Pathways Towards Habitable Planets
ASP Conference Series, Vol. 430, 2010
Vincent Coudé du Foresto, Dawn M. Gelino, and Ignasi Ribas, eds.

The Fresnel Interferometric Imager

L. Koechlin,[1] J.-P. Rivet,[2] R. Gili,[2] P. Deba,[1] T. Raksasataya,[1]
and D. Serre[3]

[1]*Laboratoire d'Astrophysique de Toulouse Tarbes, Université Paul Sabatier, CNRS, 14 avenue Edouard Belin, Toulouse, France*

[2]*Observatoire de la Côte d'Azur, Boulevard de l'Observatoire, B.P. 4229, Nice, France*

[3]*Leiden Observatory, Leiden University, P.O. Box 9513, Leiden, the Netherlands*

Abstract. We present a new "pathway" in the form of an innovative space-based telescope: the Fresnel Imager. It is a concept of two spacecrafts flying in formation, one satellite holding a diffraction array acting as entrance pupil and providing a very high wavefront quality in the visible and UV domains, the other one holding the focal instrumentation and detectors. The distance between spacecrafts would vary between 1 and 100 km, depending on the specifications, and the aperture size would be 3 to 100 meters. We present the validation prototypes realized, the spectral domains that can be explored, and the astrophysical targets.

1. Introduction

Fresnel arrays are an alternative to mirrors for large apertures in space, allowing lightweight and position-tolerant instruments. Diffractive optics based on solid transparent foils have been proposed for space telescopes by Chesnokov (1993), Hyde (1999) and Massonnet (2003). Metal Fresnel zone plates have also been proposed (Baez 1961), as well as "photon sieves" for X-ray, UV and visible focusing (Kipp et al. 2001). The principle of Fresnel Imagers is presented in detail in Koechlin et al. (2005) and Serre et al. (2009): a thin opaque foil forming the main aperture, the "Fresnel Array", is punched which numerous and specially designed subapertures which cover close to 50% of the surface. Those apertures lead to a constructive interference of the incident light, and are shaped and positioned to optimize the point spread function (PSF) while keeping the mechanical cohesion of the foil. Recently built Fresnel arrays achieve up to 7.5% light transmission efficiency (fraction of light that ends up in the central lobe of the PSF).

As light has travelled all the way to prime focus without encountering an optical surface, a very high quality wavefront is generated, which provides high resolution and high dynamic range images. On compact objects, the field covers usually 1000 Airy radii, and high dynamic range is present in all the field except on four spikes. On extended objects (larger than 50 Airy radii), high resolution remains, but the high dynamic range does not.

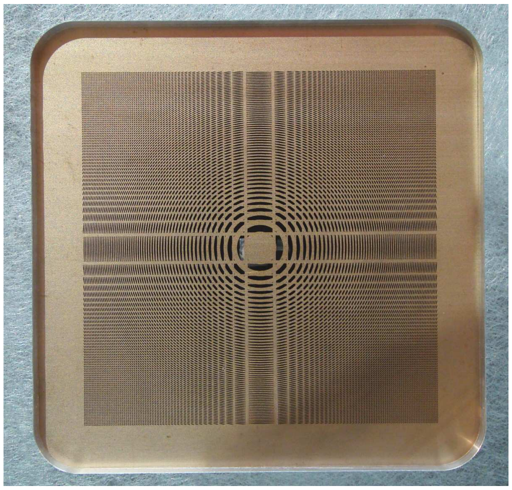

Figure 1. The 116 Fresnel zones array of testbed generation 1: CuBe foil, 75 μm thick.

There are drawbacks, e.g. long focal lengths and chromatism. Long focal lengths require formation flying of two spacecraft separated by a few kilometers for the smallest arrays (3.6 m), to hundreds kilometers for the very large arrays (100m diameter). In order to correct axial chromatism inherent to diffractive focusing, the receiver spacecraft placed at the focal plane of one of the observed wavelengths, features a reduced-size optical train, the beam cross-section being an order of magnitude smaller than the main aperture. Small diffractive optics are placed in a pupil plane (Schupmann 1899; Faklis & Morris 1989; Serre et al. 2009) and yield $\Delta\lambda/\lambda = 20\%$ bandpass for up to six scientific channels that can be set anywhere between 100 nm and 25 μm wavelengths.

During the last few years, we have worked on testbeds, and on science cases. In the second section of this paper we present the progress made on testbeds, in the third section we present astrophysical targets and strategies of development.

2. Prototypes

Different prototypes have been gradually developed or currently are, aiming to validate different aspects of the concept: global validation of the optical principle, angular resolution and dynamic range assessment, on-sky validation, and validation in the UV domain.

2.1. Generation I and II Testbeds

Generation I prototype, built in 2006, has validated wavefront quality, broad band imaging, and 10^{-6} dynamic range. It had a 8 cm apodized square aperture (Nisenson & Papaliolios 2001) made of 116 Fresnel zones carved in a metal sheet, and was working in the visible wavelengths domain. The drawing of the cutting can be seen in Figure 1. A detailed presentation can be found in Serre et al. (2009).

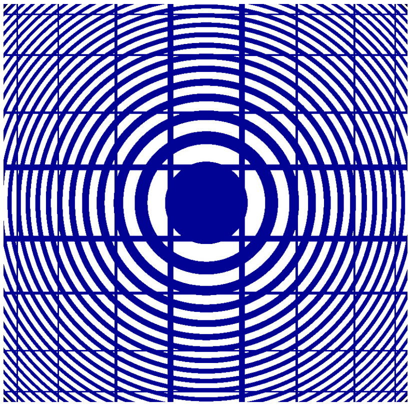

Figure 2. Orthocircular Fresnel array in testbed Generation 2, carved in 50 μm thick opaque matal sheet. Only the first 12 Fresnel zones are shown here. The Fresnel rings are held in place by bars every n Fresnel zones. n is adjusted for optimal dynamic range. The actual array features 348 Fresnel zones from center to limb (696 from center to corner.) The bars are not equidistant.

Built in 2009, the Generation II prototype is for validation on sky objects. It features a 20 cm apodized square aperture with 696 Fresnel zones and 18-m focal length at $\lambda = 800$ nm. Its optimized primary array yields a higher dynamic range and almost double throughput than Gen I: the orthogonal bars holding opaque rings have been adjusted for a tradeoff between mechanical rigidity (i.e. wavefront quality) and dynamic range (Figure 2). Other setups using different bars positioning laws, or de-centered ringed support bars that focus their diffracted light outside the field, resulted in good optical results but insufficient rigidity and have thus been discarded.

The two modules of the Generation II prototype have been set up at Nice observatory in "piggyback" of the 17.89 meter focal length Grand Refracteur. The global orientation of the Fresnel Imager to the sky targets is adjusted by the mount of the refractor, and the relative orientation of the focal module to point the array center is adjusted by two additional degrees of liberty: to and away from the main optical axis (Figure 3). Although the tip-tilt correction and nominal cameras were not present in summer 2009, we could get the first light with a "Generation I.5" testbed and the preliminary images are presented in Figures 4 and 5.

A nominal configuration should be ready by January 2010, and we plan to observe targets with high dynamic ranges such as Mars disk and satellites, Sirius AB, and other targets.

2.2. Generation III Testbed and Studies for a Space-based Fresnel Imager

As we propose UV domain science cases at high angular resolution and high dynamic range, the technologies involved in the Fresnel Imager should be validated in the specific UV domain. A laboratory testbed is currently at the conception stage, and we plan to publish the results in the next two years.

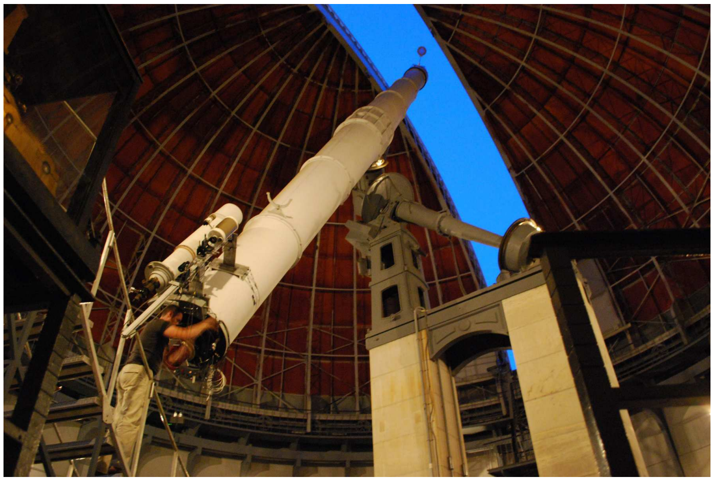

Figure 3. Nice refractor with Gen 1.5 prototype set in parallel.

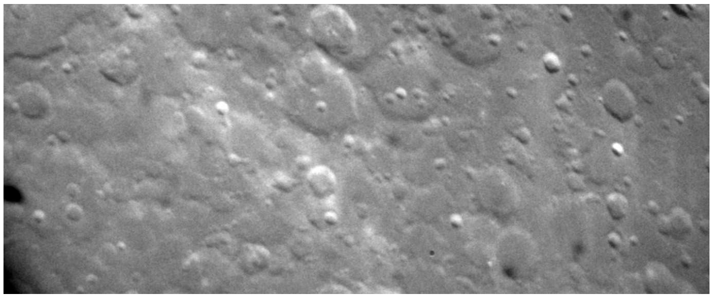

Figure 4. 520"x210" field on the moon, taken October 7th at 02:18 U.T. North is on the right. The white diagonal stripe is a ray from Tycho.

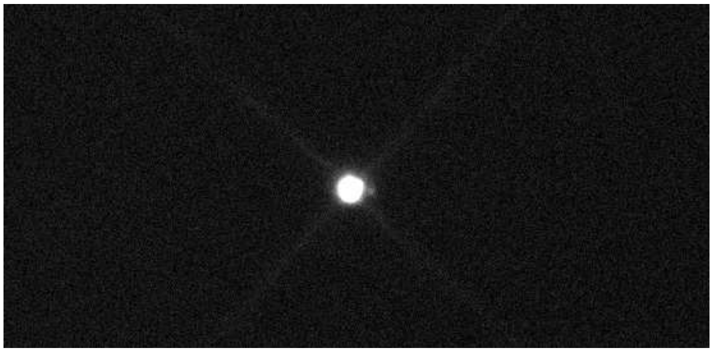

Figure 5. Binary star STF 2726 (52 Cyg) of magnitudes 4.2 / 9.5, separation 6 arc seconds. The brighter star is over-exposed.

A “Phase zero” study for a space-based project has been carried out by Centre National d’Etudes Spatiales, and ESA is currently studying larger membrane telescopes using binary Fresnel arrays.

3. Space Applications

In parallel to the concept and technology validations, we are setting up a group to investigate the science cases that are within reach of Fresnel imagers. In the frame of this work, a workshop was been held in Nice on September 23-25, 2009, in which were presented various opportunities.

3.1. Rationale for Space Mission Based on a New Technology

The visible and IR domains should be explored with large telescopes in the 2020-2030s, and 10-15 meter class Fresnel arrays would be required to be competitive in terms of angular resolution and luminosity, and benefit from their space-based status. On the other hand, a Fresnel Imager would be competitive only if the cost is low enough to overcome the barrier associated with a technology never before tested in space.

This dilemma could be solved by choosing the UV domain, the wavefront quality of a Fresnel array not being wavelength dependent. A deployable 3–4 meter Fresnel array will provide a 7 mas, diffraction limited angular resolution at a $\lambda/50$ wavefront quality. For the “after focus” instrumentation, the UV requires high wavefront quality field optics and diffractive chromatic correction: this what will be tested in our third generation testbed, in collaboration with the instrumentation groups at Network for Ultra Violet Astronomy (NUVA).

3.2. Examples of Scientific Objectives

The mission targets and instrument performances will depend on many parameters, and the best tradeoff is not defined yet, as the diffraction optics technology progresses but the astrophysical problems also evolve: some that are now very hot, may be solved by the time a mission can be launched.

However, if we provide unmatched performances in a relatively unexplored optical domain, like the UV, we play safer. For example in the domain of telluric exoplanet direct imaging, studies in the visible or IR would require a 10-meter size Fresnel array, whereas in the UV domain Fresnel arrays will be competitive even at small sizes (3-meter). Other research areas are also investigated such as solar system objects (for example multiple asteroids and Kuiper belt), stellar disks and environments (with the NUVA consortium, we are working on the preparation of a space mission on stellar disks and young planetary systems: the “Disk Evolution Watcher”), planetary systems formation, galaxies, and extragalactic targets.

4. Conclusion

Since 2004 when we started the concept, we have been testing and improving Fresnel arrays for space imaging. The results from ground-based testbeds are promising: we have validated the angular resolution, the dynamic range and the spectral bandwidth of Fresnel imagers. For the time being, we have done this on apertures of 20 cm or less, and in the visible or close IR domains. We are working on closely interdependent fronts: optical conception, space orbits and guiding, and astrophysical science projects. We investigate science cases in the IR, visible and UV domains for which the Fresnel Imager would bring significant improvements, and have found a "niche" for a first space mission in the visible and UV.

Acknowledgments. The studies on which this paper is based are financed by Université de Toulouse, Centre National de la Recherche Scientifique, Centre National d'Etudes Spatiales, Thales Alenia Space, the "Sciences et Technologies pour l'Aéronautique et l'Espace" (STAE) foundation, and Observatoire de la côte d'azur.

References

Baez, A. 1961, Journal of the Optical Society of America, 51, 405

Chesnokov, Y. M. 1993, Space Bulletin, 1, 18

Faklis, D. & Morris, G-M., 1989, Optical Engineering, 28, 592

Hyde, R. A. 1999, Appl.Optics, 38, 4198

Kipp, L. et al., Nat, 414, 184

Koechlin, L., Serre, D., & Duchon, P. 2005, A&A, 443, 709

Massonnet, D. 2003, C. N. E. S. patent: un nouveau type de tlescope spatial, Ref. 03.13403

Nisenson, P. & Papaliolios, C. 2001, ApJ, 548, L201

Schupmann, L. 1899, Die medial-fernrohre: eine neue konstruktion *für* grosse astronomische instrumente, Teubner B G

Serre, D., Deba, P., & Koechlin, L. 2009, Appl.Optics, 48, 2811