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Towards High-Precision Ground-Based Astrometry: Differential Delay Lines for PRIMA@VLTI

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Abstract.
Deriving unambiguously the orbital parameters and masses of extrasolar planets requires at least 2-dimensional information on either the positions or motions of the planet directly (currently out of reach) or, indirectly, of the host star. The latter can be done with high-precision astrometry at the 10 microarcsec level. To achieve this goal, a consortium with partners from Germany, the Netherlands, and Switzerland, in agreement with ESO, will enhance the PRIMA system at the VLTI with Differential Delay Lines. The PRIMA facility will implement dual-star interferometry at the VLTI, thus enabling narrow-angle differential astrometry. The purpose of the Differential Delay Lines in PRIMA is to increase the astrometric accuracy by separating the large OPD correction terms which are common for target and reference star from the small differential terms, and to increase the sensitivity by stabilizing the fringe pattern and thus allow for longer integrations. This paper gives an overview of the PRIMA-DDL project, which consists of developing hardware, astrometric operation tools, and data reduction software, and outlines the anticipated astrometric planet search program to be carried out with this facility.

1. The VLTI as an astrometry machine

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. When fully operational, the VLTI will provide both high sensitivity as well as milli-arcsec angular resolution on baselines of up to 200m length. The four UTs are fully operational. The first AT was installed at Paranal in January 2004. ATs 2 to 4 will be installed in early 2005 - 2006. The useful wavelength range extends from the near UV up to 25 μm in the infrared. Three interferometric instruments are already working at the VLTI, the fourth instrument is currently being built, and a fifth one is in the study phase (see also http://www.hq.eso.org/projects/vlti/instru/):

1. VINCI, the VLTI INterferometer Commissioning Instrument (Kervella et al. 2000) obtained its first 2-beam fringes in K-band with the siderostats in March 2001, and with the UTs in October 2001.
2. MIDI, the MID-Infrared interferometric instrument (Leinert & Graser 1998; Leinert et al. 2003), recorded its first fringes with 2 UTs on a 100 m baseline in Dec. 2002. MIDI is now routinely producing scientific results (e.g., Jaffe et al. 2004; Leinert et al. 2004).
3. AMBER, the Astronomical Multiple BEam Recombiner (Petrov et al. 2000) is working in the red and near-infrared, has a spectral resolution of up to 10000, and can combine three beams. Through phase closure techniques, AMBER is able to obtain images. First fringes with three UT beams were obtained in May 2004.
4. GENIE, the Ground-based European Nulling Interferometer Experiment (Gondoin et al. 2003), currently in the definition study phase, is a partnership between ESA and ESO. The instrument will be installed at the VLTI and will be both a technology demonstrator for ESA's Darwin planet finder mission and a scientific VLTI instrument.
5. PRIMA, the instrument for Phase Referenced Imaging and Micro-arcsecond Astrometry (Quirrenbach et al. 1998; Delplancke et al. 2000; Derie et al. 2003) is currently being developed at ESO. PRIMA will implement the dual-feed capability for both UTs and ATs to enable simultaneous interferometric observations of two objects - each with a maximum size of 2 arcsec - that are separated by up to 1 arcmin, without requiring a large continuous field of view. PRIMA will be composed of four major sub-systems: Star Separators, Differential Delay Lines (DDLs), a laser metrology system, and Fringe Sensor Units (FSU). The system is designed to perform high-accuracy (10 μas) narrow-angle differential astrometry in H and K-band with two FSUs and, with one FSU in combination with AMBER or MIDI, phase-referenced aperture synthesis imaging.

Ground-based interferometry is limited by differential distance between the telescope apertures due to atmospheric turbulence. This induces an almost random wobble of the fringe positions with time and thus strongly limits both the useful integration time and the measurement accuracy on the fringe positions. With a dual-feed system like PRIMA, it is possible to measure with high speed the fringes on a bright off-axis guide star and, over an Optical Path Difference (OPD) control loop, stabilize the fringes on the faint object, thus allowing longer integration times. This will increase the limiting magnitude of the VLTI with both UTs and ATs at near and mid-infrared wavelengths by about six magnitudes, to the benefit of any other interferometric instrument, if PRIMA is operated as an external fringe tracker. Moreover, if one of the two objects is used as a phase reference and if the differential OPD is measured with an accuracy of better 10 nm, the intrinsic phase of the second object can be derived with an accuracy of 2° (imaging mode) or the angular distance between the two stars can be measured with an accuracy of 10 μas (astrometry mode; in K-band on a 200 m baseline, with SNR > 50 and for angular separations $< 20''$). The baseline vector has to be known to $\approx 50\,\mu$m (Quirrenbach et al. 1998). For angular separations of $10''\ldots20''$ and half-hour integrations, a measurement error of 10 μas is comparable to the astrometric error introduced by atmospheric turbulence (Shao & Colavita 1992; von der Lühe et al. 1995). A total allowable error of 10 nm for the differential OPD on a 200 baseline means that the raw delays have eleven significant digits! Such an accuracy can only be achieved through a triple-differential measurement technique (Quirrenbach et al. 2004):

1. Observing two stars with small angular separation to reduce the effects of atmospheric turbulence on the differential OPD.

2. Measuring the optical pathlength within the interferometer with a laser interferometer metrology system. Errors are thus introduced only by the differential effect of changes within the interferometer between the starlight and the metrology beams.

3. The orbits of extrasolar planets are derived from the variation of the position of the host star over time, measured with respect to the position of one or several other (reference) stars.

The primary observable in narrow-angle differential astrometry mode is the difference of the fringe positions of the two stars, which is composed of the laser metrology monitored difference in optical path length within the interferometer and the difference of the measured fringe positions.

2. The quest for extrasolar planets

The scientific objectives of PRIMA are:

- Studying binarity of massive stars: while spectroscopic measurements are very efficient in deriving binary frequency and orbital characteristics of low-mass stars, almost no data are available for massive stars. Precise astrometry could put constraints on the duplicity statistics of massive stars, which would have a great impact on our understanding star formation in general and the formation of massive stars in particular.

- Measuring distances throughout the Galaxy: with 10 μarcsec astrometry, trigonometric parallaxes of, e.g., Cepheids, can be measured with a precision of 0.1% out to distances of 100 pc and 10% out to 10 kpc.

- Dynamics and mass distribution in the galactic center: when high-precision astrometry is combined with radial-velocity measurements, 3-D space velocities can be derived, which would improve our understanding of the dynamics, mass distribution, and history of the galactic center.

- Although limited by the availability of reference stars, 10 μarcsec astrometry would be capable of measuring the photocenter shift of starburst AGN due to supernova explosions.

However, the primary objective and main science driver for developing the 10 μas facility is the detection and characterization of extrasolar planets and their birth environments. In less than 10 years after the first detection of a planet orbiting another star (Mayor & Queloz 1995), more than 120 giant extrasolar planets have been discovered. This avalanche of results has opened a very exciting field of research: exploration of the characteristics of other planetary systems. The discoveries of the past few years have stimulated new planetary formation models leading to a new picture of planet formation. Until today, all extrasolar planets found around stars in the vicinity of the Sun have been detected by radial-velocity measurements. Searching extrasolar planets via precise astrometry is a very complementary approach. Astrometry has a different detection space and it has the advantage of being able to measure all orbital parameters and planet masses, unlike the radial-velocity method which leaves the inclination angle of the orbit (*sin i*) undetermined, thus providing only a lower limit to the mass of the planets. However, to play a significant role, an astrometric accuracy of order 10 μarcsec is needed, which is clearly illustrated by Fig. 1. Such an accuracy is beyond the performance of current instrumentation.

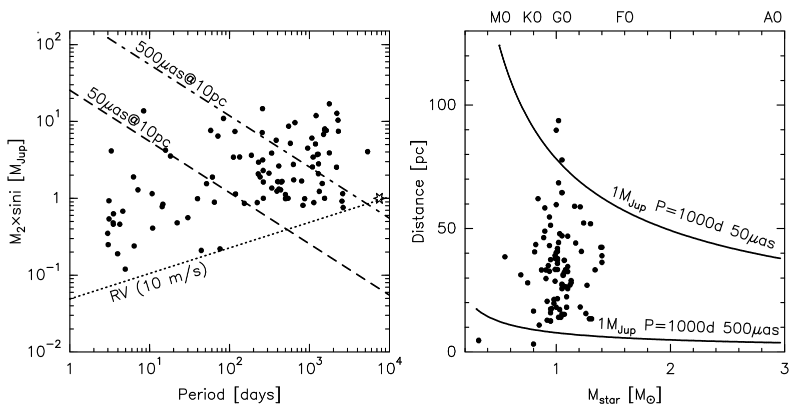

Figure 1. **Left:** Planet mass vs. orbital period, with known radial-velocity planets indicated. The dotted line shows the typical detection limit of radial-velocity surveys. Dashed lines indicate the astrometric detection limit for planets around a 1 $M_\odot$ star with PRIMA without DDLs ($5\,\sigma = 500\,\mu$as) and with DDLs (50 μas). **Right:** Distance vs. mass of planet host star. Only planets below the $5\,\sigma$ astrometric detection limit curves can be detected.

3. Differential Delay Lines and Astrometric Software for the VLTI

In order to speed up the full implementation of the 10 μas astrometric capability of the VLTI and to carry out a large astrometric planet search program, a consortium lead by the Observatoire de Genève (Switzerland), the Max Planck Institute for Astronomy in Heidelberg (Germany), and the University of Leiden/NOVA (The Netherlands) agreed with ESO to build and deliver the Differential Delay Lines for PRIMA and to provide all necessary operation and software tools to perform narrow-angle astrometry at the 10 μas level. This includes developing and building all the DDL hardware, the construction and analysis of the astrometric error budget, the establishment of an operations and calibration strategy, and the development of observation preparation and data reduction software.

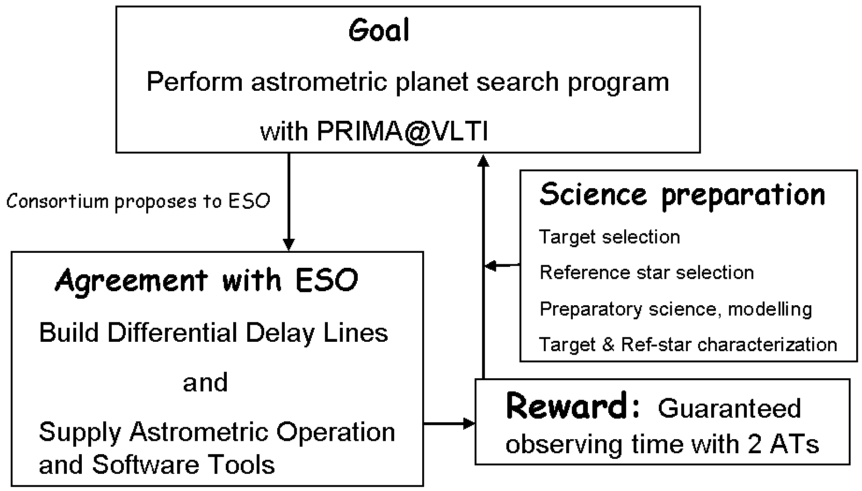

Figure 2. General overview of the PRIMA astrometric Planet Search project.

The purpose of the DDLs in differential (phase-referenced) astrometry is to increase the astrometric accuracy by separating the large OPD correction terms which are common for target and reference star from the small differential terms, and to increase the sensitivity by stabilizing the fringe pattern and thus allow for longer integrations. The DDLs will compensate the varying differential OPD between the optical paths of the two observed stars due to diurnal motion (up to 120 mm) with a resolution of < 2.5 nm. In a closed loop with the metrology system and with the help of the FSUs, the DDLs will also allow to track the fringes by applying real-time offsets. Another important function of the DDLs is to re-image the pupils in the VLTI beam-combination laboratory. The advantages (suppress the effects of the not accurately enough known differential longitudinal dispersion in air between the two astrometry beams and between the laser metrology and astrometry wavelengths) and disadvantages (differential dispersion due to the vacuum windows) of operating the DDLs in vacuum are currently under discussion. Irrespective of the final answer, which we may obtain only through measurements, the DDLs will be built to be compatible with operation in vacuum. Currently, the design of the optomechanical system, the vacuum vessels, and the internal metrology is being finished and the first prototypes of the translation stages are being tested.

A careful a priori analysis of all error terms that are relevant for the astrometric mode of PRIMA is crucial for designing and implementing the hardware, data reduction software, and a posteriori trend analysis facility. As a first step towards a full formal error budget, we have classified the different error terms and constructed a top-level error tree which includes atsrophysical, atmospheric, terrestrial, and instrumental terms as well as fringe sensing noise, baseline errors, and calibration errors (Quirrenbach et al. 2004; Bakker et al. 2004; Le Poole et al. 2004). Individual instrumental contributions like, e.g., dispersion and polarization effects, and astrophysical errors like, e.g., stellar chromospheric activity effects (see also Reffert et al. in this volume) are already studied in detail and first results will be published soon.

An astrometric operations and calibration strategy has to be developed that links the astrometric error budet, PRIMA-VLTI operations, PRIMA hardware subsystem performance, and data reduction strategy. Alternative approaches for operation and calibration strategies are currently under discussion. However, at this early stage a trade-off between alternative approaches cannot be made yet.

We are currently developing a fully automatic Astrometric Data Reduction System (ADRS), with an interactive Data Analysis Facility on top (Bakker et al. 2004; de Jong et al. 2004). The astrometric data reduction will proceed in several steps, each one building on the previous, to derive calibrated astrometric data from instrumental data streams. However, practical experience shows that simple "forward modeling" of systems as complex as PRIMA is unlikely to identify all sources of systematic error. In particular, certain astrometric error terms and trends cannot be predicted reliably or measured directly (e.g., dynamic temperature gradients in the VLTI light ducts, long-term or quasi-periodic changes of the interferometer geometry due to motions of the ground on the mountain). These error terms may have to be described with parametrized models which are derived from the astrometric data themselves. The ability to detect, diagnose, and correct such unanticipated effects is of crucial importance for the success of such a high-precision long-term astrometric program. The final calibration terms are thus derived in a non-linear and iterative, partially automatic and partially interactive fashion. The actual data reduction and application of the calibration terms will, nevertheless, proceed in a straight-forward, fully automatic and reproducible way. This implies that the data may have to be processed several times, where the starting point may not always have to be the raw data, but could be intermediate data products generated from earlier runs of the ADRS. An important aspect of the ADRS is the complete consistency, traceability, and reproducibility of the calibration and data reduction over periods of many years.

4. The astrometric planet search program

When completed in 2007, we will use the upgraded PRIMA system to carry out a large observing program to detect and characterize extrasolar planets through the reflex motions of their host stars in the plane of the sky. Two core programs are planned to be carried out mainly within the awarded guaranteed observing time over a duration of three years:

1. The first goal will be to observe all stars with known radial-velocity planets that are in reach of the VLTI and have at least one suitable phase reference star. For those star planet systems that produce a large enough astrometric signal, we will resolve the $\sin i$ uncertainty of the planet masses and measure the orbital eccentricity. For stars with multiple planetary systems we will derive the relative inclination of the orbits, an important indicator of gravitational interaction between the planets. We will follow up long-term radial velocity trends and search for new planets in longer-period orbits for which astrometry is more sensitive than the radial velocity method (see Fig. 1). We estimate that, starting 2007, we will observe $20-25$ stars with known radial velocity planets or planetary systems.

2. The second core program consists of a planet search through the main sequence and time around ~ 100 nearby stars without known planets. The

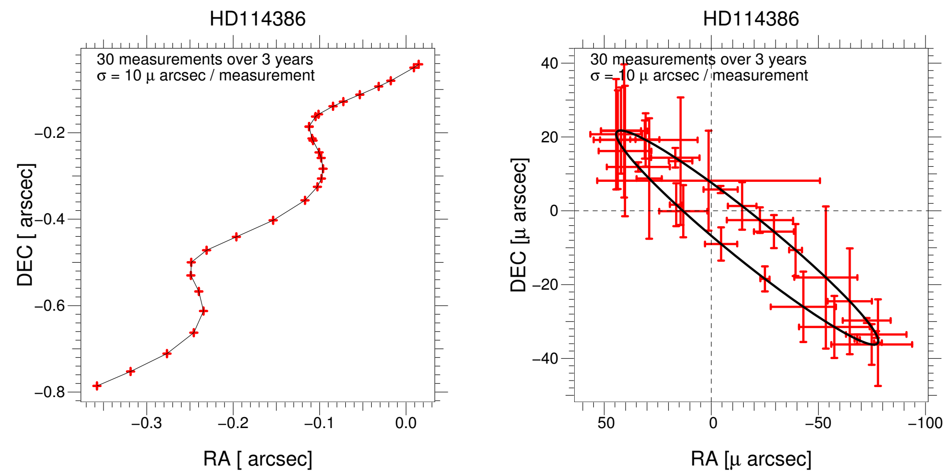

Figure 3. Illustration of parallax and orbital parameters retrieved from a global fit on the astrometric measurements for HD 114386. For this simulation we assumed $i = 84$ deg, $\Omega = 25$ deg, and 30 measurements spread on 3 years and evenly distributed over the orbital phase.

search for planets by the radial-velocity technique is restricted to stars with narrow and stable spectral lines, thus excluding A and most F stars with their broad spectral lines as well as young, chromospherically active and fast rotating stars. This prevents us from getting a comprehensive understanding of planet formation around massive stars as well as the possible orbital evolution of planetary systems in their early stages. Our astrometric planet search program will explicitly include such stars.

To ensure an efficient and success-oriented preparation of the astrometric planet search program, we have established a core Science Team that shall later be expanded. The Science team will specify the precise scientific goals and target groups of the planet search program, select the target objects, undertake all necessary scientific preparations, including preparatory observations, and plan and carry out the astrometric observing program.

5. Preparatory roadmap

To select suitable target and reference star pairs and to guarantee their astrometric stability at the 10 μas level, we are currently investigating and modeling the astrometric effects of, e.g., chromospheric stellar activity, unseen stellar and substellar companions, perspective acceleration, etc. (see paper by S. Reffert et al. in this volume). Based on these studies we are developing reference star selection criteria and preparing a users guide for PRIMA astrometric target and reference star selection.

Since many stellar parameters required to characterize the astrometric stability of a star at the 10 μas level cannot be derived from existing data or catalogs, we are also developing a preparatory observing strategy and have started our own extensive preparatory observing program. Currently, this includes both near-infrared photometric imaging and high-resulution optical spectroscopy. Near-infrared imaging of the fields around potential planet search target stars down to K = 18 is performed to find and pre-characterize potential phase-reference stars. The sensitivity and completeness of existing data bases like, e.g., 2MASS, is not sufficient to identify all stars with K = 15. . .16, in particular in the vicinity of bright (target) stars. High-resolution optical spectroscopy is used to derive basic stellar parameters, including rotation velocities ($v\,sin\,i$), metallicity, and activity (spot coverage, flares, etc). In addition, radial velocities are measured with a relative (long-term) precision of order $10\,\mathrm{m\,s^{-1}}$ to check for unwanted companions and obtain additional constraints on the chromospheric activity. We are currently investigating if, and to what accuracy, we need to measure the near-infrared colors and spectra of target and reference stars. Furthermore, it may be necessary to perform high-angular resolution (adaptive optics) imaging of at least a subsample of target-reference star pairs. All this information is compiled in a target data base which must be complete before the actual astrometric observations start.

6. Summary

Astrometry is a unique tool for dynamical studies of extrasolar planetary systems. Its capabilities to determine planetary masses and orbits are not matched by any other technique. Astrometric surveys of young and old planetary systems will therefore give unparalleled insight into the mechanisms of planet formation, orbital migration and evolution, orbital resonances, and interaction between planets. However, to play a significant role, an astrometric accuracy of order $10\,\mu$arcsec is needed, which is beyond the performance of current instrumentation. In order to speed up the full implementation of the $10\,\mu$as astrometric capability of the VLTI, the authors of this paper are complementing the PRIMA facility with Differential Delay Lines and developing all necessary operation and software tools to perform high-precision narrow-angle astrometry. Within a time frame of three years from now, we intend to launch the first such astrometric planet search program with PRIMA at the VLTI, and thus pave the road towards future more precise and extensive astrometric surveys from space.
(for more information, see http://obswww.unige.ch/Instruments/PRIMA/)

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