Fresnel Diffractive Imager: Instrument for space mission in the visible and UV

Raksasataya T.[a], Deba P. [a], Rivet J.P. [b], Gili R. [b], Serre D.[a], Koechlin L.. [a]

[a]LATT, Université Paul Sabatier, CNRS, 14 Avenue E.Belin, 31499 Toulouse, France;
[b]Obsecatoire de la côte d'azur, Bvd de lObservatoire, B.P. 4229 - 06304 Nice Cedex 4, France

ABSTRACT

We propose a new concept of diffractive optics: Fresnel arrays, for a 4 m aperture space telescope in the UV domain.

Fresnel arrays focus light by diffraction through a very thin binary mask. They form images optically and deliver very high quality wavefronts, specially in the UV. Up to 8% of the incident light is focussed, providing high angular resolution and high contrast images of compact objects.

Due to their focal lengths of a few kilometers in the UV, large Fresnel arrays will require two spacecraft in formation flying, but with relatively tolerant positioning. Diffraction focusing is also very chromatic; this chromatism is corrected, allowing relatively broad (30 to 100 nm) spectral channels in the 120-350 nm range. A 4 m aperture Fresnel imager providing 7 to 10 milli arc seconds resolution is very competitive for imaging compact and high contrast objects such as protoplanetary disks and young planetary systems, AGNs, and deep sky objects.

We have developed prototypes to validate the optical concept and related technologies : first a laboratory setup, then a 20 cm aperture ground-based prototype, which provides high contrast and diffraction limited images of sky objects in the visible and close IR. A new laboratory prototype is also being prepared for validation in the 250 - 350 nm wavelength range.

Keywords: Fresnel Imager, Diffractive focusing, Accretion disks, Ultra-violet domain

1. INTRODUCTION: OPTICAL CONCEPT AND STATE OF THE ART

For space telescopes with large apertures and light weight, we propose to replace the primary mirror by a thin membrane: a Fresnel Diffractive array. The optical concept has been described in detail in [1] . As the angular resolution is wavelength dependent, the advantages of Fresnel imager are high in the UV domain. We propose a 4m aperture Fresnel Imager operating at 120 to 300 nm.

This membrane the focuses light in a Fresnel imager is not reflective but opaque, with millions of void apertures, using an array of Fresnel rings held together by an orthogonal layout of narrow bars, the local period of bars being related to the Fresnel zones. The total area covered by the voids corresponds to almost 50% of the whole membrane.

The subapertures layout splits the incoming wavefront. One of the outgoing wavefronts is chosen, corresponding to diffraction order +1, in which 6% of the incident light is focused. The focal lengths of large Fresnel arrays are a few hundred to a few kilometers long in the UV domain, as the focal length f of a square aperture Fresnel array of size C having k_{max} Fresnel zones is given by

$$f = \frac{C^2}{8k_{max}\lambda} \quad . \tag{1}$$

Specifications	Fresnel diffractive imager prototype II
Main Array size	200 mm
Field optics diameter	45 mm
number of Fresnel zones	696
Central wavelength	800 nm
Bandpass	650 - 900 nm
Angular Resolution	0.8”
Field of view	500 ”

Table 1. Specifications of Fresnel Diffractive imager for ground based Validation on sky sources.

Formation flying of two spacecrafts is required. The second spacecraft is placed at the focal plane, where large field optics: a 60 cm telescope, forms a pupil plane. The chromatism of the Fresnel array is corrected by a small dimension diffractive mirror (in UV) of lens (in IR) placed in that pupil plane, and operating at order -1. The instantaneous bandwidth is $\Delta\lambda/\lambda \simeq 30\%$. Several such bands can be imaged sequentially, by changing the inter-spacecraft distance.

The unwanted orders of diffraction are blocked by a mask close to the pupil plane. Focal instrumentation and detectors are placed in the corrected bean.

In the next sections we present results obtained in the visible and close IR with a 200 mm aperture testbed: images of sky objects, and numerical simulations for UV based on protoplanetary disks models. We detail some science cases envisioned in the UV. The proposed techniques of detection and some targets will be described in the last section.

2. PROTOTYPE GENERATION II: GROUND-BASED VALIDATION TESTS.

As we propose a space mission with 4m-class apertures [2] , we first validate the concept by assessing the optical performances in angular resolution, throughput efficiency and dynamic range. These tests have been carried on with small aperture testbeds, as a test with a 4 m aperture would require kilometric focal lengths.

Following our generation I tests in laboratory (2005-2009)[3] , Tests on a generation II prototype are carried in 2009-2010 on the same principle, but modified for sky observation. As the objectives are to observe real astrophysical targets, the generation II prototype has been installed on a large refrector in Nice, southern France. The optics of the refractor are not used, but the tube and the mount allow steering of a 18 meter focal length ”two module” Fresnel imager.

In figure 1, prototype generation II is shown mounted on its refractor. The Fresnel array is visible at the front end on the right side of the tube, pointing at the sky. At the other end of refractor is the receptor module.

The Fresnel array used is a 200 mm apodized square aperture, 696 Fresnel zones array, the ring structure being held by means of thin orthogonal bars every 2 or 3 Fresnel zones. These bars contribute to the point spread function (PSF), but their layout has been optimized numerically before manufacturing, to keep as much as possible the high dynamic range and throughput efficiency at focus. The apodization is done by modulating the ratio between solid and void parts in Fresnel zones.

The testbed has been set up, a low altitude site close to the city of Nice, hence subject to light pollution and dust. However, this site has the advantage of being in a laminar flow from the sea and a potential for very good seeing conditions. The 200 mm Fresnel array tested on the sky has a 18m focal length at λ =800 nm.

Our optical axis runs parallel to the refractor tube and outside of it, leaving the historical refractor unmodified. The receptor module has a 45 mm aperture, to collect a 400 ” image field from Fresnel array.

Figure 1. Fresnel generation II testbed on the side of the 18 meter refractor at Observatoire de Nice. The 20 cm square Fresnel array is attached to the front end, the receptor module is the thin steerable optical bench at the rear end. The optical axis of the Fresnel imager runs in free air outside the refractor tube.

For these tests, we have chosen several criteria: angular resolution, field, dynamic range, spectral bandwidth, limiting magnitude. The sky targets chosen are binary stars with high magnitude difference, the surface of the moon, Mars, Saturn, Mars satellites, and galactic nebulae.

The outcome of these tests on the sky show a diffraction limited angular resolution (0.8"), the ability to make images within extended bright fields (fields on the moon surface), a limiting magnitude of 13.5 (in a quasi "streetlight" condition), and a dynamic range close to 2.510^{-6}. With this 20 cm aperture Fresnel imager testbed, among other targets, the satellites of Mars Phobos and Deimos have been imaged, and the Sirius AB couple has been resolved. These results and some others from our last observing run will be published soon, after a correct calibration is made.

2.1 Images from ground based observations

Our test Images were acquired on large magnitude difference binary stars, to test the dynamic range. ϵ Trianguli shown in figure 2 has been tested to measure dynamic performace of V magnitude= 5.3 and 11.3 at 4.7" separation.

Further investigations concerning the effect of spikes from the square array, affecting the contrast for extended objects, have been tested by observing the moon surface. With our 200 mm array aperture at λ =800 nm, we obtain large field images of the moon. In figure 5, the southern part of the moon is captured and shows small craters, down to 2 to 3 km diameter, corresponding to 1.5 ". The theoretical resolution is 0.8" is not reached, due to atmospheric seeing and residual misalinements.

3. PROTOTYPE GENERATION III: UV TESTBED

To validate the chromatic correction technology for the UV, a laboratory prototype (generation III) is being prepared.

A new 65 mm array has been carved, and the blazed lens in the prototype secondary module will be replaced by a diffractive concave Fresnel grating with a UV coating, under construction. This concave Fresnel grating will use only one reflection to correct the chromatism and focus the beam from the primary focal plane to the final focal plane. The tests are planned for the 2010-2011 period. There will still be two reflections in the field optics telescope upstream, required to form a pupil plane.

4. SPACE MISSION PROPOSED

We plan to propose a 4m-class mission in space, involving formation flying in orbit around L2. The diffraction limited imaging and high dynamic range capabilities preserved at short wavelengths should allow interesting science cases.

4.1 Fresnel Diffractive imager in Space, protoplanetary discs simulations

This study will assess the detection capability by a Fresnel Imager of accretion disks around protostars such as β Tauri. We compute a cicumstellar disk from an accretion model, based on[4] ,[5] ,[6] , and [7] . We then convolve the projected disk with the Point-Spread-Function of a Fresnal array computed from the specifications in Table 2. The radii and thickness of modeled discs are sampled to construct the accretion disk images at a scale adjusted to the Fresnel arrays' PSF.

The distance between the stars and the observer determines the angular dimension of the disks. These simulations show that a 4 m Fresnel Imager in the UV, having a 10 mas resolution and high dynamic range, should allow detection of disks around stars as far as 50 pc.

The Fresnel Diffractive Imager is proposed in several possible configurations, these specifications are designed for the next 10-20 years. Later, 20-meter arrays may provide a very high resolution for the study of compact objects at large diastances.

Figure 2. ϵ Trianguli (STF 201) and its companion at 4.7", magnitudes 5.3 and 11.3

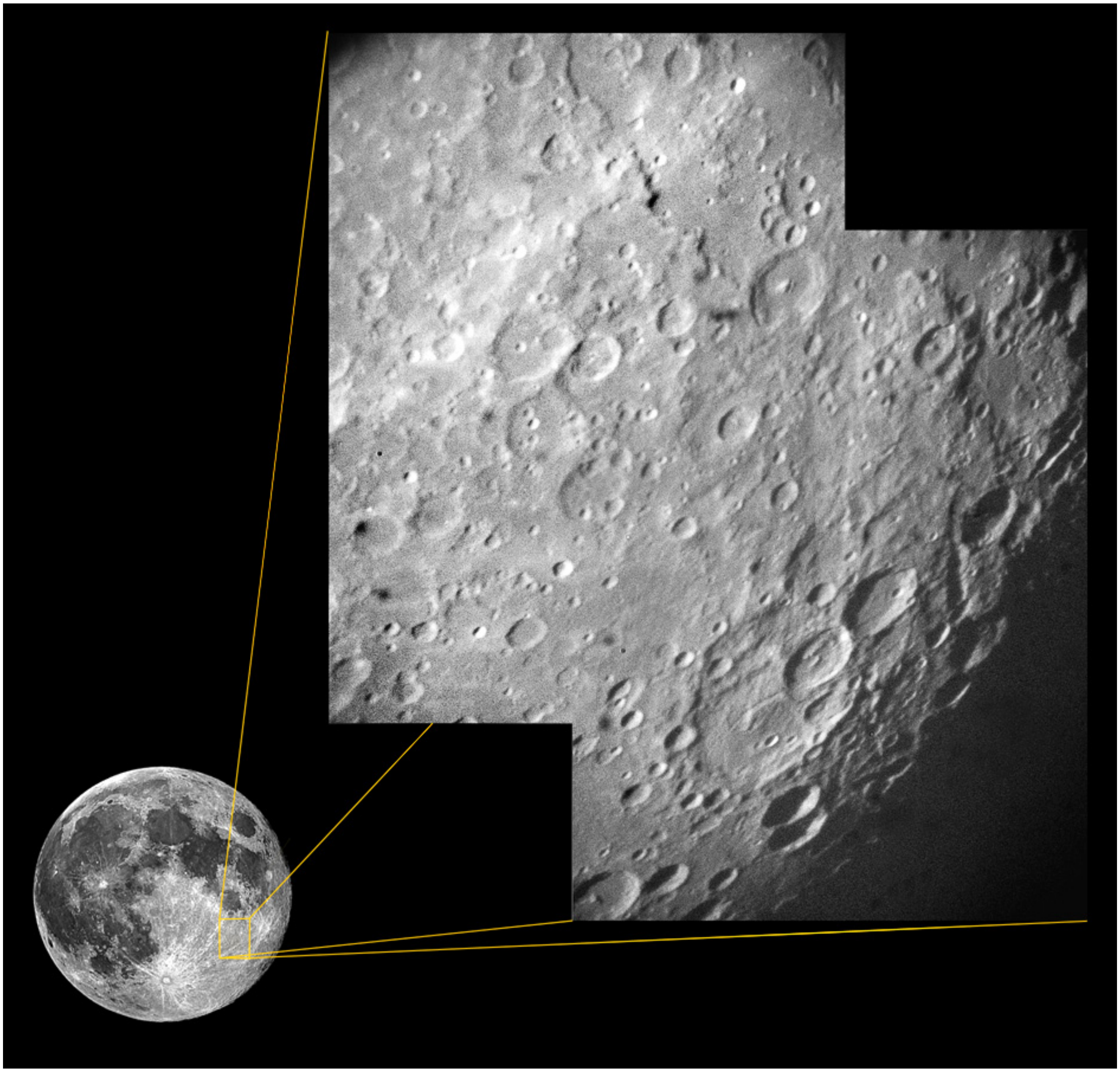

Figure 3. Mosaic of two images of moon surface showing the detail of craters on the moon surface with a 1" angular resolution. Image taken with a 200 mm square diffractive array at λ =800 nm. July 2009.

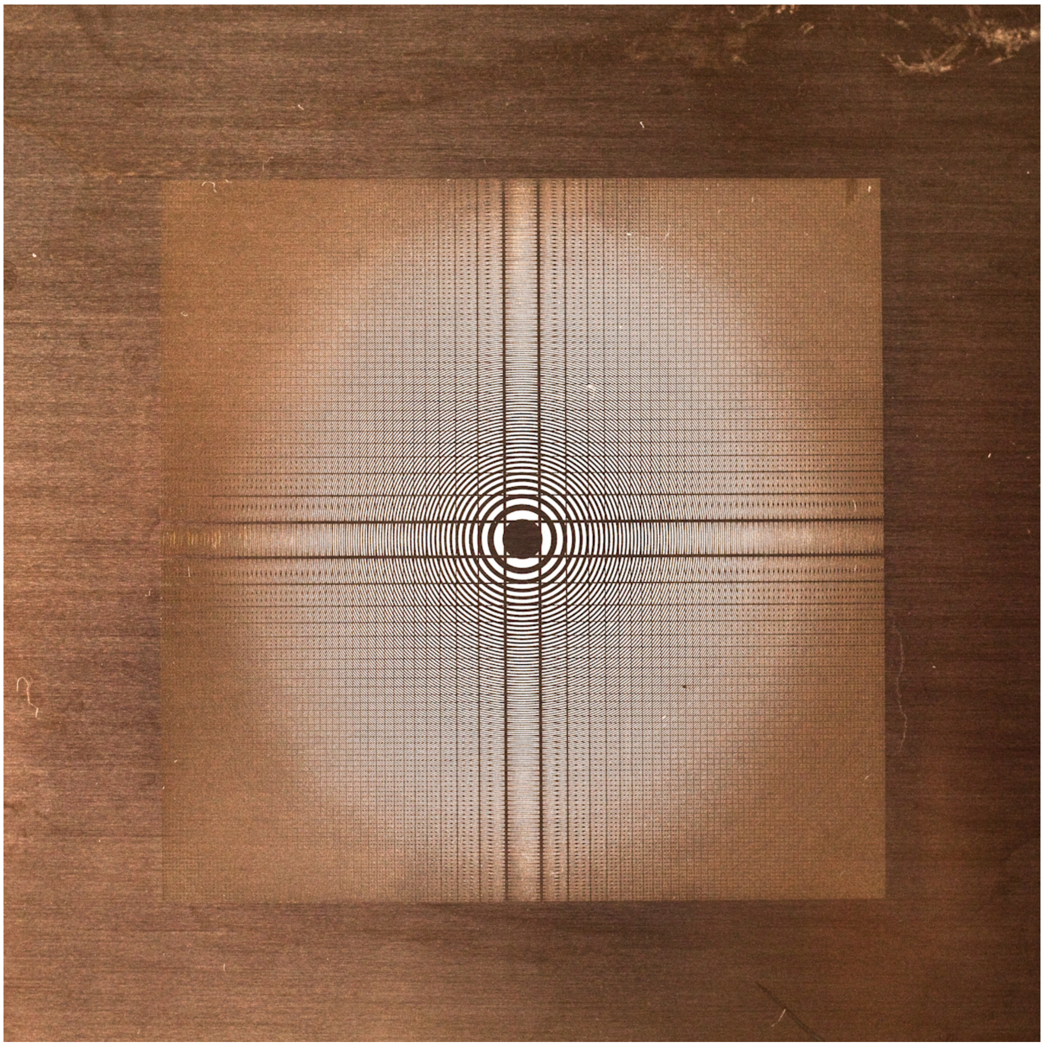

Figure 4. Fresnel Array for UV testbed: on a 65 mm square frame. It will be used for laboratory tests in the UV, from 340 to 250 nm.

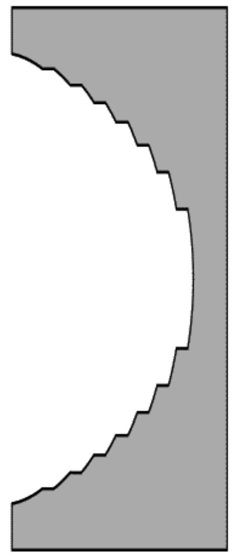

Figure 5. A diffractive concave Fresnel grating will replace the blazed lens for chromatism correction in the UV. Only the 7 central Fresnel zones are shown here.

Specifications	Fresnel Space Imager
Array size	20 m
Field optics diameter	2 m
Fresnel zones	3000
Wavelength	190 nm
Bandpass	150 - 250 nm
Angular Resolution	2 mas
Field of View	4.7 "

Table 2. Fresnel Space Imager Specifications for UV image simulations.

5. CONCLUSION

The concepts and related technologies of a Fresnel Diffractive Imager are validated in various aspects. The results from ground-based sky tests are a good cues for a space mission. Some of the aspects of formation flying have also been tested during these ground-based tests. The next study on a UV testbed will improve the Technology readiness level (TRL) and allow to refine the and science cases.

In the future, High angular resolution and high dynamic of Fresnel Imagers will provide high quality deep sky data in many spectral bands:UV, visible and IR.

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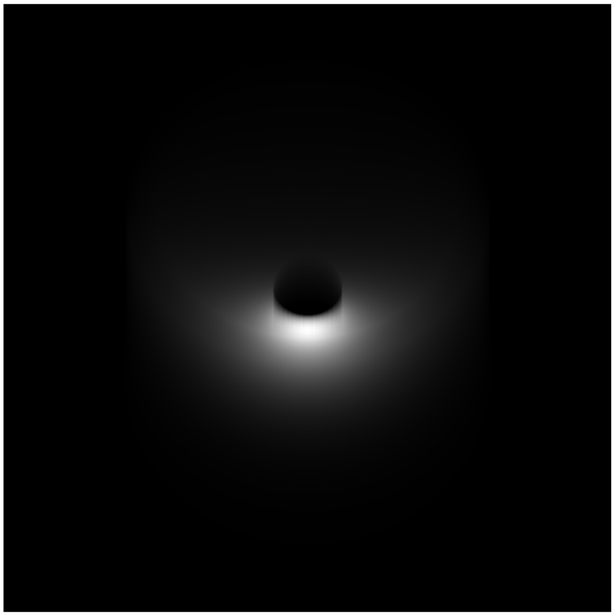

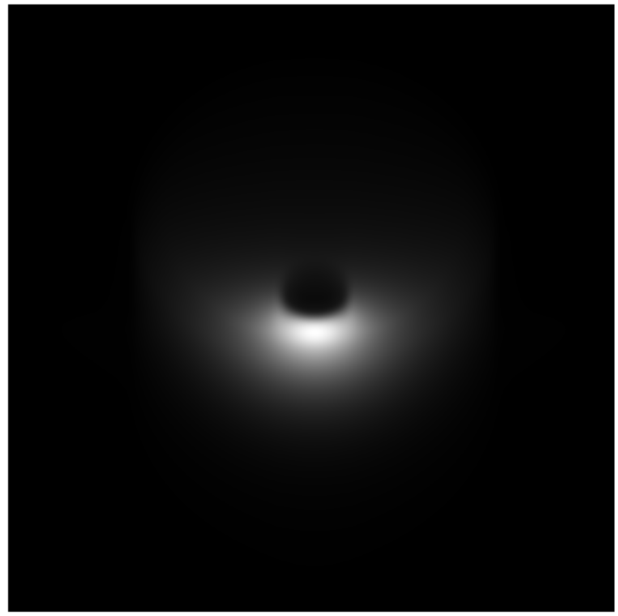

Figure 6. Left: Dust accretion disk simulated in section above at 60° inclination, Right: image obtained from convolution of a Fresnel imager point spread function (PSF) with the simulated disc

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