Fringe Tracking for future interferometers

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Abstract: The combination of several telescopes is appealing from the scientific standpoint due to the more efficient sampling of the spatial frequency plane. Among other basic requirements, the beams are to be brought and retained into a fixed phase relation, against atmospheric piston. The necessary phase measurements (and corrections) are basically linear with the number of telescopes. This suggests the possibility of a convenient modular approach based on current technology. Besides, fringe tracking may benefit from efficient beam combination schemes and technological innovations in detector and optical components for astronomy.

1 Introduction

Interferometry with N beam / telescopes is highly promising for imaging in the IR bands (1-10 μm) of resolved objects of intermediate morphological complexity, on the mas scale, as well as for astrometric measurements at the level of few ten μas. Efficient astrometry, in the sense of accurate measurement among *unresolved* objects, may be performed with a set of three or four telescopes used simultaneously or with subsequent pair-wise measurements. In the former case, some of the observing overhead may be reduced by smart operation at observatory level, which is a critical aspect for large facilities (Delplancke, 2005). Besides, efficient phase referenced imaging requires a large number of baselines, i.e. several telescopes at a time or many observations at varying sampling geometry.

It is assumed that each telescope is endowed with an efficient adaptive optics (AO) system, correcting the wavefront error (WFE) locally introduced by atmospheric turbulence. An interferometric requirement on AO is that the residual piston must be minimised, since, although negligible for individual telescope applications, it results in a critical phase disturbance for combined measurements. The piston introduced by the atmosphere on the air column over each individual telescope, however, is not corrected by AO, and must be taken care of at interferometer level. The problem complexity directly depends on the number N of telescopes rather than the number $(N \times (N-1)/2)$ of baselines: independently from the detail of combination, the phase contributions from the atmosphere are N.

Pair-wise combination (hereafter, PC) of the N beams is thus a minimum implementation of the measurement of atmospheric piston for closed loop correction within the beam transport.

The atmospheric piston induces a noise on Optical Path Difference (OPD), with a PSD depending on the current observing conditions (e.g. baseline, seeing, etc.). A typical value of RMS OPD noise for Paranal, in average conditions, for a 40 m baseline, is 20 μm. The time scale for measurement of the atmospheric OPD noise is inherited from the turbulence, and is of order of one millisecond.

The feedback loop may reduce OPD noise significantly, and the relevant control aspects related to robustness and bandwidth are crucial. An additional noise is present between the reference source and nearby stars, related to their angular separation.

2 Fringe Tracking requirements and performance

The coherence time increases with wavelength as $\lambda^{6/5}$, using standard turbulence models, reasonably applicable in the practice. At longer wavelength, it is then possible to correct the piston by software, using the phase information from a fringe sensor for coherent integration of elementary exposures with low individual SNR. At shorter wavelength, it is convenient to provide hardware correction to the beams to allow longer exposure to the science instrument. We will deal mainly with the latter case, although the considerations can be applied to the former as well, with appropriate changes. Since faint or accurate science requires long exposures, FT is crucial; implementation can be split between the tasks of measurement (by a *fringe sensor*) and control (on a delay actuator) of the N phase contributions from individual beams.

One of the beams could also be selected as reference, reducing the problem (and instrument complexity) to N1 terms. Besides, often one of the beams is affected by a transient large disturbance in phase or intensity, as experienced in many observing cases. The case of more than one telescope suffering glitches or flux dropouts may in general be considered less frequent. Measuring on all N baselines available in the PC scheme, the remaining $N - 1$ telescopes are still stabilised with respect to each other, thus improving significantly the overall reliability.

Most of the local WFE variation can be considered corrected by AO; the residual WFE is propagated with the beams and may introduce additional undesired contributions (i.e. noise) to the measured phase. Also, instrumental contributions to piston are potentially introduced by each telescope and transfer optics system.

Static or low frequency terms are in principle manageable by the FT system, under appropriate dynamic range specifications, but high frequency disturbances, e.g. the vibrations experienced by some of the current interferometers, must be taken care of separately to preserve the stellar photons for stabilisation of the external disturbances. A metrology system may take care of measuring the residual internal high frequency noise, after mitigation wherever possible; the associated actuation for control may be applied at some stage of the transfer optics. For on-axis observations of bright objects, FT may no longer be necessary, since the process of autocorrelation of a sequence of exposures with sufficient SNR may be adequate.

The beam transport strategy (in air, vacuum or fibre optics) has an impact on the auxiliary functions to be considered for a fringe sensor, e.g. an alignment system and a longitudinal atmospheric dispersion compensation system. The solutions adopted in the current VLTI fringe sensors FINITO and PRIMA FSU are described in Gai et al. (2004). They include temporal or spatial OPD modulation, e.g. usage of quadrature outputs for the ABCD detection scheme, taking advantage of orthogonal polarisation components, and spectral dispersion of the combined beam over several wavelength channels.

In principle, new fringe sensors could be implemented using the same concepts, unless advantages can be identified depending on new available technological solutions or convenient geometric schemes.

2.1 Combination performance

A simple performance comparison between the cases of pair-wise combination (PC) vs. simultaneous combination (SC) on all baselines can be performed in terms of photometric SNR. The elementary exposure time value is T ($\sim 1ms$).

Given N input beams with intensity Φ photons/s, PC requires order of $2 \times N$ pixels, whereas SC requires about $N \times (N-1)$ pixels (a factor two arises in both cases from the number of complementary interferometric outputs). The average flux intensity on each combined output is thus $\Phi T/2$ (PC) or $\Phi T/2N$(SC). Thus, the photometric SNR per output is respectively

$$SNR(PC) = \frac{1}{\sqrt{2}} \frac{\Phi T}{\sqrt{\Phi T + 2R}} \; , \text{ and } \; SNR(SC) = \frac{1}{\sqrt{2N}} \frac{\Phi T}{\sqrt{\Phi T + 2NR}} \; ,$$

where R is the individual read-out noise variance in photons.

For normal visibility measurements, in the photon limit, the residual factor on SC SNR ($1/\sqrt{N}$) can be retrieved by increasing the exposure time to NT; besides, the number of desired visibility points in this case corresponds to the available baselines, so that PC should also be repeated for about N times. Thus, the same information is retrieved in the given total exposure time, i.e. the sampling of the (u, v) plane is the same, and the techniques are equivalent (Quirrenbach, 2004). Unfortunately, this is not the case for fringe tracking applications, due to the constraint on elementary exposure, so that FT, apart a few bright targets, is likely to remain close to the photon-starved regime.

3 Implementation options

PC may be considered as intrinsically modular, so that it can be extended to an arbitrarily large number of telescopes, in principle. This is also a potentially distributed concept, in which delay lines and fringe sensors could be mounted at each telescope along the interferometer layout. In this case, existing instruments might simply be replicated, possibly with improvements where higher performance devices can be identified. In practice, this may not be the most convenient solution in terms of cost, and some cases may deserve a custom multi-beam combination, e.g. for the central hub of a Y-shaped interferometer (similar to VLA). In the case of VLTI, since the four UTs and the four ATs implement two arrays which could be used in arbitrary subsets ranging from two to eight telescopes, a multiple beam fringe sensor may be a convenient general purpose facility solution for several concepts of multiple beam science instruments. Moreover, since for most applications it is not considered convenient to mix UTs and ATs, the multiplicity to be considered could be limited to four, in the near future.

Sometimes, integrated optics is proposed as a promising solution for future, complex interferometric instruments. However, for the time being, it can not be considered an off-the-shelf technology, and bulk optics could be considered convenient at least up to a certain level of complexity. We assume that in case of combination of up to four beams bulk optics still bears advantages with respect to integrated optics.

An important simplification may be usage of bulk components processing several beams at a time. A simple concept for a four-beam combiner, not optimised with respect to component count, and an example of layout are shown in Figure 1. The PC concept is implemented by individual combination of polarisation components of each beam with two “neighbour” beams, using a symmetric intensity distribution. The possible phase variation between components, mainly due to instrumental effects, and marginally to the source, do not degrade the individual

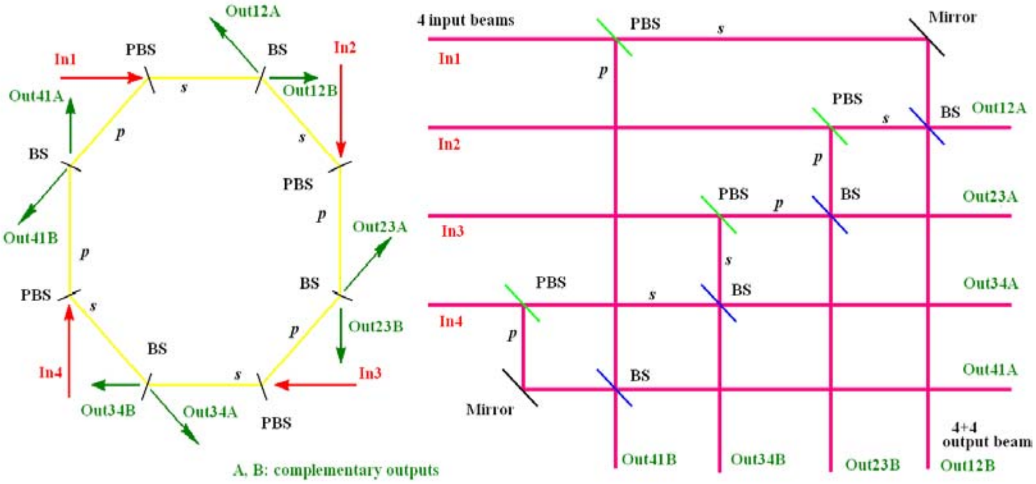

Figure 1: Concept of a four beam, bulk optics combiner for VLTI (right) and a symmetric, compact layout (left).

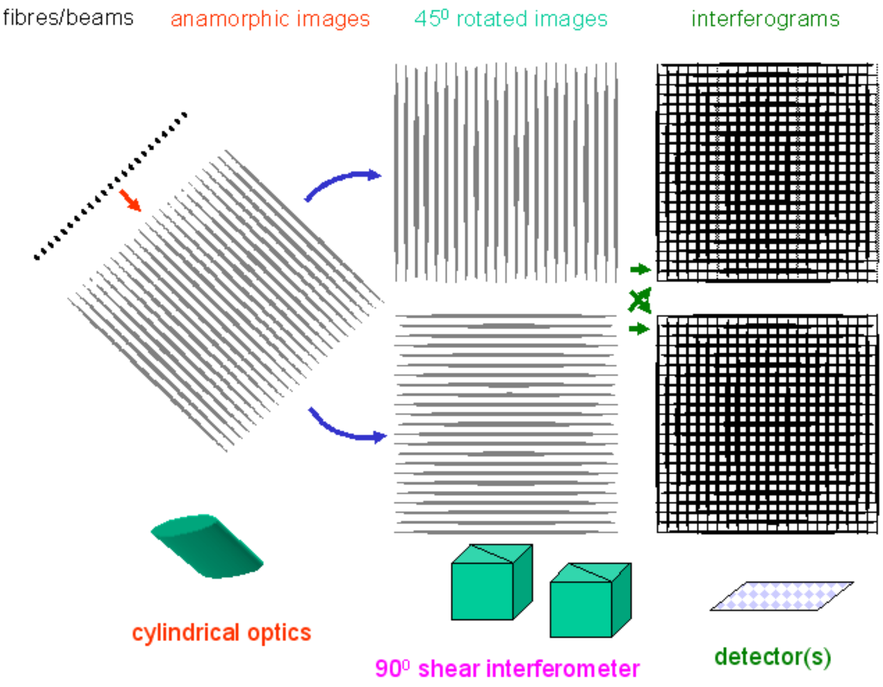

Figure 2: Concept of a multiple beam, bulk optics combiner.

visibility, but must be calibrated and taken into account for the combined measurement, i.e. a generalised closure phase.

In order to improve the engineering aspects, and to reduce the required number of components, a novel combination scheme is being evaluated (Ribak et al. 2005), and a schematic for several beams is shown in Figure 2. The concept requires anamorphic stretching of the input beam set, which is then split, and the two copies superposed to each other after rotation in order to get all possible combinations. The number of individual optical components is very low, and, although they have large size, high optical quality is required only over small regions comparable with the beam footprint. Application to four beam combination at VLTI is not optimal in the sense of Section 3 above. However, this concept has the advantage that it features nice scalability: it can be designed for N beams, retaining the capability of full combination also for a smaller number $N < N$ of beams, with graceful degradation. A laboratory implementation of the multiple beam anamorphic combiner is under evaluation at Technion, for possible application to future instruments.

4 Conclusions

Most of the fringe tracking requirements derived for current interferometers can be applied to future, large scale facilities, e.g. time scale constraints by atmospheric turbulence, high quality AO correction on each sub-aperture, and normal site quality aspects. The number of external piston contributions grows linearly with the combined telescopes, so that also the FT needs scale in the same way. Current solutions can be applied with small changes, apart optimisation and inclusion of new technologies to improve performance, reliability and cost effectiveness. New promising concepts for practical combination of several beams, based on current solutions and readily procured components, are under evaluation.

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