Fresnel interferometric Arrays as Imaging interferometers

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Abstract

We propose a concept of interferometric array based on diffractive focussing that could add a new line of instruments to the already existing space telescopes and telescope arrays. Fresnel interferometric arrays should be easier to build than equivalent resolution monolithic apertures or classical aperture synthesis arrays and allow larger fields and high dynamic range for astrophysical imaging. We present the concept and the first results of validation tests.
Among high angular resolution imaging techniques, aperture synthesis provides the highest resolutions, but requires stringent path lengths control and optical surfaces quality. Beam recombining is also a challenge in the I.R, optical and shorter wavelength domains if the number of apertures exceeds a dozen. A large number of apertures is nonetheless necessary to allow imaging of complex objects, as a simple law binds the maximum number of independent pixels in a reconstructed image to the number of individual apertures in the interferometric array providing this image (Koechlin & Perez, 2002).

The proposed Fresnel interferometric arrays allow aperture synthesis with hundreds of thousands of apertures. The previously required high precision optics are replaced by mere holes in a thin opaque foil covering the dimensions of the array. Focusing is achieved with no other optical element than vacuum and the edges of the holes; their shape and positioning alone being responsible for focalization and beam combining. The consequence of this high number of apertures is a large number of pixels and a very high dynamic range.

1. Principle

The Fresnel interferometric array can be seen either as an aperture synthesis array or as a particular case of diffractive zone plate. Beams from the individual apertures are recombined by diffraction and interference. The apertures (void rectangles or more complex shapes) are positioned so that at the first order of diffraction (2-Pi phase shift from one aperture subset to the next), an incoming plane wave is turned into a spherical outgoing wavefront.

Fresnel interferometric arrays are related to Soret zone plates (Soret 1875), and to several space projects based on them, proposed these recent years (Chesnokov 1993, Hyde 1999, Early 2002, Massonnet 2003). However, Fresnel interferometric arrays differ from these on several aspects. Their orthogonal layout makes the non-transmissive zones connected over the whole array, allowing the use of vacuum for the transmissive zones (apertures) while preserving mechanical cohesion of the whole frame. One possible transmission law T(x, y) of the array is built as follows. Let us define functions g as:

$$g(a) = 1 \text{ if } \sqrt{a^2 + f^2} \in \left[\left(k + \frac{f}{m\lambda} + \frac{1}{2}\right)m\lambda ; \left(k + \frac{f}{m\lambda} + 1\right)m\lambda\right[\quad \text{and } g(a) = 0 \text{ otherwise,}$$

a is the distance from the optical axis, *m* is the diffraction order, *k* the Fresnel zone index an *f* the desired focal length.
Using functions *g(a)* and *h(a) = 1 – g(a)* one can define a 2D transmission based on an orthogonal development of *g* and *h*:

$$T_o(x, y) = h(x)h(y) + g(x)g(y)$$

An image is directly formed by the array, the dense aperture layout leading to a compact Point Spread Function (PSF).

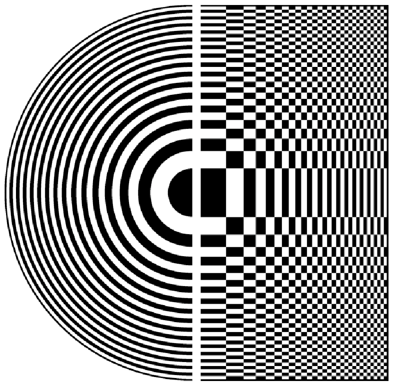

Fig. 1: Circular (Soret) zone plate & example of orthogonal Fresnel array, 15 Fresnel zones (half sides).

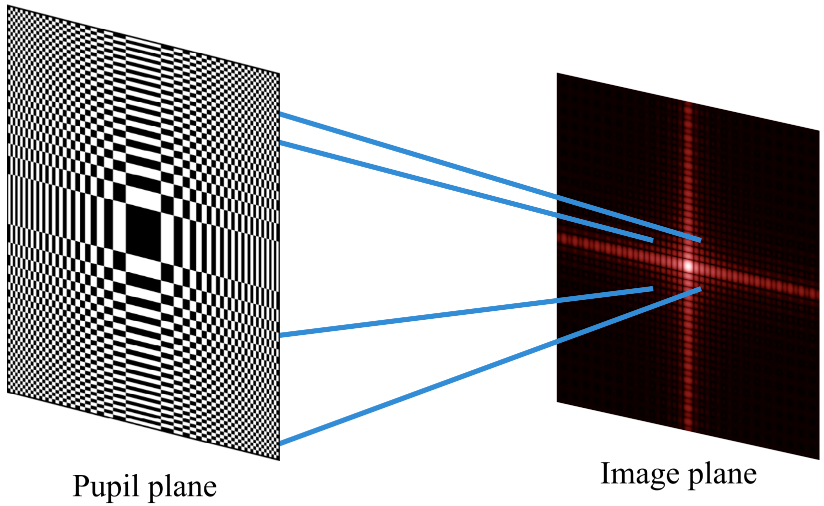

Fig. 2: Image of a point source,
low levels enhanced: power 1/4 viewing. Point Spread Function computed by Fresnel Transform.

2. Advantages

- The angular resolution of a Fresnel array is the same as that of a filled aperture having the size of the whole array.
- The use of vacuum for the individual subapertures eliminates the phase defects and spectral limitations which would result from a transparent or reflective material. Thus, the spectral span of Fresnel arrays is limited only by the characteristics of the opaque material: towards the UV by its effective opacity, towards the I.R. by its Plank emission. A thin opaque metal foil would yield a spectral domain spanning from 50 nanometers to 10 microns or more.
- The resulting wavefront quality is relatively insensitive to array warping and only limited by the precision to which the apertures are carved. This constraint is also quite loose compared to optical surfacing: a $\lambda/50$ wavefront for high dynamic range imaging requires either a $\lambda/100$ mirror, or a 200 λ precision (typically 0.1 mm) on subaperture edges in the Fresnel array proposed here.
- The dense rectangular pattern of the array (all aperture edges following two orthogonal directions) casts light at focus into a central peak flanked by two orthogonal spikes, rather than diffraction rings (case of circular aperture) or broad side lobes (diluted interferometric arrays), thus most of the field remains at very low stray light level. To further increase the dynamic range, we apodize the array by modulating from center to edge, either the dimension, the shape or the position of the subapertures, acting respectively upon the amplitude or the phase of the wavefront. We also block orders 0 and –1 of the primary array by adapted masks in the field optics.
- The large number of apertures allows a high field/resolution ratio, hence much broader fields than with other interferometers.

3. Drawbacks

- Fresnel arrays act as transmission gratings. Only a fraction: 3 to 6% of the light, depending on the subapertures shape optimization, is diffracted into order 1 and combined at focus, a major part ends up in order 0 and remains a plane wave. Thus a 5-fold increase in size is required to collect the same number of photons as a solid aperture ($\sqrt{5}$ in case of an unresolved source). However, the angular resolution is the same as that of a filled aperture of equal size. If the comparison with filled apertures is made in terms of cost per unit of information collected, rather than size per photon, Fresnel arrays may get the advantage.
- Long focal lengths are implied by the proposed diffractive focussing, therefore requiring formation flying in space: for example f=7 km for a 6-meter array operated at $\lambda \approx 1 \mu m$ and subapertures ranging from17 cm to 1 mm, center to limb. Typically a Fresnel array of size 1 can be set to have a focal length of 300 to 1000 and a "secondary" field mirror of size 0.2 to 0.05 placed at focus.
- Strong chromatism occurs as a consequence of diffractive focussing: $f \propto 1/\lambda$. However, this is corrected in a pupil plane by a small diffractive plate operating at order –1 (Schupmann 1899, Falklis, & Morris 1989). This secondary Fresnel lens is blazed to optimize transmission. The resulting correction is complete and independent of the wavelength, the spectral bandpass being limited by the size of the field optics and by the transmission characteristics of the material used for this small corrective lens.

4. First tests on a laboratory prototype

A 22-meter focal length prototype is presently being tested at Observatoire Midi Pyrénées (Toulouse, France). The primary Fresnel interferometric array (fig.3) is a 80 mm, 58 Fresnel zones, 26680 apertures grid carved into a 80 µm thick steel foil. Test sources are placed at the focus of 1270 mm focal length parabolic collimator, and the resulting parallel beam is sent to the Fresnel array.

After a 22 m propagation, te beam converges to a focal instrumentation setup (Fig. 6), which comprises a field telescope (a) to reimage the primary array onto a correcting diffractive lens (b) placed at a pupil plane, and a high dynamic range ccd camera (c) at the final image plane.

We have already tested the efficiency of chromatism correction ($\lambda \approx 500$ to 1100 nm) and the image quality with a preliminary (unblazed) corrective lens.

Fig. 3: 80 mm square primary array carved into a thin 80 µm stainless steel foil, used for optical tests.
(58 Fresnel zones, 26680 apertures)

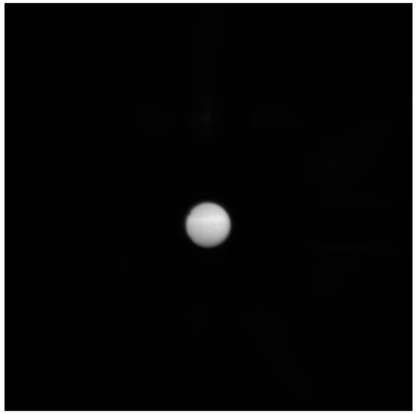

Fig. 4: a 32 arc second disk, imaged by the 80 mm achromatized test array. The disc is a 200 µm pinhole illuminated in broad band by a halogen lamp and collimated by a 1270 mm focal length mirror. The detector is a SXV-H9 ccd camera sensitive from λ = 0.5 to 1.1 µm. There is no detectable chromatic aberration. The white horizontal strip in the disc is due to the lamp filament.

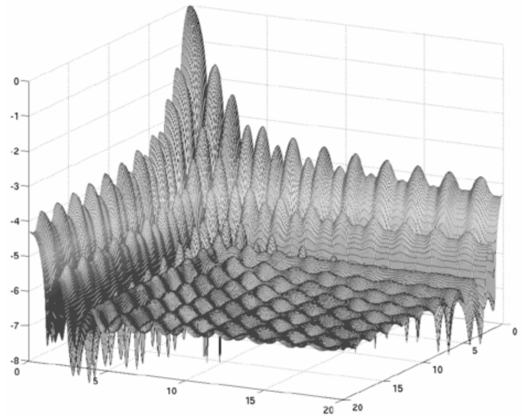

Fig. 5: Numerically computed PSF (quarter field) of an apodized 800 zone Fresnel array of size B, showing the central peak and two of the four orthogonal spikes. The dynamic range reaches 10^7 in most of the field.
Vertical: log normalized brightness.
Horizontal: distance in units of λ/B.

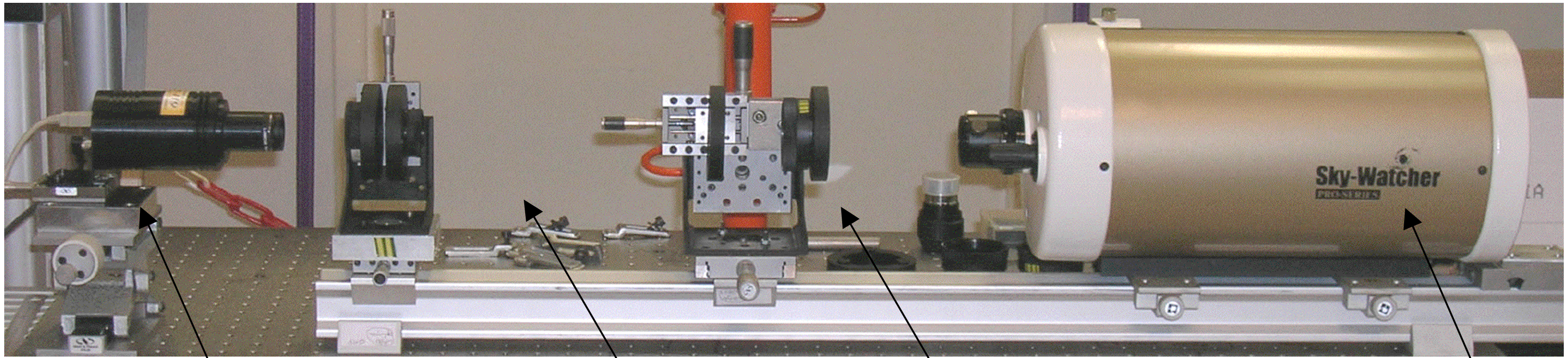

Fig. 6: Field optics and focal instrumentation

5. Should we propose a demonstrator space mission?

Fresnel arrays require formation flying in space. Although better can be done from the ground than the small prototype presented above, these will be difficult to test at real size, due to their long focal lengths. Before thinking of large space borne arrays, one should find a suitable way to test the concept in real conditions while keeping the costs of this "newcomer" acceptable by a space agency. Such a demonstrator mission should be as simple as possible, though yield some novel scientific return in addition to the technical data.

We have published a paper last year exploring the feasibility of exoplanet imaging with large (> 6m) arrays, taking advantage of the high dynamic range imaging provided by Fresnel arrays. Such large missions are reserved to thoroughly studied systems, not to a demonstrator, so, what kind of mission should be chosen?

In a "field vs. resolution" diagram (see annex 2), Fresnel arrays fill a region that is not covered by long baseline interferometry or solid aperture instruments. There is a good probability that observing there leads to interesting results. The question is: which domains of astrophysics are best suited for a demonstrator mission: stellar disks imaging? Active galaxies? Small or large solar system objects? And what would be the optimal size for a first array in space: 1m? 3m? All these questions are closely linked and intricate. This is why we are proposing to form an group of interested astrophysicists from several domains, on an international basis, to select a few promising targets and observing modes.

Conclusion

The application domain of Fresnel interferometric arrays spans from high dynamic range exoplanet detection (Koechlin, Serre & Duchon, 2005) to stellar, circum-stellar and moderately large (20” field) astrophysical imaging. It covers a lot of what can be done with space telescopes and interferometers of similar size, and these arrays should be easier to build at larger dimensions.

The concept is developed at Observatoire Midi Pyrénées by three persons from the “Signal, Image et Instrumentation” team, funded by CNRS, Université Paul Sabatier (Toulouse), and two persons at Centre National d’Etudes Spatiales (C.N.E.S.) A Ph.D. thesis on this subject is co-funded by Europe and Alcatel-Alenia Space. C.N.E.S. is funding the prototype array construction and tests since 2005.

We are looking for collaborations with people from the planetary, stellar and extragalactic communities, to prepare together a demonstrator array dedicated to test the concept in space, yet able to provide novel astrophysical results.

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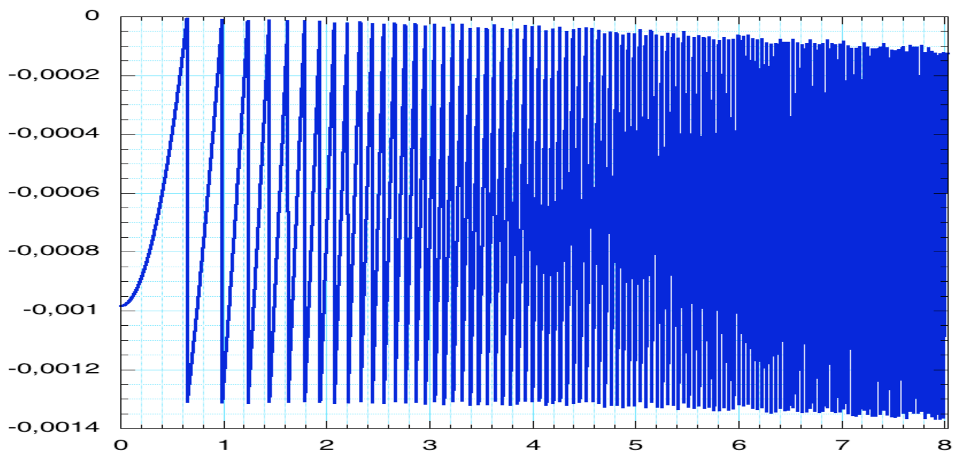
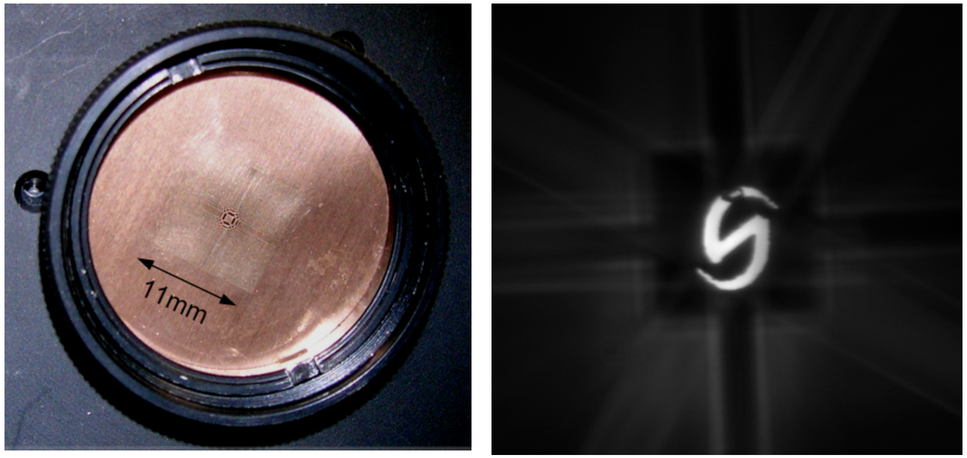
Annex 1: Latest news

We have just started testing a blazed lens made of fused silica for the correction of chromatic aberration. This 16 mm diffractive lens is put in a pupil plane and operates at diffraction order –1, correcting the order +1 chromatism of the large primary array. The lens profile had been computed by D.Serre to completely correct chromatic aberration on a broad spectral band. The blaze angle is optimized for 600 nm, where the transmission to order 1 is better than 98%. At other wavelengths there is no chromatic aberration, as the correction scheme is not wavelength dependant, but the transmission to order 1 decreases. It stays above 80% from 510 to 730 nm.

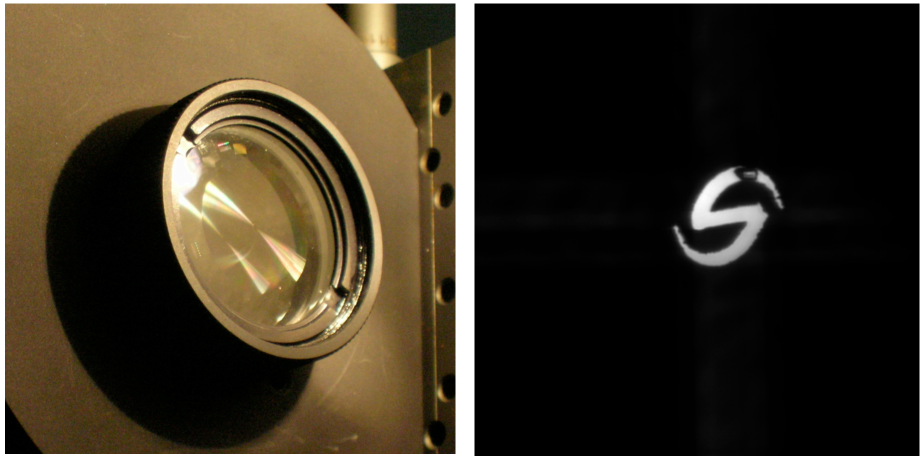


Half profile of the blazed fused silica diffractive lens. Units are in millimetres.

Below are the “first light” pictures made September 21, 2006 on a target representing a 72 arc second mock galaxy made with a 450 microns drawing, laser-cut into a metal sheet similar as the one used for the primary array. One can see the effects of laser carving at a microscopic scale, the upper “arm” is showing incomplete cuts.
The two following pictures show the images obtained with the previously used metal diffractive lens (left) and the new high quality fused silica diffractive lens (right). With this now available tool, we are starting a qualification procedure involving a series of optical tests on the PSF of Fresnel arrays.



“Before”
Chromatic correction with preliminary metal diffractive lens. One can see the stray light from order 0 of the corrective lens



“After”
Chromatic correction with blazed fused silica diffractive lens. One
see the better resolution and dynamic range.

Annex 2:

Field vs. resolution diagram comparing different techniques and instruments. Fresnel arrays are represented in blue with their size noted in meters, solid aperture instruments and techniques are in red, long baseline interferometry is in green. The domain covered by a given technique or instrument extends towards the right (lower resolutions) and towards the bottom (smaller fields) of its marked position. This indicative diagram is not meant to be precise and shows only two criteria among other important ones, such as sensitivity or dynamic range. It is just showing that large Fresnel arrays cover a domain not covered by other space instruments.