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L. Koechlin

P. Deba

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ASTROPHYSICAL TARGETS OF THE FRESNEL DIFFRACTIVE IMAGER

L. Koechlin(1), **P. Deba**(1), **T. Raksasataya**(1)

(1) *Laboratoire d'Astrophysique de Toulouse-Tarbes. Université de Toulouse, CNRS. 14 av. Edouard Belin, 31400 Toulouse FR.*

Abstract

The Fresnel Diffractive imager is an innovative concept of distributed space telescope, for high resolution (milli arc-seconds) spectro-imaging in the IR, visible and UV domains. This paper presents its optical principle and the science that can be done on potential astrophysical targets.

The novelty lies in the primary optics: a **binary Fresnel array**, akin to a binary Fresnel zone plate. The main interest of this approach is the relaxed manufacturing and positioning constraints. While having the resolution and imaging capabilities of lens or mirrors of equivalent size, no optical material is involved in the focusing process: just vacuum. A Fresnel array consists of millions void subapertures punched into a large and thin opaque membrane, that focus light by diffraction into a compact and highly contrasted image. The positioning law of the aperture edges drives the image quality and contrast.

This optical concept allows larger and lighter apertures than solid state optics, aiming to high angular resolution and high dynamic range imaging, in particular for UV applications. Diffraction focusing implies very long focal distances, up to dozens of kilometers, which requires at least a two-vessel formation flying in space.

The first spacecraft, "the Fresnel Array spacecraft", holds the large punched foil: the Fresnel Array. The second, the "Receiver spacecraft" holds the field optics and focal instrumentation. A chromatism correction feature enables moderately large (20%) relative wavebands, and fields of a few to a dozen arc seconds.

This Fresnel imager is adapted to high contrast stellar environments: dust disks, close companions and (we hope) exoplanets. Specific to the particular grid-like pattern of the primary focusing zone plate, is the very high dynamic range achieved in the images, in the case of compact objects.

Large stellar photospheres may also be mapped with Fresnel arrays of a few meters opertaing in the UV. Larger and more complex fields can be imaged with a lesser dynamic range: galactic or extragalactic, or at the opposite distance scale: small solar system bodies. This paper will briefly address the optical principle, and in more detail the astrophysical missions and targets proposed for a 4-meter class demonstrator:

– Exoplanet imaging, Exoplanet spectroscopic analysis in the visible and UV,
– Stellar environments, young stellar systems, disks,
– Galactic clouds, astrochemistry,
– IR observation of the galactic center,
– Small objects of our solar system.

1 Introduction

This Fresnel imager project is a formation flying telescope, in orbit around the Sun-Earth L2 Lagrangian point. The low gravity gradient at L2 authorizes distances of a few kilometers between the two spacecraft, while keeping the propellant needs reasonable for a long mission life.

Several proposals for using Fresnel zone plates in space formation-flying missions have been made in the recent years. Among others: by Chesnokov (1993) [1], Hyde (1999), [7], Early (2002) [4], and Massonnet (2003) [11]. The optical concept proposed here is different in several aspects, e.g. the use of vacuum as an optical element, the interferometric approach, the order zero masking, the main array design, based on the large number of subapertures necessary for high dynamic range images (Koechlin, Perez, 2002) [8].

The optical principle has been exposed in previous publications (Koechlin et al., 2005, 2006, 2007) [2] [12] [13]. Light is focussed by diffraction through holes punched into a large foil, forming millions of subapertures, there is no mirror nor lens involved in the primary optics: just opaque material and vacuum. The manufacturing constraints are released compared to optical surfacing, and the weight is reduced.

In 2007, we have submitted a proposal for a 3.6 m aperture array mission to ESA in the frame of the "Cosmic Vision" plan (Koechlin et al., 2007) [10]. This proposal has not been accepted, but we have made progress since. A laboratory prototype, and a phase zero study presently in progress at CNES allowed us to refine the instrument concept, the observing procedures, and the choice of astrophysical targets, which we present here.

2 Optical principle

The shape and positioning law of the void subapertures create a compact Point Spread Function (PSF). The subapertures cover a total of slightly less than 50% fo the total square aperture area. (fig. 1).

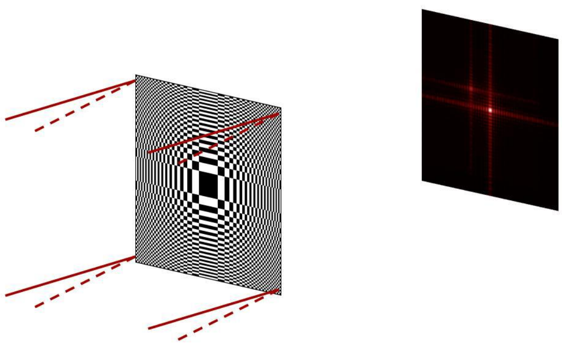

Figure 1: Image formation by a Fresnel Array. Here, a double point source is imaged by an orthogonal geometry one.

A Fresnel array can be seen either as aperture synthesis, or as a particular case of diffractive zone plate. The subapertures are arranged on a concentric Fresnel zone rings layout, so that a 2π phase shift occurs between neighboring rings, at order +1 of diffraction. As a consequence of this positioning law, an incoming plane-wave is split into several spherical outgoing wavefronts, one of them (order +1) containing from 5 to 8% of the incident light. An image is directly formed by this order +1 wavefront which yields a compact and high-contrasted Point Spread Function (fig. 2). The denser the subaperture layout, the higher the dynamic range for compact object images, (Koechlin & Perez 2002) [8].

Thanks to the orthogonal pupil shape, stray light escaping the central lobe of the PSF is confined within two orthogonal spikes. The rejection rate at 6 resels can reach 10^{-8} in the four quadrands of the freed field. This is akin to "Apodized Square Aperture" (Nisenson & Papaliolios, 2001)[16], but apodization is obtained here by modulation of the subapertures shape and position, driving the transmission and phase shift. PIAA designs are also envisioned for the future (Guyon 2005) [6].

As astrophysical targets need to be observed on relatively large wavebands, one cannot directly exploit the order +1 focus of a Fresnel Array, due to strong axial chromaticity: its focal distance is wavelength dependant. For a square array of size

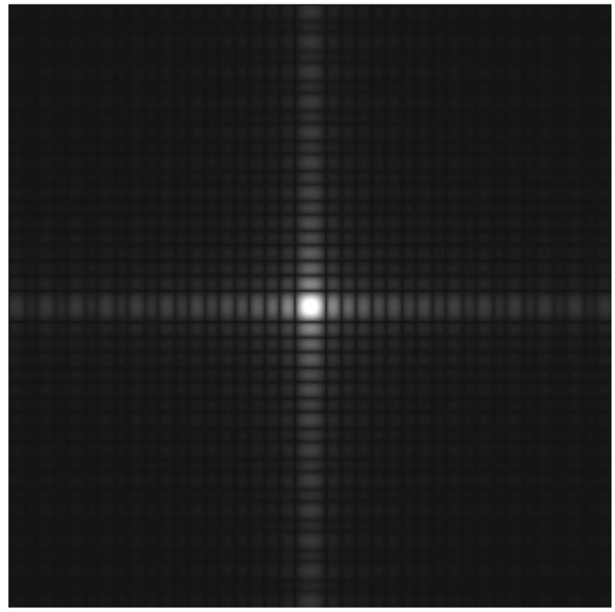

Figure 2: Example of Point Spread Function of an apodized Fresnel Diffractive Array. The brightness scale has been strongly flattened for display, to reveal the faint residual light in the four quadrants of the field.

C_{gr} having N Fresnel zones from center to limb, the order +1 focal distance F at wavelength λ is:

$$\boxed{\mathbf{F \approx \frac{{C_{gr}}^2}{8\,N\,\lambda}}} \tag{1}$$

Such an aberration would cause a blurred PSF except for very narrow spectral bandwidths. However, we achieve broadband imaging with a complete correction of the chromatism: based on a century old principle, a second diffractive element, placed in a pupil plane (Schupmann 1899) [14], applies a rigorously opposite chromatic aberration to that of the Fresnel array (Falklis & Morris 1989) [5]. Therefore, the wavelength dependence of the final focal plane is cancelled.

The correction scheme is illustrated in (fig. 3). It consists of:

- The field optics of diameter D in the receiver spacecraft, located at $F(\lambda_C)$ when observing in a λ_C-centered spectral band, plays two roles in the correction scheme. First, gathering the uncorrected, thus partially defocused beam from the order +1 of the Fresnel array, which yields a spectral bandwidth $\Delta\lambda/\lambda \simeq 1,41\,D/C_{gr} \approx 0.2$. Second, reimaging the primary Fresnel array onto a pupil plane where a chromatic diffractive element is located: a special diffractive Fresnel mirror or lens operating at order −1.

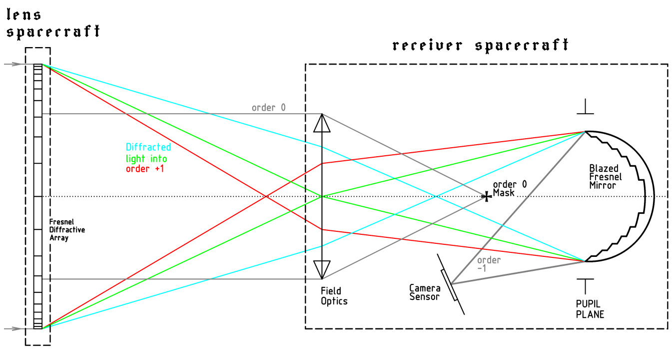

Figure 3: Synoptic diagram of an achromatized Fresnel Diffractive Imager. In the ultra-violet domain ($\lambda < 250$nm), a blazed Fresnel Mirror plays the major role in the chromatism correction scheme.

- A mask placed at the focus of the field optics in order to block out the order zero and order -1 beams of the primary Fresnel array that partially end up into the field optics. This is required for high dynamic range imaging. This could also be achieved by a central obturation of diameter D in the main array ($\mathrm{D} \ll \mathrm{C_{gr}}$) or the corresponding in the pupil plane, and an adaptation of the apodization.
- The third element is diffractive: a small Fresnel mirror or Fresnel lens that operates at order -1 . It both compensates for the chromatic aberrations and focuses the beam at the final image plane. Its Fresnel zones and those of the primary Fresnel array are homothetic, and conjugated by the field optics. At this level, broadband imaging is effective.

Contrarily to the primary Fresnel array, the Fresnel mirror or Fresnel lens in the chromatic corrector is blazed to avoid additional energy loss : its efficiency at order -1 exceeds 90 % over the $\Delta\lambda/\lambda \approx 0.2$. The optical throughput of the instrument reaches 4 to 6 %, not taking into account the detector.

The beam compression performed by the field optics permits the chromatic corrector to have a small size: typically $\mathrm{C_{gr}}/100$.

3 Instrument specifications and Mission characteristics

The achromatic image formed by the chromatic corrector in the receiver spacecraft is sent to different onboard instrumentation channels. Actually, several chromatic correctors can be placed side by side in a mosaic layout, each adapted to a specific waveband and feeding specific instrumentation. In a two-satellite configuration, only one channel at a time can be fed by the main array, the selection of which being done by adjusting the attitude of the receiver spacecraft, to project the pupil plane on the selected channel entrance.

3.1 Angular resolution

The angular resolution ρ is driven by diffraction, and limited by the main size $\mathrm{C_{gr}}$ of the opaque foil:

$$\rho = \frac{\lambda}{\mathrm{C_{gr}}} \tag{2}$$

$\mathrm{C_{gr}}$ =3m to 30m class projects have been studied, leading to resolutions $\rho = 0.5$ to 10 milli arc seconds, depending on the wavelength λ : from 120nm to 5 microns, depending on the science goals.

3.2 Instantaneous field of view

The total unvignetted field of view θ of a Fresnel Imager is driven by the size D of the field optics *and* the relative bandwidth $\Delta\lambda/\lambda_\mathrm{C}$:

$$\theta \approx \frac{1}{\mathrm{F}}\left(\mathrm{D} - \frac{\mathrm{C_{gr}}\,\Delta\lambda}{\sqrt{2}\,\lambda_\mathrm{C}}\right) \tag{3}$$

In high dynamic range applications, contrarily to the nuller approach, all the field –except the first 5 resels and the spikes of the PSF– is at high dynamic range. However, eq. (3) makes appear a compromise between instantaneous field of view on the one hand, and spectral bandwidth on the other. The field of view is all the more so narrow as the bandwidth is broad. This involves little field compared to classical telescopes: assuming a 0.15 relative spectral bandwidth, we get 1000 Airy radii. Nevertheless, 1000x1000 resel images will be produced, which is equivalent to a few arc seconds.

So, for example with N=700 Fresnel zones, D = 0.6m, and $\mathrm{C_{gr}} = 3.6$m, the images produced will be 1000x1000 resels. The imaging channels of the focal instrumentation will feature 2000x2000 to 4000x4000 pixels.

3.3 Observable sky

At a given time of the year, the observable sky will be a $\pm 20°$ wide circular band, centered on a meridian perpendicular to the sun direction, the width of this band depending on the baffle protecting the primary array from direct sun. As the sun-L2 direction rotates, a target at the equator will be observable continuously for a month (more at higher declinations). All the sky will be coverable in five months.

A fraction of the mission time will be dedicated to reshaping the formation: changing the inter-spacecraft distance according to the waveband chosen, or shifting target directions. A 2000 m/s embarked ergol reserve, using electric propulsion, allows 5000 reconfigurations. the reconfiguration times will be 1 to 4 hours and will use 40 % of the mission time.

3.4 Spectral coverage

There are bandpass limitations for a given spacecraft configuration, these entailed by the realtive size of the field optics at the focal plane, compared to the size of the primary array. Basically:

$$\Delta\lambda/\lambda_{\mathrm{C}} \simeq 1,41\mathrm{D}/\mathrm{C}_{\mathrm{gr}} \tag{4}$$

at the center of the field, where D is the diameter of the field optics and C_{gr} the size of the primary array. The chromatically corrected band can be shifted arbitrarily by changing the inter-spacecraft distance, assuming the corresponding focal instrumentation channel has optics adapted to that wavelength domain.

The central wavelength of each channel will be shiftable by adjusting the inter-spacecraft distance F, but high rejection rates and dynamic ranges will only be achieved close to the nominal blaze wavelength of each chromatic corrector ($\Delta\lambda/\lambda_{\mathrm{C}} < 0.1$ to 0.2).

For the first mission proposed, the Fresnel array size will be limited to 4 meters. The targets and focal instrumentation will be in the UV domain, where the angular resolution and high quality wavefront provided by Fresnel arrays give an edge over competition. For future missions (hoping there will be one or more!) larger arrays: 10 to 30 m, will allow to take full advantage of the optical principle. Visible and IR targets will be proposed, with dedicated spectral channels and instrumentation in the receiver spacecraft.

3.5 Spectral resolution

These spectral channels will feed a 20x20x100 spectroimager or a 1x1x40000 high spectral resolution instrument. The bandwidth being narrower at the edge or the field, the imager and spectro-imager channels may share the same observing time, the central pixels being used for the spectro-imager with a dedicated detector.

Depending on the scientific programs, quite different sctral resolutions are required. Exoplanet study for example requires relative resolutions of $\simeq$ 100 for detecting spectral signatures of O_3 or CO_2 by direct imaging, while astrochemistry of dense galactic clouds or exoplanet spectra by transit require spectral resolutions of 10000 or more.

3.6 Dynamic range

The image quality given by the main array is not dependant on the wavelength, allowing $\lambda/50$ wavefronts for all λ, and a raw dynamic range in the order of 10^{-8} in all the field except the central resels and four spikes. This should allow exoplanet study down to 10^{-9} contrasts.

The dynamic range is defined as the ratio of: the average intensity in the image field outside the central lobe of the Point Spread Function (PSF) and outside its thin orthogonal spikes *over* the central lobe intensity. Due to the convolution of the PSF spikes, the dynamic range decreases for extended objects and dense fields such as large galactic clouds (not covered entirely by the instrument field) or angularly extended solar system objects, but the angular resolution and imaging capabilities remain quasi equivalent to that of a solid aperture of the same size: Fresnel arrays have a spatial frequency coverage equivalent to that of a solid aperture and do not suffer aliasing problems.

3.7 Throughput

As exposed above, Fresnel arrays focus only a fraction the light. The rest is blocked or scattered in other diffraction orders. One usually compares the astrophysical instruments in terms of equivalent diameter. The proposed scientific programs of a 4m (respectively 40m) Fresnel imager will correspond to that of an equivalent 1.5 m (respectively 15 m) diameter telescope in terms of collected light and 4 m (respectively 40m) in terms of angular resolution. For point sources on a diffuse background, the brightness per unit angle in the PSF is that of a 2.1 m (respectively 21m) diameter aperture in space: this will be the case for spectral analysis of angularly unresolved sources.

Rather than comparison in terms of diameters, one should compare in terms of cost per scientific return. As Fresnel arrays are much lighter and tolerant in manufacturing precision, a given throughput should be obtained at lower cost. This will be one important outcome of the phase zero study undertaken at CNES.

4 Expected state of the art and other flying instruments when the Fresnel Imager is programmed

A Fresnel Imager mission can only be proposed if it is cheaper and/or supplies more science return compared to competitive technologies. As it can be used over a broad spectral domain and has capabilities in terms of resolution and dynamic range, the number of instruments to which it needs to be compared is large. At present, the following high resolution imaging instruments should be operating in the years 2020-2025, for the UV, visible and IR domains:

- JWST
- Herschel
- FUSE
- PLATO
- WISE : Widefield Infrared Survey Explorer, Universe, Search for Earth-like Planets
- LUVO : Large Ultraviolet/Optical Telescope
- Kepler : Search for Earth-like Planets
- SIM : PlanetQuest
- The different TPF-"C", "I", "O" projects: Search for Earth-like Planets
- Life Finder, and Planet Imager
- SI : Stellar Imager.

5 Scientific targets

5.1 Sellar environments and close binary stellar systems

For example *o* Ceti and companion, symbiotic stars, B_e stars envelopes and accretion disks. Observing in the UV does not imply observing only sources that have their maximum emission in the UV. The environment of red giants or many "red" sources is rich in the UV domain.

5.2 Forming stellar systems, Protoplanetary discs

- In the UV and visible : stellar and exoplanet precursors at moderate spectral resolution.
- In the close IR with 20 to 30m class arrrays: Exoplanet spectra, young stellar objects and planetary systems.

5.3 Terrestrial Exoplanets

This will not be reachable with a 4m aperture, furthermore in the UV. However, 40-meter class arrays will provide enough angular resolution in the IR. 10-meter class arrays should detect and provide spectral analysis capability on a few targets within a 10 parsecs radius.

5.4 Jovian Exoplanets

At 120 nm wavelength, a 3.6 m aperture yields 7 mas angular resolution. It is enough for resolving a planet orbiting at 0.07 AU from a 10 pc distant star. It's also sufficient for mapping the photospheres of neighboring giant stars, hot accretion disks, as stated above.

At the other end of the proposed range: $1\mu m$ wavelength, the angular resolution would go down to 0.06 arc seconds, and still allow the direct detection of a Jupiter at 15 AU.

5.5 Small objects of the solar system

Although not providing, by far, the linear resolution of a dedicated planet probe, a large Fresnel imager at post around L2 will provide opportunities of very high angular mapping of almost any object at or beyond Mars orbit, with little timing constraints.

5.6 Galactic physics, AGN

The vicinity of these highly contrasted compact objects has been poorly studied from earth or from space, due to the PSF wings of adaptive optics systems and the dynamic range of the HST.

5.7 Vicinity of SgrA*

Due to the strong density near the plane of the galactic disc, below 1.6μm wavelength, the absorption axceeds a factor 100. There will be a tradeoff between angular resolution and sensitivity, and only large array (>10m) will be competitive with JWST. However, the galactic center is a hot and evolving topic. A lot can be learned form the high resolution astrometric, spectral, and photometric observations of this matter in extreme conditions.

6 Conclusion

The field of potential science with Fresnel imagers is very large and promising. It deserves being investigated in more depth. We ask for your comments and help: the project is now taking shape, but will need a large support of the astronomical community to reach the critical mass necessary for funding a full fledged space mission.

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