Persee: a nulling demonstrator with real-time correction of external disturbances

Cassaing F. ^{a,h}, J.M. Le Duigou^{b}, K. Houairi ^{a,b,h}, S. Jacquinod ^{c}, J.M. Reess ^{d,h}, F. Henault^{e}, B. Sorrente ^{a,h}, M. Barillot^{f}, P. Laporte ^{g,h}, G. Rousset^{d,h}, V. Coudé du Foresto ^{d,h}, M. Ollivier ^{c}

[a]Office National d'Etudes et de Recherche Aérospatiales, Optics Department, BP 72, 92322 Châtillon Cedex, France;
[b]Centre National d'Etudes Spatiales, 18 Avenue Edouard Belin, 31401 Toulouse Cedex 4, France;
[c] Institut d'Astrophysique Spatiale, Centre Universitaire d'Orsay, Bt 121, 91405 Orsay, France
[d]LESIA, UMR 8109, Observatoire de Paris, 5 place Jules Janssen, 92190 Meudon, France;
[e]Observatoire de la Côte d'Azur, Avenue Nicolas Copernic, 06130 Grasse, France;
[f]Thales Alenia Space, 100 Bd du Midi, 06322 Cannes-la-Bocca, France
[g]GEPI, [h]PHASE, the high angular resolution partnership between ONERA, Observatoire de Paris, CNRS and University Denis Diderot Paris 7;

ABSTRACT

Nulling interferometry is one of the most promising methods to study habitable extrasolar systems. Several projects, such as Darwin, TPF, Pegase, FKSI or Aladdin, are currently considered and supported by R&D programs.

One of the main issues of nulling interferometry is the feasibility of a stable polychromatic null despite the presence of significant disturbances, induced by vibrations, atmospheric turbulence on the ground or satellite drift for spaceborne missions. To reduce cost and complexity of the whole system, it is necessary to optimize not only the control loop performance at platform and payload levels, but also their interaction.

In this goal, it was decided in 2006 to build a laboratory demonstrator named PERSEE (Pegase Experiment for Research and Stabilization of Extreme Extinction). PERSEE is mostly funded by CNES and built by a consortium including CNES, IAS, LESIA, OCA, ONERA and TAS. After a definition phase in 2006, the implementation of the sub-systems has now begun and the integration in Meudon near Paris by GIS-PHASE (LESIA, ONERA and GEPI) is planned in 2008.

This paper details the main objectives of PERSEE, describes the definition of the bench, presents the current status and reports results obtained with the first sub-systems.

Nulling interferometry is one of identified methods to study habitable extrasolar systems. In this context, several space-based projects have been proposed such as Darwin or its demonstrator Pegase. During the Pegase phase 0 study in 2005, CNES oriented its work towards a reduction of cost and complexity which are major issues in this kind of systems as shown by the recent results of the Cosmic Vision selection. A good understanding of the free flying requirements and their correct mitigation between the payload and the spacecrafts is a key point to achieve successfully such missions. The goal is to reduce as much as possible the constraints applying on the spacecrafts and rely on a very efficient active payload. We decided to study this question from an experimental point of view, coupling a nulling interferometer derived from the state of the art of nulling interferometry breadboards (MAII, Synapse) with a GNC simulator able to introduce realistic perturbations in the set-up. A laboratory breadboard, named PERSEE (Pegase Experiment for Research and Stabilization of Extreme Extinction), was decided in 2006 and funded by CNES R and D. It will be built in Paris at LESIA by a consortium including CNES, IAS, LESIA, OCA, ONERA and TAS. After a definition phase in 2006, the

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E-mail: Ferderic.Cassaing@onera.fr

implementation of the sub-systems now begins and the integration is planned in 2008. The main goal is the demonstration of a stable (10 h) polychromatic null in the 1.65-3.3µm band with a 10-4 mean rejection rate and a 10-5 stability despite the introduction of realistic perturbations.

Keywords: Interferometry, fringe tracking...

1. CONTEXT

The spectral characterization of exoplanets in the infrared requires very challenging instruments based on dark fringe interferometry (or nulling) and accurate free flying. The recent outcome of the ESA Cosmic Vision selection for the 2015-2025 period ruled out the Darwin mission.[?] One of the main reasons is a too low global technology readiness level. Hence a hard work has still to be done in R& D to demonstrate the feasibility of such a mission. Of course, this will probably lead to a full demonstration of a deep and stable null (10^{-5} stable at the 10^{-9} level) on ground in the required spectral band (6-20 µm). Another axis is trying to reduce as much as possible the complexity of the spacecrafts to reduce the so far huge cost of such a mission. A better understanding of the free flying constraints imposed by the nulling requirements and their good balancing between the active payload and the spacecrafts is a key issue to successfully achieve such ambitious missions.

Starting from the Pegase context - which was studied in 2005 at phase 0 level[1] and recently proposed to ESA[2] - CNES and French laboratories initiated a breadboard called Persee to study this question from an experimental point of view. The idea is to couple a nulling interferometer, derived from the Synapse **ref Th Brachet?**and MAII **ref Weber spie 04**state of the art, a GNC simulator able to introduce realistic perturbations in the breadboard, and a real-time cophasing system. Persee is not intended to explore very deep nulling in the 6-20µm band, as this will probably be the objective of other breadboards, but focuses on the maximum level of perturbation that can be accepted by the interferometer, and more precisely the active internal loops controlling the optical path difference (opd) and the pointing. This paper presents the detailed goals, the status of the definition and the first results obtained on the fine pointing control loop.

2. GENERAL DESCRIPTION OF PERSEE

Persee is developed by a consortium composed of CNES, ONERA, LESIA, IAS, OCA and TAS. It will be implemented at LESIA in Paris. In 2006 a definition phase was completed and submitted to a review in April 2007. The implementation of the sub-system is now started. The final integration will start by end 2008 and should last about one year. In 2009, the breadboard will be open to european participation.

Persee is made of XX subsystems, detailed in the next section. We emphasize here on the global specifications.

2.1 Overall specifications

The detailed goals of Persee are the following:

1. Reach an average null of 10^{-4} with a 10^{-5} stability over a few hours in 5 spectral bands in [1.65 - 3.3] µm,
2. Validate fringe acquisition with a drift speed up to 150 µm/s,
3. Characterize the external noise allowed for the two active loops (opd and tip/tilt),
4. Investigate the interaction between the opd/tip-tilt/flux loops,
5. Demonstrate the differential stability between the nulling and cophasing sensors,
6. Investigate the calibration procedures, taking into account measurements from the cophasing loops,
7. Validate the full operation with realistic external disturbances (star/fringe acquisition, tracking, unloading of small-stroke fine correctors),
8. Study the effects of polarization.

2.2 Spectral bands

In order to be as representative as possible of the Pegase mission, and taking all the constraints into account, the spectral band of Persee was set to 0.6 - 3.3 µm. The 0.6 µm lower limit is imposed by the gold coating of the mirrors. The upper limit is a direct consequence of cost consideration. Going beyond 3.3 µm would mean a very effective detector (of the HAWAI type), too expensive.

This large band is divided in many subbands, named following the astronomical convention (table 1). The nuller IR bands (H+K+L) cover an octave, with 5 channels (spectral resolution R=10). Even if most Pegase target stars are brighter in the visible, NIR bands are better for fringe tracking as the central star is less resolved and the optical transmission is higher. Two channels (I&J) allow central fringe identification. The FP band was originaly R (best use of silicon camera), but as explained later, the I band is now prefered.

Table 1. Spectral allocation for Persee.

Wavelength (µm)	Name	Usage
[0.6-0.8]	R	alignment + provision for FP
[0.8-1.0]	I	FS channel 1 + FP
[1.0-1.5]	J	FS channel 2
[1.65-2.5]	H+K	nulling measurements (channels 1..4)
[2.5-3.0]	-	unused (water absorption)
[3.0-3.3]	L	nulling measurement (channel 5)

2.3 Operating modes

Persee will support several operating modes, summarised in table 2:

- fringe acquisition: the opd can be much larger than the coherence length of the FS. It is thus necessary to perform a fringe search, by moving the ODL or waiting for the fringes to pass while the spacecrafts drift. Because of the size of the baseline in the Pegase context, the speed of the fringes can reach several tens of µm/s.
- fringe tracking: the goal is to stabilize the fringes at the 2.0 nm rms level. The stability can be split in two main terms: a noise (typical time scale is 100 s) and a long term drift (typical time scale of 10 hours).

Table 2. Operating modes of Persee.

Mode	Input condition	Output performance
Detection	$v_{ODL} = 0$, $dOPD/dt$ <150 µm/s	$v_{ODL} = 0, RSB_{V^2} > 5$
Acquisition	$v_{ODL} = 0$, known drift	max($\|OPD\|$) <5 µm, max($\|dOPD/dt\|$) <X µm/s
Tracking	$OPD <$ X µm, $dOPD/dt <$	σ_θ <30 mas, σ_{OPD} <1 nm

The fringe sensor is the key equipment of Persee. The measurement noise is the major contributor to the opd budget and is then a critical parameter. Furthermore the capacity of fringes acquisition with a high initial drift is also a major issue that simplifies the free flying control architecture at satellite level. Last, the long term stability between the opd measured by the FS and the IR opd is a third major topic, as illustrated by the recent results of nulling breadboards (see **ref Th Brachet?**, **ref Weber spie 04**). Recent work at ONERA and IAS has been carried on these subjects under CNES R and D contracts ($^?$).

3. DETAILED DESCRIPTION OF PERSEE

The global setup is illustrated in Figure 1, and main characteristics of the sub-systems are listed in tabler̃eftab-caract.

Figure 1. Overview of the Persee bench (as designed by TAS in June 2008).

Table 3. Main characteristics of the Persee sub-systems. Status: D=under end of Definition ; I= under integration,

Subsystem	Responsible	Spectral band	WFE	Transmission	Status
Source	OCA	I+J, H+K+L			D
Optical train	OCA+TAS	R,I+J, H+K+L			
FRAS	ONERA	R or I			
Combination	CNES+IAS+ONERA	I+J+K+L			D
FS	ONERA	I+J			I
IR camera	LESIA	H+K			I
IR monopixel	IAS ?	L			D
Perturbation	TAS+LESIA+ONERA	-			
Bench operation	LESIA				

3.1 Source and separation modules

To guarantee a good spatial coherence and a high wavefront quality, the star simulator is made of a f=0.75 m parabola illuminated at its focus with single-mode fibers (SMF) carrying the light from a dedicated injection bench. Because it is not possible to transmit in a single SMF the whole spectral band of Persee, several fibers closely linked by a dedicated connector are used. The separation along a vertical axis makes the source unresolved by the horizontal interferometer baseline. At the output of the parabola, a mask delimits the two Persee beams.

For the H, K and L bands, a Xenon lamp is selected, injected into a fluorid glass SMF from Le Verre Fluoré, with a cutting wavelength of 1.65 µm. The source for the cophasing system is a combination of ASE, SLED, laser diodes or the Xenon lamp if the SNR is sufficient, injected through silica SMFs.

3.2 Optical train

The M1 flat mirrors at 45 deg incidence represent the side spacecrafts of a Bracewell type space interferometer.[3] They transform the collimated beams from the separation module into two parallel counter-propagating beams.

M2 and M3 simulate the beam-compression function, common to most of the proposed interferometry missions. They form symmetric decentered afocal systems. Of course the real magnification (by instance 20 for Pegase) cannot be represented and scale factor will have to be applied to extrapolate results to real systems. The performed trade-off leads to M=3, mainly because of the limited allowable inertia of M1 (used for perturbation injection) and of the coupling of introduced tip/tilt perturbations at this level with the flux imbalance (gaussian output of the collimator). The diameter of the beams is 40 mm near M1 and 13 mm after M3.

M4 and M5 are reflective flat mirrors, converting the two counter-propagating beams to parallel horizontal beams with the same direction. In addition, a special feature is that M4 combined with M1 form a geometrical achromatic phase shifter (APS) of π. As a π-APS is required for the null to be achromatic, and since this function is naturally present in the periscopic design of Pegase, Persee will first test this simplest possibility to implement the π-APS. In addition, a more classical system based on dispersive prisms (like in Synapse or MAII, see **ref Th Brachet?**, **ref Weber spie 04**) is included in the design to correct for any source of differential chromatism (mainly introduced by the combining plates). In case of unexpected problems with the geometric APS (alignment difficulty, polarisation issues), the geometric APS can be removed and the dispersion corrector can easily be converted to a π-APS.

M6 is a flat mirror used for piston/tip/tilt correction. A 30 deg incidence angle has been selected to minimize differential polarization effects coming from the different position of M6a and M6b. M7 and M8 form a cat-eye optical delay-line (ODL) used for opd perturbation/correction and for pupil conjugation. XXdétailler ?

D1 is used to extract the FP beam, originally in the R band, from the main beam just before the beam combiner. It was first intended to be a dichroic plate. The optical coating analysis showed that the best design is to reflect the R band and transmit all the IR channels. But the complexity of the coating and the induced chromatism lead us to implement an alternative solution with annular mirrors: the outer ring (10 mm$\leq D \leq$13 mm) is reflected toward the FP sensor while the main beam (0 mm$\leq D \leq$8 mm) goes through the inner hole towards the combination stage. This design allows the FP to use any spectral band: to minimize the number of sources, the current choice is to use the same I source than the FS.

D2 is another dichroic plate used to separate the nuller and the FS bands. As it is located after the beam combiner, it only influence the nulled output at SMF injection through the total WFE budget. The nulled and the constructive beams are coupled by parabolic mirrors M11 in two SMFs from Le Verre Fluoré and sent to the detection system.

3.3 Fine-pointing sensor

To minimize differential paths, the FP sensor is common to both beams, and most folding mirrors share the same mounts. Beams reflected by D2 are reflected by M13 towards a common lens of 50 mm diameter and 275-XX mm focal length with a camera at its focus. The relative arrangement of the D2-M13 mirrors allows to reduce the baseline and introduce the differential angle required to separate the two star images on the camera. The main part of the FP is a focal-plane camera, from Imperx XXref. A XX YYYxYYY Region Of Interest, including both fields, is read at 300 Hz.

3.4 Combining module

In order to maximize symmetry between the two beams, the combination is based on a kind of Modified Mach Zehnder (MMZ) set-up.[4] With a symmetric layout of the beam splitter parts, it can provide two nulled achromatic outputs. An adequate and very precise positioning of one of the beamsplitters enables to generate the four ABCD outputs spatially in the FS spectral range. The induced phase don't affect the IR nulled outputs and is chromatic in the FS band, but without hampering the detection performance.

To minimize differential paths, the combining stage is common to the nuller and the FS. The tight integration of these two functions is the heart of Persee as it reduces the differential stability requirements between the cophasing metrology and the nulling interferometer. The difficulty translates to the optical coatings of the beam-splitting plates, that have to cover the 0.8-3.3 μm range with stringent phase dispersion properties. Recent work carried at the Fresnel Institute oriented us toward a three-layer silicium/YF3 based coating with a few 0.1 nm rms uniformity of the layers thickness.

The 30 deg angle is required to obtain a good balance between *s* and *p* polarization transmission and reflection factors in the MMZ. The beamsplitters are made of CaF2 with an appropriate geometrical design to avoid straylight. It is a proposed improvement of the system which was validated on the Synapse breadboard with a 10^{-4} nulling in the K band.

The combining module is described in more details in a companion paper.[5]

3.5 Fringe sensor

A spatial modulation has

In order to reach a high sampling rate with a minimum number of pixels, a coaxial beam combiner is the most relevant to combine the two beams. To cope with the stability requirements and the fast fringe drift, a spatial modulation is used without any moving part. Such a FS has already been investigated in our team for stellar interferometry on ground.[6]

The light from each of the four $\pi/2$ phase-shifted output is dispersed and focused on 4 monopixel In-As-Ga detectors per spectral channel.

The four outputs of the MMZ are sent pairwise (after reflexion on D2) to two spectrometers, where dichroic plates divide them in two spectral channels I and J. Light is then routed through small lenses and multimode fibers to analog single-pixel PIN detectors, made of silicon (I band) or InGaAs (J band).

The FS module is described in more details in a companion paper.[7]

3.6 Nulling detection

Detection in the H and K bands is based on a camera using a Picnic 256x256 focal plane. The IR fringes of the nulled output (D) are dispersed using a direct-vision prism providing a simultaneous access to 4 IR channels. The very low noise of this camera allows excellent signal to noise (SNR) ratio with a high frequency bandpass in the nulling mode (SNR >20 at 100 Hz) which will improve the results as compared to previous systems based on monopixel detectors (Synapse, MAII). It also allows a somewhat lower transmission of the interferometer (about 1% from M1 to detection, including the quantum efficiency of the detector, 0.05 % from source to detection).

In addition, to cover the L band (5th spectral channel), a monopixel InSb detector from Judson (XX?) will be used with reduced performances ($SNR \simeq$10 at 0.5 Hz).

3.7 Perturbation injection and correction module

The M6 mirrors are the main correctors for the FS and FP sensor. They are mounted on a very precise piezo-system, a PI S316-10 system with opd and tip/tilt capability (table 4). In a first step, only the M6 mirrors will be used, for the correction of static errors (alignment) and laboratory disturbances. Then, the M6 mirrors will be used to introduce and correct small perturbations.

In a second step, the M6 mirrors will be used to compensate for the dynamic perturbations injected on M1. On one arm, M1a will introduce small-range opd while on the other arm, M1b will introduce tip/tilt (table 4). Last, in a third step, long stroke opd perturbations will be introduced using a high resolution (1 nm) / long stroke (1 cm) optical delay line (ODL). Another identical ODL is then required on the other arm for correction, driven by the FS from the desaturation of the M6 mirrors. This ODL will first be implemented by mounting the M7-M8 cat's eye on a commercial translation stage and could be replaced later by a more representative ODL, such as the ODL developed by TPD-TNO under an ESA R & D contract.[8]

Perturbation mirrors M1a, M1b and M7-M8a will be driven by a calculator simulating the GNC residues. The perturbation will be the superposition of parabolic or linear drifts (coming from the differential movements of the spacecrafts under the differential solar pressure effects) and higher frequency effects (due to by instance reaction wheels on board the spacecrafts). Typical perturbation profiles will be derived from a study of the Pegase GNC performed by EADS-ASTRIUM under a CNES R & D contract.[9]

Table 4. Characteristics of the active mirror mounts (type: P=Perturbation, C=Correction).

Mirror	Type	Mode	Actuator	Mount	Stroke	Resolution
M1a	P	opd	piezo	Newport P752	10 µm	0.5 nm
M1b	P	tip/tilt	piezo	PI S330	100 arcsec	10 mas
M6a-b	C (P)	opd/tip/tilt	piezo	PI S316	XX??	XX??
M7-M8a	P	opd	XXstep/voice coil?	Newport XMS 50	XX?	XX?
M7-M8b	C	opd	XXstep/voice coil?	Newport XMS 50	XX?	XX?

XX Compléter avec fréquence ou autre info ? Béa/Philippe?

XX M6 total required stroke is ±100 arcsec assuming a ±10 arcsec alignment precision.

3.8 Electronics and computer system

To minimize external disturbances, all the sources and electronic units (except for the FP camera) are deported outside the main optical bench through optical fibers.

The heart of the computer system is a PXI rack from National Instrument which hosts the real-time Labview software for the FS and the FP and interface cards (Digital AcQuisition for the FS analog detectors, Camera link for the FP camera, and Digital to Analog Conversion for the command of the two M6 piston-tip-tilt mirrors). It is linked to a standard PC under Labview which hosts the Graphic User Interface and provide flexible communication with other subsystems, such as the IR Camera or the GNC simulator. In a first step, datafiles of preliminary computed disturbances will be used.

4. STATUS OF PERSEE

4.1 Integration of the cophasing system

In order to setup the cophasing system before the integration on the Persee bench, a preliminary integration is currently ongoing at Onera. A preliminary MMZ (MMZ1, detailled in[7]) will be used to replace the final MMZ (MMZ2, detailled in[5]). One channel of one spectrometer will be used backwards, to inject a source from a SMF. The MMZ1 is then used backwards and acts a star simulator, generating two beams collimated beams. These beams are then sent to the M6 mirrors in autocollimation, which reflect them back to MMZ1, whose three outputs can be analysed by the spectrometers (the fourth output being sacrified for the backwards beam injection). A beam splitter between MMZ1 and M6 mirrors is used to feed the FP after reflexion on M6.

First tests of the fine pointing loop were performed in 2007. The specification of this control loop is to reach a 600 mas performance (optical, at MMZ input level, which means an equivalent of 30 mas on the sky in the case of Pegase by instance) with a 100 Hz frequency bandpass.

The rms level of the tip/tilt residuals as a function of the total number of photons is illustrated by fig. 6. They are equivalent to a about 100 mas rms level for N=105 photons/s (worst case of Pegase by instance). The bandpass is currently limited to about 5 Hz due to a limitation of the reading frequency at 33 Hz in this first step. This will be easily improved to about 1 KHz in the next steps. The conclusion is that this sub-system can reach the required performance quite easily and it will be implemented in Persee with up-dated control laws and reading frequency.

XXXXXXXXXXXXXXX BEA, tu as une image ?

Figure 2. Preliminary integration of the Persee cophasing system at Onera.

5. OTHER SUBSYSTEMS

XXX retours bienvenus... source ? MMZ2 commandé ?

6. CONCLUSION

The Persee breadboard detailed definition is now nearly completed. First subsystems are already under integration. In particular, the fringe sensor sub-system is currently integrated at Onera on a dedicated breadboard with a preliminary MMZ.[7] The next months will be dedicated to sub-system integration and validation.

Integration of the whole bench will start in fall 2008 at LESIA in Paris. Persee should begin in late 2009 to test various control laws and perturbations models. Then, it should be open to proposal.

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REFERENCES

[1] Le Duigou, J. M., Ollivier, M., Cassaing, F., Sorrente, B., Fleury, B., Absil, O., Mourard, D., Rabbia, Y., Escarrat, L., Malbet, F., Rouan, D., Léger, A., Cledassou, R., Delpech, M., Duchon, P., Meyssignac, B., Guidotti, P.-Y., and Gorius, N., "Pegase : a TPF-I/Darwin pathfinder ?," in [*Space Telescopes and Instrumentation I: Optical, Infrared, and Millimeter*], Mather, J. C., MacEwen, H. A., and de Graauw, M. W., eds., **6265**, Proc. Soc. Photo-Opt. Instrum. Eng. (2006). Date conférence : June 2006, Orlando, USA.

[2] Ollivier, M. et al., "Pegase: an infrared interferometer to study stellar environments and low-mass companions around nearby stars," in Danchi et al..[10] Date conférence : June2008, Marseille.

[3] Bracewell, R. N., "Detecting non solar planets by spinning infrared interferometer," *Nature* **274**, 780 (1978).

[4] Serabyn, E. and Colavita, M. M., "Fully symmetric nulling beam combiners," *Appl. Opt.* **40**, 1668–1671 (Apr. 2001).

[5] Jacquinod, S., Cassaing, F., Duigou, J.-M. L., Barillot, M., Ollivier, M., Houairi, K., and Amans, J.-P., "PERSEE: description of a new concept for nulling interferometry recombination and opd measurement," in Danchi et al..[10] Date conférence : June2008, Marseille.

[6] Cassaing, F., Fleury, B., Coudrain, C., Madec, P.-Y., Di Folco, E., Glindemann, A., and Lévêque, S., "An optimized fringe tracker for the VLTI/PRIMA instrument," in [*Interferometry in optical astronomy*], Léna, P. J. and Quirrenbach, A., eds., **4006**, 152–163, Proc. Soc. Photo-Opt. Instrum. Eng., SPIE, Bellingham, Washington (2000).

[7] Houairi, K., Cassaing, F., Le Duigou, J.-M., Sorrente, B., Jacquinod, S., and Amans, J.-P., "Persee, the dynamic nulling demonstrator: recent progress on the cophasing system," in Danchi et al..[10] Date conférence : June2008, Marseille.

[8] van den Dool, T. et al., "The darwin breadboard cryogenic optical delay line darwin," in [*International Conference on Space Optics*], (June 2006).

[9] Villien, A. et al., "Gnc for the pegase mission," in [*17th IFAC Symposium on Automatic Control in Aerospace*], (June 2007). Toulouse.

[10] Danchi, W. C., Delplancke, F., and Schöller, M., eds., [*Optical and Infrared Interferometry*], **7013**, SPIE (2008). Date conférence : June2008, Marseille.

[3] Serabyn E. et al., Applied Optics, Vol. 38, No 34, pp 7128-7132, 1999 [4] Brachet F., " Etude et développement d'un déphaseur achromatique pour l'interférométrie en frange noire " PhD report, university of Paris-Sud (XI), 2005 [5] Weber V., Barillot M. et al. "Nulling interferometer based on an integrated optics combiner ", SPIE Conference Astronomical Telescopes and Instrumentation, Glasgow, 2004 [6] Sorrente B., Cassaing F. " Performance study of the fine control loops of Pegase ", ONERA technical report RT 2/11647 DOTA