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IMAGING INTERFEROMETRY USING INTERFEROMETRIC REMAPPED ARRAY NULLING

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Abstract. We present a beam combining technique capable of direct instantaneous imaging. The particularity is that the image (or PSID, *point source intensity distribution*) is formed in a pupil plane. We present the concept on a theoretical basis, comment on the PSID for on- and off-axis sources and finally compare it to Fizeau imaging. Future experiments and reflections about this concept are finally considered.

1 Introduction

The combination of long baseline interferometry and high dynamic range technique is foreseen for future spatial mission like DARWIN/TPF. In a direct imaging context Labeyrie (Labeyrie *et al.* 2003) proposed the hyper-telescope (HT) or pupil densification concept which aims at forming a filled output pupil from a diluted array of telescopes, which is, in other words, a 2D generalization of Michelson interferometry (Fig. 1a). Although a tremendous signal to noise gain can be achieved using the HT concept, some problems can occur in the image interpretation of complex sources. The IRAN is conceptually very close to the HT, and preliminary studies tend to show that it is more suitable for interferometric imaging in the classical way. The first section of this paper is recalling the Michelson (HT) image formation. A second section is describing how images are obtained with IRAN. Then an intuitive comparison with the Fizeau mode is made. Finally, we briefly present the possibility to couple IRAN with a coronagraph.

2 Summary of the Hyper-Telescope (Michelson) Concept

This “densified pupil” is then used to form a focal plane image. The image can be divided into 2 components: a fringe pattern due to the telescope array

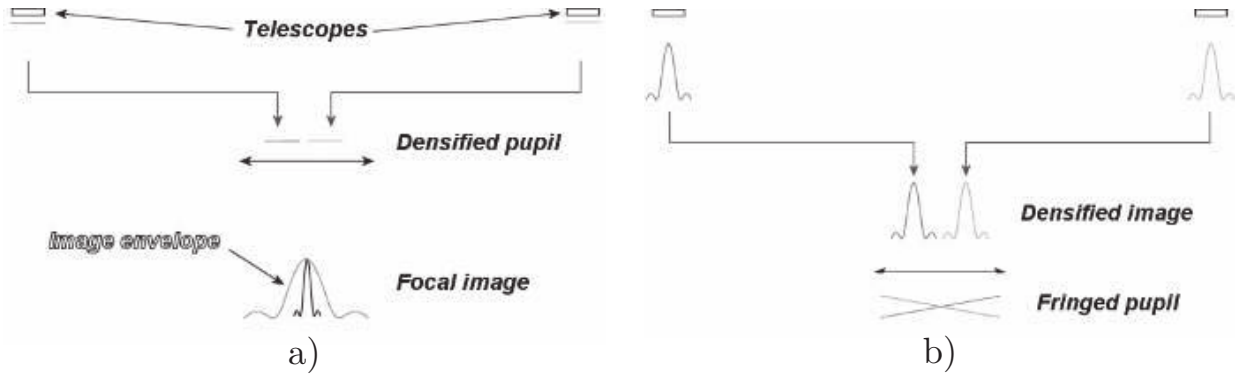


Fig. 1. The hyper-telescope **a)** *versus* IRAN **b)** beam recombination. The IRAN pupil-PSF is the result of the $\frac{N \times (N-1)}{2}$ fringe pattern relative to each baseline (fringed pupil).

arrangement, and a modulating envelope related to the diffraction pattern of single apertures (*i.e.* elementary array aperture scaled in the densification process). It is well known in two telescopes Michelson interferometry that when pointing off-axis from a source, the envelope is moving slower (proportionally to the densification factor) than the fringe pattern, so that the white fringe intensity decreases when it reaches side lobes of the modulating envelope. Thus, image interpretation become difficult if objects are present beyond the FOV defined by the first lobe of the envelope (also called the Zero Order Field).

3 IRAN Concept

3.1 Beam Recombination

Contrarily to classical multi-aperture recombination in OLBI where optical path difference is modulated in order to extract the fringes signature, the IRAN principle is to directly form a fringed pupil. Each of the $\frac{N \times (N-1)}{2}$ pairs of apertures produces two tilted wavefronts in the pupil and form fringes by coherent addition. The beam combination therefore involves an image plane, where we have brought them closer to each other, and preserving their optical axis parallel. A common lens then re-images the pupil according to the described fringe formation process (Fig. 1b).

3.2 On Axis Point Source

All the fringes relative to each baseline give rise to a pseudo-PSF which we call “Point Source Intensity Distribution” (or PSID) with a stronger coherent peak. The coherent addition of all the cophased fringe pattern is similar to the interference pattern (*IP*) of the N apertures geometrical configuration, that is,

$$IP(u, v) = FT \left(\sum_{i=1}^N \delta_{x_i, y_i} \right).$$

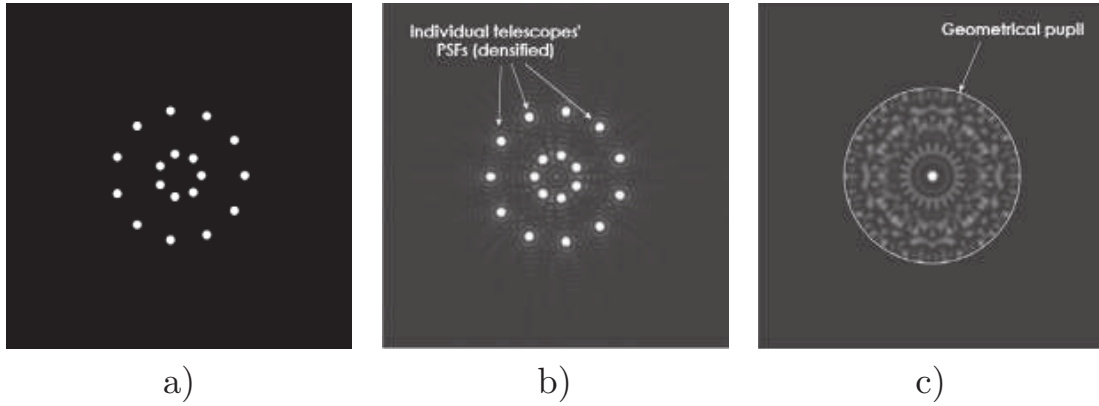


Fig. 2. Illustration of an IRAN image. **a)** The telescope configuration, **b)** the densified images and **c)** the resulting PSID in the pupil plane.

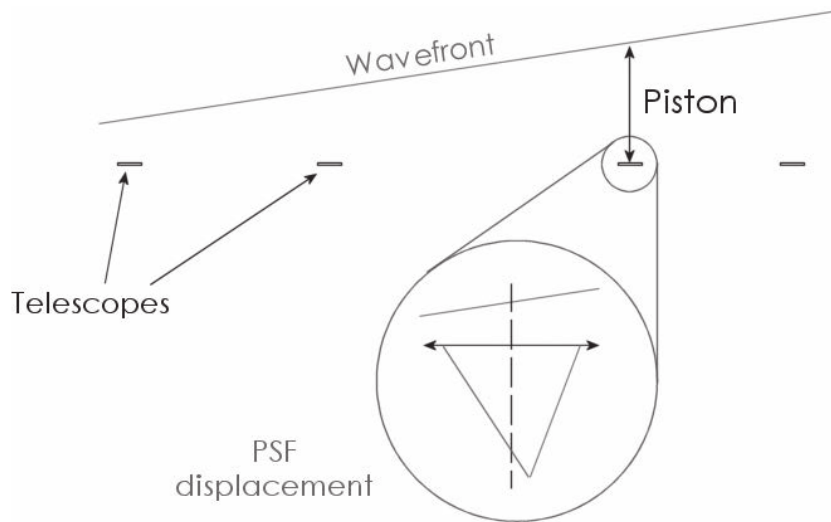


Fig. 3. Keys to understanding the off-axis source effects on the IRAN PSF.

3.3 Off-axis Point Source and Object/Image Relationship

If we consider an off-axis point source, then the corresponding wavefront will be tilted against the instrument optical axis. As depicted in Figure 3, each diffraction pattern at the focus of each telescope will be displaced with the same amplitude, in the same direction. As these patterns are transported to the recombiner, each of them carries a global piston phase shift (shown in Fig. 3), corresponding to the optical path difference relative to the zero-OPD case (on-axis source). These pistons affect each fringe pattern associated to each baseline, and translate them according to the differential piston contributions. We demonstrated formally (Vakili *et al.* 2003) that the PSID is preserved, making it almost **invariant by translation**. Indeed, the pupil being fixed imposes that it does not translate at all with the fringe pattern and therefore cannot be qualified of “invariant” by translation. Nevertheless, interesting possibilities of image reconstruction can be applied (under study) since the modulation of this interference pattern is uniform over the entire FOV (see below).

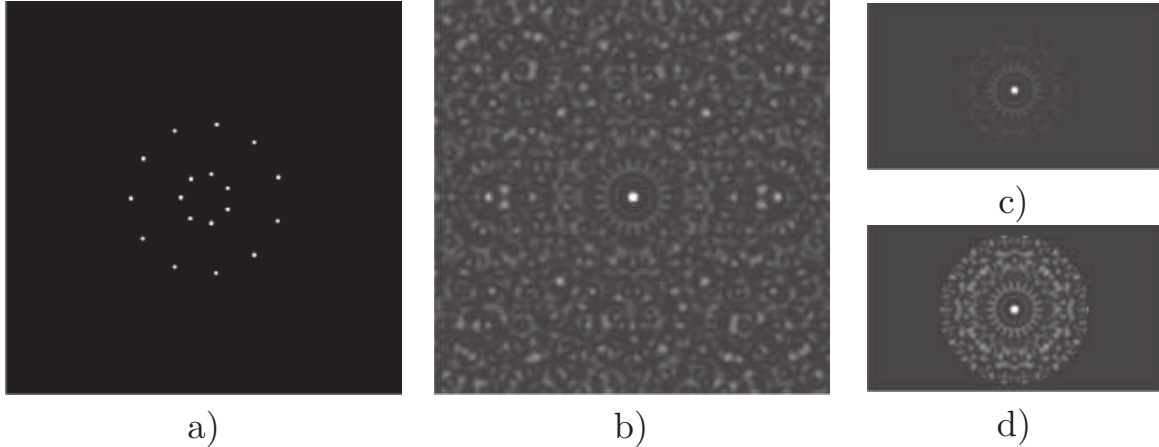


Fig. 4. Analogy to the Fizeau recombination. **a)** Positions in an array of telescopes (the “ δ array”). **b)** The Fourier transform of this δ array. **c)** The fizeau PSF which is **b)** modulated by the PSF of a single aperture. **d)** The IRAN pupil PSF which is **b)** modulated by the pupil function of a single aperture.

3.4 Field of View

As shown in Figure 2c, the PSID is limited by the geometrical pupil image of single apertures (supposed to be identical). This means that the FOV is only limited by the optical FOV of individual telescopes. The linear dimension (FWHM) of the coherent peak (angular size λ/B) depends on the inter-PSF distance in plane b) of Figure 2, and the FOV depends on the size of the pupil image which can theoretically be arbitrary large. But regarding the energy conservation, the bigger the pupil image, the lower the energy in the coherent peak, so a compromise must be found depending on the science objectives.

4 Analogy with the Fizeau Recombination

In a Fizeau configuration, one states that the output pupil is homothetic to the entrance pupil, and that the focus image is the Fourier Transform of this output pupil, with the bonus of being invariant by translation. We can decompose the Fizeau image formation in 2 steps. Take an arbitrary geometrical arrangement of apertures, which can be mathematically written as a sum of kronecker δ in a 2D plane. Then, convolve this array with identical telescopes’ pupil functions. By Fourier transforming this function, we obtain the Fizeau PSF, which is the Fourier transform of the δ array, modulated by the Fourier transform of the telescope pupil function, *i.e.* the Airy pattern (Fig. 4c). The IRAN works the same, with the difference that, instead of convolving the telescope pupil function to the δ array, we convolve the PSF (*i.e.* Airy pattern) of each telescope (supposed to be identical). By Fourier transforming this function, we obtain the IRAN PSF, which is the Fourier transform of the δ array, modulated by the fourier transform of the Airy pattern, *i.e.* the telescope pupil function (Fig. 4d). This strong analogy helps understand why the object-image relationship is preserved.

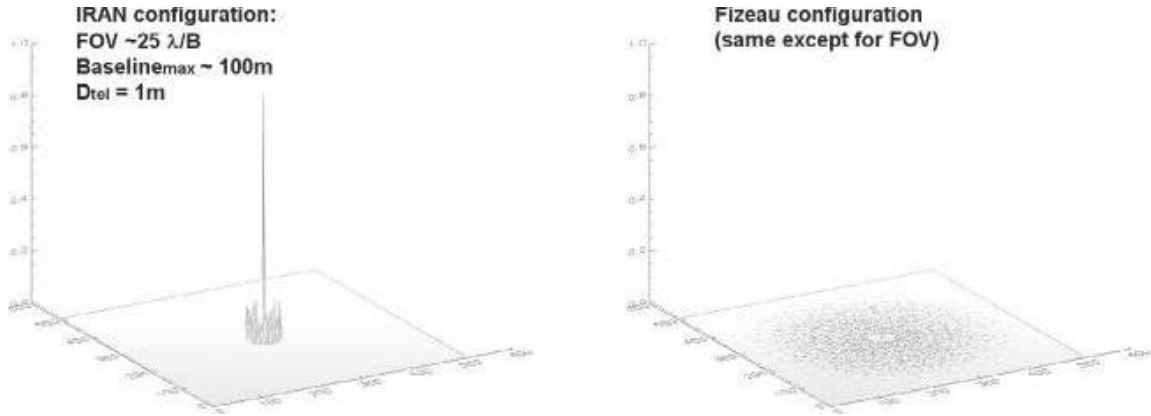


Fig. 5. Comparison of the IRAN gain against a classical Fizeau mode, where the maximum baseline is 100 m, the apertures diameter is 1 m, and the FOV is about $25 \lambda/D$. The gain here is ~ 16 (peak-to-peak intensity ratio).

In order to estimate the intensity gain for a given telescope configuration over a classical Fizeau image, we can translate the dilution of the flux over the modulating envelope: the pupil shape, which determines the FOV in the IRAN case, and the single aperture diffraction pattern for the Fizeau image (determined by the aperture diameter parameter D_{tel}). Under these considerations, we can derive the following approximation,

$$\text{Gain} = \frac{B^2}{D_{\text{tel}}^2} \frac{1}{\text{FOV}_{\lambda/D}^2}$$

where $\text{FOV}_{\lambda/D}$ is the field of view expressed in units of λ/D , B is the maximum baseline of the array configuration, and D_{tel} the apertures diameter. Figure 4 illustrates the gain of the IRAN versus Fizeau beam combination in a configuration where $\text{FOV}_{\lambda/D} = 25\lambda/B$, $B = 100$ m and $D_{\text{tel}} = 1$ m. It should be noted that if you want to increase the FOV, you will reach a limit where the gain will become a loss because the dilution of the PSID energy will occur on a relatively large array compared to the fringe size.

5 Nulling Mode

By defining a PSF in the pupil plane, we had some reflections about using “equivalent” high dynamic range imaging techniques like coronagraphy for the IRAN. We checked whether an analog to focal plane coronagraphy (*i.e.* phase or occulting mask) could be used successfully, but we found that only pupil interference set-up (A.I.C, Gay & Rabbia 1996) could provide the desired nulling effect (see Vakili *et al.* 2003 for further details).

6 Future Prospects

Our team is at the moment evaluating the performance and feasibility of the IRAN concept in a laboratory experiment. Once validated, a detailed study of the optimal multiple-aperture beam recombination has to be carried out for a future operational test instrument.

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