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The Fresnel Interferometric Imager

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Abstract The Fresnel interferometric imager is a new kind of high angular resolution space instrument for the UV domain, and the related astrophysical targets. This optical concept is meant to allow larger and lighter apertures in space than solid state optics. It yields high dynamic range images and same resolution as that of a solid aperture of the same size. The long focal lengths of the Fresnel imager (a few kilometers) require operation by two-vessel formation flying in space. The first vessel holds a large and thin opaque foil punched with thousands of holes: the interferometric array, the second vessel holds the focal instrumentation.

This Fresnel imager has been designed for mapping high contrast stellar environments: dust disks, close companions and (we hope) exoplanets. Compact objects such as large stellar photospheres may be imaged with array sizes of a few meters in the UV. Larger and more complex fields can also be imaged, although with a lesser dynamic range, such as small fields on galactic clouds or extragalactic fields, or in an other domain: small solar system bodies.

We present the first images obtained on artificial sources with an 8 cm laboratory testbed array having 26680 apertures, the measured dynamic range of these images and their diffraction limited angular resolution.

A 3m class probatory space mission will be studied and follow a validation path, It has been submitted as a proposal to the ESA Cosmic Vision program.

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1 Introduction

This Fresnel imager is an interferometric device in which the light is focussed by means of holes punched into a large and thin foil, forming many thousands of subapertures. This punched foil: the Fresnel Interferometric Array, acts as the primary focussing element of a large virtual telescope. This large aperture contains no mirror nor lens: just opaque material and vacuum. The positioning law of the numerous subapertures edges, which is close to, but different from that of a Fresnel zone plate (Soret, 1875), causes focalisation by diffraction and is efficient in a broad wavelength domain ($100nm$ to $20\mu m$). For a given image quality, the subaperture positioning is very tolerant compared to optical surfaces or path length control in interferometers.

This project is at its first stages, started in 2004 at Université Paul Sabatier Toulouse (Koechlin., Serre, Duchon, 2004) and supported by the French Space Agency: Centre National d'Etudes Spatiales (CNES).

The validation tests were made optically and numerically. The optical testbed array is an 8cm x 8cm array of58 Fresnel zones, materialized by 26680 apertures carved into a $80\mu m$ thin stainless steel foil. It has a 23 meter focal length at $600nm$ wavelength and is located in a clean room at Université Paul Sabatier. Collimated test targets of various shapes, contrasts and sizes have been imaged by this array at wavelengths from 450 to $800nm$.

The numerical tests involve computed Fresnel propagation through all the optical elements of large arrays: up to 800 Fresnel zones. They allow testing of large arrays, which, if tested optically, would require kilometer-long optical paths, difficult and expensive to implement.

For similar size arrays, the optical and numerical tests give results in agreement with one another, and show high dynamic range diffraction limited imaging. They have been published in (Serre, Koechlin, Deba, 2007).

Following our validation tests, a proposal for a 3.6 m aperture array mission has been submitted to the European Space Agency (ESA) in the frame of the "Cosmic Vision" plan(ESA proposal, Koechlin et al., 2007). The answer should be known by the time this paper is printed. The proposed space Fresnel array is a large (e.g.,3.6 x 3.6 meter) square opaque foil with 350 to 600 Fresnel zones: 10^5 to 10^6 void subapertures. This "Fresnel Interferometric Imager" would orbit the L2 Earth-Sun Lagrangian point, the main spacecraft being the focussing element: the Fresnel interferometric array; the other spacecraft holds the field optics and detectors.

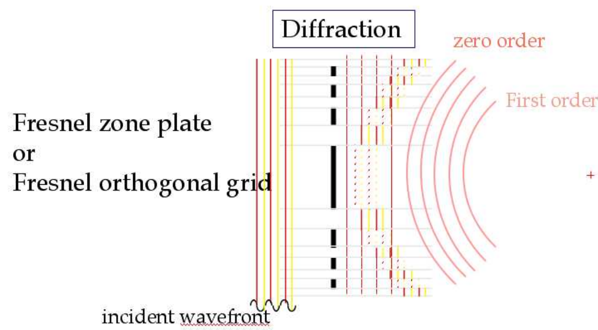

Fig. 1.— Focalisation by diffraction (1D example) : an incoming plane wave is turned into a convergent wavefront when a 2π phase shift occurs from one aperture to the next in line.

2 Optical principle

Focusing is achieved with no optical element: the shape and positioning of the subapertures being responsible for beam combining by diffraction (fig. 1). This array can be seen either as an aperture synthesis array or as a particular case of diffractive zone plate. The subapertures are positioned so that a 2 π phase shift occurs at the first order of diffraction between neighboring zones. As a consequence of the subaperture positioning law, an incoming plane-wave is turned into a spherical outgoing wavefront containing a fraction (5 to 10%, depending on the subapertures layout) of the incident light. An image is directly formed by the array (fig. 2), the dense subaperture layout leading to a compact and highly contrasted Point Spread Function (PSF). The principle is explained in more detail in Koechlin, Serre, Duchon (2005).

The consequence of this large number of subapertures is the possibility of is high dynamic range imaging (Koechlin, Perez, 2002) . In addition, it is potentially efficient over a very broad wavelength domain.

Several proposals for using Fresnel zone plates in space formation-flying missions have been made since 1993: by Chesnokov (1993), Hyde (1999) Early (2002), and Massonnet (2003).

Our Fresnel interferometric array differs on several aspects from zone plates: its layout makes the non-transmissive zones connected throughout the array, allowing the use of vacuum for the transmissive zones (void subapertures) while preserving mechanical cohesion of the whole frame. It is based on an interferometric approach, an orthogonal geometry, uses vacuum instead of an optical active medium, and has high dynamic range astrophysical applications (Koechlin, Serre, Duchon, 2005).

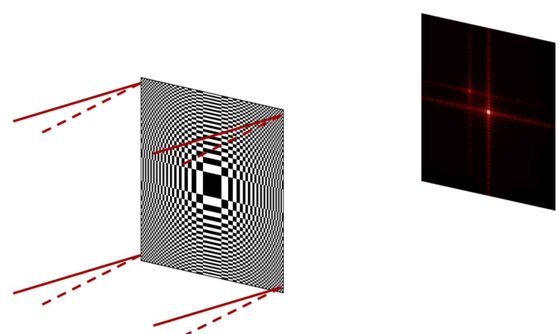

Fig. 2.— Orthoconal Fresnel array and associated image in the case of a double point source: 2D example of focalisation by diffraction.

3 Spectral coverage

Diffractive optics are very chromatic, and until recently they were usable only for narrow spectral bands. However, the chromaticity issue has been addressed by Falklis & Morris (1989), Chesnokov (1997), Hyde (1999), and solved using an optical principle by Schupmann (1899). Falklis & Morris have built in 1989 an optical setup yielding achromatic images with diffractive optics. We have designed a new version of this chromaticity correction scheme in our testbed, and conceived the blazed diffractive Fresnel lens operating at order -1, adapted to the primary orthogonal Fresnel array (used at order +1.) This small size blazed divergent Fresnel lens is the active element in the chromaticity correction optics.

With our testbed, we have made broadband images in the visible : $\Delta\lambda/\lambda = 0.4$ i.e. $400 - 800nm$, chromatically corrected and diffraction limited. High dynamic range $(2 * 10^{-6})$ has also been achieved as will be developed in a following section, but with smaller bandpasses: $\Delta\lambda/\lambda < 0.15$ due to the leaks for wavelengths non adapted to the blaze angle of the corrector.

For wavelengths beyond the waveband limits, the chromaticity is still corrected but the luminosity and angular resolution degrade due to vignetting. In order to prevent vignetting, the spectral bandpass has to be limited to $\Delta\lambda/\lambda \simeq 1,41D/C_{gr}$ at the center of the field, and less at the edge, D being the diameter of the field telescope (e.g. 68 cm) and C_{gr} the side of the square primary array (e.g. 3.6 m, which in that case would mean a $\Delta\lambda/\lambda = 0.2$ corrected spectral bandwidth.)

Although the instantaneous bandwidth is limited by the secondary optics diameter, as explained above, the wavelength domain potentially covered by the large primary Fresnel array is very broad: it stops where the vacuum stops being transparent... well, in fact where the opaque material stops being opaque and non radiative.

The chromatically corrected band can be shifted arbitrarily within the broad spectral range of the primary Fresnel array, but only one band at a time can be observed. The shift in waveband is done by shifting the average position of the image plane along the optical axis. In a formation flying instrument, this would be done by changing the inter-spacecraft distance.

The limits of the global spectral domain are set in the IR by the temperature to which the foil forming the primary array can be passively cooled: its Planck emission at a temperature of for example 130 k hampers high dynamic range observations at wavelengths beyond 5 microns, whereas a Fresnel array cooled to 50K̃ would allow observations up to 25 microns.

The limit towards the far U.V. is set by the opacity of the foil starting to become transparent at short wavelengths. The problem comes from the phase defects caught by the wavefront while passing through the unperfectly smooth foil material: this will cast an aberated image superposed to the correct one and hinder the dynamic range. At present we have measured the dynamic range in the visible, but not yet studied the opaqueness and properties of possible foil material in the U.V.: a 100 nm limit is conjectured. A "phase zero" study currently starting at CNES will address this question, find suitable material for the foil in the UV, and give a value for the wavelength limit.

Short wavelengths will also be limited by the decrease in reflectivity of the field optics mirror (coating).

4 Mission design

The Fresnel Imager that we propose shares an exoplanet detection capability with the NASA TPF-C or TPF-I projects, or with the ESA Darvin project, while being less specialized for this goal. A 3.6x3.6m size for the Fresnel array has been chosen to fit unfolded as a rocket payload. Our rationale is to favour simplicity and feasibility, while preserving scientific goals. If a mission proves the efficiency of the Fresnel Interferometer concept, then much larger arrays can be envisioned.

The proposed 3.6 m Fresnel Interferometric Imager would be short wavelength oriented. It is designed to cover the spectrum with six adjustable bands from Lyman α to close I.R. with angular resolutions from 7 mas at Lyman α , to 57 mas at 1 μ m. These bands provide an instantaneous $\Delta\lambda/\lambda = 0.2$ spectral coverage for a given inter-spacecraft distance. From one band to another, the spectral coverage will not be simultaneous : only one spectral band at a time will be observed in this two-spacecraft formation-flying configuration.

Six dedicated channels will cover each a spectral band with their dedicated diffractive blazed corrector, focal instrumentation and detectors. They will share the same 3.6 m primary Fresnel array and the same 68 cm main mirror of the field optics.

Downstream, all channels will provide imaging capabilities (860x860), two or three of them will have coronagraphic optics and low dispersion spectro-imaging capabilities, the others will have a high dispersion spectro fed from the center pixels of image the field. Hence, for each channel there will be two detectors, one for broadband imaging and one for spectral analysis of a local zone of the field.

5 Field

The field of a Fresnel imager is somewhat smaller than that of a standard telescope, due to the fact that the long focal lengths (up to a few kilometers) and the limited size of the field optics at primary focus (where a small standard telescope is used as "field lens") limit the angular field to 6 arc seconds in Lymann α and 52 arc seconds at 1 micron wavelength. These figures will be sensibly larger if a larger secondary is used, but the rationale for the Fresnel imager is to waive the need for a large standard telescope in space, putting the burden large diameters over the thin foil primary.

In high dynamic range applications, contrarily to the nuller approach, almost all the field will be at high dynamic range: rejection rates superior to 10^{-8} and only a small solid angle in zodiacal and exozodiacal lights (the area covered by the PSF and its spikes) are contributing to noise at a given point in the field.

6 Dynamic range and throughput

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 (see fig. 4, over the maximum intensity in central lobe of the PSF.

The numerical simulations for a 350 Fresnel zone array reach a 10^{-8} dynamic range. A consequent improvement of these values is expected with the implementation (in the optical prototype and in the numerical simulations) of a coronagraphic system. 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 remains unchanged.

The optical test images have been made on artificial targets in the visible domain, with a stainless steel primary Fresnel array and a small fused silica diffractive corrector lens in the pupil plane, blazed for 600 nm. The optical tests made with $\Delta\lambda/\lambda = 0.15$ at the 58 Fresnel zones primary array yield a 2 10^{-6} dynamic range.

Further validation is required for the UV domain: optical tests are planned in the near-UV range for the months to come. What will change is the blaze angle, towards lower values. The groove spacing has to be homothetic to the Fresnel zone structure of the primary array, thus it is not directly wavelength dependant. The quality of the diffractive corrector is of prime importance for dynamic range, as the light leaking out from diffraction order -1 may end up polluting the field.

Another issue concerning the Fresnel arrays is the throughput: only a small fraction of the incident light is focussed. 50% or more is blocked by the opaque parts of the array, then, the light is then spread into different diffraction orders: e.g. for a basic orthogonal layout, such as in fig. 3, 40% of the total incoming light goes into order zero, 4.1% into order -1 and 4.1% into order +1, which is the only one interesting for imaging. The higher orders of diffraction undergo a very rapid decrease in brightness: $B(m) = 4/(\pi^4 m^4)$ as a function of diffraction order for m odd and $B(m) = 0$ for m even, they contribute in a negligible manner to the total.

We are currently working on three axes of possible improved designs for the Fresnel primary arrays:
- Fractal, as in fig. 4,
- Radial Locally Apodized, as in fig. 5,
- Spergle Type Modulation, as in fig. 6, a multi aperture extension of the modulated mask by Kasdin, Vanderbei, Littmann, and Spergel (2005).

Increasing the transmission efficiency up to 10 % is possible with these alternate designs for the subapertures shapes and layout, while improving the dynamic range further. Including a central obscuration mask in the Radial locally apodized design, having itself apodized edges over several Fresnel zones as in a Webster Cash occulter (Cash, 2006) will release the need for the present mask presently used in our design to block the light from order zero of the primary. To further increase the dynamic range, a Phase Induced Apodized Aperture (PIAA) (Guyon 2003) or PIAAC (Guyon 2005) can be implemented in a Fresnel array: the two elements could be put after the chromatic corrector. One could also directly directly use the primary Fresnel array as an active element of the PIAA, by altering the position law of subapertures in order to obtain the desired wavefront shape.

Pending these long term improvements, the array shapes illustrated in figs. 3 to 6 are going to be measured for transmission and dynamic range, both numerically, and optically in our testbed.

7 Angular resolution

At 120 nm wavelength, a 7 mas angular resolution is provided by the 3.6 m aperture. 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 an example of the broad range of possible targets in the UV domain.

At the other end of the proposed range: $1\mu m$ wavelength, the angular resolution would go down to 0.06

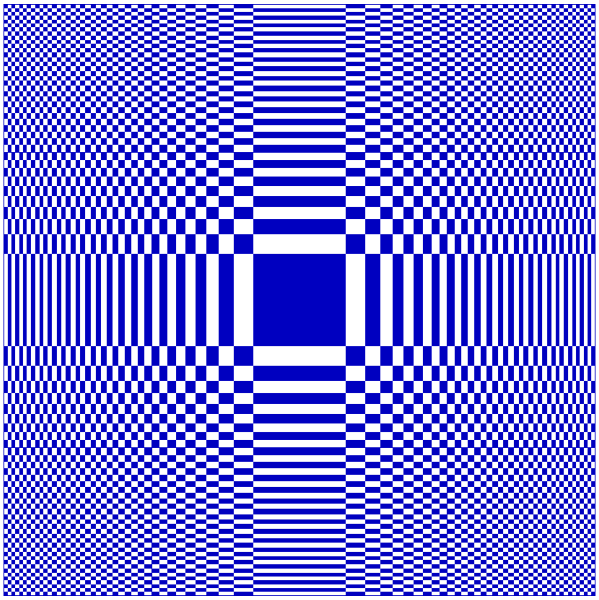

Fig. 3.— Basic Orthogonal carving Fresnel array. The 20 first central Fresnel zones are displayed. The actual testbed array has 58 zones, which corresponds to 28880 rectangular subapertures.

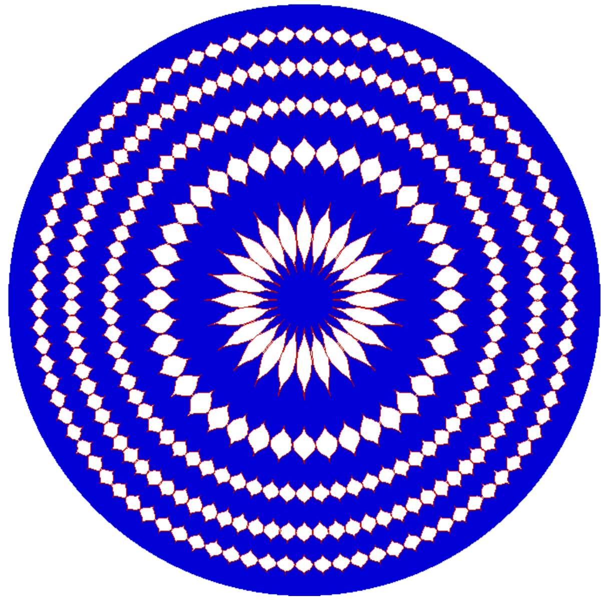

Fig. 5.— Radial Locally Apodized transmission carving Fresnel zone plate. Only the first central Fresnel zones are displayed.

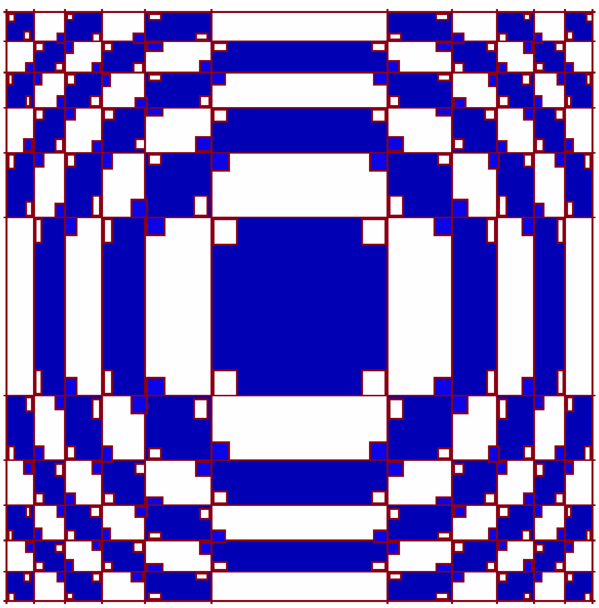

Fig. 4.— Fractal carving Fresnel array. Only the first central Fresnel zones are displayed. The apparent curvature of the lines holding together the different zones is an illusion: they are straight and orthogonal.

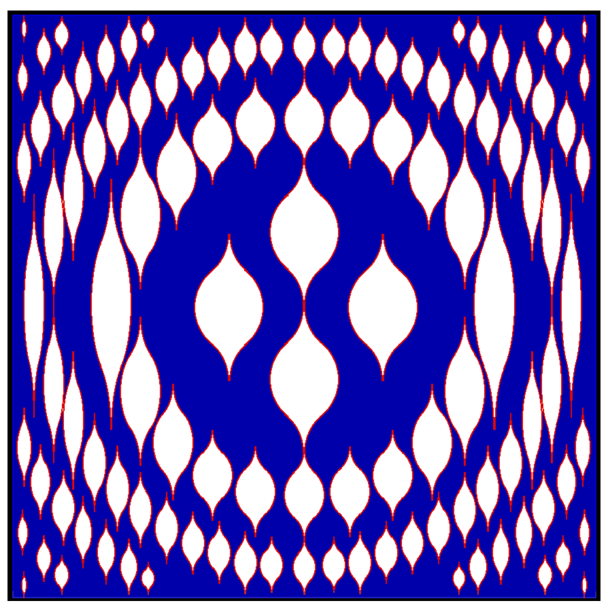

Fig. 6.— unidirectional width modulation transmission carving Fresnel array. Only the first central Fresnel zones are displayed.

arc seconds, and still allow the direct detection of a Jupiter at 15 AU. Once the planet image is separated from it's star, a measure of the exoplanet spectral signatures becomes possible. The spectral resolution and spectrum S/N in that case will be limited, due to the necessary residual starlight subtraction after detection : The expected rejection rates provided by Fresnel arrays are in the order of 10^{-8}, whereas $planet/star$ contrasts up to 10^{-9} are planned to be observed. The Signal over noise ratio has been calculated spectra made at spectral resolution 50. Some examples have been presented in our ESA proposal for a Fresnel imager (Koechlin et al. 2007) and more are available in Denis Serre's thesis work: (Serre, 2007).

8 Scientific objectives

The proposed mission will observe mostly in the UV, but also in the visible and close I.R. domains, using six different spectral channels in the secondary spacecraft optics. The choice of wavelengths for each band depends on the target missions and a possible choice is in our ESA proposal for a Fresnel imager.

-In the UV : spectro-imaging at high spectral resolution for exoplanet direct detection and exoplanet transits, stellar photosphere imaging, galactic clouds observations, extragalactic objects.
- In the visible : stellar and exoplanet measurements at moderate spectral resolution.
- In the close IR : Exoplanet spectra, young stellar objects and planetary systems.

The central wavelength of four of these channels will be adjusted to obtain a quasi-continuous coverage from Lyman α to 400 nm, and two additional channels will cover part of the visible and close I.R. The central wavelength of each channel will be displacable to some extent, but high rejection rates and dynamic ranges will only be achieved close to the nominal wavelength of each channel ($\Delta\lambda/\lambda < 0.2$), the central wavelength for each band being determined by the blaze angle of the corresponding chromatic corrector. For a primary array transmission efficiency of 8% ; the proposed scientific program of the Fresnel imager will correspond to that of an equivalent 1.3 m diameter telescope in terms of collected light and 3.6 m 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 diameter aperture : (this will be the case for spectral analysis of angularly unresolved sources).

9 Conclusion

In addition to being a possible precursor of very large lightweight apertures in space, the peculiarity of the Fresnel imager proposed here is its dynamic range and capability to operate over a interesting spectral domain: 120 nm - 900 nm, for the study of astrophysical objects and phenomena. In order to have a chance of being launched and see starlight, this project needs support from the astronomical community. Thanks to the help of Ana Ines Gomez de Castro at Universidad Complutense de Madrid, Alfred Vidal Nadjar at Institut d'Astrophysique de Paris, Margarita Karovska at Harvard Smithsonian Center for Astrophysics, Roser Pello in Observatoire Midi-Pyrénées Toulouse, and many others, we are currently starting an international group from the various domains of astrophysics that can be explored with the Fresnel Imager.

You are very welcome if you think that the proposed mission may be of some use for your domain of astrophysics: please contact the authors.

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