Exoplanet study with the Fresnel Interferometric Imager

Laurent Koechlin, (P.I.)
Paul Deba,
Truswin Raksasataya,
Equipe Signal Image & Instrumentation
Laboratoire d'Astrophysique de Toulouse-Tarbes
Observatoire Midi-Pyrénées (OMP)
UMR 5572 - Signal Image & Instrumentation
14 avenue Edouard Belin
31400 Toulouse, FRANCE

Introduction

In this white paper, we present what could be achieved in the domain of exoplanet study with a Fresnel imager. We quickly remind the proposed method, as it has already been presented to ESA in the CV proposal we sent last year. The Fresnel Imager proposal made for ESA has been summarized and adapted for publication in a special issue of "Experimental Astronomy". It presents is some evolution with regard to the initial proposal. It should be available on line in the next few weeks.

We focus on the new aspects developed this year: on the work made on bread board prototypes to improve the TRL, and on the exoplanet space study strategy.

A "phase zero" study is being carried out in Toulouse. Three classes of Fresnel imagers and their corresponding science cases have been studied: 3-4m, 10-15m, and 20-30m. Some of this work is presented here, but the results are still preliminary, the study conclusions are to be available in October 2008.

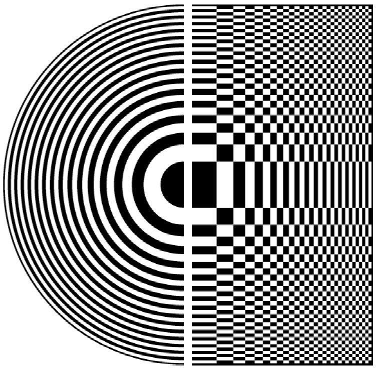
Principle of the imager

In this first part, we quickly recall the optical principle. The Fresnel imager is a two spacecraft formation-flying mission, the main spacecraft holds the focusing element: the Fresnel array; the other spacecraft holds the field optics, focal instrumentation and detectors. Depending on the wavelength domain and array sizing, he spacecraft are separated by a few hundred meters to a few tens of kilometers.

The Fresnel array is a large and light opaque foil punched with 10^5 to 10^6 void subapertures. The cumulated subaperture area represents close to 50% of the total foil surface. Focusing is achieved with no optical element: the shape and positioning of the subapertures being responsible for focusing a fraction (6 to 9%) of the incident light. One consequence of this high number of subapertures is a high dynamic range imaging capability.

This interferometric array can be seen either as an aperture synthesis array, or as a particular case of diffractive zone plate. An image is directly formed by the array (no need for a recombiner), the dense subaperture layout leading to a compact and highly contrasted Point Spread Function (PSF).

Fresnel arrays differ on several aspects from zone plates. Their layout makes the non-transmissive zones connected throughout the array, allowing the use of vacuum for the transmissive zones (subapertures) while preserving mechanical cohesion of the whole frame.



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

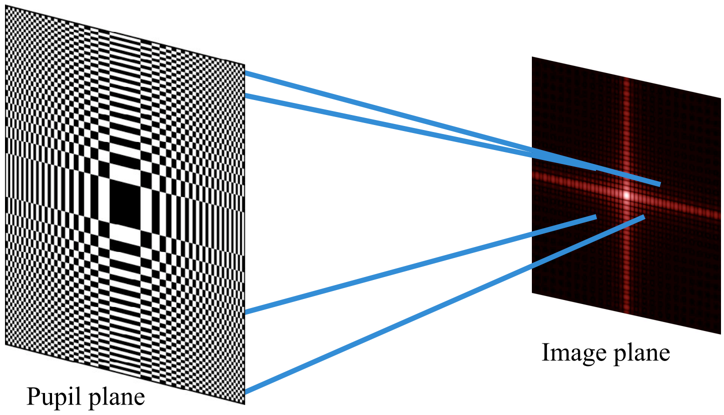


Image of a point source (Point Spread Function computed by Fresnel Transform).

One important feature is that he resulting wavefront quality is restricted only by the precision with which subapertures are carved. This constraint is loose compared to optical surfacing: For the large arrays proposed in space, a λ/50 quality wavefront is obtained with a 0.1 millimeter precision of subaperture positioning in the plane of the Fresnel array. The required precision in the perpendicular (propagation) direction is in the order of a centimeter. The precision to which subapertures in a Fresnel array have to be positioned for a given wavefront quality is not wavelength dependant, which makes it very competitive in the UV domain.

–Chromatism occurs as a consequence of diffractive focussing. This chromatism is cancelled by a small diffractive element in the focal instrumentation. However, for a given inter-spacecraft distance, the bandwidth is limited to $\Delta\lambda/\lambda = 25\%$ due to the size of the field optics in the secondary spacecraft. The field is also limited by the size of the secondary optics: with a secondary optics aperture 1/10th the size of the primary array, the resulting field/resolution ratio is close to 1000x1000, independent of the array size and wavelength.

Progress made on the optical validation prototype, concerning exoplanet detection and study

Using new designs of the binary Fresnel arrays, we have improved the light transmission and dynamic range of the Fresnel imager. The highest dynamic range achieved in the visible with the lab prototype is now beyond 10^{-6}, with a 116 Fresnel zones array.

Prototype array: 80 mm, 116 Fresnel zones (26680 apertures), laser carved into a 100 μm thick metal foil. In the background through the array is seen the artificial source collimator. The 5-μm precision positioning of the apertures in the array yields a λ/50 wavefront, independently of the wavelength. The light transmission at order one has improved from 4 to 6%, and the dynamic range of the PSF has reached 10^-6 in the visible.

Numerical simulations by Fresnel propagation confirm the results obtained optically, and predict a dynamic range close to 10^{-8} for an apodized 300 Fresnel zones array. Signal / Noise simulations including various sources of noise (residual star light, photon noie, thermal noise, zodiacal and exozodiacla lights) show that detection of spectral lines in exoplanet spectra is feasible with 10 hours exposure times and 4-m aperture arrays.

In order to validate the high dynamic range in the UV, optical tests are planned on lab sources. We expect financing for soon. A third ground based validation test concerns high dynamic range sky sources in the close IR. A 20 cm aperture, 20-meter focal length prototype is now financed and starting construction. First high dynamic range images on stars is scheduled for autumn 2009.

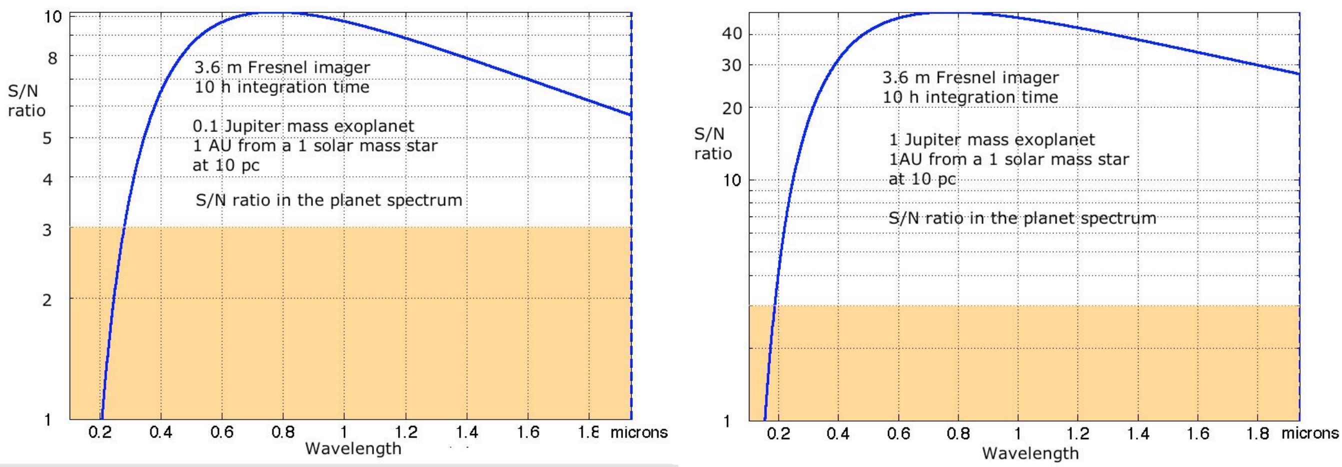
Study of exoplanetary images and spectra

In the UV at 120 nm, the 7 mas angular resolution of a 4 m array is enough for resolving a planet orbiting at 0.07 AU from a 10 pc distant star. At fixed aperture size and target luminosity, there will be a trade-off between spectral resolution and exposure time. Numerical simulations taking into account internal and external noise sources show that a spectral resolution of 50 and a 10 hours exposure time allows a sufficient S/N ratio on a 0.1 Jupiter mass: see illustrations below.

In the IR at 15 to 20 µm wavelength, the angular resolution of a 30 m array will not suffice for a 0.07 AU separation, but the larger collecting area allows high spectral resolutions for the chemical study of a 1 AU orbit telluric planet, at a much higher spectral resolution if necessary.

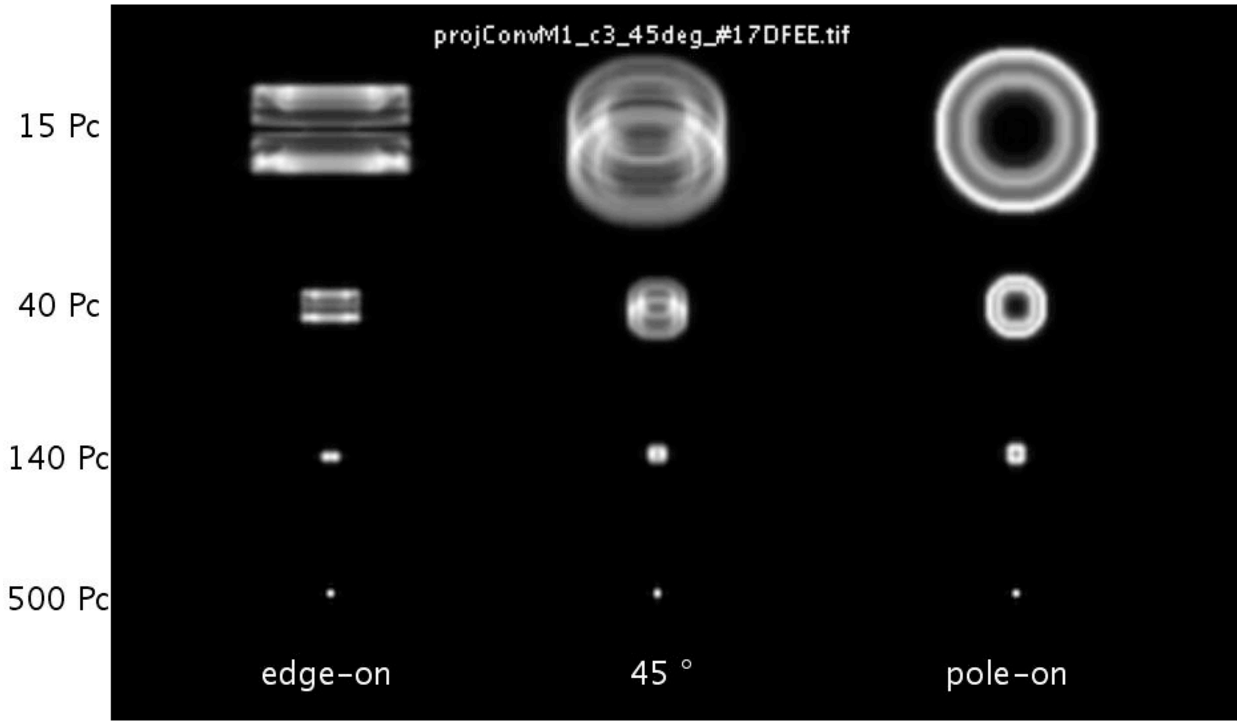
The numerical simulations take into account the residual star light in the PSF, diffusion in the focal plane optics, zodiacal and exozodiacal lights. A Fresnel imager is very robust regarding perturbation by exozodiacal light: its compact PSF rejects the light from most of the exosystem except for the close vicinity of the planet.

The lines that could be searched in the transiting exoplanets spectrum, have been exposed in the initial proposal.
In the UV with a 4m-class array:
– Hydrogen at 121.6, Carbon at 130.5 nm, Oxygen at 130.2 and 133.5 nm, 0zone at 300 nm, Na & K at 600 to 900 nm (hot Jupiters), 03 at 800 nm.
– H_2O at 1.8 µm, $C0_2$ at 1.9 µm. NH3 between 3 and 4 µm, CO between 4 and 5 µm.
– 0_2 at 760 nm, chlorophyl break at 700 nm (possibly at different wavelengths depending on the stellar spectrum). Other lines, such as H_2O at 1.4 & 1.8 µm, and CO_2 lines between 4.2 & 4.5 µm could be a motivation to shift the reddest channel further into the I.R.
More lines may be observed further in the IR, with the 30m class arrays.



Signal / Noise ratio in the spectrum as a function of wavelength ($\lambda/\Delta\lambda$=50) for respectively a 0.1 Jupiter mass (left) and a 1 Jupier mass (right) exoplanet at 1 AU from a solar type star at 10 pc. Ten hour exposure time on a 4 m Fresnel array, rejection rate 2 10^{-8}. The fall in S/N ratio below 230 nm is due to the decrease in number of photons from the solar type spectrum. At the other end of the observable spectrum, the decrease in angular resolution of a4 m aperture limits the wavelength to 1.9 microns.

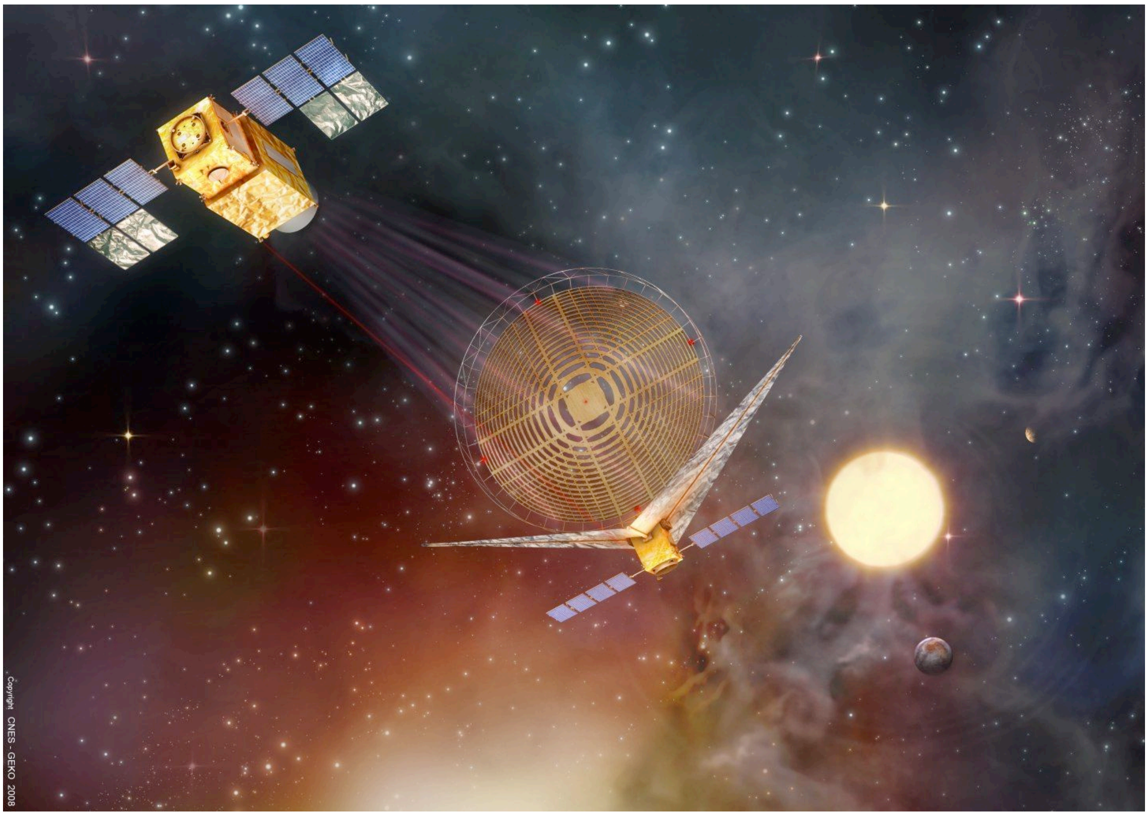
As stated in the 2007 proposal, the observations of extra-solar protoplanetary disks allow understanding the physical evolution and chemical composition at epochs preceding and contemporaneous with the formation of exoplanets. Chemical abundances are determined by physical conditions such as density, temperature and the incident radiation field. The UV radiation field plays a fundamental role in the chemical evolution of the disks:



Emissivity of a protostellar disk (central part of the disk: the 1D emissivity model of a protoplanetary disk in the UV at 150 nm wavelength (by Brigita von Rekowsky and Ana-Ines Gomez de Castro) has been circularly extended to a 2D projection.
Projections at different angles have been scaled to represent what would be seen at the distance of several potential targets (15 to 500 parsecs), and then convolved by the PSF (including the spikes) of a 30-meter Fresnel imager in the UV at 150 nm.
Theses circularly symmetrized and field limited models do not represent realistic protoplanetary discs, but they show that the angular resolution and dynamic range of a Fresnel imager will be sufficient to provide valuable data.

Formation flying and orbit requirements

The mission lifetime expected is 5 to 10 years, extendable to 15 years. We have studied the ergol consumption as a function of the number of targets, wavelengths domains (implying inter-spacecraft distance modulation), and reconfiguration times. With an on-board ergol reserve of 500 m/s, from 5000 to 10000 target images can be taken on scattered “all sky” targets. To achieve that, slow reconfiguration rates will be applied, with typically a 3-hours time for a 2 degree target shift, leading to 50 to 70% of the total mission time spent for data acquisition, the rest being used for spacecraft reconfiguration. This ratio depends on the target list optimization. For example, if long integration times are used for the survey of a few exoplanetary systems, this usable observing time ratio may rise above 80%.



Artist's view of a 10-m Fresnel imager. The Fresnel zones and interd-spacecraft distance are not at scale.

The current Phase zero study has already confirmed that L2 only is suitable for valuable science with a Fresnel imager in formation flying. The spacecraft holding the Fresnel array and baffle will be applied periodical orbit maintenance corrections, the secondary spacecraft holding the field optics, spectral channels and detectors will be set to follow the primary at the position required by the focal length and optical axis direction. The configuration modifications (target shifts and wavelength domain changes) will be applied to the lightest satellite: the one holding the large Fresnel array and baffle.

Payload instruments

The proposed two-spacecraft formation-flying Fresnel Interferometric Inager is as follows:

A first spacecraft constitutes the **"Fresnel Array Spacecraft"**.

This spacecraft holds the primary optics: the Fresnel interferometric array. It gathers incident light and focuses it into an image plane where the second spacecraft is located. its dimensions drive the angular resolution. Its number of Fresnel zones drive the dynamic range. It will be the larger, but the lighter of the two spacecraft.

A second spacecraft constitutes the **"receiver spacecraft"**.

This second spacecraft holds the secondary optics of the telescope and the focal instrumentation. It receives the light focussed by the primary array and reimages the target onto detectors, adapted to different spectral bandwidths and focal instrumentation: imagers, spectro-imagers. Likewise, it removes chromatism. Its entrance aperture determines the angular field and spectral coverage. All science channels share the same field mirror, but have different optical trains downstream. Navigation channels use the zero diffraction order of the main array and the field optics of the focal spacecraft.

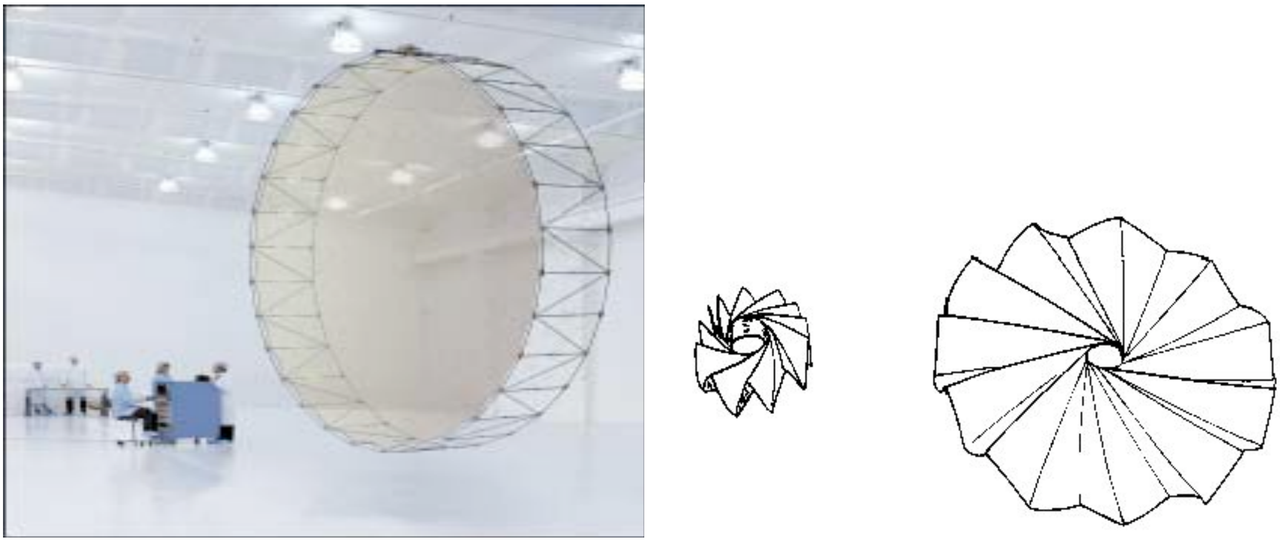
Primary optics

Three classes of missions have been defined : "3 to 5 meter" – " 10 to 15 meter " – " 30-meter "

The following guidelines have been chosen:

Primary array size (Cgr):	3 < Cgr < 30 m
Number of Fresnel ziones (N):	600 < N < 3000
Entrance pupil of the receptor spececraft optics:	0.5 < D < 2.2 m
Wavelength domain:	120 nm < λc < 5000 nm
Number of focal instruments channels	1 < Nchan < 6

Due to the necessary folding of large arrays for launch, we have identified "off the shelf" deployment techniques for large structures at the millimeter precision required: for exmaple the "ASTROMESH" technology.



Astromesh structure and its deployment

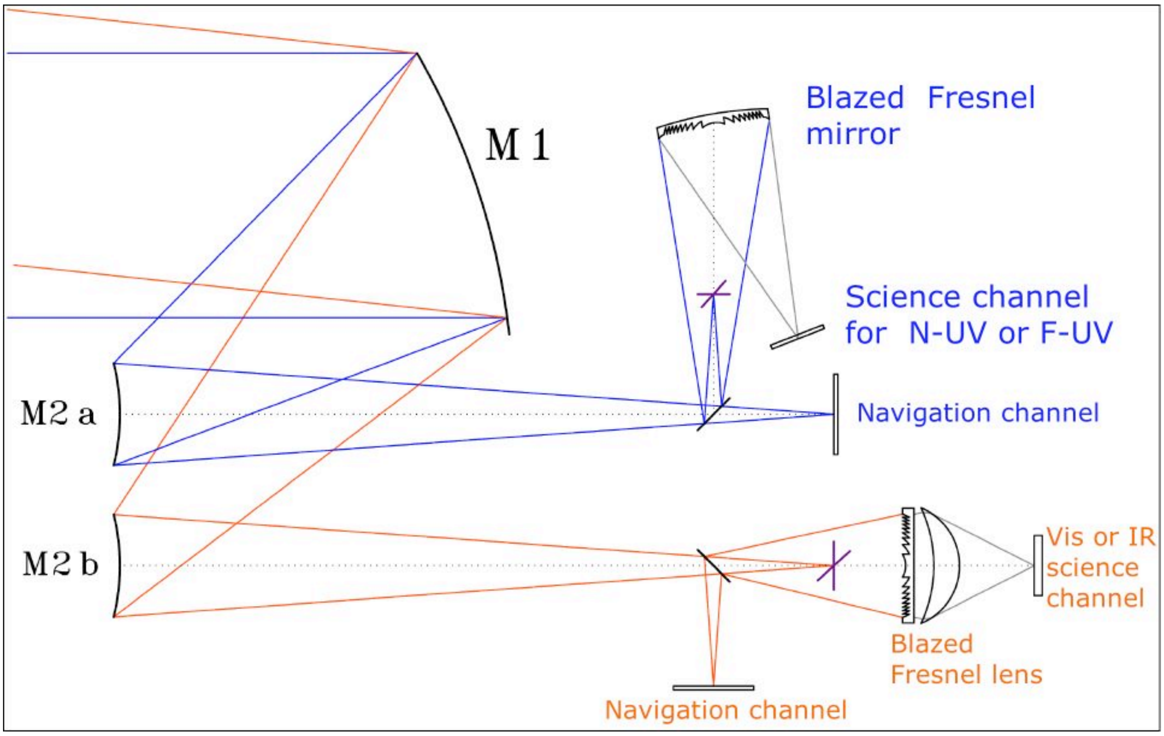
Secondary optics

The secondary optics consists of a "field telescope". The size ratio between Primary array and Field optics aperture is typically 1/10 to 1/15. This telescope plays the role of a field lens. It is a 2-mirror Cassegrain off axis combination. It is placed near the focal plane of the primary array. Its does not image the sky, but re-images the primary array onto a pupil plane, where the chromatic corrector is placed.

The field mirror diameter is driven both by the desired spectral bandwidth per channel and by the desired field. With a "field mirror" 1/10th the size of the main array, one can achieve a 1000 x 1000 field / resolution ratio at the central wavelength of each channel or an unvignetted 25 % relative spectral bandwidth at the centre of the field, or any combination thereof. Several channels may cover adjacent or not wavebands.

All channels will share the main array and the first reflecting mirror of the field telescope in the focal spacecraft. Depending on the attitude of the focal spacecraft, the beam will be sent onto different small secondary mirrors and the pupil will be imaged over various optical channel correctors and detectors, each optimized for a given spectral band and application.

We have studied configurations from two to six wavelength channels, ranging from 100 nanometres to 10 microns, each with a 27% relative spectral bandwidth, sampling from 1.4 to 140 arc seconds fields, depending on the wavelength domain and array size. Due to the optical behaviour of the Fresnel array and the size ratio chosen between primary and secondary apertures, the 1000*1000 resolution elements field ratio remains a constant for all configurations.



Principal optical elements and ray propagation inside the" focal" spacecraft. M1 is the field mirror, which is placed at the focal plane of the main array. Its dimensions are typically 1/10th of that of the main array. M2a and M2b are the secondary mirrors of the fiels optics. They are adapted to different spectral domains and send the light in corresponding channels. The channel into which light is sent can be switched with no movable part inside the spacecraft: by tilting the attitude of the entire spacecraft. The navigation channels share some optical path with the science channels, but do not use the same diffraction order nor the same focal plane as the science channels.

Conclusion

We have limited this presentation to a few pages, to what we have improved compared to last year, and to the scope of exoplanet study.
The present space observation simulation and lab prototype results are promising, but of course, a probative space mission will only be financed if a large support of the astrophysical community is gathered. We are working hard on that, and hopefully seeing the first results.

Bibliography

[01] L. Schupmann, "Die Medial Fernrohre : Eine neue Konstruktion for grosse astronomisch Instrumente" (B.G Teubner, Leipzig, 1899)

[02] R. A. Hyde, "Eyeglass : Very Large Aperture Diffractive Telescopes" Applied Optics 38, No. 19, 4198-4212, (1 July 1999).

[03] L.Koechlin, J-P. Perez : "A limit in Field-resolution ratio for interferometric arrays", Wesley A. Traub, Editor **SPIE** Proc Vol. 4838 411-415, "Interferometry for optical astronomy, II" Hawaii, août 2002.

[04] L. Koechlin, D. Serre, P. Duchon "High resolution imaging with Fresnel interferometric arrays : suitability for exoplanet detection", Astronomy & Astrophysics vol. 443, 709-720 (2005).

[05] Yuri M. Chesnokov,"A Space-Based Very-High Resolution Telescope", Russian Space Bulletin, 1993, vol. 1 No. 2.

[06] J.T. Early "Solar sail – Fresnel zone plate lens for a large aperture based telescope", AIAA 1705, 3773-3778 (2002).

[07] D. Massonnet, brevet C. N. E. S. : "Un nouveau type de télescope spatial", Ref. 03.13403 (2003).

[08] Dean Faklis & G. Michael Morris, "Broadband imaging with holographic lenses ", Optical Engineering, Vol. 28 No.6, p 592-598 (June 1989).

[09] Phase 0 study on the "Fresnel Interferometric Imager" at C.N.E.S, Toulouse, France. Emmanuel Hinglais is responsible for this study starting now (The pre-phase 0 occurred during the 2007 first semester)

[10] H.W. Moos et al., Overview of the Far Ultraviolet Spectroscopic Explorer Mission, Astrophys. J. Letters, 538, L1-L6, 2000

[11] K.R. Sembach et al., The Deuterium-to-Hydrogen ratio in a low-metallicity cloud falling onto the Milky Way, Astrophys. J., Suppl. Ser., 150, 387-415, 2004.

[12] N. Lehner et al., Far Ultraviolet Spectroscopic Explorer Survey of the Local Interstellar Medium within 200 Parsecs, Astrophys. J., 595, 858-879, 2003

[13] G. Hebrard, H.W. Moos, The Deuterium-to-Oxygen Ratio in the Interstellar Medium, Astrophys. J., 599, 297-311, 2003

[14] G. Hebrard et al., FUSE Determination of a Low Deuterium Abundance along an Extended Sight Line in the Galactic Disk, Astrophys. J., 635, 1136-1150, 2005

D. Charbonneau et al., Detection of an extrasolar planet atmosphere, Astrophys. J., 568, 377-384, 2002
[15] A. Vidal--Madjar et al., An extended upper atmosphere around the extrasolar planet HD209458b, Nature, 422, 143-146, 2003

[16] A. Vidal--Madjar et al., Detection of Oxygen and Carbon in the hydrodynamically escaping atmosphere of the extrasolar planet HD209458b, Astrophys. J. Letters, 604, L69-L72, 2004

[17] A. Lecavelier des Etangs, A. Vidal--Madjar, J.C. McConnell, G. Hebrard, Atmospheric escape from hot Jupiters, Astron. Astrophys., 418, L1-L4, 2004

[18] D. Ehrenreich et al., The transmission spectrum of Earth-size transiting planets, Astron. Astrophys., 448, 379-393 , 2006

[19] L.J. Richardson et al., A Spitzer infrared radius for the transiting extrasolar planet HD209458b, Astrophys. J., 649, 1043-1047, 2006

[20] G.E. Ballester, D.K. Sing, F. Herbert, The signature of hot hydrogen in the atmosphere of the extrasolar planet HD 209458b, Nature, 445, 511-514, 2007

[21] A large UV-optical telescope for characterization of the atmospheres of extrasolar planets and satellites, 39TH ESLAB Symposium on Trends in Space Science and Cosmic Vision 2020, held 19-21 April 2005, Noordwijk, The Netherlands. Edited by F. Favata, J. Sanz-Forcada, A. Giménez, and B. Battrick. ESA SP-588. European Space Agency, 73L, 2005

[22] D. Deming et al., Infrared radiation from an extrasolar planet, Nature, 434, 740-743, 2005

[23] D. Charbonneau et al., Detection of thermal emission from an extrasolar planet, Astrophys. J., 626, 523-529, 2005
[24] D.L. Richardson et al., A spectrum of an extrasolar planet, Nature, 445, 892-895, 2007

[25] C.J. Grillmair, et al., A Spitzer spectrum of the exoplanet HD189733b, Astrophys. J., 658, L115-L118, 2007

[26] H.A. Knutson et al., A map of the day-night contrast of the extrasolar planet HD189733b, Nature, 447, 183-186, 2007

[27] Karovska, M., Schlegel, E., Hack, W., Raymond, J. C., & Wood, B. E. 2005, ApJ, 623, L137

[28] Karovska, M., Hack, W., Raymond, J., & Guinan, E. 1997, ApJ, 482, L175 Chugai, N.N., and Yungelson, L.R., 2004, Astron. Lett., 30, 65.

[29] Aikawa & Herbst, 1999; A&A, 351, 233

[30] Aikawa & Herbst 2001; A&A, 371, 1107

[31] Gomez de Castro et al 2006; ApSS, 303, 33

[32] Herczeg et al 2004; ApJ, 607, 369

[33] van Dishoeck et al 2006; Faraday Discussions, 133, 231