BRISE: a multipurpose bench for cophasing sensors

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ABSTRACT

The Cophasing Sensor (CS), which measures the disturbances between the sub-apertures, is a key component of multiple-aperture telescopes. As multiple-aperture telescopes become more ambitious, requirements for the CS become more demanding: low flux (for stellar interferometers), sub-nanometric accuracy (for interferometric nullers), image with very small contrast (for wide-field telescopes such as spaceborne Earth imagers), larger number of beams (for all applications).

Focal-plane sensing is a solution to cope with all these requirements, with a very simple opto-mechanical setup. Two implementations have been investigated at ONERA: *phase retrieval*, using the sole focal-plane image, and *phase diversity*, based on the joint analysis of a focal and an extra-focal images. Phase diversity can measure any mode on any source, while phase retrieval is more suited to real-time piston/tip/tilt measurements on an unresolved (or partially resolved) source.

To evaluate accurately the performance of CS or other high-resolution devices, ONERA has built a multipurpose bench called BRISE (Banc Reconfigurable d'Interférométrie sur Sources Etendues). BRISE mainly includes an extended scene and a reference point source, a deformable mirror, a focal-plane CS, afocal input/output ports to interface with other instruments, and a general purpose code MASTIC (Multiple-Aperture Software for Telescope Imaging and Cophasing).

BRISE has already been (or will be) used for several applications, such as the validation of CSs for Earth imaging or nulling interferometry, or the exploration of advanced nulling techniques. This paper describes the bench and the investigated CSs, the experiments performed on BRISE, and reports main results such as nanometric accuracy or three-beam nulling.

1. CONTEXT

Multiple Aperture Optical Telescopes (MAOT) are considered for high-resolution spaceborne missions such as Earth imaging[1] or astronomy.[2,3] MAOTs are most often deployed after launch or based on free-flying spacecrafts. To perform real-time correction of mechanical disturbances in these MAOTs, a critical component is the Cophasing Sensor, whose goal is to measure the MAOT aberrations.

Aberrations of a MAOT can be divided in two classes. The first class is the shape error of each sub-aperture (all Zernike modes starting from defocus), which can be measured by a wavefront sensor such as the ones used in adaptive optics.[4] The second class is the positioning error of each sub-aperture (differential piston and and absolute tip/tilt), which can be measured by a fringe sensor such as the ones used in stellar interferometry and a combination of tip/tilt sensors.

When designing a MAOT, putting all these sensors together quickly leads to an unreasonable complexity. Moreover, these "classical" sensors are most often based on pupil-plane measurements, and thus are operated on an unresolved or slightly resolved source, and in a pair-wise mode for interferometry. They most often introduce differential paths. An alternative solution is to use a single cophasing sensor that can measure accurately, for any kind of objects, all the modes of interest over all the sub-apertures simultaneously. This is possible with a focal-plane sensor, which intrinsicly provides an interferometric combination of all the sub-apertures.

To test performance of CSs, ONERA has built the BRISE bench (Banc Reconfigurable d'Interférométrie sur Sources Etendues). It includes a beam-generator, a generic focal-plane CS and an easy interface to visitor instruments. Its main feature is the accurate generation of phase perturbations, in the multiple-aperture case (now) or single-aperture case (soon).

BRISE has been designed in 2002 in the framework of a study for Earth imaging,[1] using experience from a previous bench[5] and stellar interferometry from the ground.[6] It was built in 2003 and is operated since 2004.[7]

Section 2 describes focal-plane cophasing sensors. The section 3 describes in details the BRISE bench. Results obtained on BRISE are reported in section 4.

2. PRINCIPLE OF THE FOCAL-PLANE COPHASING SENSORS

Two main kinds of focal-plane CS can be distinguished, as described here-below.

2.1. Phase Retrieval

Phase estimation from focal-plane data (or *phase retrieval*) suffers in the general case from phase ambiguity. However, in some cases, some modes can be estimated. For example, in the Young holes experiment, it is well known that the differential piston between two apertures can be derived from the fringe position. This can be generalized to a larger number of sub-apertures. An example showing how the PSF is affected by aberrations will be illustrated in section 4.1 with three sub-apertures. In good conditions, an estimator of piston/tip/tilt on each aperture can be derived from the analysis of the sole focal-plane data.[8–11]

2.2. Phase Diversity

In a more general case, when observing an unknown object o or estimating Zernike modes of index $i \geq 4$, phase retrieval is not possible from the sole focal-plane data. Unless one has strong structural information about the phase and/or about the object, the lack of information considerably limits the performance of phase-retrieval methods. Phase diversity is a technique that was proposed to add information about the unknown phase.[12,13] The idea is to collect at least one additional image, which differs from the focused image by a known phase variation (cf Fig. 1). A simple way to introduce the known aberration is to use a beam splitter and two detectors, one of which being defocused.

This technique has been successfully used by many authors for wavefront sensing[14–19] or for object restoration, as in solar imaging through turbulence.[20,21] It uses a simple optical setup, an imaging camera which records (simultaneously if possible) the focal-plane and extra-focal-plane images. The complexity is reported on the data processing, which is not a major problem now thanks to the advances in computers. The inverse problem (phase estimation from the data) can be solved via a numerical iterative processing. The main issue is the availability of real-time algorithms, under investigation at ONERA.

A recent PDS improvement is the *marginal* estimator developed at ONERA.[17,19] The marginal approach, consisting in integrating the object out of the problem to perform only an aberration estimation, gives better results on monolithic telescopes at low SNR than the most widespread *joint* restoration of the object and the aberrations from focal-plane data. This result has also been verified for MAOTs.[22]

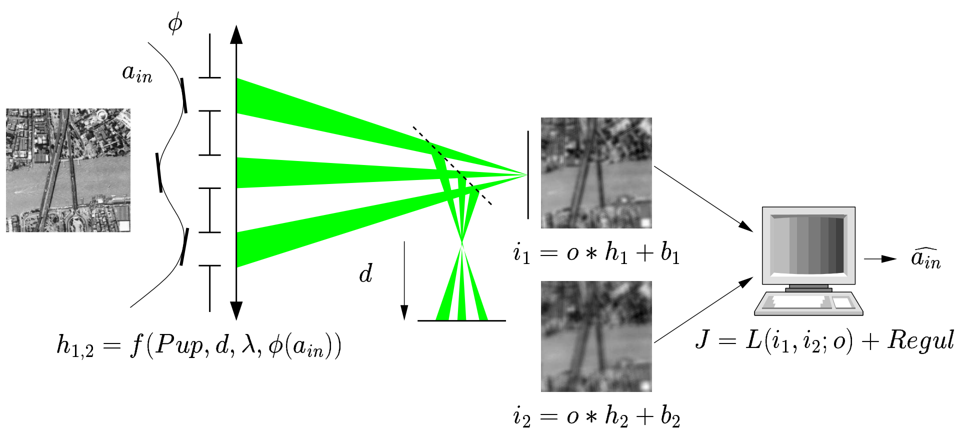

Figure 1. Principle of a Phase Diversity Sensor (PDS) implemented near a MAOT focal-plane.

3. THE BRISE BENCH

A schematic view of BRISE is shown in Fig. 2. BRISE is mainly composed of five sub-systems, detailed here-below. The spectral band is currently set by the refractive components in the detection module optimised in the [0.55 ; 0.83] μm range, but the all-reflective bench can be operated in a much larger domain.

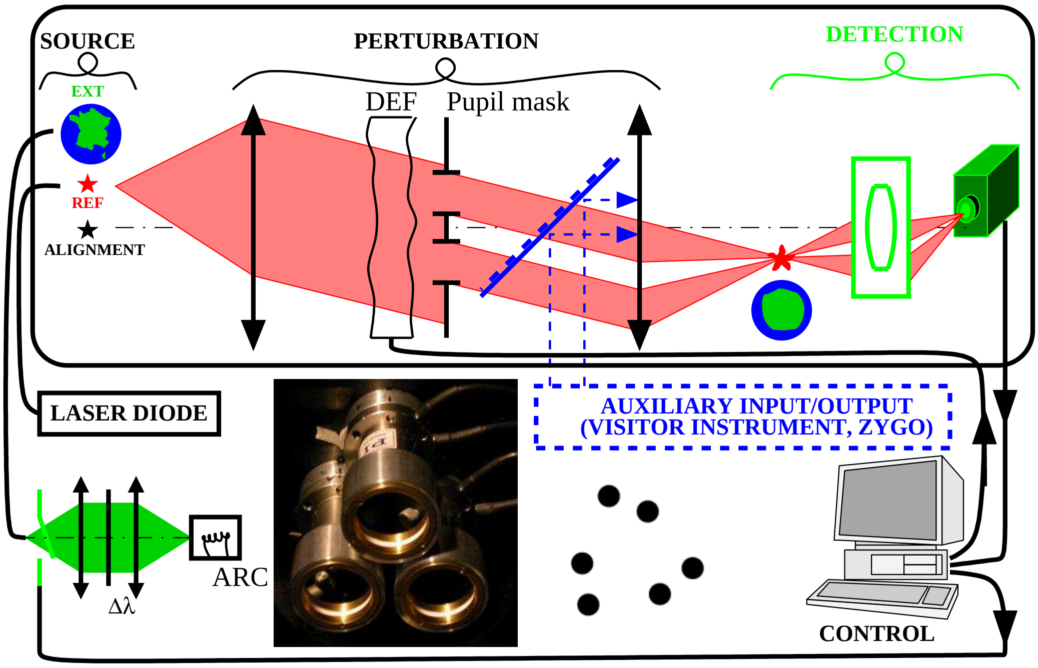

Figure 2. Schematic view of BRISE and photograph of the deformable mirror (DEF).

Special care has been given to the control of errors that could limit CS performance or their estimation. The two objects EXT and REF are observed simultaneously in a small field through very close paths, to minimise the effect of field aberrations, vibrations or air turbulence. A very accurate Optical Path Difference (OPD) calibration can thus be achieved on extended sources thanks to the high SNR of the REF measurement. To reduce air turbulence or temperature-induced drifts, BRISE is enclosed inside a wooden hut located in a temperature-controlled room. All the electronics and sources are located outside the hut. An additional metallic baffling on the bench minimises volume and temperature gradients around the beams. Active pneumatic supports isolate BRISE from vibrations.

3.1. The source module

Two kinds of objects can be used on BRISE:

- The extended object is an holographic plate mounted in a removable support and enlighted by the output of a multi-mode fibre fed by an arc lamp. A set of various Earth scene (Fig. 3 left) or astronomical objects is available.
- The reference object is the direct output of a monomode fibre, fed by a He-Ne laser operating at 633 nm or the arc lamp.

These two objects are put side by side in the focal-plane of the perturbation module by a roof-top mirror. Small optical benches outside the hut are used to couple the sources in the optical fibres, and to simply control the spectral band and the intensity by filters inserted by the operator.

3.2. The perturbation module

The goal of the perturbation module is to collimate the source, uniquely defines the aperture configuration (position and diameter D of the sub-apertures), reflects the beam on a deformable mirror DEF used to introduce phase perturbations, and focuses the beam towards the CS in a focal-plane. The DEF is in autocollimation to ensure circular (sub-)apertures. The autocollimation also creates a focal-plane image near the source with magnification -1, which is routed to the detection module by a folding mirror. The focal length of the collimating and focusing optics (1225 mm) is set by the wavelength and the diameter (B=60 mm) of the DEF. A planar mirror is also available for full-aperture measurements without perturbation. The collimated beam can also be sent to (or input from) an external device, such as another CS or a reference interferometer such as our Zygo interferometer.

The aperture configuration is defined by a pupil mask. Fig. 3 right shows the most used mask, with three D=20 mm sub-apertures, and the 12 sub-aperture mask from the Earth imaging study.[1]

The deformable mirror (DM) is the main component of this module. For multiple-aperture CS considered here, the DM must include a calibrated piston/tip/tilt generator with a stroke of several wavelengths. Usual DMs with a continuous surface deformed by PZT actuators can not introduce a pure piston on a sub-aperture without changing the high order modes. Moreover, they are affected by PZT drift. We have thus manufactured a specific segmented DM (DEF hereafter) with three planar mirrors of diameter 21 mm (Fig. 2). Two mirrors are mounted on Physik Instrument piston/tip/tilt S-316.10 platforms, the third on a dummy support in the same material. Each platform has three 120° PZT motors with nanometric closed-loop control on an internal strain gauge. The most critical issue during BRISE manufacturing was the cophasing of DEF. The PZT stroke, about 12 μm, being much smaller than the mechanical dispersion on the height of the platforms, intermediate wedges, manually-polished to better than $\pm$1,5 μm, and tinsels have been inserted between the platforms and their common support to pre-align the three mirrors within the PZT stroke (Fig. 2).

Another DM is currently under integration, in parallel of the DEF mirror. It is a 13-motor bimorph mirror, with a B=30 mm pupil diameter. Its shape is controlled in real-time by an adaptive optics control-loop.

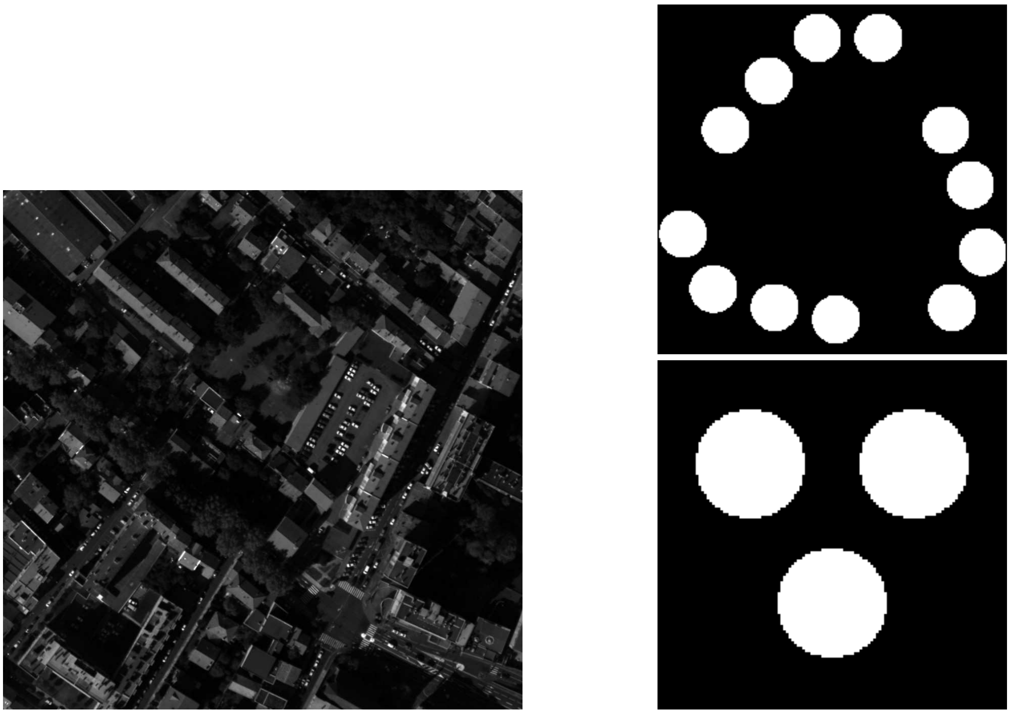

Figure 3. Left: extended scene used for simulations and experiments. Right: masks with 3 and 12 sub-apertures.

3.3. The detection module

The goal of the detection module is to record the focal-plane or pupil-plane image of the object after propagation through the perturbation module. In addition, it includes a cophasing sensor by phase retrieval/diversity.

This module is based on a water-cooled 1317×1035 pixel Roper camera with a 6.8 μm pitch. To correctly sample the focal-plane image, an optical relay re-images the output of the perturbation module on the camera with a small magnification. For very small integration times, to minimize vibrations, the camera shutter can be mounted on the external coupling benches. An additional lens can be inserted to re-image the pupil on the camera for alignment.

The focused and defocused images are simultaneously recorded on the same CCD thanks to a beam-splitter and folding mirrors in the relay optics. The defocus amplitude can be manually tuned by a micrometric translation stage. The camera field is large enough to simultaneously collect the focused and defocused images of the EXT and REF objects, as illustrated on Fig. 4.

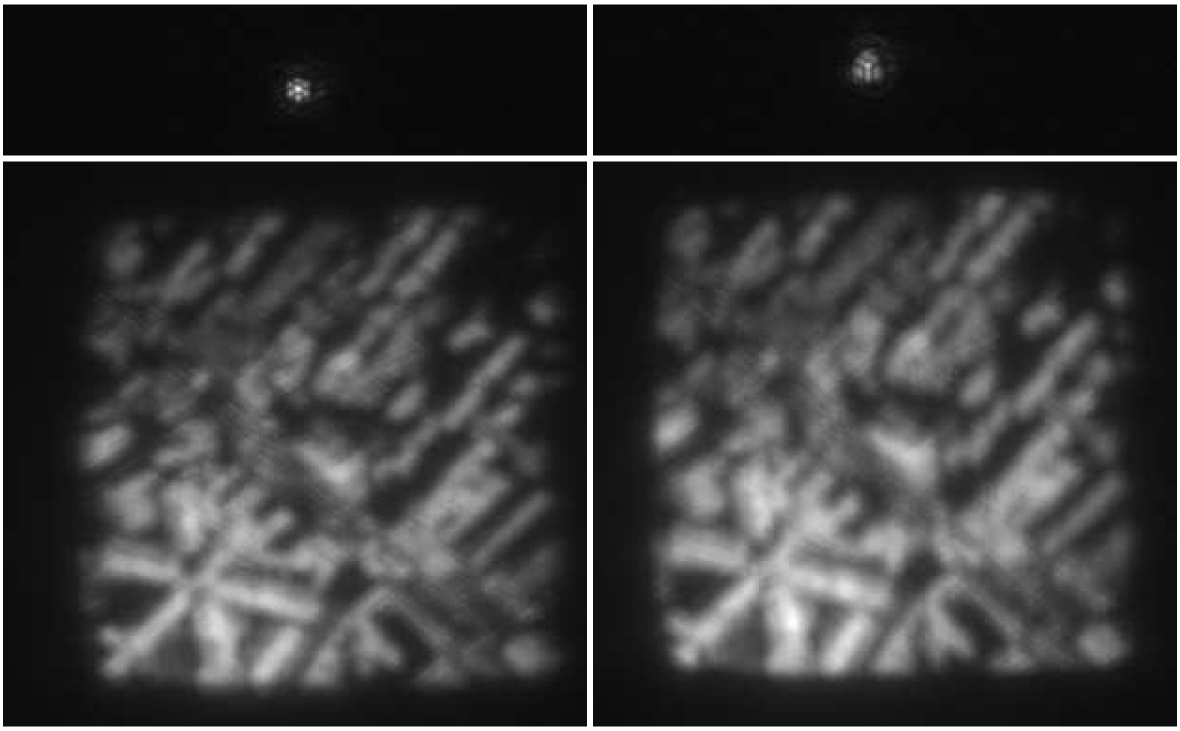

Figure 4. Focused (left) and defocused (right) experimental images of the extended scene (bottom) and reference point source (top).

3.4. The control module

The main goal of the control module is to synchronously drive the DEF and the camera. Three computers on an Ethernet network are used with an hardware trigger. One PC controls the DEF motion via six voltages. The second PC is dedicated to the image acquisition of the detection module. Both PCs implement low-level drivers under C/Windows and a client/server architecture. Data are transfered to the Unix work station and stored on a local disk with external backup through the LAN.

A Tcl/Tk Graphical User Interface is used to set the main experiment parameters (exposure time, windowing, number of images,...) and to prompt the user for additional inputs (object, mask, filter, etc). All the configuration is stored in a log file with each data file for later reference.

Two operating modes are currently supported. In the measurement mode, a file of voltages is read and successively applied on DEF; for each set of voltages, one or more images are taken and data are written on disk for off-line processing. In the command mode, a few pre-defined DEF modulation patterns are applied and IDL is automatically run after image acquisition to derive, from the images, the incremental voltages to apply on the DEF. The few algorithms and modulation patterns available make this one-step closed-loop mode very useful for alignment (identification and superimposion the 3 Airy disks in the focal-plane by tip/tilt correction), coherencing (scan the OPD and identify the central fringe), and cophasing (fine correction of residual piston/tip/tilt). A full closed-loop mode will be available soon.

3.5. The software module MASTIC

All data reduction are performed with the MASTIC (Multiple-Aperture Software for Telescope Imaging and Cophasing) IDL code. MASTIC contains two main parts. The *direct model*, for simulation of the BRISE bench, produces images from known object/aberrations and experimental parameters in a user-defined log-file (pupil configuration, wavelength, etc.). It is mostly based on an inverse Fourier transform.[10] The *inverse problem*, for phase retrieval or phase diversity, estimates the phase (or the object) from the focal-plane image(s) and the known direct model and experimental parameters (log-file). Two classes of algorithms are available to solve the inverse problem: iterative algorithms (based on the numerical minimization of an error criterion computed by the direct model), and single-pass algorithms (for real-time CS) when an analytic solution exist, which can be the case for MAOTs.[11]

A critical issue is the calibration of the direct model, which must be as close as possible to the physical model. The most critical parameter is the numerical pupil *i. e.* the 2D support in pixels over which the Zernike phase screens are applied. This lead to the use of non-integer coordinates for the sub-aperture centers and diameters in MASTIC. Consequently, experimental parameters must be accurately estimated as described in next section (figure 5).

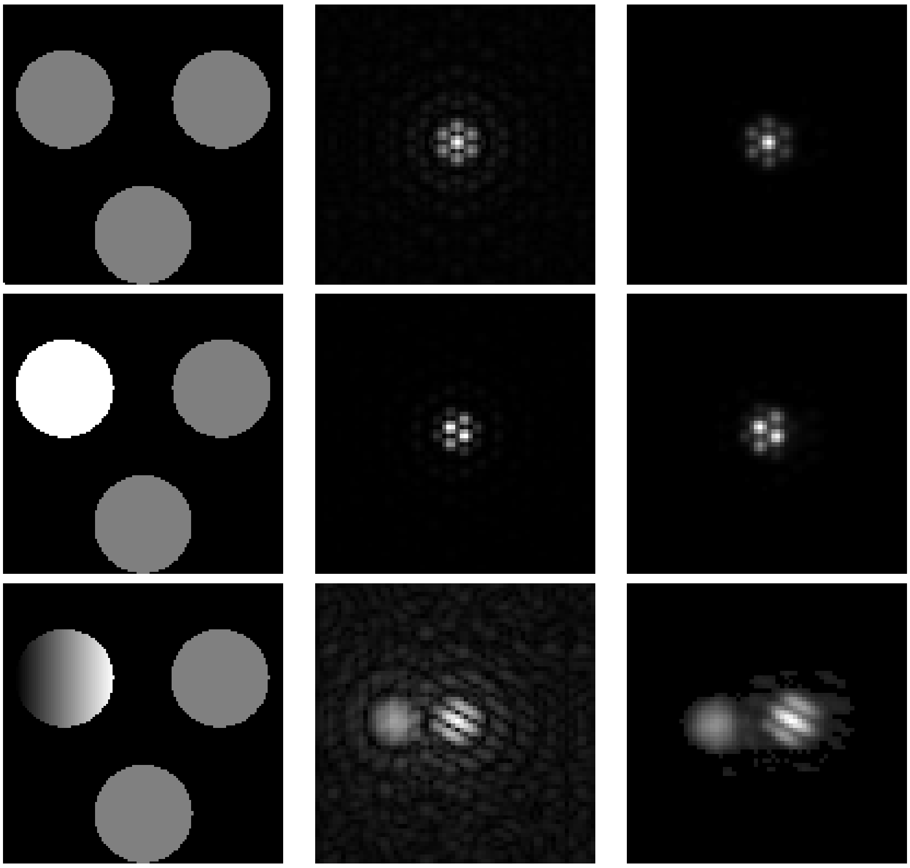

Figure 5. Agreement experimental results with BRISE (right column) and the direct model used for data processing with MASTIC (center column), in response to a given known phase perturbation (left column). *Cf text for details.*

4. EXPERIMENTAL RESULTS ON BRISE

This section describes the first tests we made with BRISE and results obtained with different sensors.

4.1. Characterization of BRISE

The first tests we made were dedicated to the bench calibration, so that the numerical direct model accurately matches experimental results. This is illustrated by Fig. 5, which shows the images obtained with MASTIC and BRISE in response to a phase perturbation. First, images are taken without aberration (line 1). Then, a piston of $\lambda/2$ is introduced on one sub-aperture to shift the fringes (line 2). Last (line 3), a tilt of $2.44\lambda/D$ is introduced, which makes a PSF shift in the focal-plane so that its first dark ring is tangent to the one of the two other superimposed PSFs, in which Young fringes perpendicular to the baseline can be seen.

Another critical issue is the bench stability. Since we are only dealing with differential pistons/tip/tilt between the sub-apertures introduced by DEF, the global shift of the focal-plane image can be removed. This last software step allows to get rid of most of the weak turbulence inside the bench. Fig. 6 plots the temporal evolution (without any voluntary-introduced perturbation) of the differential piston between the sub-apertures. This figure shows that the rms WFE is in the nanometric range when the beam is reflected by the DEF mirror, and in the deci-nanometric range when the beam is reflected by the REF mirror. The difference between the two is the noise introduced by the PI platforms, because of the closed-loop on their internal strain gauge. Repeatability tests for the cophasing sensors were thus performed with the REF mirrors, which corresponds to the operating condition in closed-loop (phase perturbation near 0).

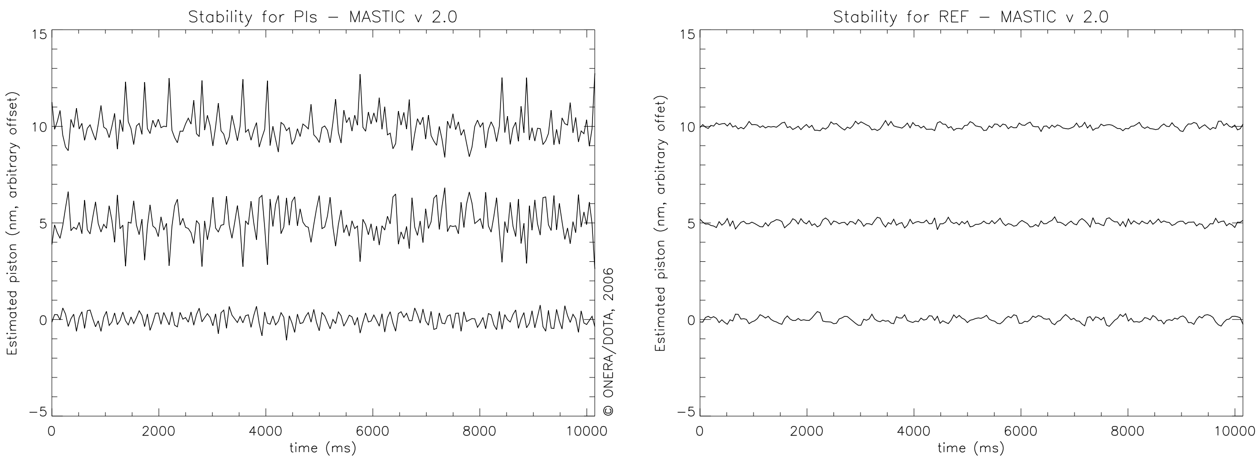

Figure 6. Temporal evolution of the differential piston for DEF mirror (left) and REF mirror (right).

4.2. Cophasing an astronomical interferometer

BRISE has been designed when ONERA was involved in the VLTI.[23] The beam diameter of the sub-apertures (21 mm) is thus compatible with the 20 mm VLTI beams. For second generation VLTI instruments, focal plane CS will become more interesting as more beams will be used, and thus can be tested on BRISE.

The main use of BRISE now is to test CSs dedicated to nulling instruments. The main requirement is the stringent accuracy required. For example, ESA specifications for DWARF (the DarWIn[2] AstRonomical Fringe sensor developed for ESA by Kayser-Threde/ONERA/Alcatel Space) are sub-nanometric real-time measurements for piston/tip/tilt and measurement from defocus to spherical aberration. DWARF has been defined at ONERA,[24, 25] manufactured by Kayser-Threde[26] and tested on BRISE as a visitor instrument. It is based on a commercial telescope and focal-plane camera, with phase retrieval and phase diversity capability. Detailed results can be found in the companion paper.[27]

BRISE will also be used for Pegase, the DARWIN precursor proposed by IAS and supported by CNES.[3] R&T programs are currently ongoing at ONERA to define the fine cophasing loops (OPD and tip/tilt) of the instrument and to manufacture/test some prototypes. The goal is to include them in a future global Pegase breadboard, to demonstrate on-ground stable wideband nulling using only light from the observed source.[28]

4.3. Cophasing a wide-field imager

Phase diversity is one of the very few techniques that can be operated to cophase a MAOT on an extended object.[29] It has thus been selected in the framework of high-resolution Earth observation from Space, for example with a decametric telescope in the GEO orbit.[1,30] Tests have been performed on BRISE with the extended scene to validate the behaviour of this CS. To provide an accurate independent phase reference, the phase retrieval sensor was used, operated from the image of the unresolved source in the nearby field. But of course, the image of this unresolved source was not used for phase diversity processing.

Figure 7 left presents the piston measured at high flux on a given sub-aperture as a function of the piston introduced by the DEF, for the reference point source at $\lambda_r = 633\,\text{nm}$ and for the extended scene illuminated with white light and using a spectral filter of width $40\,\text{nm}$ centered around $\lambda_e = 650\,\text{nm}$. For each introduced piston, three measurements are performed and reported on this figure. The point-source measurements exhibit an excellent linearity between roughly $-\lambda_r/2$ and $+\lambda_r/2$, at which points the expected modulo 2π wrapping occurs. With the extended object, the curve is linear on a slightly smaller piston range. Some features are different on this curve with respect to the one obtained with the reference point: the slope is not exactly unity, although this would not be a major problem in closed loop, and the sort of smooth wraparound that occurs around $+\lambda_e/2$ is somewhat surprising and currently interpreted as a consequence of the spectral bandwidth.

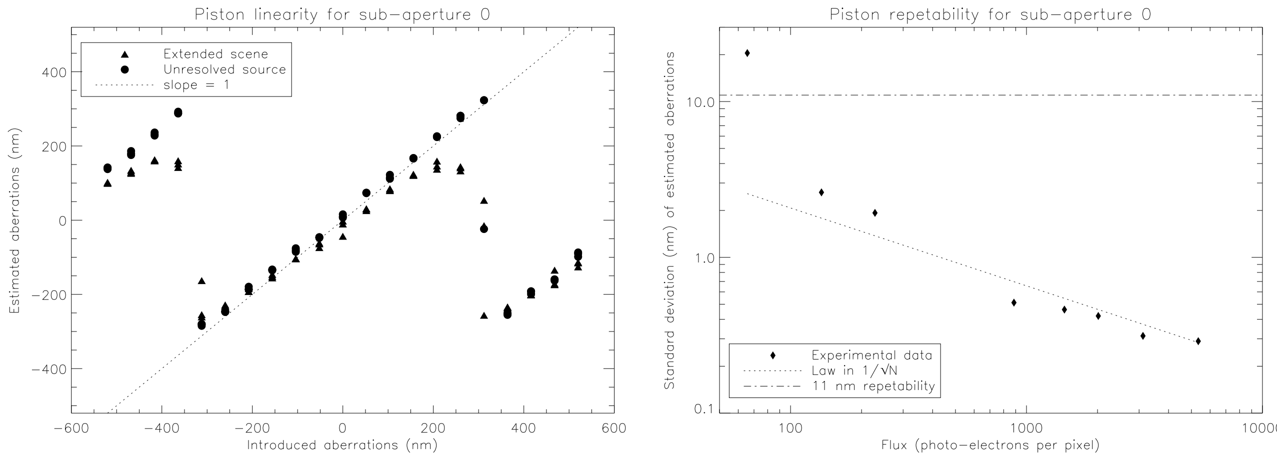

Figure 7. Piston measurements with the extended object. Left: Piston measured on the first sub-aperture, as a function of the piston introduced by the DEF. Right: Repeatability of the piston measured on the first sub-aperture, as a function of the average photon level per pixel.

Figure 7 right shows the repeatability obtained on the piston measurement with the extended object. The standard deviation of the estimated piston is, as expected, dominated by detector noise for low flux and inversely proportional to the square root of the number of photo-electrons per pixel (photon-noise regime). It is for instance below $1\,\text{nm}$ as soon as the average flux is above 1000 photo-electrons per pixel.

4.4. Advanced nulling techniques

Thanks to its very good stability and its deformable mirror, BRISE can also be used for nulling experiments.

A first application is the study of coupling distorted wavefronts in single-mode fibres. In the framework of an ESA contract led by Kongsberg, the amplitude and phase of the coupled beam will be measured experimentally for different amplitudes and natures of aberrations, in order to validate theoretical predictions.[31] These tests will use the bimorph deformable mirror.

A second application is three-beam nulling. Although it has never been designed for nulling, BRISE offers the unique feature of combining three beams with independent piston/tip/tilt control. We took advantage of this to make what we believe to be the first three-beam nulling test. With a very quick setup (multi-axial combination of the three beams in a single-mode fibre) and a single scan, a null of 100 has been reached around λ=635 nm.

5. CONCLUSION

The BRISE bench is now complete, with main characteristics summarised in Table 1. The sub-nanometric accuracy goal is reached, and the bench is now producing interferometric measurements with three piston/tip/tilt controlled sub-apertures.

Table 1. Main characteristics of BRISE.

Parameter	Value	Unit	Comment
Full spectral band	[0.4 ; 1]	μm	In current CS. IR extension underway
Reference source wavelength	0.633	μm	
Field of the extended object	$\simeq$250x250	pixels	
Maximal aperture diameter	B=60	mm	With current deformable mirror
Aperture configuration	$3\times(D$=20)	mm	With current deformable mirror
	any		With REF mirror (no phase perturbation)
	any		With 30 mm full aperture future bimorph mirror
Perturbation amplitude	$\simeq\pm4$	μm	With current deformable mirror
Total camera field	1317$\times$1035	pixels	
Beam height	160	mm	Above the table

BRISE, in conjunction with the MASTIC software, has been used for several applications. The main goal is the validation of cophasing sensors, from real-time phase retrieval with a single focal-plane image of a star to phase diversity with the focused and defocused images of a very extended scene. Preliminary three-beam nulling tests have also been performed (null ratio$\simeq$100).

Measurements confirm the applicability of focal-plane techniques for Earth imaging or nulling interferometry with challenging requirements. At the cost (nowadays negligible) of an increased computing power compared to usual pupil-plane techniques, focal-plane techniques benefit from a simple opto-mechanical setup and the cability to be fed by many beams simultaneously. Work is currently in progress to derive an analytical estimator for real-time phase diversity.

Next tests will analyse the coupling in IR single-mode fibres of calibrated wavefronts with the first ten Zernike modes or the cophasing sensors for the PEGASE mission. BRISE can also be used for other purposes since the number of beams can be tuned from 1 to any value by changing the aperture mask. BRISE is open to any visitor instrument fitting in 100$\times$70 cm^2 (without the Zygo interferometer, Fig. 8).

Figure 8. Photograph of BRISE (right side) with the Zygo interferometer (center) and the Darwin Fringe Sensor DWARF (left side) installed as a visitor instrument.

6. ACKNOWLEDGEMENTS

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