A Giant Step: from Milli- to Micro-arcsecond Astrometry
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The ESPRI project: narrow-angle astrometry with VLTI-PRIMA

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Abstract. We describe the ongoing hardware and software developments that shall enable the ESO VLTI to perform narrow-angle differential delay astrometry in K-band with an accuracy of up to 10 μarcsec. The ultimate goal of these efforts is to perform an astrometric search for extrasolar planets around nearby stars.

Keywords. instrumentation: interferometers, techniques: high angular resolution, techniques: interferometric, astrometry, planetary systems, infrared: stars

1. Overview: VLTI, PRIMA, and the ESPRI project

The ESO Very Large Telescope Interferometer (VLTI) consists of four stationary 8.2-m VLT "Unit Telescopes" (UTs), four movable 1.8-m "Auxiliary Telescopes" (ATs), and six long-stroke dual-beam delay lines (DLs). It provides baselines of up to 200m length and covers a wavelength range that extends from the near infrared (1 μm) up to 13 μm.

PRIMA, the instrument for Phase Referenced Imaging and Micro-arcsecond Astrometry at the VLTI, is currently being developed at ESO. It will implement the dual-feed capability for two UTs or ATs to enable simultaneous interferometric observations of two objects that are separated by up to $1'$. PRIMA is designed to perform narrow-angle astrometry in K-band with two ATs as well as phase-referenced aperture synthesis imaging with instruments like Amber (Petrov *et al.* 2000) and Midi (Leinert *et al.* 2003). PRIMA is composed of four major sub-systems: Star Separators (STS), a laser metrology system (PRIMET), Fringe Sensor Units (FSUs; see Sahlmann *et al.* 2008), and Differential Delay Lines (DDLs) (Quirrenbach *et al.* 1998; Delplancke *et al.* 2000; Derie *et al.* 2003). The first three subsystems are currently being tested at ESO, but the fate of the DDLs, which are crucial for reaching high astrometric precision, was insecure until 2004.

In order to speed up the full implementation of the 10 μarcsec astrometric capability and to carry out a large astrometric planet search program, a consortium lead by the Observatoire de Genéve (Switzerland), Max Planck Institute for Astronomy, and Landessternwarte Heidelberg (both Germany), is currently building the DDLs for PRIMA and develops the astrometric observation preparation and data reduction software. The facility is planned to become fully operational in early 2009. In return for its effort, the consortium has been awarded guaranteed observing time with PRIMA and two ATs to carry out a systematic astrometric Exoplanet Search with PRIMA (ESPRI).

2. The method: narrow-angle astrometry with PRIMA

A two-telescope interferometer measures the delay between the wavefront sections from a star as they arrive at the telescopes. However, atmospheric piston perturbations usually prohibit accurate measurements of this delay in absolute terms. To circumvent this problem, a dual-star interferometer like PRIMA measures the differential delay between two stars. When their angular separation is smaller than the isoplanatic angle of the atmosphere ($\approx 10''$ in K-band), the piston perturbations of the two wavefronts are correlated and the differential perturbations ($\Delta\mathrm{OPD}_{\mathrm{turb}}$) average to zero rapidly (Shao & Colavita 1992). If one of the stars is bright enough to measure its fringe phase within the atmospheric coherence time, it can be used to stabilize the fringes on the other star (fringe-tracking), thus allowing for much longer integrations and hence increasing the number of observable objects. In order to obtain fringes on the detector, the external delay difference, which is directly related to the angular separation ($\Delta\alpha$) via the interferometer baseline (B), must be compensated with optical Delay Lines in the interferometer. At zero fringe position external and internal delays are equal. For astrometry, the two stars are supposed to have intrinsic phase (Φ) zero. The laser-monitored internal delay ($\Delta\mathrm{OPD}_{\mathrm{int}}$) together with the residual differential fringe phase ($\Delta\mathrm{OPD}_{\mathrm{FSU}}$) is then the primary observable of the interferometer (see Fig. 1).

In PRIMA, the dual feed is realized with Star Separators (STS) at the Coudé foci of the telescopes, which pick up two sub-fields with the target and astrometric reference star and feed them as separate beams to the DLs. In order to minimize the effects of air turbulence in the tunnels, the two star beams are sent parallel through one main DL. The large optical path difference (OPD) between the two telescopes, that is to first order common to both stars, is thus compensated without introducing further differential perturbations. Due to the non-zero angular separation between the two stars and the diurnal motion, there is however also a variable differential OPD between the two stars. After the main DLs, the beams of two stars are therefore sent to separate DDLs that operate in vacuum and provide a much smaller stroke ($\leqslant$60 mm). On a 100 m baseline, 10 μarcsec correspond to 5 nm OPD, which defines the total error budget for DDLs, fringe detection, and metrology. The beams from the two telescopes are then interferometrically combined in the PRIMA Fringe Sensor Units (FSU). The measured fringe phase of the brighter star is used to control the DLs and DDLs and to stabilize the fringes of the fainter star. A second FSU, that can now integrate much longer, measures the fringe phase of the fainter star. An approximation to the internal OPD in the interferometer is measured by the on-axis end-to-end laser metrology system PRIMET.

Based on the error budget and preliminary exposure time calculator, the minimum K-band brightness of reference stars required to reach 10 μarcsec is $\mathrm{K} \leqslant 14$ mag (Tubbs *et al.* 2008). The maximum separation between target and reference star is $\approx 15''$. Figure 2 shows the dependence of astrometric accuracy on stellar brightness for $10''$ separation.

3. Differential delay lines and astrometric data reduction software

Hardware developments: The design of the DDLs has been developed by the consortium in close collaboration with ESO. The DDLs consist of Cassegerain-type, all-aluminum retro-reflector telescopes (cat's eyes) with $\approx$20 cm diameter that are mounted on stiff linear translation stages. A stepper actuator at the translation stage provides the long stroke of up to 60 mm, while a piezo actuator at M3 in the cat's eye provides the 1 nm resolution fine stroke over $\approx 10\,\mu$m. Together with an internal metrology system, the DDLs are mounted on a custom-made optical bench in non-cryogenic vacuum vessels. The cat's eye optics has been successfully tested at MPIA and is currently being integrated with the other DDL components and prepared for acceptance tests in Geneva (see Fig. 3).

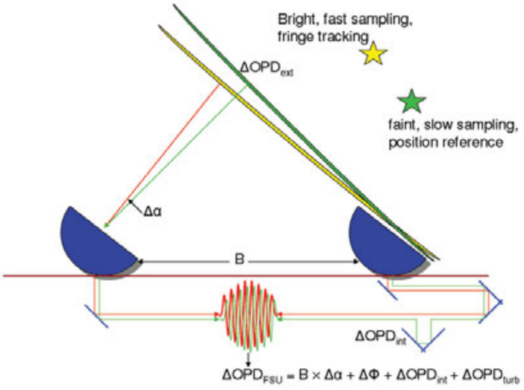

Figure 1. Measurement principle: astrometry with differential delay interferometry.

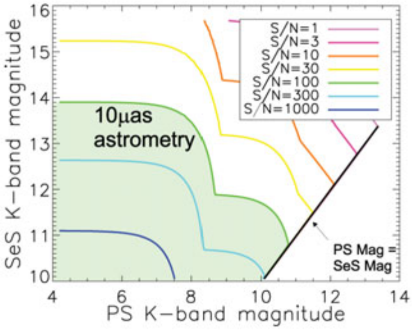

Figure 2. Dependence of astrometric accuracy of PRIMA with two ATs on stellar brightness for 10″ separation between primary (PS) and secondary (SeS) star and 30 min integration.

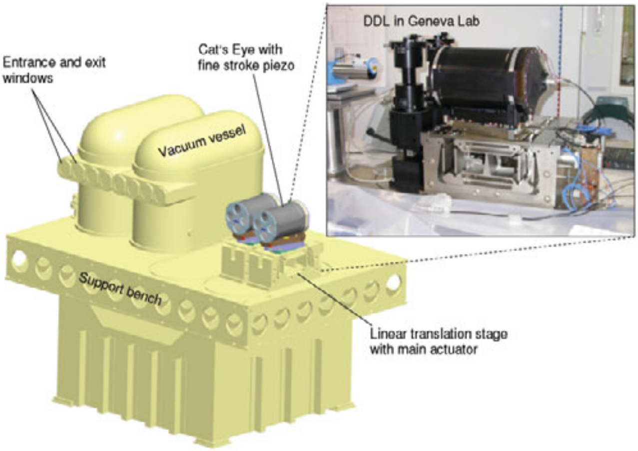

Figure 3. Final design of the Differential Delay Lines and photograph of the first DDL cat's eye on the translation stage in the Lab at Geneva observatory (setup for acceptance tests).

Software developments by the ESPRI consortium include Observation Preparation Software for PRIMA astrometry and the complete astrometric data reduction system (see Fig. 4). Data reduction from raw instrumental data to calibrated delays will proceed fully automatically with two pipelines and a set of calibration parameters that is re-derived every few months from all available PRIMA astrometry data (Elias *et al.* 2008). The software packages will be delivered to ESO prior to commissioning of the instrument and will be available to all users. The conversion of calibrated delays into astrophysical quantities like, e.g., planet orbits, is the responsibility of the user.

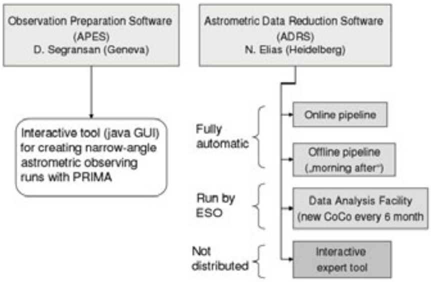

Figure 4. Overview of astrometric software developments for PRIMA.

4. Science goals: the Exoplanet Search program

Starting in spring 2009, we want to carry out a systematic astrometric Exoplanet Search with PRIMA (ESPRI), which will address the following key questions: *(i)* Precise determination of the planetary mass distribution, *(ii)* Detection of new Saturn- down to Uranus-mass planets around nearby stars, *(iii)* Formation and evolution of multiple planetary systems, and *(iv)* Exploring planet formation as a function of stellar age and mass. With these objectives in mind, we have defined three lists of potential targets, containing in total nearly 900 stars: *1.* Stars with known radial velocity planets, *2.* Nearby main-sequence stars within 15 pc around the Sun, and *3.* Young stars with ages 5-300 Myr within 100 pc around the Sun. We are currently carrying out an extensive preparatory observing program to identify suitable astrometric reference stars and to characterize the planet search target stars (Geisler *et al.* 2008). With a final detection rate for reference stars of 10-15%, we will then monitor $\approx 100-150$ stars for astrometric signatures of extrasolar planets. The scientific program and detection spaces are described in more detail in Launhardt *et al.* (2008 - IAU 249).

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