Multiple-beam fringe tracking for the VLTI

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Summary. The performance of interferometric instruments is strongly linked to the quality of piston stabilization. Next generation VLTI instruments plan to use 4 to 8 beams simultaneously. In the current VLTI implementation, the maximum number of beams that can be phased using FINITO and PRIMA/FSU simultaneously is 5. Therefore, a new fringe sensor is required for the VLTI.

When cophasing a large number of beams, other approachs than the classical complex pairwise combination should be considered. Focal-plane wavefront sensing allows the cophasing of a large number of beams with a very simple opto-mechanical device and can also measure high-order modes, such as tip/tilt/defocus/... This solution has been selected in other projects such as DARWIN or Earth observation.

Experimental results, obtained with a laboratory breadboard tested on the BRISE bench at ONERA, confirm the validity of this approach for nanometric measurements and make such a simple fringe sensor an attractive component for the 2nd generation VLTI.

1 Multiple-beam fringe tracking at VLTI

Most projects for VLTI 2nd generation instruments plan to use at least 4 beams (4 ATs dedicated to interferometry, or 4 UTs for maximum sensitivity), or even 8 beams (4 UTs+4 ATs). To reach their maximum performance, these instruments require active correction of the Optical Path Difference (OPD) between the beams and of the WaveFront Error (WFE) of each beam.

Correction devices are available at VLTI: all telescopes include a tip/tilt actuator, UTs are equiped with a deformable mirror (DM), and a dedicated location exists in the ATs. Four delay lines are available and provision has been made for 8. The situation is different for the sensors. To the best of our knowledge:

- The OPD between 2 pairs of beams can be measured with PRIMA/FSU (in K) and between 3 beams simultaneously with FINITO (in H).
- The WFE can be measured on the UTs by MACAO (in the visible). But the path in the tunnel (turbulence and static WFE) is not seen. There is no wave-front sensor for the ATs.
- Tip/tilt in the lab can be measured (for $\leq$4 beams) with IRIS (IR).

The performance of 2nd generation instruments would thus be increased by a new sensor in the VLTI lab that would allow the simultaneous measurement of the OPDs between 4 to 8 beams and their tip/tilt. The WFE can even be measured, at least for the lowest modes, to allow pre-compensation by MACAO or *a posteriori* calibration or real-time correction with DMs in the ATs. This single sensor would work in a single IR band to save photons for the scientific instruments.

Such a multi-beam multi-purpose sensor has already been investigated at ONERA for two other projects with similar requirements. The first one is DARWIN [1], where the real-time cophasing (piston/tip/tilt with nanometric accuracy) of the 6 sub-apertures is one of the main challenges. Measurement of the WFE (from defocus to spherical aberration) during operation is also required for calibration. A laboratory breadboard DWARF (DarWin AstRonomical Fringe sensor) has been defined and validated [2].

The second project deals with Earth imaging from the GEO orbit [3]. For a good on-ground resolution, a large deployable telescope is required, with a sufficiently-filled aperture. A critical issue is then to measure differential piston/tip/tilt, for typically 10 sub-apertures, on very extended scenes.

2 Solutions for multiple-beam fringe sensing

Two solutions are most classically used for fringe sensing. The first one is coaxial (or amplitude) combination in a pupil plane, with a beam splitter. This pairwise combination is widely used in stellar interferometry, often with temporal modulation [4], or with spatial modulation [5] as proposed by [6]. There are several drawbacks for this solution: the complexity quickly increases with the number of beams, only unresolved (or slightly resolved) sources can be used, and only the differential WFE can be measured. The complexity can be reduced by integrated optics, but in this case tip/tilt or WFE can not be measured.

The second solution is multiaxial (or wavefront) combination in a focal plane. In this case, an arbitray number (typically smaller than 20) of parallel beams are arranged, with a non-redundant configuration [7], in front of a focusing device and a detector. The complexity is then transfered on data processing, to solve for the inverse problem: given the observed image in the focal plane, what is the phase distribution in the pupil plane that gave birth to it ? Several approaches can be used:

- Phase retrieval: when the object is known (unresolved reference star), only the focal plane is used. Although phase retrieval is known for centrosymmetric pupils (case of monolithic telescopes) to lead to a sign ambiguity on the even part of the phase, a non-redundant multiple-beam configuration allows to uniquely solve for piston/tip/tilt [8].

- Phase diversity: 2 images are taken, in the focal plane and in an extra-focal plane (or with any other known aberration). In this case, the two data sets allow to fully retrieve the two macro-unknowns (object and phase): phase ambiguities are resolved and the object can also be estimated [9].

Different algorithms have been validated at ONERA: an iterative MAP (Maximum a Posteriori) resolution, and an analytical approximate algorithm for real-time piston/tip/tilt measurement by phase retrieval.

The pupil-plane and focal-plane approaches were compared in the framework of DARWIN and Earth observation. Performance are comparable, but a focal-plane sensor was selected for both applications, because of the simple hardware, the large number of beams, the ability two measure the absolute value of high-order modes, or the operation on complex objects.

3 Experimental results on the BRISE bench

A multiple-aperture testbed has been built to validate the two cophasing algorithms: Phase Retrieval for unresolved sources, and Phase Diversity for extended scenes. The main components of BRISE (Banc Reconfigurable d'Imagerie sur Scnes Etendues, described in [10]) are:

- An unresolved (monomode fiber + He-Ne laser) and an extended (photographic plate + white cell) object.
- An aperture mask with three sub-abertures and three planar mirrors on piezo-electric calibrated piston/tip/tilt plateforms.
- The cophasing sensor, which simultaneously records the focal and extrafocal images of each object in a single frame of a CCD camera.
- A control software and an efficient isolation against environmental disturbances (air turbulence, vibrations, thermal drifts).

Figure 1 shows experimental results for linearity. A 30-point piston slope from -500 nm to +500 nm is applied on a given sub-aperture. The estimated piston with phase retrieval (left, with three measurements for each piston value) or phase diversity (right) is linear between $\pm\lambda/2$ and wrapped as expected. A saturation effect appears for phase diversity, that remains to be fully understood; however, this is not an issue in closed loop. Because diffraction is chromatic, whereas our numerical model is monochromatic, the spectral bandwidth is an important parameter to optimize. Measurements were made at $\lambda = 650$ nm with $\Delta\lambda$=40 nm for phase diversity and $\Delta\lambda$= 10, 40 and 80 nm for phase retrieval. This shows that a rather large spectral range ($\Delta\lambda = \lambda/8$) can be used.

Figure 2/left shows experimental results for repetability, in the case of phase retrieval with λ=650 nm. Values agree with the simulation and clearly show the photon-noise $1/\sqrt{N}$ law. For low fluxes, the sensor is dominated by the detector noise. But the 0.75 nm repetability specified for DWARF is reached in the correct magnitude range.

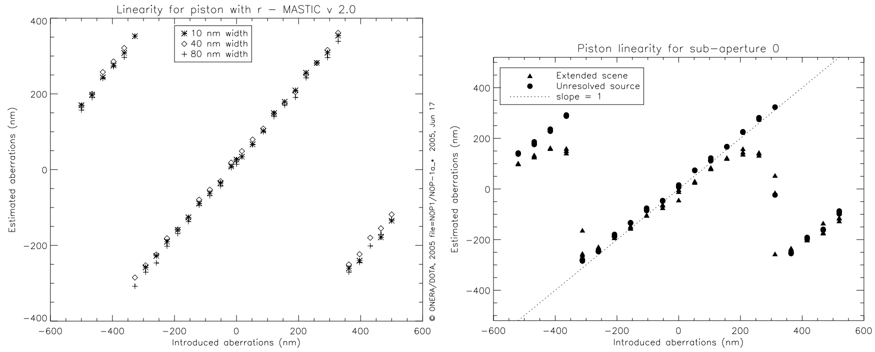

Fig. 1. Piston Linearity for phase retrieval and different bandwidths (left) and comparison between phase diversity and phase retrieval (right).

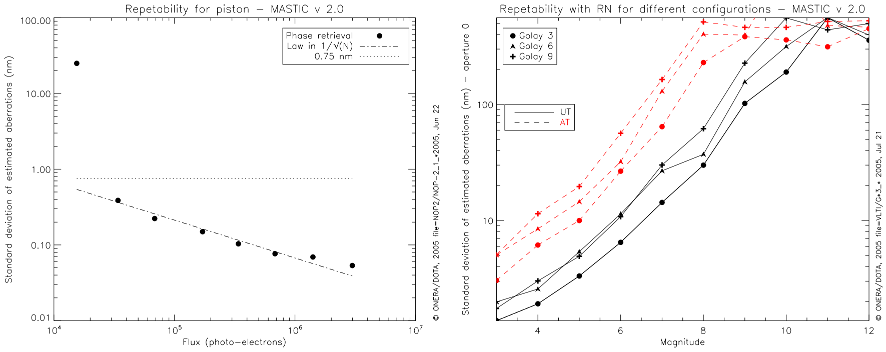

Fig. 2. Piston repeatability with phase retrieval estimated for DARWIN (left) and VLTI (right).

Figure 2/right shows very preliminary simulation results in the case of VLTI. The number of sub-apertures was varied between 3 and 9 (based on Golay configurations for simplicity). The piston measurement error slightly increases with the number of apertures. For a $\lambda/10$ accuracy in K (200 nm), the limiting magnitude is about 9-10 (resp 7-8) for the UTs (resp ATs).

4 Conclusion

This communication has shown that a simple setup (telescope + focal-plane detector fed by all the beams with a good aperture configuration) is an attractive solution to measure piston and a few WFE modes on a large (3 to a few tens) number of sub-apertures with an arbitrary (even fully resolved) object. The first experimental tests performed on BRISE have validated nanometric piston/tip/tilt repeatability with 3 sub-apertures. Additional tests with more modes/apertures are under way.

Such a compact device is an attractive solution for a multi-purpose 2nd generation sensor at VLTI, that would perform all real-time measurements in the lab (piston/tip/tilt/high order modes) with an arbitrary number of beams (3 to 8) in a single IR band. It could also, with a (densified) homothetic pupil-mapping, work with very extended objects.

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