The VLTI Fringe Sensors: FINITO and PRIMA FSU

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ABSTRACT

FINITO is the first generation VLTI fringe sensor, optimised for three beam observations, recently installed at Paranal and currently used for VLTI optimisation. The PRIMA FSU is the second generation, optimised for astrometry in dual-feed mode, currently in construction. We discuss the constraints of fringe tracking at VLTI, the basic functions required for stabilised interferometric observations, and their different implementation in the two instruments, with remarks on the most critical technical aspects. We provide an estimate of the expected performance and describe some of their possible observing and calibration modes, with reference to the current scientific combiners.

Keywords: Instrumentation: interferometers; techniques: interferometric; instrumentation: high angular resolution

1. INTRODUCTION

The ESO VLT was designed with the purpose of being able to implement an advanced interferometer, VLTI[1], eventually combining up to four 8 m Unit Telescopes (UT) and several 1.8 m Auxiliary Telescopes[2] (AT). The telescopes are all endowed with either tip-tilt correction systems (AT), or higher-order adaptive optics (MACAO[3]) on UT. The maximum baseline achievable with UT is about 100 m, whereas the largest AT baseline is close to 200 m. The telescope beams are transferred in air, inducing significant longitudinal dispersion. It is therefore necessary to distinguish between the monochromatic phase associated to the optical path difference (OPD) and the overall group delay (GD) achieved on a finite wavelength range. Longitudinal dispersion has to be accounted for and compensated in the fringe sensor design.
The instruments currently installed at VLTI are VINCI, used for initial commissioning and for several scientific observations in the initial life of VLTI; AMBER[4], which recently observed its first fringes, combining two or three beams in the near IR (J, H, K bands); MIDI[5], which in the initial year of activity produced significant scientific results, for combination of two beams in the thermal IR (N band, 10 μm). In the framework of a collaboration between ESO and the Astronomical Observatory of Torino, part of the Italian National Institute of Astrophysics (INAF-OATo), FINITO[6] (operating in H band) was developed. As the first fringe sensor (FS) at Paranal, it has a crucial engineering function: support to the interferometer set-up and fringe tracking optimisation. The other first generation combiners (VINCI, MIDI, AMBER) do not have the time resolution for identification of noise sources in the frequency range associated to atmospheric turbulence, thus could nor be used in the fringe tracking loop.
The implementation of the Phase Referenced Imaging and Microarcsecond Astrometry (PRIMA[7]) facility, which is considered as a second generation instrument for VLTI, is in progress. Most of the PRIMA sub-systems are assigned by ESO as industrial contracts. PRIMA comprises a dual Fringe Sensor Unit, consisting of FSU B for fringe tracking on the bright object and FSU A, used only in Astrometric mode, for measuring the faint object OPD.
Phase Referenced Imaging: first generation instruments are mainly dedicated to visibility modulus measurement, with some spectral dispersion capability in the bands used. Accurate measurement of the interferometric phase with respect to a reference object allows reconstruction of bidimensional structure parameters of the observed source, with an end result corresponding to aperture synthesis imaging as in the radio range, in the limiting case of a very large number of baselines. The disadvantage with respect to the radio case, operating in wave regime, is that instead of post-facto combination of phase and amplitude measurements in a correlator, in the visible and infrared (IR) range, in photon regime, we work with

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individual intensity measurements of each geometric combination. Filling the *u-v* plane is slow and more cumbersome, requiring a dedicated observation for any point. Nonetheless, the resolution achievable with VLTI imaging in the near IR is of few milliarcseconds (mas), appealing for several applications ranging from solar system objects, to stellar structures, to extragalactic sources. Besides, even in case of unresolved objects, the possibility of accurate measurement of target separation to a fraction of the resolution bears the promise of fundamental progress in determination of basic stellar parameters, as binary orbits, thus individual stellar masses and improvement of the mass-luminosity relation.

Microarcsec Astrometry: the goal for astrometric measurements is set to 10 microarcseconds (μas), allowing determination of the orbits of extra-solar planets within an horizon of several tens to few hundred parsecs. Astrometry requires two identical FSUs.

Interferometer operation requires good rejection of the disturbance induced by atmospheric turbulence (piston), whose statistics can be derived from the Kolmogorov models used for adaptive optics (AO). This is achieved by the fringe tracking loop, in which the fringe sensor measures the current OPD between the telescope beams, and an actuator operates to counteract the disturbance with respect to the nominal value. The OPD must anyway follow a nominal trajectory depending upon the observation geometry, evolving with the target sidereal motion. The FS requires a comparably bright reference source, also depending on the desired level of stabilisation; provided the fringe tracking loop operation is ensured, the scientific instruments can perform long exposures on much fainter sources (or – for the mid-infrared – sum coherently many short exposures), limited by photon budget, instrument stability and the variation of observing conditions.

In Section 2, we recall some basic atmospheric parameters with reference to the average VLTI conditions and we describe some of the basic functions of a fringe tracking loop, as well as their requirements and planned implementation at VLTI. Section 3 describes the polychromatic interferometric signal and identifies the OPD and GD parameters in the signal model, deriving some consequences for measurement implementation. Section 4 reports the concept, technical characteristics, expected performance and status of FINITO, with some of the results currently achieved, the problems encountered and the work in progress. Section 5 describes the PRIMA FSU design, the estimated performance and main differences with respect to FINITO. Section 6 draws some consequences of the FSU characteristics on observing modes and calibration. Finally, we draw our conclusions on the current status and the perspective for future developments.

2. FRINGE SENSING AT VLTI: CONDITIONS AND INTERFEROMETER SUB-SYSTEMS

An interferometer can be described as a complex assembly of sub-systems, in spite of the underlying simple concept of physical measurement. The principle is that coherent combination of sections of a stellar wavefront, separated by a large baseline vector $\boldsymbol{B}$, can provide information on the source, sampled at the spatial frequency associated to the baseline (projected to the source), i.e. at much higher resolution than that of single individual telescopes. Below, we review the main effects of atmospheric turbulence and AO residuals, the expected input noise distribution, and the set of sub-systems required for implementation of the fringe tracking loop.

2.1 Impact of AO on coherent flux and noise on optical paths

Interferometry requires necessarily an adaptive optics (AO) system, for collecting areas larger than the atmospheric coherence length, and interferometric performance depends on AO efficiency. The "coherent" flux associated to a flat wavefront is reduced from the nominal value (corresponding to full aperture if no atmospheric turbulence were present) to a smaller value, which can be roughly scaled vs. wavelength as the Strehl ratio, i.e. for the 8 m Unit Telescopes (UT) with MACAO (60 elements curvature AO system) about 40% in H band (1.48-1.79 μm) and 60% in K band (2-2.5 μm). Similar figures are expected for the 1.8 m Auxiliary Telescopes (AT), endowed with tip-tilt correction. Apart flux reduction, interferometric equipment is not affected by the coherence length of atmosphere r_0 (Fried parameter), as the input wavefront sections are made effectively flat, thanks to AO and spatial filtering.

AO is effective only on each local wavefront section, and the relative phase fluctuates as a consequence of atmospheric turbulence over the time scale of the coherence period t_0, ranging from few milliseconds in the visible range to few ten ms in the near infrared (NIR) and few hundred ms in the thermal (medium) infrared (MIR). The OPD between two telescope beams is affected by such fluctuations (usually translated in linear units), also defined as atmospheric piston. Typical RMS values[8] at Paranal, in average conditions, are of order of 20 μm, which is the value used for the design of both FINITO and PRIMA FSU. The piston PSD can usually be approximated by a power law, with slope -2/3 up to a cut-off frequency $\nu_c(OPD)$ depending on wind speed V and baseline B as $\nu_c(OPD) = 0.22 \cdot V / B$ and slope -8/3 at higher frequency. The low frequency range has positive slope, for convergence; the high frequency part is independent from

baseline. Detailed descriptions are based on the structure functions of atmospheric turbulence, but a simple model suffices for most common cases of fringe tracking.
The differential OPD (DOPD) noise between different sources has decreasing correlation with their increasing angular separation θ , improving at longer wavelength; the DOPD PSD has slope -2/3 between the cut-off frequencies $\nu_{c1}(DOPD) = 4.08/\pi B$ and $\nu_{c2}(DOPD) = 1.43e-3 \cdot V^{5/6}/\pi\theta$. The high frequency PSD is about twice that of OPD, corresponding to full decorrelation, whereas the low frequency has positive slope close to 4/3. The definition follows that of isoplanatic angle for AO, as the physical source is the same: ratio between coherence length and typical turbulence height.

2.2 Delay lines

In a noiseless world, the sole purpose of delay lines[9] (DL) would be to carry the optical beams from the individual telescopes to the combination laboratory, over a distance set to match the external delay associated to the current source position, and moving to track its sidereal motion. Since DL are in any case moving devices, it appears natural to allocate at this level also the additional correction of OPD noise, on top of the nominal trajectory. The DL is implemented by a cat's-eye retroreflector mounted on a long stroke mechanical carriage. The cat's-eye focal mirror is mounted on a piezoelectric stage for fine adjustment. One of the basic design choices of VLTI is to use non-evacuated DL, although the possibility of using air-tight *differential* delay lines (DDL) for astrometric applications, is considered for PRIMA. Due to longitudinal dispersion in the refractive medium of the interferometer arms, there is a separation between the balance points of monochromatic phase (zero OPD) and of group delay (zero GD), defined over the measurement spectral range.
The DL receives the OPD controller commands and applies the required correction. The DL accepts commands at 2 kHz sampling frequency and has a 130 Hz bandwidth.The maximum internal OPD of $\pm 120m$ allows observation as far as 60° from zenith for baselines up to 140 m, or a pointing range of up to 40° from zenith for the longest baseline of about 200 m (on ATs). At the moment, DL 1, 2 and 3 are available, whereas DL 4, 5 and 6 are being installed.
The PRIMA DDL should compensate for the small sidereal distance between primary and secondary stars; the DDL range is set to 60 mm, and implementation *in vacuo* suppresses the differential longitudinal dispersion between the sources.

2.3 Dual feed

Interferometric instruments based on amplitude combination generally have a small field of view, comparable to the telescope diffraction limit. Besides, sending a large field over long distance imposes impractical requirements on the transfer optics size (beams are compressed, so that angles are magnified) and detector format.
Observations of faint sources, stabilised by fringe tracking, require simultaneous usage of two combiners: the FSU, set on the (bright) primary star for real time OPD measurement, and the scientific instrument, performing long exposures on the (usually faint) secondary target. This requires dedicated equipment at each telescope, to pick up the beams from the two sources; it is implemented in the simplest way on a focal plane, positioning two small mirrors or dichroics, and focusing the beams into the DL. For VLTI, this device is the Star Separator[10] (STS). The STS has significant impact on calibration (see below), since one key requirement is the possibility of feeding the *same* source to both instruments, in order to define the common zero OPD. Implementation of the STS has been awarded to TPN-TNO (Delft, NL).
Without STS, each FSU can only support on-axis observations, i.e. the same target is fed to both FSU and scientific combiner, apart the small offset allowed by the alignment system, of order of one arcsecond. In this case, the FSU and instrument may still be fed by two distinct stars, as the UT diffraction image is much smaller (Airy diameter ~140 mas in K band), so that the case may be adequate for close binaries or for sampling structured objects with a bright core for tracking. With adoption of the STS, the VLTI field of view increases to several ten arcsecond around sufficiently bright reference stars, for both FINITO and PRIMA FSU.

2.4 Metrology

Several sources of OPD noise are expected to be local to the VLTI environment, surely due to the atmospheric turbulence in the non-evacuated DL, and possibly from instrumental effects. In principle, the interferometer might be stabilised by the fringe tracking loop alone, also against these disturbances, but in order to ease identification of the noise sources, and above all to link subsequent observations and alleviate the calibration requirements for the highest precision measurements, a metrology system[11] is foreseen. The PRIMA metrology system will monitor the internal optical path from retro-reflectors located in the telescopes (upstream of the star-separator) to the FSU A and FSU B beam-combiners; in principle, its information might be used either in closed loop, as additional data to the OPD Controller, or in open loop, as a contribution to data reduction.

2.5 The OPD controller

The OPD controller is the computer which receives the fringe sensor measurements, implements the real-time control law of the fringe tracking loop and send the so-called "real-time offset" to the active Delay Line(s). For PRIMA a second OPDC (called dOPDC) will be implemented to take care of the differential OPD control loop, which involves also the PRIMA metrology system.. The OPDC is also in charge of generating the fringe search trajectory applied to the DL, of detecting the presence of fringes based on the SNR received from the fringe sensor and to handle the FT loop closure and opening when the flux or the fringes are lost.
Optimisation of the control algorithms will be a crucial development phase for VLTI, in order to fully exploit the instrument potential. The OPD controller sampling frequency is 2 kHz. With the current settings (FINITO 2 ms integration time) the closed loop unity gain frequency is about 15 Hz, providing a typical residual RMS OPD of 150 nm.

2.6 The Fringe Sensor Unit

The Fringe Sensor Unit (FSU) is the *sensor* of the OPD control loop. Both FINITO and the PRIMA FSU A/B, described below, have the purpose of measuring the current phase among telescope beams and provide this information to the OPD controller. The basic function is instantaneous OPD detection, against atmospheric turbulence.
Both FINITO and PRIMA have a common set of sub-systems, whose functions are listed below, with different implementation in terms of optical configuration and layout. PRIMA FSU has however been optimised for astrometry (interface with PRIMA metrology and better accuracy).

2.6.1 Pupil, image and OPD alignment system

VLTI delivers the telescope beams in the interferometric laboratory with a well defined angular (image alignment) and lateral (pupil alignment) accuracy, thanks to the ARAL[12] system. However, in order to cope both with ARAL residual errors (FINITO and PRIMA) and with the effect of differential atmospheric dispersion between the scientific instrument wavelength and the fringe sensor wavelength (FINITO), both fringe sensors are endowed with alignment systems, consisting of flat mirrors mounted on remotely controlled actuators, with different optical layout.
The angular range is of order of the telescope pointing precision, and the resolution is a small fraction of the diffraction limited image, to achieve high coupling efficiency, retaining most of the coherent photon flux. The fifth degree of freedom is the beam longitudinal position, i.e. its phase with respect to the local reference (provided by ARAL / LEONARDO), which must be adjusted to the μm level to locate the highest coherence position and achieve common "zero phase" among the instruments, by "*OPD alignment*".
The alignment system allows to set or correct a small offset among instruments, which is useful to compensate for longitudinal and transversal atmospheric dispersion among different spectral bands. Besides, it might provide the possibility to perform observations at a small distance from bright sources, independent from dual feed.

2.6.2 Spatial filters

The residual "incoherent" flux from AO residuals on each beam mainly contributes phase noise, and it is reduced by spatial filtering. It corresponds to a stop on an intermediate focal plane, selecting only the central part of the diffraction image. Spatial filtering could be implemented by either a pinhole or fibre optics, but the latter has better throughput due to the wavelength dependence of coupling efficiency. Both FINITO and the PRIMA FSU implement spatial filtering by fibre optics, also used to distribute the optical beams. Single mode fibres are required, before combination, in order to preserve the beam phase; after combination, multimode fibres might be used, but for FINITO and PRIMA FSUs single mode fibres are still required by imaging constraints of the detection system.

2.6.3 Detection system

Although the OPD measurement requires in principle a very limited number of pixels, corresponding to the few optical outputs, the noise performance of discrete photon sensing devices vs. modern, integrating array detectors impose the latter, at the moment, as the only acceptable choice. Since NIR array detectors are split in quadrants, driven in parallel, it is convenient to spread the optical outputs among them, taking advantage of the multiplexed readout to further improve the noise performance, reducing the pixel rate. This concept[13] has been first implemented in FINITO, and then adopted for the PRIMA FSU. The practical implementation requires arrays of optical fibres, imaged on the same logical pixels in each quadrant. To minimise read-out time and noise, the fibre core must be re-imaged within a single pixel, acting as individual photometer; thus the adoption of single mode fibres.

2.7 Visibility degradation induced by phase noise

The residual OPD noise of the fringe tracking loop is the RMS composition of the residual input (mainly atmospheric) noise, of the fringe sensor noise, and of the actuator noise.
The specification for residual OPD with VLTI fringe tracking is 100 nm RMS over 3 minutes for a bright target (typically mH = 8 on UTs). This induces an instrumental visibility degradation in K band observations below 1%, i.e. negligible with respect to other instrumental sources, e.g. beam decorrelation due to residual wavefront errors.

3. INTERFEROMETRIC SIGNAL AND FRINGE SENSING

The monochromatic interferometric signal at wavelength λ obtained from a source at zenith generating the flux F, collected by two telescopes with area A, over the exposure time T (in which the conditions can be considered stationary), in an optical channel with transmission τ, visibility V and phase φ, over a detector with quantum efficiency QE, for an OPD x in air (refractive index n), is

$$s(\lambda) = F \cdot (2 \cdot A) \cdot \tau \cdot QE \cdot T \cdot \left[1 + V \cdot \sin\left(\varphi + \frac{2\pi}{\lambda} n \cdot x\right)\right] \quad (1).$$

The polychromatic signal is obtained by superposition of the monochromatic terms over the spectral range:

$$S = \int s(\lambda) d\lambda = \int F \cdot (2 \cdot A) \cdot \tau \cdot QE \cdot T \cdot \left[1 + V \cdot \sin\left(\varphi + \frac{2\pi}{\lambda} n \cdot x\right)\right] d\lambda \quad (2),$$

where source emission, instrument parameters (transmission, phase, visibility) and quantum efficiency are described by suitable spectral distributions. Different optical channels are described by different distributions of one or several parameters; e.g., the complementary outputs of an ideal combiner have the same parameters, but the phase has a constant difference of π radians.
The internal delay associated to a generic pointing position compensates the current external delay, and is defined to match the group delay between the interferometer arms, at the effective wavelength of observation λ_0. It can be introduced in the above expressions after group delay subtraction (this also describes residual longitudinal dispersion):

$$S = \int s(\lambda) d\lambda = \int F \cdot (2 \cdot A) \cdot \tau \cdot QE \cdot T \cdot \left\{1 + V \cdot \sin\left[\varphi + \frac{2\pi}{\lambda}\left(n \cdot x + (n - n_0) \cdot p\right)\right]\right\} d\lambda \quad (3),$$

where n_0 is the group refraction index of air at λ_0. Internal delay follows a trajectory to track sidereal motion.
Due to finite spectral bandwidth, the polychromatic interferogram is no longer an infinite sinusoidal, but has modulation dropping to small values beyond the *coherence length*; however, it includes several fringes, so that it is not a single-valued function, and the measurement of a single instance of signal from Eq. (2) or (3) is not sufficient to provide a robust solution for the OPD, which is the desired quantity. The mathematical degeneration is removed by generating several signal instances, with known phase relation, in order to constraint the solution. A possible approach is by modulation of the OPD, at a rate faster than atmospheric turbulence, collecting subsequent signal samples for analysis; this is the *temporal modulation* technique used in FINITO. Besides, it is possible to generate simultaneously different signal outputs, with different instrumental phase φ; this is the *spatial modulation*, used in the PRIMA FSU.
The implementation of the OPD / GD measurement algorithms is described in another contribution to this Conference[4].
The simplest version of the interferometric signal is described by the "ABCD" model, whereas high precision measurements require usage of a complete formulation, as in Eq. (3) above. The noise performance on the OPD / GD estimate is often derived in terms of the operating wavelength, scaled by SNR, visibility V and a geometric factor α depending on the measurement scheme:

$$\sigma(OPD) = \alpha \frac{\lambda}{V \cdot SNR} \quad (4).$$

Since the desired performance is usually a small fraction of the wavelength, to ensure nm-level astrometry or imaging at comparably high contrast, the photometric SNR in normal observations must be high, above all if visibility is reduced.

It is usually convenient to separate different operating regimes, since at the beginning, after preliminary alignment steps, we need *fringe detection*, i.e. coarse identification of the zero OPD position, over a long range (e.g. $\pm 100\,\mu m$), with sufficient resolution to identify the central (*white light*) fringe, which has the highest contrast; then it is possible to switch to *fringe tracking*, with higher resolution and smaller dynamic range. In VLTI, it is assumed to have two measurements running at the same time on the FSU: OPD modulo λ_0 (hereafter, "OPD" tout-court) and GD, necessary to lock on the white light fringe in spite of occasional OPD peaks, which might induce a *fringe jump* in the control loop. The former identifies the interferogram phase as for the case of a sinusoidal (monochromatic) signal, with limited dynamic range (within $\lambda_0 / 2$), whereas the latter discriminates among nearby fringes to identify fringe jumps, allowing their suppression by the OPD Controller, over a range comparable to a significant fraction of the coherence length. The two measurements are sometimes used in different regimes, mentioned as *cophasing* and *coherencing* respectively, which may also be selected depending on source brightness and desired measurement accuracy. This is also due to the different time scale involved: OPD modulo λ_0 is usually measured on the millisecond (ms) sampling rate, whereas GD is evaluated over tens of ms.
Particular care has to be taken about the beam polarisation components: the orthogonal contributions are independent, i.e. mutually incoherent; instrumental polarisation is likely to be relevant, due to the large number of reflections in the VLTI optical train, and variable with the telescope selection and pointing position; eventually, also the intrinsic source polarisation may in some cases be relevant. It is convenient to separate the combined output by polarisation, as done in the PRIMA FSU, or extract one polarisation component as photometric signal, as in FINITO.

4. FINITO

FINITO (Fringe-tracking Instrument of NIce and TOrino) is developed in the framework of a collaboration between ESO and the Astronomical Observatory of Torino; the concept was verified in a prototype by the Observatoire de la Côte d'Azur (Nice, F). It is a combination unit fed by either two or three telescope beams, and it operates in H band ($\lambda\lambda = 1.5 - 1.8\,\mu m$); the conceptual layout is shown below in Fig. 1.
A portion (H band) of the stellar light is directed to FINITO by dichroics. The Alignment and Compensation Unit (ACU) comprises flat mirrors mounted on piezo tip-tilt platforms (for image alignment and compensation of the differential Transverse atmospheric dispersion with the scientific instrument), themselves mounted on translation stages (for OPD alignment). This system allows differential pointing over a field of 1" on sky (for UTs, i.e. 440" in the lab).
The OPD and GD measurements are based on temporal OPD modulation: the OPD is modulated internally by Finito using a piezo driven expansion ring changing the length of the fiber on one (or two) of the beams. Modulation is triangular, in closed loop with sampling frequency 12.5 kHz, using an auxiliary metrology system operating at 1312 nm. The fibres are single mode and polarisation maintaining, to avoid crosstalk between independent modes. The fibre modulators are critical devices, produced for FINITO by Institut de recherche en Communications Optiques et Microondes (IRCOM – CNRS, Limoges, F). The metrology signal is inserted and extracted in the stellar beam using dichroics. The maximum modulation stroke is 20 µm, programmable in steps of H band fringes (~1640 nm). The metrology beams are sent to a dedicated beam-combiner, through a set of polarisers used to generate a pair of output components in quadrature (π/2 phase difference), i.e. a simplified form of the ABCD scheme.

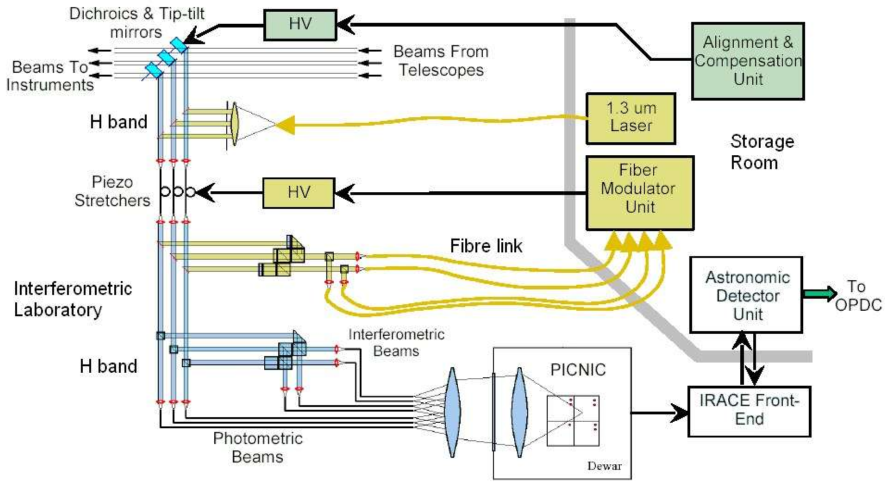

Fig. 1 - Conceptual layout of FINITO.

Metrology signals (4 per interferometric pair) are routed to photodiodes located in the electronic cabinet outside the interferometric laboratory by SM fiber patchcords. The closed loop modulation has been proven to work reliably for modulation rates of up to one H-band wavelength per 1.25 ms (800 Hz).
The stellar beams are fed to Glan-Taylor polarisers, which extract one component used as photometric signal. The polarisation maintaining fibres of the modulators are birefringent, so that the modulation of the two components is different. The polarisation component transmitted by the polariser is fed to a three-way beam combiner, in which the reference beam (labelled 0) is split in equal intensity fractions, independently combined with each modulated beam (respectively 1 and 2). This produces four interferometric outputs, i.e. two pairs of complementary outputs, for the combination 0-1 and 0-2 respectively.
The three photometric and four interferometric outputs are relayed to the cryostat by single mode fibres; on the detector side, the fibres are mounted on V-groove arrays with μm level accuracy, and imaged on a Rockwell PICNIC array detector. Two pixels per quadrant are read in parallel (with one spare channel), to optimise the detector performance. The array is read out synchronously with the OPD modulation by an ESO IRACE system.
The FINITO control electronics consists of three independent Local Control Units (LCU) are used, respectively for the alignment system (ACU), the modulation loop (FMU), and for computing FINITO measurements from the IRACE data (ADU). The output of FINITO are three signals; SNR used for fringe detection and decision to close/open the fringe tracking loop, OPD phase and OPD coherence (equivalent to GD). The three outputs are written on VLTI reflective memory network.

The limiting magnitude for a 150 nm RMS residual OPD had been initially estimated to be around mH =13 to mH = 14 on UTs, based on the nominal VLTI transmission and a 0.6 FINITO internal transmission (per modulated beam), for good seeing conditions (coherence time = 8 ms), with an integration time from 1 ms to 10 ms. Performance on the Auxiliary Telescopes is expected to be scaled , because of the smaller apertures, by about 3 mag.

The warm opto-mechanics of FINITO was delivered to ESO – Garching (D) for assembly and integration with the detector and system test on November, 2002, and installed at Paranal on July, 2003 (Fig. 2).
A sequence of engineering and commissioning runs was performed using exclusively VLTI 40-cm Siderostats (July 2003, November 2003, March 2004).
After system tests in Garching, FINITO internal transmission has been estimated to 0.25 (each beam propagates through 38 optical surfaces). Combined with the change in detector quantum efficiency (0.8 measured vs. 0.5 expected) the impact on limiting magnitude is about 0.5 mag.

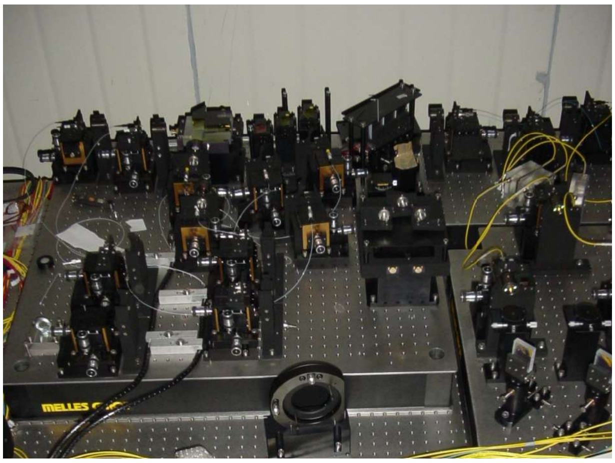

Fig. 2 - FINITO in the VLTI combination laboratory, on June 2003; the combination unit with astronomical and metrological outputs, with part of the injection and modulation sub-systems.

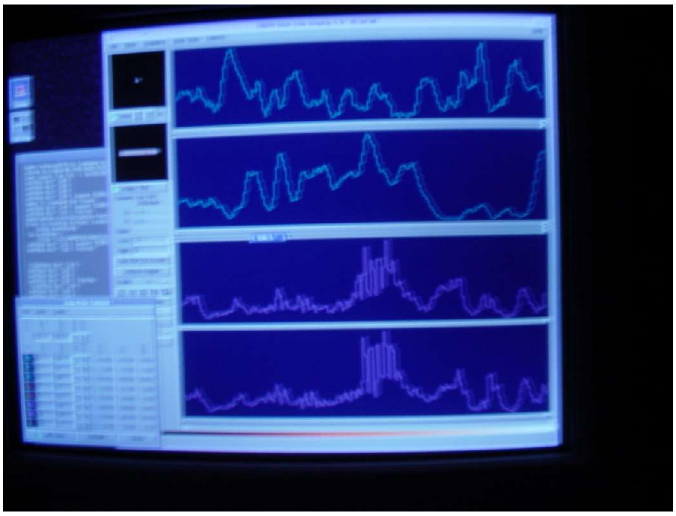

Fig. 3 – Sample of interferometric and photometric outputs, on siderostats, in open loop, during June 2003 system set-up. Performance limited by scintillation on 80 mm siderostat aperture.

Another issue was the detector noise, featuring a significant (and unexpected) $1/f$ component. The immediate consequence is that the expected improvement on noise performance provided by multiple non-destructive read-out is lost. On 2 ms elementary exposure, the effective read-out noise (RON) is ~37 electrons, i.e. much larger than the expected 6 electrons. The impact on RON-limited faint limiting magnitude was estimated to about 2 mag. This preliminary estimate must however be refined, since considering that fringe tracking works with comparably high SNR in elementary exposures, the impact of RON might be reduced to about 0.5 mg in practical cases.
The telescope flux detected by FINITO is another critical area. The overall throughput, from UT to the FINITO detector, was found to be one order of magnitude below the theoretical flux. The causes of this low throughput are still not well understood and might be internal to FINITO or due to low coupling efficiency into FINITO fibres, e.g. due to excess WFE in some part of the system, to be identified and corrected.
One major source of difficulty during commissioning on Siderostats was the large and fast fluctuations of the flux coupled into FINITO fibres. Typically the flux changed by a factor 10 within 25 milliseconds and it dropped out every few seconds. A disturbance specific to siderostat operations is surely *scintillation*, since the useful pupil is limited to 80 mm; besides, this does not totally justify all observed phenomena. In fact, similar fluctuations have been observed, coupling UT3 beam into FINITO during one night. However there were no flux drop outs when the MACAO system was operated. The most probable cause of these fast fluctuations is turbulence in the light ducts (from UT3 to DL tunnel), where external air encounters tunnel air of different temperature. This issue will be investigated in the coming months by local measurements. The infrared camera of IRIS (VLTI infrared tip-tilt sensor, to be integrated in Paranal by end of 2004) will also be used to measure the image quality and stability in the interferometric laboratory.
These fluctuations complicated a lot the closure of the fringe tracking loop and FINITO coherence measurement. For the former, a three state machine has been implemented in the OPDC to handle the initial fringe search and detection and the recovery after fringes have been lost (usually due to a flux drop out). This logic has proven to be able to track fringes during several minutes, in spite of frequent flux drop outs (with very short lock interruption during such events). For the coherence measurement, the interferometric signals must be normalised using the photometric signals, in order to compute the fringe amplitude as function of OPD modulation. The normalisation formula and the calibration procedure have been improved and the coherence signal of FINITO was finally usable to measure the position of the fringe packet (no feedback of the coherence has been implemented yet). In most of the cases, the loop locks back on the same fringe after a low flux event.
The current residual OPD is typically 200 nm RMS when FINITO modulation amplitude is 5 fringes and about 150 nm RMS for 3 fringes amplitude. The causes of this dependency are not yet clear.
FINITO will be tested for the first time on a UT pair in August, 2004.

5. THE PRIMA FSU

In June, 2002, ESO awarded the contract for construction of one PRIMA FSU (unit B) to a team led by Alenia Spazio, and including the OATo team for support to design, implementation and test, with direct responsibility in performance analysis, algorithm definition and implementation, and procurement of the detection system. The final specifications on many technical aspects of PRIMA were updated also based on the FINITO experience.

The PRIMA FSU concept is fully static and somewhat simplified with respect to FINITO, since most of the complexity is transferred to the stringent requirements on individual components. It is fed by two telescope beams, and implements spatial modulation in K band (2-2.5 μm). The alignment system has five degrees of freedom per beam: two lateral (decenter) for pupil alignment, two angular (tilt) for image alignment, and a longitudinal term for OPD alignment. It is implemented by two subsequent tip-tilt platforms controlled by a kynematics matrix for conversion between optical and mechanical degrees of freedom. Four phase outputs are generated, taking advantage of the independent polarisation components, modulated before the combiner by a $\lambda/4$ delay unit on one beam. The combiner is a splitting cube with nominal transmission / reflection 50% on each beam; the real component specifications are above 45% for both transmitted and reflected components. After combination, the polarisation components are separated by polarising beam splitters and individually injected into four optical fibres (also acting as spatial filters) carrying the optical outputs to a PICNIC detector. The specifications are quite close to the nominal ABCD model.

The PRIMA FSU has a strict interface with the metrology system: the laser beam is injected into the combiner (acting as beam splitter) toward both telescopes, in the image of the telescope obscuration, retro-reflected and extracted after combination to provide direct monitoring of the optical paths followed by stellar photons. This adds significant constraints to the beam combiner specifications: e.g., the splitting coating works on amplitude in the external region, used by the stellar beams, and on polarisation in the metrology area.

The achromatic phase shift introducing the delay between polarisation components is implemented by triple internal reflection within a K-prism in Infrasil. A glass compensator on the unmodulated beam provides equalisation of the optical path in the dispersive medium, minimising chromatic dispersion. For all other components, symmetry between the two arms is a key specification, in order to reduce instrumental effects.

The fibre link to the detection system has challenging engineering specifications, not only because single mode K-band fibres are not commonplace. The fibre bundle is fed directly into the detector criostat, in order to minimise the thermal background, which in the long wavelength range of K band is relevant; in the criostat, the fibre ends must retain a stable and precise geometry with respect to the detector, during operations, in spite of hundreds of thermal cycles during the instrument lifetime of several years. The four fibres are mounted onto a precision mechanical reference, and aligned by means of feed-through actuators with five degrees of freedom: two lateral, one longitudinal (for image magnification) and one rotational, to match the same pixels on all four detector quadrants. In FINITO, the same functions are implemented by warm opto-mechanics on the bench. The fibre array is custom manufactured by Le Verre Fluoré (F).

The four spots corresponding to the fibre cores are imaged onto the detector by a collimator – camera system, also including a prism, used to generate low dispersion spectra rather than images. Most of the flux (about 70%) is concentrated into the central band, and the remaining fraction is split into the two side bands in nearby pixels. On-chip charge diffusion is taken into account, in the spectrograph design and in performance analysis.

All photons are used for both OPD and GD measurements; OPD performance is mostly driven by the central (large) band, whereas the GD measurement requires comparison of the differential phase shift among spectral channels. This is performed by least square fit to the global signal model, thus improving the expected performance by nearly one order of magnitude with respect to the initial ESO specification. In principle, the central band might be sampled for OPD measurement at higher rate than the side bands, used only for GD evaluation; the baseline concept is to read anyway all channels at the OPD rate, using multiple non-destructive readout, and performing digital integration of the measured flux for lower rate GD estimate, as this has simpler technical implementation and slightly better noise performance in the most common operating cases. The operations might be improved for particular cases (e.g. faint magnitude, lower precision observations), in future, also based on the initial results on the sky.

The expected performance of OPD / GD measurement depends from elementary exposure time; with 2.5 ms exposures, in average to good meteorological conditions, the limiting magnitude for OPD measurement on UT is K = 12.5 mag for 10 μas astrometry (30 nm noise threshold), K = 14 mag for K band imaging and K = 15.5 mag for N band imaging. Again, performance on AT is scaled by 3.3 mag.

The GD performance has larger range of exposure time, since it is used mostly for astronomical measurement and low frequency correction of fringe jump events. With careful tuning of the exposure time between 5 ms to 2 s, accordingly to magnitude, the GD performance is retained below the 10 μas astrometry threshold (30 nm) up to magnitude K = 18 mag.

For fainter cases, the number of fringe jumps becomes significant, so that the performance may still be retained by implementation of an efficient filtering scheme in data reduction, suppressing the undesired events.
Since spatial modulation is used, the sampling rate is compatible with OPD control loop frequency of 40 Hz, corresponding to 56 nm residual atmospheric piston in closed loop (single pole model).
The Preliminary Design Review was passed in March, 2003, and the Final Design Review was successfully completed in September, 2003. At this point, ESO issued the approval for manufacturing both units (A and B, nominally identical) of the PRIMA FSU. Procurement is in progress, and delivery is planned for the first half of 2005, with three months scheduled between delivery of FSU A and B.
Recently, a suggestion has been presented in ESO for labelling the two PRIMA FSUs with more appealing (and manageable) names: APOLLO and ARTEMIS. This is not yet an official decision.

6. OBSERVING MODES AND CALIBRATION

The basic observing mode of a two beam observation, with a scientific combiner and a FSU, requires a sequence of steps. The first is star acquisition in each telescope beam, ensuring that the image of each star, at the focal plane of each telescope, is picked up by the STS and sent towards the appropriate DL, then injected in the instruments.
The visibility is usually calibrated thanks to *calibrators*, i.e. unresolved stars (or stars with small and/or known diameter). In a sequence of measurements, the ratio of visibilities derived on target and calibrators should factor out the large instrumental contribution to visibility, assuming stability throughout the measurement. In general, also the calibrator colour should be close to that of the target, to reduce chromatic errors.
Using FINITO and AMBER with three telescopes, it is possible to evaluate simultaneously the visibility on two baselines, i.e. different sampling of the source spatial frequencies if the baseline modulus is different, and bidimensional measurement if the three telescopes are not aligned (baseline vectors not parallel). This simultaneous measurement provides an important physical information on the source structure, i.e. the *closure phase*, since the atmospheric piston cancels out when measuring the phase of the three visibilities. The sum of the detected phases is zero for a totally unresolved (point-like) source, whereas it retains information on the structure of a resolved source. In practice, instrumental phase contributes to the measurement, but this can be calibrated on unresolved stars, which are in any case required as visibility calibrators.
With three aligned telescopes, the bidimensional sensitivity is lost; the combination of UT 1, 2 and 3 is quite close to this condition. However, this provides another promising possibility, i.e. *baseline bootstrapping*. The visibility of a resolved object drops due to the different phase associated to different target points, mutually incoherent. The measurement of low visibility carries high information on the source structure, but if the same object must be used also as a reference source in the same band then the efficiency of fringe tracking drops significantly, as from Eq. (4) above. With the UT1-UT3 combination, the baseline is close to 100 m, so that an object with size 5 mas has negligible visibility; besides, using UT2 as intermediate (reference) beam for FINITO, both UT1-UT2 and UT2-UT3 combinations have nominal visibility close to 60%, which preserves low OPD noise and efficient stabilisation for AMBER in J, H or K band, i.e. a significant measurement of the low visibility value on the longest baseline.

The phase referenced imaging (PRI) mode of PRIMA requires one FSU for fringe tracking and one other instrument (AMBER or MIDI) for visibility measurement, whereas the astrometric (MA) mode requires two identical FSUs operated simultaneously on the primary and secondary stars. In the latter case, switching the sources between the FSUs provides a convenient technique for suppression of many common mode environmental and instrumental errors, removed by the differential measurement. Also, the zero phase is defined in the calibration configuration, feeding the same reference source to both FSUs: the only phase difference between the star and itself is due to the instrument.
However, the targeted astrometric accuracy requires very good knowledge of the instrument response, in terms of phase as well as of transmission. The performance and sensitivity analysis of the PRIMA FSU shows that variations to the system transmission and phase of order of 0.5% and 1 degree, respectively, are sufficient to take the instrument response close to the limiting systematic error of 2.5 nm specified for the GD measurement, compatible with the 10 μas astrometry requirements for calibrated measurement sequences. The most convenient definition of calibration is at the level of complete interferometer, as any part not measured is likely to have significant contributions, at this level.
The technique proposed for calibration is based on Fourier Transform Spectroscopy. Applying a modulation to the OPD, over a range significantly larger than the coherence length, the instrument output follows a large section of the interferogram signal; the Fourier transform of such signal gives the overall intensity distribution (modulus) and phase of the measurement. In order to factor out effectively the source emission from instrument transmission, its temperature

must be known with a precision ranging from few ten degrees for red stars (3500 K) to several hundred degrees for blue stars (T = 25000 K). A laboratory reference source may not be suitable for such calibration technique, because it is very difficult to ensure that the local source system, down to beam injection, preserves throughout the instrument lifetime its nominal transmission and phase characteristics to the desired level. Besides, some stars are supposed to be stable at the desired level, and their spectral characteristics can easily be verified to the necessary precision by different instruments and techniques. However, calibrating the system on sky requires significant observing time overheads.

Implementation of this calibration concept on the sky requires that the interferometer is stabilised, i.e. that the fringe tracking loop is closed, and this matches quite well the calibration configuration described above. The same bright star, fed simultaneously to both FSUs, defines the common zero phase for astrometry. One FSU is operated close to the zero OPD condition suitable for efficient tracking, and the other is fed with a variable offset, in order to perform the desired OPD scan. The minimum requirement for implementation of this calibration sequence is availability of STS on the selected telescopes, of the metrology system to measure the internal differential OPD, and of the two PRIMA FSUs. When the DDL will be available, they will further reduce the sensitivity to environment noise, and at the same time provide even more robust implementation of the calibration procedure.

This calibration procedure is suitable also for FINITO, in which one of the combination channels can be used to close the fringe tracking loop, whereas the latter is calibrated. The same target is fed to both channels by separate DLs or DL + DDL, picked up from two telescopes with two STSs, one of them set in calibration configuration to split the star between the two channels, and the other feeding 100% of the stellar flux to the FINITO reference beam (split internally). However, a dedicated interface to VLTI metrology has to be implemented for nm-level calibration performance.

CONCLUSIONS AND POSSIBLE FUTURE IMPROVEMENTS

Implementation of VLTI is proceeding well in spite of the instrument complexity. The available scientific combiners cover the near to thermal infrared range, and the FSUs delivered or in construction will provide support for accurate observations with either two or three beams, and may eventually deliver the capability for morphological measurement at the mas level and astrometric measurement down to the μas level.

A number of performance limiting issues have been encountered (e.g. fast injection variations probably due to turbulence in the light ducts); some have already been solved, whereas others still require improvements of the interferometer (infrared tip-tilt sensor in the laboratory – IRIS, fast tip-tilt actuator – in the STS- closing the light ducts with glass plates). In spite of larger disturbance than expected, the fringe tracking loop has been repeatedly closed with FINITO and siderostats, with encouraging performance results, given the constraints. Several noise sources still have to be significantly reduced, but work is in progress. We can expect that in the coming months the optimisation of VLTI, with a prime role of FINITO and, in due time, of PRIMA, will provide progressively improving performance.

The current instrument complement is adequate for two and three beam observations; however, it can be improved on several sides. FINITO operation might benefit of a better integration with the metrology system, now completely defined, and with reasonable efforts the temporal modulation may be replaced by the more efficient spatial modulation. Detector performance and optical throughput might be improved by component upgrade. However, for the near future it will fulfil the relevant functions of VLTI fringe tracking optimisation and three beams observations. The upgrade perspective may be evaluated in the more general framework of evolution of the whole VLTI instrument complement.

In order to achieve significant imaging capability, it is necessary to combine at least four telescopes (either UT or AT), with a geometry suitable to adequate coverage of the *u-v* plane. Again, this in principle will provide imaging at the mas scale and astrometry at the μas level; the most immediate benefit with respect to repeated two-beam measurements is a saving in telescope time by a factor two or more, depending upon the number of elementary apertures and their geometric distribution, and much better observing flexibility, since it is no longer necessary to switch telescopes or wait for sidereal motion to turn the baseline.

However, measurement simultaneity factors out a number of instrument and observing aspects, and deep integration of high performance interferometer sub-systems with optimised observation, calibration and data reduction procedures will provide the most relevant improvement with respect to the current case. It is difficult to allocate numbers to this aspect without a more detailed assessment of the current overall performance and limitations, but we can expect significant gains toward the limiting resolution and magnitude associate to the baselines and photon budget.

Besides, the simultaneous measurement of several sources at the same time, on two or more combined telescopes, in a “multiple feed” combination, might also prove useful: the phase referencing may become more robust, for both imaging and astrometry, and “bootstrapped” fringe tracking, using a second, fainter reference source in support to the primary star (e.g. in an intermediate position with respect to the science target), may provide a significantly larger sky coverage and/or lower residual OPD noise on the third observed object, with respect to current capability. Some experiments may be planned on the current VLTI instruments, properly selected.

The current experience, developed by several European teams on instrument solutions and component characteristics for efficient beam combination, and acquired thanks to the first generation of VLTI instruments, allows to identify promising design concepts for next generation multiple beam combiners, either used as FSU or as "pure science" devices. Several EU scientists involved in the VLTI instruments and in other interferometric experiments are currently joined in a coordinated effort to provide easier access to interferometer scientific usage by the astrophysical community at large, and to focus the requirements and characteristics of future developments, under a Joint Research Activity (JRA n. 4) of the EU 6th Framework Program. We work to make this interference as constructive as possible.

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REFERENCES

1. Glindemann et al., "VLTI technical advances – present and future", 2004, these proceedings.
2. Koehler, B. et al. 2004, these proceedings.
3. Arsenault, R. et al. 2004, Proc. SPIE 5490: Advancements in adaptive optics, in press
4. F. Malbet et al., "Astrophysical potential of the AMBER/VLTI instrument", *Interferometry for Optical Astronomy II*, SPIE Vol. 4838, p. 917, 2003.
5. C. Leinert et al., "The 10 micron instrument MIDI - getting ready for observations on the VLTI", *Interferometry for Optical Astronomy II*, SPIE Vol. 4838, p. 893, 2003.
6. M. Gai et al., "*The FINITO fringe sensor for VLTI*", Proc. Conference "Beyond Conventional Adaptive Optics", Eds. M. Vernet, R. Ragazzoni, S. Esposito, N. Hubin, 329-334, ESO Topical Meetings, vol. 58, 2002.
7. F. Delplancke et al., "Phase-referenced imaging and micro-arcsecond astrometry with the VLTI", *Interferometry in Optical Astronomy*, Eds. P. J. Lena, A. Quirrenbach, SPIE Vol. 4006, p. 365, 2000.
8. S. Menardi, A. Gennai, *Technical Specifications for the PRIMA Fringe Sensor Unit*, VLT-SPE-ESO-15740-2210, issue 2, 2001.
9. Derie, F. et al. 2004, these proceedings.
10. F. DelplanckeF. et al., 2004, these proceedings.
11. S.A. Leveque, "Metrology for phase-referenced imaging and narrow-angle astrometry with the VLTI", *Interferometry in Optical Astronomy*, Eds. P. J. Lena, A. Quirrenbach, SPIE Vol. 4006, p. 388, 2000.
12. S. Morel et al., 2004, these proceedings.
13. M. Gai, L. Corcione, G. Massone, "*Near IR fringe tracking for VLTI: the FINITO detection system*", Proc. Workshop "Scientific Detectors for Astronomy", Eds. P. Amico, J.W.Beletic, J.E.Beletic, Kluwer Acad. Publ., p. 341, 2003.
14. Bonino, M. Gai, L. Corcione, G. Massone, "*Instrument models and algorithms for VLTI Fringe Sensor Units: FINITO and PRIMA FSUs*", this Conference