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Fringe tracking for VLTI and LBT

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Abstract. The Osservatorio Astronomico di Torino is developing a Fringe Sensor Unit (FSU) for VLTI, in collaboration with ESO. The requirements for interferometric observation at VLTI are reviewed, describing the function of an FSU and its interaction with the instrument complement. The cases analysed are FINITO and the PRIMA FSU. Their basic operating assumptions are described, deducing performance parameters as a function of the magnitude. Specifications for fringe tracking at LBT are deduced by comparison with the VLTI case and from general scientific requirements.

Key words. Techniques: interferometric – Instrumentation: interferometers – Stars: fundamental parameters

1. Introduction

Interferometry was discovered two centuries ago (around 1801) as a laboratory phenomenon by T. Young. Utilisation of interferometric techniques for astronomical observation was then proposed (Fizeau , 1867), suggesting the possibility of accurate measurement of stellar diameters, but at the time the technological challenge involved was too great. The first practical results were obtained less than one century ago (Michelson , 1921), with what was later known as the Michelson stellar interferometer, for measurement of diameters and binaries separation. The error induced by atmospheric fluctuations was estimated in the order of 10% to 20%.

After World War II, the development of radio equipment made available to the astronomers an entirely new vision of the sky; interferometry rapidly became the standard observing technique, taking advantage of the macroscopic operating wavelength and the associated relaxed tolerances. Radio equipment operates in the wave regime: the radiation field vector is measured directly, instead of the intensity as done at shorter wavelength. The recorded signal is correlated with any other acquired instance, i.e. N radio telescopes

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can efficiently sample at the same time $N \times (N-1)/2$ baselines. The equivalent optical set-up requires fractioning by N the flux, with heavy sensitivity penalty; current interferometers in the visible or near infrared range do not foresee combination of more than two or three beams, usually. It can be shown that the brightness distribution (i.e. structure) of an object on the sky is mapped into a complex visibility function; with a set of measurements of individual visibility components, properly selected, an acceptable approximation of the original image can be restored. Efficient sampling of regions on the sky by means of telescope arrays has been demonstrated by radio astronomers, who developed the techniques for reconstructing images from a set of observations providing an adequate coverage of the frequency plane, usually referred to as the (u, v) plane; see e.g. Thompson et al. (1986).

In the last few years, interferometry in the near infrared and visible range is undergoing a fast evolution, thanks to the development of precision opto-mechanical engineering, real-time control, and detectors. Now several interferometric arrays are in operation or close to completion; the most ambitious ground based projects are the Very Large Telescope Interferometer (VLTI), developed by the European Southern Observatory (ESO) at Cerro Paranal (Chile), with the support of several national astronomical communities, and the Keck interferometer. The former is described in Glindemann et al. (2000), and the latter in Colavita & Wizinowich (2000); therein, references to relevant interferometric literature are available. The status of VLTI and its scientific instrumentation (AMBER, MIDI, VINCI) has also been presented in these proceedings (Richichi , 2001).

Hereafter, we review the main technical issues involved in the implementation of interferometry, in particular with respect to the need for fringe tracking, in Section 2. The VLTI instrumentation will take advantage of two fringe tracking subsystems: the Fringe-tracking Instrument of NIce and TOrino (FINITO) and the Phase Referenced Imaging and Micro-arcsecond Astrometry facility (PRIMA). Below we describe the architecture and operation of FINITO in Section 3 and of PRIMA in Section 4. In Section 5, we take advantage of the previously discussed elements to outline a possible implementation related to the Large Binocular Telescope (LBT). Finally, we draw our conclusions on the different applications to which the instruments are best tailored.

2. Interferometric requirements

The purpose of a FSU, in the VLTI operating scheme, is the measurement over short periods of the optical path difference (OPD) among telescope beams, in order to identify the piston disturbance induced by atmospheric turbulence. The OPD information is fed to the Delay Line (DL) control loop, which acts to compensate them by means of a fast actuator. The scientific instruments (SI) take advantage of the stabilized optical path, increasing the coherent exposure time from fractions of seconds to hundreds of seconds, with a significant sensitivity improvement in the faint limiting magnitudes, or with higher visibility accuracy on bright targets. Thus, the FSU function corresponds, in the interferometric framework, to that of a wavefront sensor for an adaptive optics system, since it is the sensor of the fringe tracking loop.

Interferometry is subject to the requirements related to models and measurements of atmospheric turbulence developed for adaptive optics. Hereafter, we adopt the modelling developed for the ESO VLTI and described in Ménardi & Gennai (2000). Above a cut-off frequency $\nu_c = 0.22 \ v/B$, depending on meteorological conditions (wind speed v) and observing configuration (baseline $B = 8 - 200 \ m$), the power spectral density (PSD) of OPD disturbance, vs. frequency ν, is approximated as

$$PSD_{OPD}(\nu) = S_0 \cdot \lambda_0^2 \cdot r_0^{-5/3} \cdot v^{5/3} \cdot \nu^{-8/3} \, ,$$

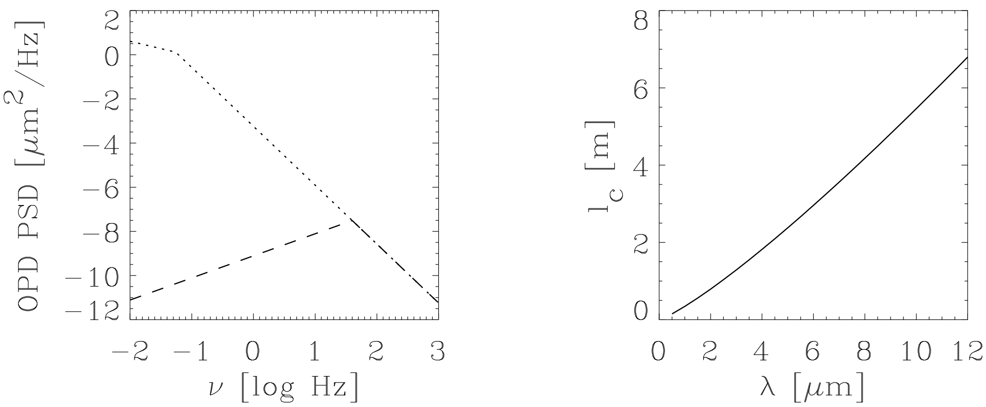

Fig. 1. Left: OPD PSD vs. logarithmic frequency in open (dotted line) and closed loop (dashed line). Right: coherence length l_c vs. observing wavelength.

where λ_0 is the reference wavelength, r_0 the Fried parameter, and $S_0 = 0.0039$ in average VLT conditions. At intermediate frequency, the spectral index is $-2/3$, whereas at low frequency the index is positive. A representation of the PSD is shown by the dotted line in Fig. 1 (left). The case considered is related to a $B = 40\ m$ baseline, $v = 10\ m/s$ wind speed, and $r_0 = 0.1\ m$ at $\lambda_0 = 550\ nm$. The PSD at low frequency is removed effectively by the DL control loop implementing the fringe tracking; a representation of the result provided by ideal feedback, with simple noise averaging and a 40 Hz bandwidth, is shown by the dashed line in Fig. 1 (left). The residual RMS noise is reduced from $\sim 20\ \mu m$ in open loop to about $2\ nm$ in closed loop. Fringe tracking supports the capability for long exposures on the scientific beam combination units; this gives access to faint targets, i.e. to larger fractions of the sky.

As for the adaptive optics case, the correlation of turbulence for two points on the sky decreases with their angular distance θ in a wavelength dependent way. Below its first corner frequency $\nu_c^{(1)} = 4.08/(\pi B)$ the PSD of the differential (or anisoplanatic) OPD can be approximated by the power law $S_{dOPD}(\nu < \nu_c^{(1)}) \sim \nu^{4/3}$; in the intermediate regime, up to the second corner frequency $\nu_c^{(2)} = 1.43 \cdot 10^{-3}\ v^{5/6}/(\pi\theta)$, the spectral index is close to $-2/3$; at higher frequency, the perturbation on the two points is totally decorrelated: $S_{dOPD}(\nu > \nu_c^{(2)}) = 2S_{OPD}(\nu)$. Correlation angular distance increases with wavelength: we expect a range of effectiveness for the fringe tracking loop of order of $10 - 20$ *arcsec* in K band, and $60 - 90$ *arcsec* at $10\ \mu m$. The accessible area around bright reference sources is much larger when observing in the thermal IR.

The increase with wavelength of coherence length (and similarly coherence time), from the adaptive optics models, is as $\lambda^{6/5}$, as shown in Fig. 1 (right). However, even in the thermal IR, baselines longer than $5 - 10\ m$ require fringe tracking to ensure OPD stabilisation and therefore allow long interferometric exposures.

Using three or more telescopes at a time, simultaneous measurement on several baselines is performed; here we consider the case of three beam observation. The three telescopes can be labelled as 1, 2 and 3; each is affected by an independent piston contribution η_n, $n = 1, 2, 3$, induced by atmospheric turbulence. Interferometric combination of telescopes m and n aims at measurement of the relative phase, $\phi_{mn} = \theta_{mn} + \eta_m - \eta_n$; the corresponding component of the target visibility distribution is associated to the term θ_{mn}. The composition of the three possible measurements effectively suppresses the atmospheric perturbations, as the disturbances are balanced out:

$$\phi_{12} + \phi_{23} + \phi_{31} = \theta_{12} + (\eta_1 - \eta_2) + \theta_{23} + (\eta_2 - \eta_3) + \theta_{31} + (\eta_3 - \eta_1) = \theta_{12} + \theta_{23} + \theta_{31} \, .$$

The summed phase is an invariant, the complex closure phase (Jennison , 1958); together with the closure phase amplitude, it provides an astrophysical insight on the target structure: the real part of the visibility is the Fourier transform of the symmetric part of the image, whereas the imaginary part is its anti-symmetric component. Practical implementation of the closure phase technique requires fringe tracking over two baselines at a time; the third baseline is automatically stabilised (apart noise propagation).

3. FINITO

The Osservatorio Astronomico di Torino, in collaboration with ESO, is engaged in the development of a fringe sensor unit (FSU) to be installed at VLTI. The instrument concept was tested in a laboratory prototype developed by the Observatoire de la Côte d'Azur (Nice); the final version is therefore named FINITO, for Fringe-tracking Instrument of NIce and TOrino. The new instrument adheres to the current optical prescriptions of VLTI, standard VLT electronics, and a high sensitivity array detector. The integration of FINITO is in progress, and its delivery to ESO is expected to be in Autumn, 2002; the instrument architecture and operation is described in Gai et al. (2001). FINITO is the only FSU currently planned supporting simultaneous observations on three beams, allowing closure phase measurements in the near and mid IR range.

FINITO is an interferometric instrument based on amplitude (afocal) combination of two or three telescopes beams, operating in H band ($\lambda\lambda = 1.48 - 1.78\ \mu m$), using fibre optics for spatial filtering and optical path modulation. FINITO will be fed by either the 40 cm siderostats, the 1.8 m Auxiliary Telescopes, or the 8.2 m Unit Telescopes.

The FINITO capability of operating with small separation on the sky between the primary and secondary source allows to scan complex sources, with the individual telescope resolution ($\sim 50\, mas$, K band), in either visibility or closure phase measurement configuration. By comparison, the interferometric resolution with $B = 100\ m$ baseline, in K band, is related to a fringe period $\lambda/B = 4$ milli-*arcsec*.

The functional scheme of FINITO is shown in Fig. 2. The VLTI beams are fed through an optics providing longitudinal and lateral compensation of the chromatic mismatch between the FSU and the scientific instrument, operating at different wavelength. The optical path of each beam is modulated by piezoelectric devices, stretching a monomode, polarisation maintaining optical fibre, developed by IRCOM; the modulation law is controlled in closed loop by a metrology laser beam at shorter wavelength ($\lambda_L = 1310\, nm$), injected before and extracted after the modulators. The single mode fibre acts as a spatial filter, suppressing the phase noise associated to the most aberrated parts of the wavefront. The two beam combiners are individually optimised to provide four metrology outputs in quadrature (with a more uniform sensitivity over the modulation period), and four astronomical outputs in phase opposition to achieve the maximum sensitivity. The two polarisation components of the telescope beams are affected by different instrumental phase contributions, so that one of them is removed, to preserve the OPD estimate accuracy, and used as a photometric measurement on each beam for normalisation of the interferometric outputs. The four plus three outputs are conveyed via fibre optics to a PICNIC array detector,

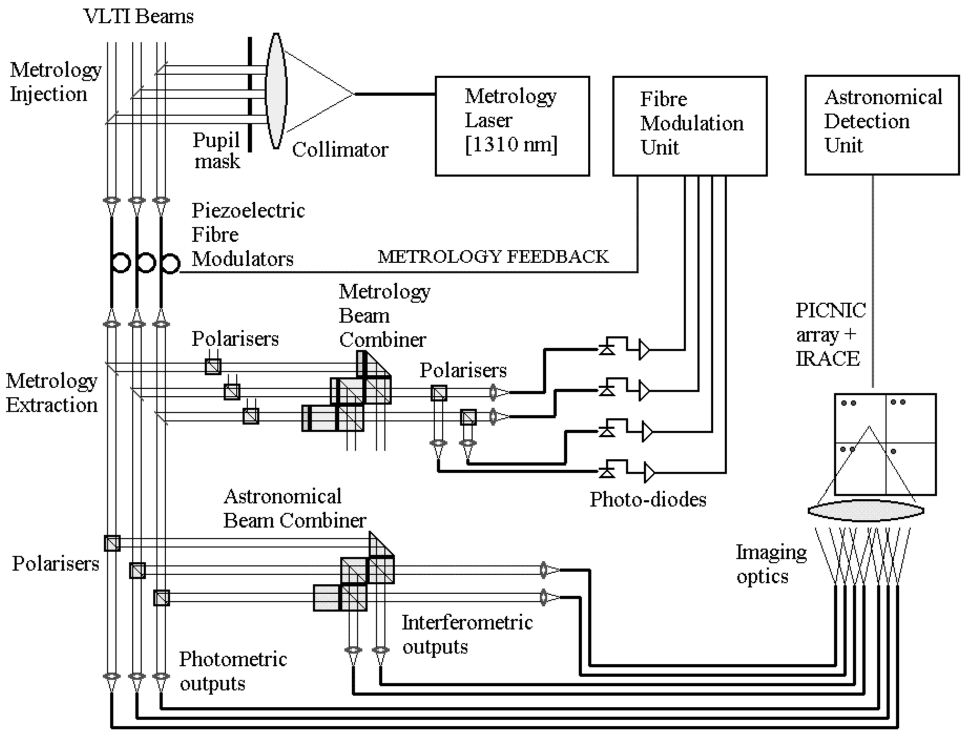

Fig. 2. Conceptual schematic of FINITO

driven by the ESO IRACE electronics.
The interferogram phase detection, on a time scale of the order of 1 ms, provides an OPD estimate which is forwarded to the DL Controller for real-time correction. The targeted limiting magnitude is $H \simeq 12\,mag$ on UT, for a threshold of 30 nm on OPD sensing noise; with a more relaxed imaging requirement of $\lambda/20$ OPD sensing noise, assuming a fine tuning of the elementary exposure time, and adequate meteorological conditions, the limiting magnitude is close to $H \simeq 16\,mag$ for observations in K band, and $H \simeq 18\,mag$ at 10 μm.

4. PRIMA

The concept of PRIMA has been studied specifically for VLTI (Quirrenbach et al. , 1998), but it is applicable to other large dilution interferometers as well. The field of view of the VLTI single feed is small, about 2 *arcsec*, due to the large beam compression. However, it is possible to measure simultaneously two objects separated by a comparably large angular distance, as allowed by the isoplanatism constraints, selecting the corresponding patches on the sky and feeding them separately to the combination lab and the instruments. This alleviates significantly the technical requirements, and allows integration on faint scientific targets within appropriate distance from a bright unresolved source, used as a reference. PRIMA is based on four main functional units:
– *Star Separator (STS),* picking up the selected regions at a suitable focal plane of each telescope, collimating the beams and sending them along the main DL;
– *Metrology,* providing an accurate measurement of the internal optical paths, be-

tween combination units and telescopes, corresponding to the position on the sky;
– *Differential Delay Line (DDL),* correcting for the OPD between the primary and secondary regions, and therefore measuring their coarse angular separation;
– two identical *Fringe Sensor Units,* one used for OPD stabilisation, and the other providing an high resolution phase measurement for high precision astrometry.
The separation between two point-like sources is given by combination of the DDL and FSU phase information, in *astrometric mode.* Visibility measurements in different baseline combinations can be used to perform reconstruction of the brightness distribution on the sky, in *imaging mode*, using as detector either one FSU or one of the scientific combination units, AMBER or MIDI, depending upon the desired astrophysical information and therefore operating wavelength. Measurement accuracy is ensured by the metrology system and an advanced calibration scheme including prescriptions for switching the beams at different levels of the interferometer. This implements a differential measurement technique aimed at suppressing systematic errors, similarly to medium IR observations.
PRIMA is a modular instrument: the overall interferometer configuration can therefore be tailored accordingly to the observing needs. In particular, the STS can be used in combination with FINITO as FSU and one of the scientific combiners (e.g. AMBER) to support the three beam observing capability over the large field of view accessible, i.e. up to 1 *arcmin* diameter, compatibly with atmospheric conditions. The PRIMA FSU will operate in K band, with possible upgrade to H, K or H + K to improve sensitivity and reduce wavelength competition with the near IR instruments. The PRIMA FSU sensitivity takes advantage of static operation, optimised optical concept and larger accessible spectral bandwidth, achieving a potential limiting magnitude of order of $K \simeq 13\ mag$ on UT, for 30 nm OPD sensing noise (10 $\mu arcsec$ astrometry), $K \simeq 17\ mag$ for imaging in the near IR, and $K \simeq 19\ mag$ for imaging in the thermal infrared bands. The industrial calls for tender for manufacturing of the PRIMA sub-systems are being issued by ESO at the time of writing.

5. LBT

The status of LBT and its interest to the Italian astronomical community have been presented in these proceedings (Miglietta , 2001). The key aspects of the LBT interferometer (LBTI) are that it is a low dilution instrument, endowed with an high order adaptive optics. It works as a Fizeau type (homothetic) combiner, producing on the interferometric focal plane a large field image with comparable resolution on both directions (25 *mas* fringe period, 100 *mas* Airy disc diameter in K band). Coverage of the (u, v) plane is thus eased because each observation provides information over a large frequency domain, so that complex structures can be reconstructed efficiently with a small number of different baselines (Bertero & Boccacci , 2000). The high order (or multi-conjugate) adaptive correction foreseen on LBT also provides a superb interferometric sensitivity, because of the very high instrumental visibility.
The common alt-azimuthal mount results in a significant system simplification, because the optical paths from each arm are intrinsically balanced and no delay line is required. The minimised internal optics improves the throughput, above all at longer wavelength, and reduces the instrumental disturbances. LBTI can implement the capability for phase referenced imaging with minimum upgrade of its facilities: with respect to PRIMA, only the star separator and fringe sensor functions are required, as a first step; also, the metrology requirements are relaxed because of the compact structure. A fringe tracking loop is still required, for both near and thermal IR, from the considerations of Section 2. A simple implementation concept is shown in Fig. 3: the reference target is picked up from an intermediate combined focal plane and fed to

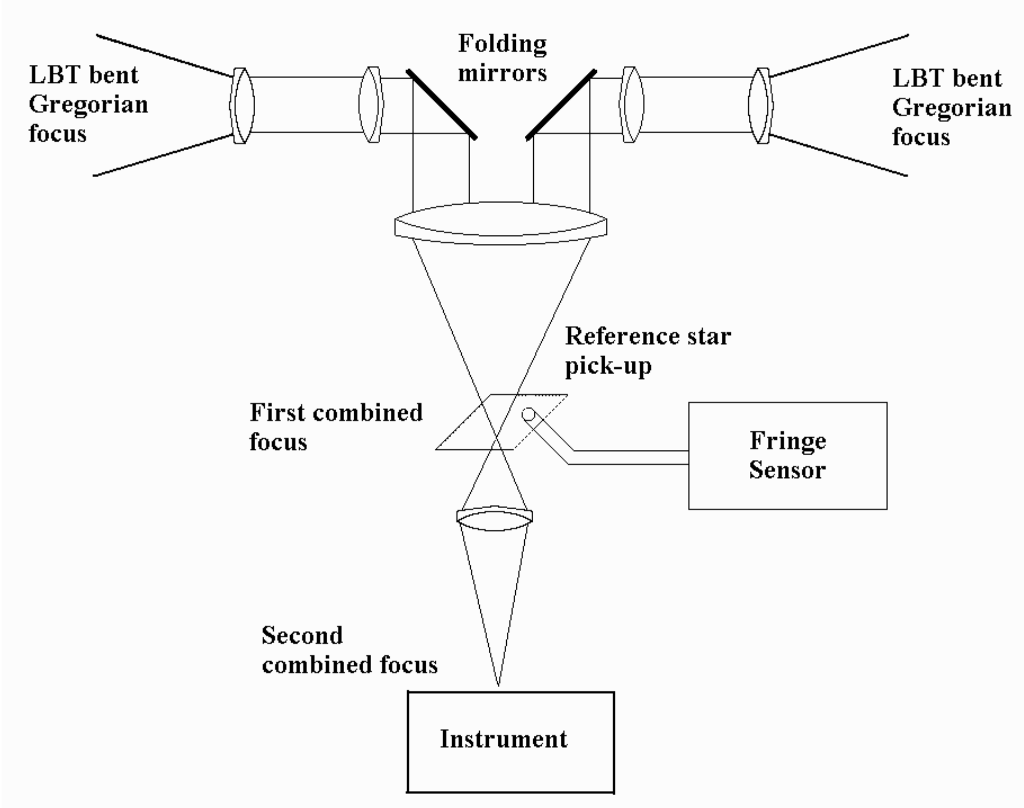

Fig. 3. Implementation concept of beam combination and OPD stabilisation on LBTI.

the fringe sensor, which provides the OPD information to an actuator in the combination train, closing the stabilisation feedback loop; the combined beams reach the scientific instrument (interferometric camera or spectrograph) through a relay optics.

The performance of an LBT fringe sensor depends upon several implementation choices: operating wavelength (H, K or H + K), structure of the reference target pick-up, phase detection strategy. Retaining the basic concepts of FINITO and the PRIMA FSU, thanks to the higher adaptive correction and throughput, the limiting magnitude for imaging can be improved to $H \simeq 17\ mag$ for imaging in K band, and $H \simeq 19\ mag$ at 10 μm. Suitable design trade-offs are to be defined accordingly to operation and performance requirements.

6. Conclusions

The limiting reference source magnitude achievable by VLTI (on UT) and LBTI, with an appropriate fringe tracking subsystem, is roughly comparable, so that jointly they can observe nearly anywhere on the celestial sphere, with a coverage of order of a few times 1% of the sky. However, they are quite different instruments, best tailored for complementary, rather than competitive, astrophysical measurements. The resolution achieved by VLTI is unchallenged; besides, the (u, v) plane for an extended target is covered much more efficiently by LBTI. So, VLTI appears optimal for high resolution measurements on morphologically simple sources, whereas LBTI is more suited to complex objects, sampled at lower, but rather uniform, resolution.

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