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Direct Imaging in Interferometry: Concept of a Pupil Densifier using Single-Mode Fibers

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Abstract: We present a test bench designed to study the performances of interferometric imaging systems. It aims at comparing the aperture synthesis, Fizeau and densified pupils beam combination schemes, mainly in the framework of the second generation instrument VIDA (VLTI Imaging with a Densified Array) of the VLTI. It allows identification of the technical requirements like photometry and cophasing correction. A Fizeau assembly using a multi-apertures mask associated with a wavefront sensor has been achieved. A densified assembly has been studied. It allows pupil rearrangement and spatial filtering by using single mode fibers. The technical specifications of the fiber densifier are described here. The influence of the gaussian intensity distribution of the fibers in the direct image is also briefly discussed.

1 Introduction

The Observatoire de la Côte d'Azur is involved in the VIDA proposal (VLTI Imaging with a Densified Array), a second generation instrument for the VLTI. VIDA is a direct imaging system based on a densified pupil beam combiner (Lardière 2005). The goal is to apply the hypertelescope principle (Labeyrie 1996), initially foreseen for a large cophased array, in the context of a few sub-apertures like the VLTI. This instrument allows to produce direct snapshot imaging in optical interferometry at high angular resolution and at high sensitivity and dynamic-range for compact objects in the visible and infrared wavelengths. In order to prepare the feasibility studies, an interferometric imaging test bench called SIRIUS is developed. This research is done in collaboration with french institutes: the LISE (Laboratoire d'Interférométrie Stellaire et Exo-planétaire) for the simulations and the specifications, the IRCOM (Institut de Recherche en Communications Optiques et Microondes) for the optical fibers implementation and the LUAN (Laboratoire Universitaire d'Astrophysique de Nice) for the image processing.

The bench seeks to compare the imaging capabilities of interferometric beam combination systems: aperture synthesis imaging, Fizeau and densified pupils direct imaging. The pupil densification significantly improves the dynamic of the signal with respect to the Fizeau scheme. Most of the light is concentrated in a central interference peak surrounded by a halo of side-lobes. A Fizeau assembly has been achieved and a densification assembly using monomode optical fibers has just been designed. The main interests of the fibers are the spatial filtering properties and the flexibility of the system. Indeed, the densified imaging requires the rearrangement in real time of the projected pupil on the sky before combining the beams.

The SIRIUS optical bench works in the visible wavelengths. Studies are expected on simple objects such as resolved stars and binaries, the purpose being to estimate the accuracy of the fundamental parameters of the object in different measurement conditions. A multi-aperture mask reproduces the configuration of the VLTI array with the four unit telescopes and next with eight apertures by adding four auxiliary telescopes. The bench is also dedicated to study other array configurations up to eight beams. A wavefront sensor (WFS) installed before the mask allows a direct control of the piston on each of the sub-apertures in the imaging beam with a precision higher than $\lambda/50$. Besides, the WFS will be the estimator of the cophasing devices used with the densification assembly.

2 Technical specification of a pupil densification system

The Pupil densification process modifies the entrance pupil in a densified exit pupil by increasing the size of the sub-apertures (Labeyrie 1996) with respect to their relative distances. This homothetic transformation is performed by moving nearer the positions of the sub-pupils centers without changing the overall pattern as a "conformal" Michelson scheme. It can also be achieved by zooming each sub-pupil. Both schemes give the same direct image, except that the magnification is increased by the "periscopic" effect of the Michelson recombination. For practical considerations, the diameters of the sub-apertures are zoomed and the position of the sub-apertures centers are retained. The densification factor corresponds to the ratio of the output and input diameters.

The technical specifications are derived from criteria measuring the quality of the direct image. The degradations are quantified by studying the intensity of the central peak and the energy dilution from the central peak to the speckles halo. The cophasing requires an accuracy of $\lambda/4$ in real time for the classical direct imaging mode (Lardière 2005). For that purpose also, the differential photometry should be limited to 10% between the beams. The polarisation axes must be aligned with an accuracy higher than 2.5°. The bench has been designed to maintain the chromatic effects lower than the diffraction effects for a spectral bandwidth of $80nm$ with a white light.

3 SIRIUS densification module

Each beams of the Fizeau Mask is injected in a polarization maintaining monomode fiber, through an injection module (see Fig.1). A polarizer is put after the source to define the axis of polarization. A delay-line, integrated in the injection module, is used on each arm to correct the intrinsic optical path defaults of the system. The lengths of the fibers are adjusted to cancel the chromatic dispersion (Vergnole 2005) by rolling and stretching the fiber with an optical fiber delay-line. The cophasing module is based on a fiber length modulation system, where the fiber is wound around a piezo-electric ceramic. The exit module of the fibers collimates each beam with the right diameter. Three levels of densification are provided by three interchangeable sets of collimation.

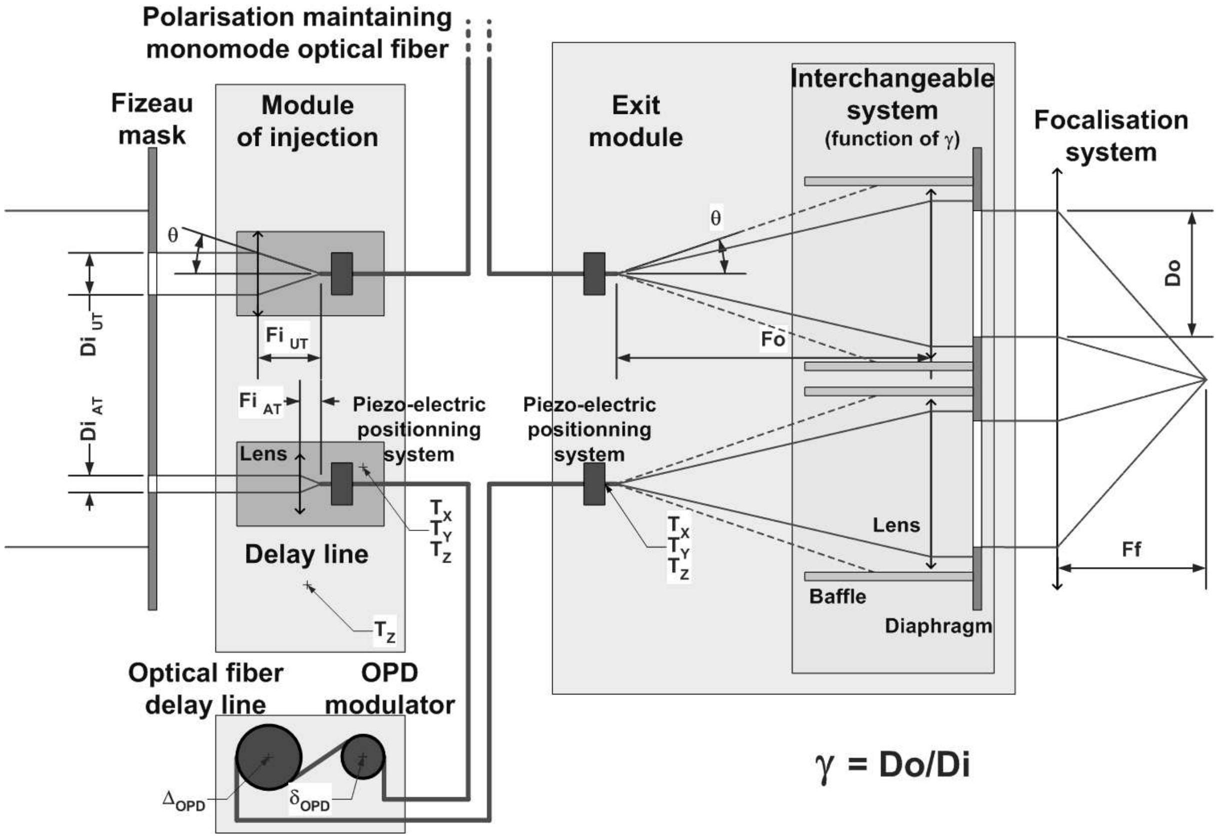

Figure 1: SIRIUS densification module

The maximum of flux is transmitted and the differential photometry is minimized by optimizing the coupling ratio of the fibers with the injection module. For that, this module consists of an achromatic lens and a nano-positionning system composed of piezo-electric translators on three axes to bring the fiber core to the focus of the lens. Numerical simulations show that a loss of 10% is produced by a shift of $0.4\mu m$ or by a defocus of $10\mu m$ of the input fiber core.

To superimpose accurately the spots at the imaging focus, the tilt of each beam is corrected by the exit module upstream of the focalisation system. Each module is also composed of an achromat and three piezo-electric translators. A photometric difference of 10% between two sub-images is induced by a radial shift of $0.35mm$ or a defocus of $3\mu m$ of the output fiber head from the focus of the collimator.

Preliminary tests show that the balance of the length of the fibers should be better than $100\mu m$ in the visible wavelength with a $80nm$ bandwidth. The stroke of the cophasing module is about $100\mu m$ and the resolution can reach $\lambda/100$ with a servo control.

For a given input pupil configuration, the three levels of densification correspond to three focal lengths and three diaphragm diameters. The output pupil diameter Do depends on the input diameter Di of a sub-pupil and on the level of densification γ : $Do = \gamma Di$. The focal length is chosen to properly adjust the diaphragm diameter Do with the gaussian field distribution at the output of the fiber, as explained in the following part.

4 Influence of the gaussian intensity distribution of the optical fibers

The efficiency of the densification is affected by the gaussian output intensity distribution on each of the sub-pupils, compared to a uniform intensity distribution. The problem is to properly fit the unlimited gaussian field to define an output pupil disc with the diaphragm. The properties of the direct image have been studied by numerical simulations.

The gaussian intensity distribution is defined as $I(r) = I_0 e^{\frac{-r^2}{{w_0}^2}}$ with I_0 the maximum of the on-axis intensity. w_0 is called the gaussian beam radius corresponding to the radius where the intensity is equal to $1/e = 0.368$ time the on-axis intensity. I_0 is normalized so that the total transmitted energy is equal to 0.80, which is the optimum coupling efficiency of a monomode fiber. The normalised beam radius is defined as $k = Ro/w_0$, with Ro the diaphragm radius.

If k is equal to 1, 63% of the energy is transmitted. If the diaphragm radius is low ($k = 0.5$), the intensity distribution is almost uniform but little energy is transmitted. The image is similar to the one obtained with a uniform disc but a global loss of energy is observed. If the diaphragm radius is high ($k = 2$), most of the energy is transmitted but the flux is concentrated at the middle of the sub-pupil, as if the sub-apertures are disjointed or as if the global pupil is diluted. The image is similar to the one obtained in the Fizeau case or partially densified case and some energy is diluted from the central peak to the side-lobes.

As the main interest of the densification is the sensitivity gain, the goal is to maximize the signal (central peak) and to minimize the speckles halo (side-lobes). It is shown that there is an optimum ($k = 1.1$) for the width of this diaphragm, which is a trade-off between the losses of transmission and the efficiency of the densification.

Compared to the uniform beam, the global loss of energy reaches 27%, taking into account the 20% due to the coupling ratio of the fiber. The gaussian beam shows a decay of the Strehl ratio, which must be taken into account for very high dynamic range applications as coronography.

5 Perspectives

The mechanical aspects of the fiber beam combiner and densifier are under study. The realization and the integration of all the elements should be achieved before the end of the year, which will allow us to test and exploit the densified imaging mode from the beginning of 2006. We plan also to test this imaging device on the sky by installing our densifier at the Coudé focus of a large telescope. Afterwards, it is foreseen to install a coronograph at the densified focus, as already proposed for VIDA.

References

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