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FIRST RESULTS FROM A LABORATORY HYPERTELESCOPE WITH SINGLE-MODE FIBERS

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Résumé. In the future, giant optical interferometric arrays will be developed with kilometric baselines and a large number of telescopes. Such arrays could have direct imaging capabilities if optimized beam combiners are used. This paper aims at studying the performances of an interferometric beam combiner using single mode fibers and the hypertelescope principle. A laboratory testbed called SIRIUS has been developed. We present here the results obtained and analyzed with the help of a numerical simulator. Direct images have been obtained at the densified focus of SIRIUS. It is shown that the fibers improve the quality and the stability of the direct image. The computed images allow to reproduce the effects of differential photometry and the influence of optical path difference (OPD) variations. OPD's errors less than $\lambda/10$ and differential photometries less than 60% are required to keep the quality of the direct image. The excellent comparison between experience and simulation clearly shows the simplicity of the fibered pupil densifier. It also gives us a great confidence in the extrapolation of these results and specifications for future arrays with a very large number of apertures.

1 Introduction

Conceptual design studies are mandatory to define future kilometric optical interferometers. In this context, an interferometric testbed, called SIRIUS, has been developed to study the recombination schemes for direct imaging with the densified pupil concept (Labeyrie 1996). It has been shown (Lardière 2007) that, compared to the Fizeau mode (Fizeau 1868), the pupil densification improves the sensitivity gain without loss of field of view.

SIRIUS aims at studying the performances of densified pupil beam combination schemes, for the long term purpose of direct imaging of astronomical complex sources. An IDL simulation software has been written for helping in the definition of the testbed and for correctly understanding the results. This simulator, called HYPERTEL, is made in two main parts. The first one aims at simulating images of a complex sources as seen through an interferometer and for different types of beam combination. The second part analyses these images or the SIRIUS raw images for calculating the interesting parameters of the PSF.

The main interest of SIRIUS is to allow identification of the technical requirements like differential photometry and cophasing tolerances. The technical specifications are derived from criteria measuring the quality of the direct image in the focal plane, in terms of intensity distribution. The degradations are quantified by studying the on-axis irradiance decrease or the energy dilution from the central peak to the surrounding halo (Patru 2008, Patru 2007b). For that, we use here two main criteria. The on-axis intensity I_0 equals to the amplitude of the central peak. The encircled energy E_0/E_{tot} is defined as the ratio of the fraction of energy contained in the central peak on the total energy in the image.

The pupil densification scheme has then been developed with the goal of using up to 8 single-mode fibers (Reynaud 2001, Delage 2000). Single-mode fibers allow spatial filtering and offer a more compact and flexible solution for beams combination (Patru 2007a). Furthermore, using single-mode fibers allows a simple optical

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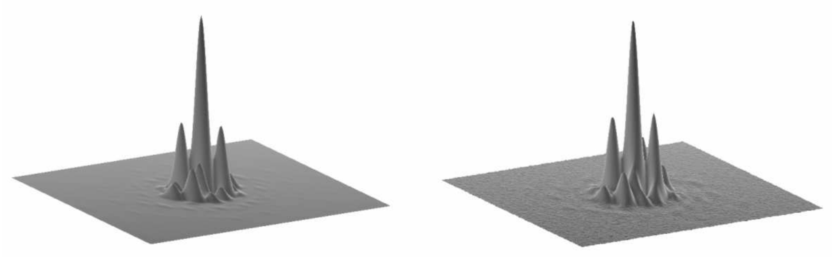

Fig. 1. The comparison between the simulated PSF (left) and the experimental PSF (right) shows a very encouraging agreement.

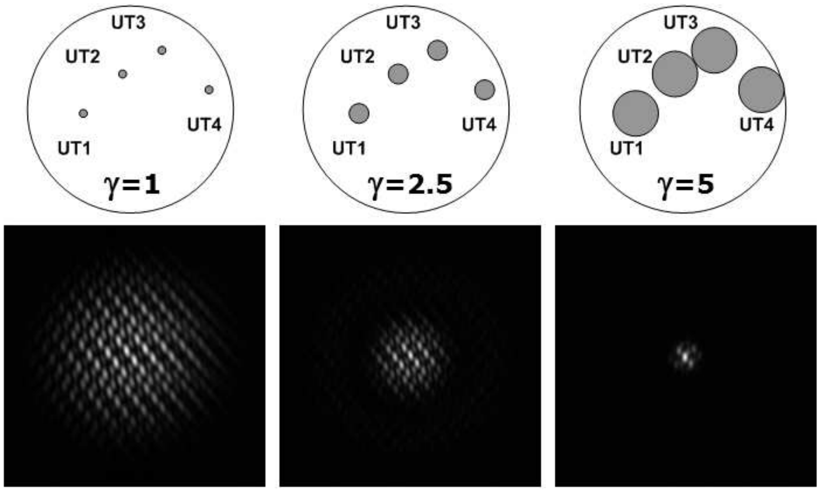

Fig. 2. Variable densification. Output pupil (up) and PSF (down) obtained on SIRIUS with the 4 UTs configuration in Fizeau mode (without fiber), in partial densification mode and in maximal densification mode (from left to right). The three images have the same maximum intensity level but the exposure times are completely differents, showing clearly the intensification of the signal kept by the densification operation. For the Fizeau images, the exposure time is $250ms$, whereas it is $25ms$ in the partial densified image and $5ms$ in the maximum densification image.

implementation of the hypertelescope principle. For this work, we have used a mask reproducing the UT1-UT2-UT3-UT4 configuration of the VLT Interferometer. Each UT is represented by a hole of $2.7mm$ and the largest baseline UT1-UT4 has a length of about $47mm$ on the mask.

The technical specifications have been described by Patru 2005, Patru 2008. This paper summarizes the results and comparisons with numerical simulations detailled by Patru 2007c.

2 Characterization of the instrumental PSF

There is a very good adequation between the simulations and the SIRIUS experiment, as shown in the figure 1. As foreseen in the simulation, the intensification of the signal with the increase of the densification factor can easily be seen on the densified images. For the same maximum amplitude in the image (Fig. 2), the exposure time in the maximal densification case is $5ms$, against $25ms$ in the partial densification case. It corresponds to an intensification of 5, which is in very good adequation with the densification factor difference $(\gamma_{max}/\gamma_{max/2})^2 = (5.5/2.5)^2 = 4.9$. The exposure time in the Fizeau mode is about $250ms$, but it is difficult to compare it with the densification mode, due to the fact that it has been recorded without fibers and with another light source.

In the maximum densification case, the encircled energy in the central peak reaches $E_0 = 36\%$, compared

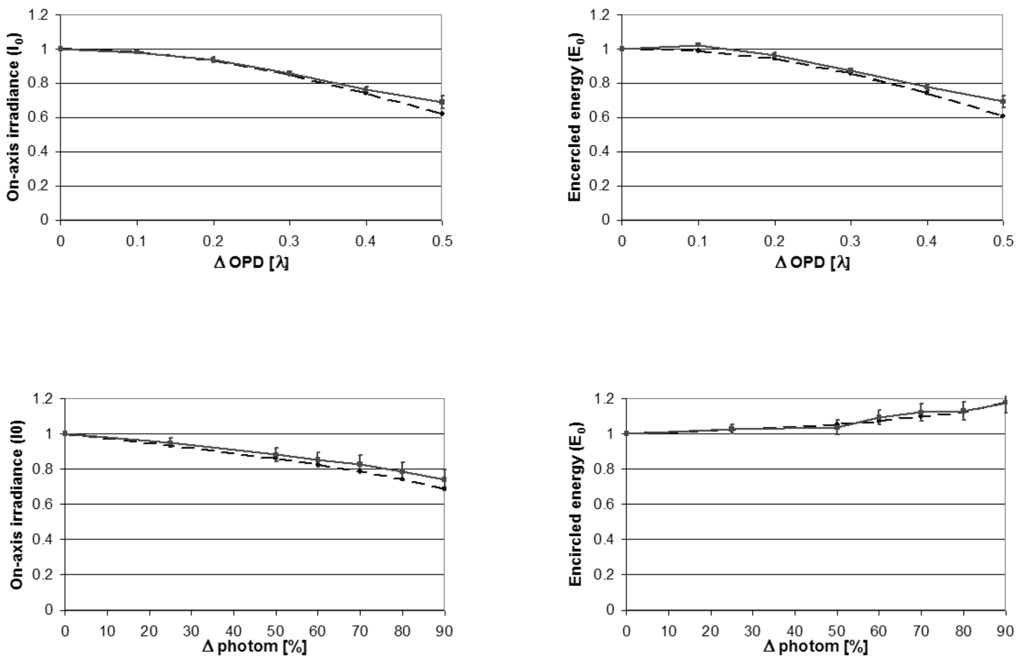

Fig. 3. Evolution of the on-axis irradiance (left) and the encircled energy (right) of the PSF as a function of the piston (top) and the photometry (bottom) on the UT1 beam. SIRIUS data (full line) and simulation data (dashed line).

to $E_0 = 38\%$ with the simulations. In the partial densification case, the encircled energy reaches $E_0 = 4\%$, compared to $E_0 = 6\%$ in the theoretical case.

With the choice of spatial filtering with single mode fibers at the entrance of the densified combiner, the perturbations of the combined beams at the densified focus are only changes in photometry and variations of pistons. Thus we have used the SIRIUS testbed to deeply characterize these effects. The measurements have been compared with the numerical simulations and are presented in the next subsections.

3 Effects of the differential pistons on the PSF

To quantitatively characterize the influence of the residual pistons on the image quality of the densified images, we have introduced known delays and recorded the images during the time of stability of the experiment. The figure 3 shows the evolution of the imaging parameters of the PSF with 4UTs as a function of the increasing piston on one of the four beams. For that, the piston is increased step by step on the UT1 beam, from 0 to $\lambda/2$.

The on-axis irradiance and the encircled energy decreases of 10% for an OPD of $\lambda/4$. For an OPD higher than $\lambda/4$, it is more critical : first the halo increases and then the central peak is destroyed. As the OPD equals to $\lambda/2$, two peaks predominate instead of one, so that the right peak of the image cannot be located.

It has been shown that the cophasing requirement is $\lambda/4$ to maintain below 10% the energy dilution from the central peak to the halo. But this study is limited to an optical path variation of only one beam. In practice, phase fluctuations of all the beams have to be taken into account. A cophasing requirement of $\lambda/10$ is chosen, which retains more than 90% of the energy in the central peak.

4 Effects of the differential photometry on the PSF

The next purpose is to characterize the influence of the differential photometry on the PSF quality. The figure 3 shows the evolution of the imaging parameters of the PSF with 4UTs as a function of the photometric decrease on one of the four beams. For that, the focus of the injection is modified on the UT1 beam, whereas the generated OPD is corrected with the cophasing system. The same operation is reproduced step by step in order to decrease the flux from 100 to 10%.

The on-axis irradiance decreases, due to the photometric attenuation on the UT1 beam. However, the encircled energy of the central peak and the halo level are not much affected. Thus the differential photometry induces a global photometric decrease in the image without destroying the quality of the direct image.

5 Discussion

The first results obtained on SIRIUS show a very good adequation of the imaging parameters between simulated and experimental images. These results validate the simulation and the concept of the fibered pupil densifier.

The flexibility of the fibers are obviously very useful to rearrange the densified output pupil, depending on the deformation of the entrance pupil as seen from the sky. Moreover, this fibered system is very stable in time since the alignment is preserved during several months so as to keep the beams on the CCD detector.

An other advantage of the fibers is to greatly ease the system adjustment. The interest is to decorrelate the entry and the exit of the assembly, which allow to separate the problems. The alignment procedure concentrates on the degrees of freedom on the injection module, on the exit module, and then on the OPD equalization with the cophasing system. The densified image is properly restored if the beams remain in phase at least at $\lambda/10$.

Thanks to the spatial filtering properties of the single-mode fibers, any entrance perturbations are converted in photometric fluctuations or piston variations. We have shown that a densified image is much less sensitive to the differential photometry as the differential pistons. A differential photometry of about 60% is tolerable. Thanks to the single-mode fibers, a disturbed wavefront is filtered at the entry by reducing the flux and by generating differential photometry. This does not affect so much the quality of the direct image, but induces mainly a global decreasing of the flux and a low uniform decreasing of the contrast in the image. Thus, the spatial filtered image gains in quality and in stability.

6 Conclusion and prospects for the future

The densifier SIRIUS has a real potential for imaging compact objects on the sky, by improving some technical aspects. The cophasing on the sky remains the main hard point. The next step is to study the admissible level of atmospheric turbulence and to deduce the required specifications for the injection in the fibers and the cophasing of the beams to preserve an image of quality. Afterwards, it is foreseen to design and test a fringe sensor unit.

The fibered solution suits perfectly the ground interferometers with a simple optical scheme easy to adjust. In the middle term, applications are envisaged on the sky, to begin with pupil masking on a monolithic telescope, and after with a similar concept on an existing interferometer, as the VLTI, CHARA, NPOI, MROI or OHANA.

Références

Delage L. et al. 2000, Appl. Opt., 34, 6406
Fizeau A.H. 1868, C.R. Acad. Sci. Paris, 66, 932
Labeyrie A. 1996, A&A Suppl. Ser., 118, 517
Lardière O. et al. 2007, MNRAS, 375, 977
Patru et al. 2005, SF2A, 263
Patru F. et al. 2006, Proc. SPIE, 6268, 57
Patru F. et al. 2007a, MNRAS, 376, 1047
Patru F. 2007b, Ph.D. Dissertation, Université de Nice Sophia-Antipolis
Patru F. et al. 2007c, in preparation
Patru F. et al. 2008, in preparation
Reynaud F. et al. 2001, C.R. Acad. Sci. Paris, 2, 99