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NULLING STABILIZATION IN THE PRESENCE OF PERTURBATION

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Abstract.
Nulling interferometry is one of the most promising methods to study habitable extrasolar systems. In this context, several projects have been proposed such as ALADDIN on ground or DARWIN and PEGASE in space.

A first step towards these missions will be performed with a laboratory breadboard, named PERSEE, built by a consortium including CNES, IAS, LESIA, OCA, ONERA and TAS. Its main goals are the demonstration of a polychromatic null with a 10^{-4} rejection rate and a 10^{-5} stability despite the introduction of realistic perturbations, the study of the interfaces with the formation-flying spacecrafts and the joint operation of the cophasing system with the nuller. The broadboard integration should end in 2009, then PERSEE will be open to proposals from the scientific community.

1 Introduction

The spectral characterisation of exoplanets requires challenging instruments. PEGASE, proposed to ESA's Cosmic Vision, is dedicated to the spectrometry of hot Jupiters and brown Dwarfs from 2.5 to 5 μm with its three formation-flying spacecrafts. ALADDIN, located in the Antarctic, will operate in the L band. These two nulling interferometers can be seen as DARWIN pathfinders and share a major issue: the need for nanometric stability which can't be reached without a cophasing system because of mechanical or atmospheric disturbances on the optical path. A laboratory breadboard called PERSEE has been designed to show the feasibility of these missions.

After a brief presentation of PEGASE, this paper focuses on PERSEE: we perform the system analysis, describe the breadboard, and finally emphasize the interferometric recombination and the cophasing system.

2 PEGASE

2.1 Scientific goals

The study of habitable extrasolar planets is certainly one of the most exciting and challenging topics for the next decades. PEGASE will study the conditions in which these planets are formed and the environment in which they evolve, both for solar-type and peculiar stars. Other objectives are the spectroscopy of hot Jupiter (Pegasides) and brown dwarves, and the exploration of the inner part of protoplanetary disks. Operating in the $[1.5 - 6]\mu m$ spectral band with a spectral resolution $R = 60$, PEGASE will perform the spectroscopic characterization of exoplanetary systems and provide the dust size distribution from the very neighbourhood of the star to several A.U. from it. At last, it will validate in real space conditions nulling and visibility interferometry with formation flying.

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The contrast (star/planet flux ratio) ranges from 10^3 to a a few 10^4 in the considered wavelength range. As the desired angular resolution at $2.5 - 5\ \mu m$ implies aperture dimensions of several hundred meters and the terrestrial atmospheric absorption limits the ground-based observations to some narrow bands, a space-based free flying interferometer is proposed. The desired extinction will be implemented using the Bracewell set up (Bracewell, 1978), i.e. a Michelson interferometer with a π achromatic phase shift between the two apertures, and a rotation of the baseline around the line of sight. Figure 1 shows the transmission map of such a device with a dark fringe on the central parent star while the baseline is adjusted so that a bright fringe coincides with the supposed weak companion. A full description of PEGASE can be found in Le Duigou et al., 2006 and in Ollivier et al., 2007.

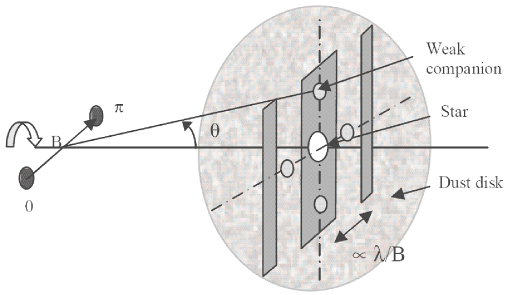

Fig. 1. Basic principle of a Bracewell interferometer

2.2 PEGASE design

PEGASE is a two 40cm-aperture interferometer for nulling and interferometric imaging. It is composed of three free-flying satellites (2 siderostats and 1 beam combiner) with baselines capable of varying from 50 to 500 m.

The main instrument is an IR interferometer and performs precise measurements either in stellar interferometry mode (V^2) or in destructive mode (nulling) in the $[1.5 - 6]\mu m$ range. In V^2 mode, the visibility of the object is extracted whereas in nulling mode the size and orientation of the baseline are adjusted to position the first bright fringe on the faint companion. The main instrumental challenge is to achieve both a very high angular resolution (0.5 to 5 mas) and a high extinction power of the parent star light. PEGASE includes the following three subsystems:

- an achromatic π-phase shift is introduced in order to center the dark central fringe on the bright central object. It will be geometrically implemented using a field reversal by reflexion with the two siderostats and two planes mirrors as described in Serabyn, 1999. Besides, dispersive prisms will compensate the likely small chromatic effects, they will be comparable with the ones used by the Synapse or MAII breadboard (Brachet, 2005; Weber et al., 2004).

- A cophasing system with a fringe sensor operating in the $[0.8 - 1.5]\mu m$ range and delay lines is used to accurately cophase the main instrument but it also has scientific by-products of interest.

- A fine pointing system with a camera operating in the $[0.6 - 0.8]\mu m$ range and tip/tilt mirrors is used to precisely correct the tip/tilt errors in order to ensure a very good intensity matching between the two arms.

3 PERSEE

In order to demonstrate the feasibility of PEGASE, it has been decided to develop of a laboratory breadboard of the payload. This breadboard will validate the principle of real time OPD and tip/tilt correction for achieving a polychromatic nulling despite the introduction of realistic perturbations. Firstly, we will introduce perturbations simulating a free-flying formation mission; later, PERSEE could be used for studying atmospheric perturbation effects on a polychromatic nulling.

3.1 Breadboard objectives

The main goal is to join a nulling interferometer with OPD and tip/tilt control loops. Main focus will be put on the following points:

- Obtain an average null of 10^{-4} with a 10^{-5} stability over a few hours in several spectral bands between 1.5 μm and 5 μm.
- Validate fringe acquisition with a drift speed up to 150 $\mu m/s$.
- Characterize the noise and the maximum external drift allowed for the two active loops (OPD and tip/tilt).
- Investigate interaction between the OPD/tip-tilt/flux loops.
- Demonstrate the differential stability between the nulling and cophasing sensors.
- Investigate the calibration procedures, taking into account measurements from the cophasing loops. Calibration can be performed before the nulling measurement (estimation and correction of non-common path aberrations) or after the nulling measurement (estimation of the leakage from perturbation residuals measured by the real-time sensors).
- Validate the full operation with realistic external disturbances (star/fringe acquisition, tracking, unloading of small-stroke fine correctors).
- Study the effects of polarization.

3.2 System analysis

Serabyn (2000)
showed that, in the case of a point source, the null depth is a linear sum of several contributions:

$$N = N_\phi + N_I + N_\lambda + N_{pol} \tag{3.1}$$

N_ϕ and N_I represent, respectively, the OPD matching and the intensity balancing between the two beams; N_λ takes in account the phase dispersion across the passband and N_{pol} the difference of polarization.

An error budget analysis has been carried out and a maximum tolerable error of $5 \times 10^{-5} \pm 5 \times 10^{-6}$ has been assigned for OPD and polarization, and of $10^{-5} \pm 10^{-6}$ for intensity and chromatism. Since the most difficult reachable requirements are related to OPD and intensity imbalances, we will exclusively focus on them in the following.

It can be shown that:

$$N_\phi = \left(\frac{\pi \delta_c}{\lambda}\right)^2 \qquad N_I = \frac{1}{16}\left(1 - \frac{I_2}{I_1}\right)^2 \tag{3.2}$$

where δ_c is the OPD at the band center and I_i the coupled intensity of beam i.

Assuming the Strehl approximation for calculating the coupling efficiency (Ruilier and Cassaing, 2001), this foregoing error budget analysis leads to a specification of 15 nm rms per axis for the pointing accuracy and to a transmission ratio between the two arms of the interferometer of 99%. Besides, for the shortest observation wavelengths, the OPD stability must be lower than 1 nm rms.

3.3 Breadboard description

First of all, PERSEE includes a source unit generating two interferometric quality wavefronts from 0.6 μm to 3.5 μm: the flux of a blackbody is injected through a single-mode optical fiber at the focus of a parabolic mirror. Then, two plane mirrors representing the siderostats inject realistic disturbances simulating the position error and various noises (mainly solar pressure and reaction wheel microvibrations). Then, the correction are carried out by optical delay lines and tip/tilt mirrors. At last, an infrared camera measures the destructive and constructive outputs of a modified large spectral band Mach-Zehnder interferometer (MMZ) to compute the

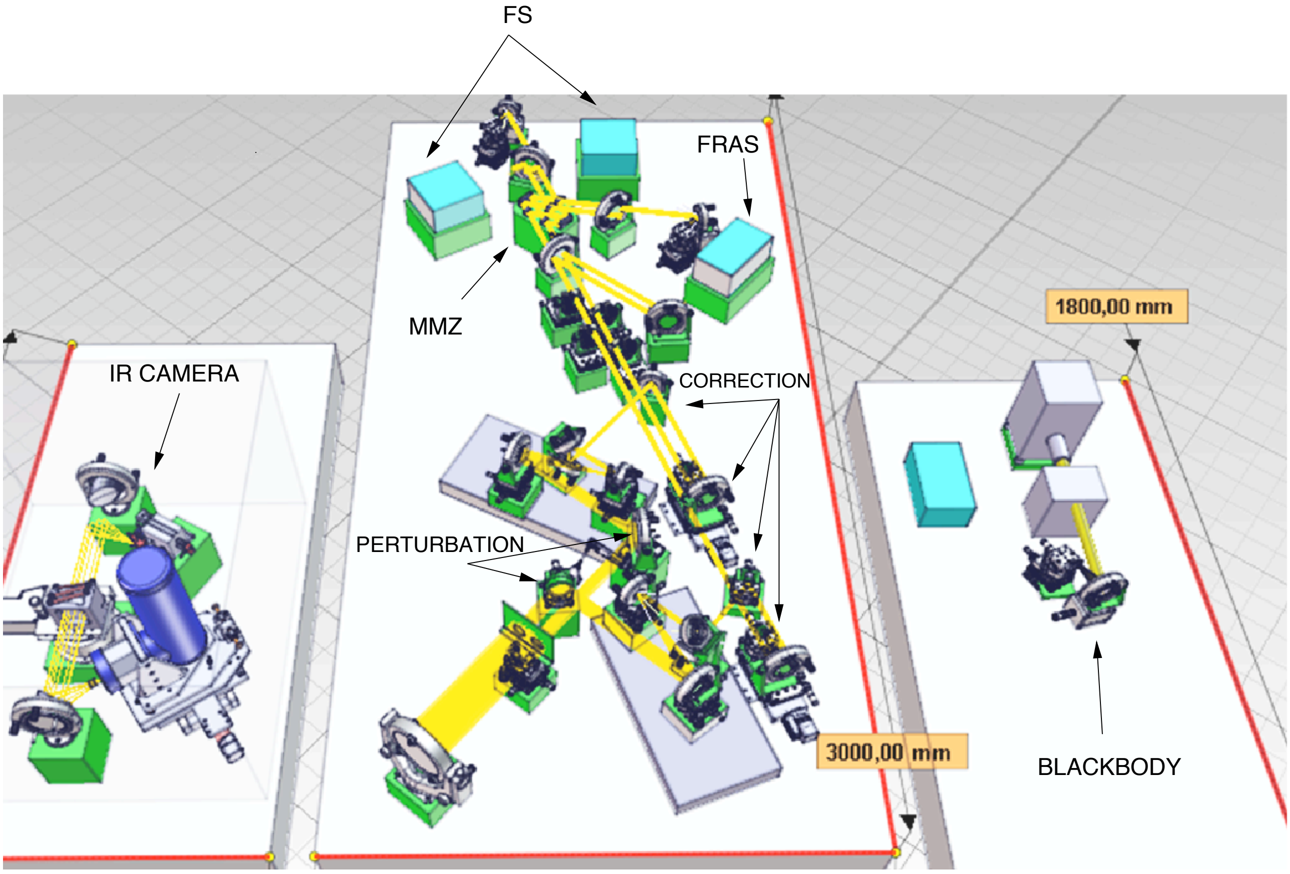

Fig. 2. TAS's optomechanic design of Persee

null depth in several spectral channels in $[1.6-3.5]$ μm. Figure 2 shows that the source unit (on the right) and the detection (on the left) are deported in order to move away as much as possible sources of thermal noise.

We measure the tip/tilt and the OPD within two distinct spectral bands. The tip/tilt is measured by a Field Relative Angle Sensor (FRAS) in the $[0.6-0.8]$ μm spectral range and tip/tilt mirrors correct the angular orientation of the beams. The optical path difference (OPD) is measured by the MMZ, used as an ABCD interferometer, in the $[0.8-1.5]$ μm spectral band and optical delay lines compensate OPD errors.

At last, the interferometric recombination is also carried out by the same MMZ which performs a spatial intensity modulation of the fringes with 4 outputs in quadrature A, B, C and D: B and D correspond respectively to the bright and dark fringes, A and C correspond to the inflection points.

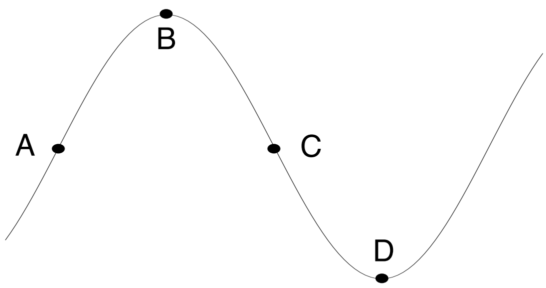

Fig. 3. Spatial modulation of the MMZ interferometer with its 4 outputs in quadrature A, B, C and D.

In the $[0.8-1.5]$ μm spectral range, the four outputs of the MMZ are used for the OPD measurement while in wavelengths from 1.6 μm to 3.5 μm B and D are used to compute the null depth. The study and the definition of the MMZ is carried out by IAS in collaboration with ONERA.

The joint operation of the cophasing system and the nuller enables the minimization of the differential optical paths between the nulling measurement and the nuller; thus the MMZ is of the highest importance because it allows to remove differential errors between the measurements and the null depth.

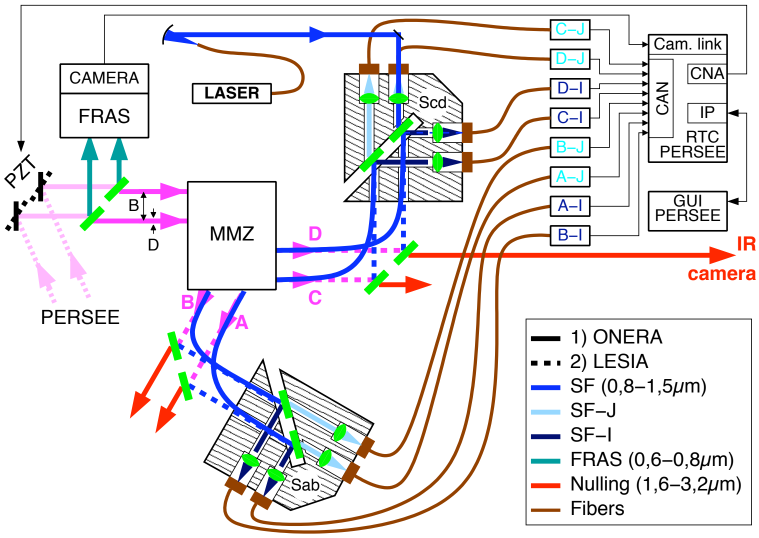

Fig. 4. Principle of the cophasing loop with the different steps of integration and tests (at ONERA then at LESIA).

3.4 Cophasing device

Figure 4 shows the principle of the cophasing system: the measurement of the OPD is performed by an ABCD interferometer and delay lines compensate the OPD. In the $[0.8 - 1.5]$ μm spectral band, the MMZ is used to measure the OPD. Each output is dispersed into 2 spectral channels to ensure dark-fringe tracking by removing the main ambiguities introduced by fringe jumps. The main requirement is that the residual OPD must be lower than 1 nm rms. To reach this specification, the sampling rate will be of about 1 kHz.

Before the final integration of PERSEE, the cophasing loop will be tested and optimized at ONERA. Since the rest of PERSEE is developed in parallel, the main optical train won't be operational; accordingly, the beam will be injected through an output of the MMZ which will thus be used both in order to divide and to recombine the beams as shown in Figure 4.

Finally, the fine pointing control loop has already been tested at ONERA and the interaction between OPD and tip-tilt loops will be studied in large measure at ONERA.

4 Conclusion

The demonstration of the feasibility of nulling interferometers under realistic operating conditions needs laboratory breadboards. As a consequence, PERSEE has been designed and it should be able for the first time to demonstrate a polychromatic null with a 10^{-4} rejection rate and a 10^{-5} stability despite the introduction of realistic perturbations.

Its definition has been achieved in 2007 and tests of the tracking loops have begun. Its integration will begin in 2008 at Observatoire de Paris-Meudon and tests should be carried out by the end of 2009. Then, PERSEE will be opened to scientific community proposals.

5 Acknowledgments

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