

We split this paragraph in 2 sections :

1st Formation Actuation means and mode
2nd Control & actuation implementation and performances

Control & Actuation, means and mode

The Lens spacecraft manages attitude and orbit corrections (orbit control), which is a classical actuation, whereas the Receiver spacecraft handles the fine command & actuation of the formation flying. Table 3 synthesises this formation flying actuation.

Table 3. Actuation on Lens & Receiver spacecraft

	Lens spacecraft	Receiver spacecraft
Attitude actuators	Large and heavy wheels	Small wheels
Desaturation	Hydrazine or electrical propulsion	Cold gas or electrical propulsion
Propellant for safe, coarse pointing, and acquisition modes	Hydrazine	Hydrazine
Propulsion for fine pointing mode	-	Cold gas or electrical propulsion
Compensation of solar pressure disturbance on lens shield	-	Solar sails

- attitude and desaturation actuators are the same for all modes,
- hydrazine in coarse pointing and acquisition mode is mainly used for focal distance changes,
- hydrazine is also used for Earth to Small Lissajous transfer, orbit corrections and eclipse avoidances,
- The Lens spacecraft doesn't have propulsion for fine pointing: in formation flying, it's the role of the receiver spacecraft to control the fine relative position.

Actuation implementation and performances

Around Earth-Sun L2, the main disturbance on formation flying is solar pressure on the lens shield, which has a great effect on lateral control (see §4.2).
In order to compensate this disturbance, solar sails can be added on the receiver spacecraft. Thus more than 90% of solar pressure disturbance is counterbalanced. For instance, for a 10 m diameter lens, the equipped receiver spacecraft has to compensate 50 µN, it would need 400 µN without solar sails.

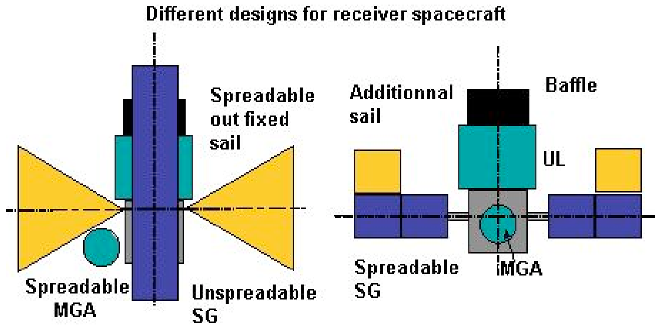

Fig. 9. Two configurations of solar sails on the Receiver spacecraft

The remaining compensation and "Fresnel pointing" (relative position control of the formation and attitude control of Receiver spacecraft) are managed by a fine propulsion system on the Receiver spacecraft. Three solutions for fine propulsion are put forward:

1) Proportional cold gas propulsion. This solution is inspired from the Microscope propulsion, whose thrust ranges from 1 µN to 500 µN. Table 4 summarizes its main features for a Fresnel formation with a 10 m diameter lens.

Table 4. Option "Proportional cold gas propulsion" on Receiver spacecraft

Disturbance force to compensate	50 µN
Lateral position precision (see §5.2)	0.5 mm
Response time	500 s
Thrust range	[25 µN ; 2mN]
Cold gas consumption for 10 years	70 kg

2) Pulse cold gas propulsion. At defined intervals T, thrusters provide a pulse of determined force. Table 5 summarizes the main features for a Fresnel formation with a 10 m diameter lens.

Table 5. Option "Pulse cold gas propulsion" on Receiver spacecraft

Disturbance force to compensate	50 µN
Lateral position precision (see §5.2)	0.5 mm
Thrust value	10 mN
Interval T between 2 pulses	600 s
Number of pulses for 10 years	550.000
Cold gas consumption for 10 years	60 kg

3) Electrical propulsion. This solution still seems a little bit "immature" but remains very attractive for upcoming developments.

For fine attitude control, reaction wheels represent the most simple and reliable solution. Since there is no

usable magnetic field in L2, the main issue is their kinetic momentum desaturation.
Concerning the receiver spacecraft, one will prefer a smooth and continuous desaturation of small wheels, using a cold gas or electrical propulsion. The reason is that there are very accurate pointing constraints, and it becomes therefore necessary to limit micro vibrations.
Concerning the lens satellite, a high angular momentum has to be counterbalanced, because of the solar pressure on the shield. For this purpose, we can use a large and heavy wheel, which spins slowly. Then this wheel is regularly desaturated (about each day) with hydrazine propulsion.

Table 6: orders of magnitude for fine attitude control of both spacecrafts (as in previous tables, it's based on a 10 m diameter lens).

	Receptor satellite	Lens satellite
Max Torque (1 axis)	5 µN.m	250 µN.m
Angular momentum over one day	0.5 N.m.s	20 N.m.s
Propellant used for desaturation	Cold gas	Hydrazine
Consumption for 10 years (3 axis)	3 kg	30 kg

Table 7: Total hydrazine needs for the two satellites.

	V	mass
During transfer from Earth to Large Lissajous	60 m/s	45 kg
Transfer from Large to Small Lissajous	240 m/s	165 kg
Orbit corrections (for 10 years)	40 m/s	24 kg
Eclipse avoidances	20 m/s	12 kg
Focal and target shifts	500 m/s	280 kg
Total	860 m/s	526 kg

Note that we have to add about 50 kg of hydrazine for the 10 m diameter lens satellite, in order to desaturate its wheels. This could be significantly reduced if the observing modes balance the radiation pressure torque on the lens shield.

6- CONCLUSION

The optical concept of this proposed formation flying mission is validated by the results obtained: optically with a testbed lab prototype, and numerically with special purpose optical software developed at the Laboratoire d'Astrophysique de Toulouse-Tarbes (LATT).
Some aspects of the formation flying two-module system will be simulated using a 19m long refractor mount, leading to ground based observations on real sky sources.
A phase zero study is now in progress at CNES, the results of which will hopefully open the way to new mission scenarios.
The space segment and, in particular, the Guidance Navigation & Control of the Fresnel formation flying constitutes the first part of this preliminary study. For this aspect of the space system, the fine navigation (Super Stellar & Lateral Sensor) and the fine relative position control with cold gas (or electric propulsion for long life mission) are the most critical but feasible technologies. Solar sails on the receiver spacecraft would save an important mass of propellant (volume, for cold gas) during fine pointing.

In conclusion, the important thing to highlight here is that no technical show-stopper appeared up to now. This new generation of diffractive focussing instruments has an important role to play in the future of astrophysics space science missions, while some technical aspects request important studies to bring up their TRL.

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