The PRIMA facility
Phase-Referenced Imaging
and Micro-arcsecond Astrometry

Françoise Delplancke

ESO, Karl Schwarschildstrasse 2, Garching bei München, Germany

---

Abstract

This article describes dual-field interferometry, in particular PRIMA, the Phase-Referenced Imaging and Micro-arcsecond Astrometry facility of the Very Large Telescope Interferometer. It uses the simultaneous detection of fringes of 2 stars in a narrow angle and the accurate measurement of their respective positions. PRIMA aim is threefold: i) to increase the VLTI limiting magnitude with off-axis fringe tracking, ii) to reconstruct images with a resolution of 2mas in K-band, 10mas in N-band, and iii) to perform differential narrow-angle astrometry with an accuracy of 10μas. This article exposes the fundamental and technical limitations of such a technique and presents how PRIMA will try to solve the practical problems of measuring 100-meters long optical paths with nanometric accuracy in a ground based interferometer.

Key words: interferometry, VLT, imaging, astrometry

---

1 Introduction

Ground based interferometer performance is mainly limited by the atmospheric turbulence. Variable index of refraction of the air column above each telescope changes randomly both the angle of arrival and the time of arrival of the coherent photons on each aperture. The time of arrival variation results in a fast jitter of the observed fringe positions in the beam combiner. The order of magnitude of this jitter reaches more than 40μm Peak-to-Valley (PTV) and has a typical time-scale of some milli-seconds (for the K-band). The jitter of the angle of arrival induces a problem to superimpose the beams coming from

---

Email address: `fdelplan@eso.org` (Françoise Delplancke).

various telescopes on top of each other or to inject them into monomode optical fibers. To get a good efficiency and limit the photometric losses, an angle or tip-tilt tracker has to be used with a bandwidth of typically 10 Hz. Thus to observe fringes, one is obliged to take short exposures both in the fringe tracker and in the angle tracker and the sensitivity of the interferometer is strongly limited as shown in (Shao & Colavita 1992a) and (Haniff 2007b).

The fringe jitter results in loosing as well a very important information: the position (phase) of the fringes. The absolute position of the fringes is linked to both the position of the object photo-center on the sky (astrometry) and to shape of the object (Haniff 2007a) (Quirrenbach 2001). Indeed one measurement by a two-telescope interferometer (one baseline) is giving one point (and its symmetric relative to the center) of the Fourier transform of the object image. The visibility of the fringes is the amplitude of the complex number in the Fourier transform; the position of the fringes is the phase of this complex number. It can be shown that most of the information on the object shape is contained in the phase.

Thus it is very important to recover the phase information from the fringes with an accuracy much better than 2π (or one wavelength). Two strategies can be applied: phase-closure and phase-referenced imaging (Booth 1985). Phase-closure is based on the simultaneous observation with 3 or more telescopes. It can be shown that the sum of the phases on any baseline triangle is independent of the atmospheric turbulence (Monnier 2000). This technique is used by AMBER, the near-infrared instrument of the Very Large Telescope Interferometer (VLTI) and by many other optical and infrared interferometers in the world. Phase-referenced imaging measures, one baseline at a time, the phase of the object with respect to a reference star whose phase is assumed null (i.e. is centro-symmetric) (Ulvestad 1999). The differential astrometric information is also included in the measurement.

PRIMA, the Phase-Referenced Imaging and Micro-arcsecond Astrometry facility, has been developed since 2000 in order to fight the effects of the atmospheric turbulence and to bring the imaging and astrometric capabilities to the VLTI instruments. The principle of narrow-angle differential interferometry is described in section 2. PRIMA scientific goals, with emphasis on the observation of circumstellar disks and the detection of planets, are given in section 3 and the high level requirements to reach these goals in section 4. Of course such a technique has some physical limitations in terms of accuracy, limiting magnitude, sky coverage... that are detailed in section 5. Moreover, operating an interferometer on the ground, in the air (i.e. not under vacuum) and with real telescopes that can shake and bend, is not as simple as predicted by theory. The technical problems that have been experienced on the VLTI and that PRIMA will have to fight are described in section 6. Finally, the various sub-systems of PRIMA, how they interact and how to operate the full system to get the best accuracy possible are presented in sections 7 and 8 respectively.

2 Principle of narrow-angle dual-feed interferometry

PRIMA is a narrow-angle dual-feed interferometric method based on the simultaneous observation of 2 stars within the same telescope field of view (see section 5 for the limitations on this field of view). The method is presented and described in detail in (Shao & Colavita 1992b). The bright star is used for fringe tracking: short exposures on this star allow measuring the atmospheric turbulence and stabilizing the fringes thanks to a closed loop. One can then integrate longer on the fainter object, which is affected by almost the same turbulence if it is close enough (narrow-angle). The difference of position of the fringe envelopes as seen by the instruments (one on each star) is given by the following equation (see also figure 1):

$$\Delta OPD = \vec{\Delta s} \cdot \vec{B} + \phi + dOPD_{atm} + dOPD_{int}. \quad (1)$$

where ΔOPD is the difference in position of the fringes of both objects (OPD= Optical Path Difference), $\vec{\Delta s}$ is the angle vector on sky between them, $\vec{B}$ is the baseline vector, ϕ is the phase of the object complex visibility (or the sum of the phases of both objects if the reference is not centro-symmetric), $dOPD_{atm}$ is the random contribution of the atmospheric turbulence (differential between both stars) and $dOPD_{int}$ is the internal differential OPD, also called constant term, introduced by the interferometer. The atmospheric contribution $dOPD_{atm}$ is a random phenomenon with a zero mean and averages out to zero with time. Its magnitude depends on the atmosphere quality, on the star separation and on the baseline length (see section 5). The $dOPD_{int}$ has to be measured with an internal metrology as the positions of all mirrors in the optical train cannot be known a priori with nanometric accuracy.

If the positions of the fringe envelopes are measured with dedicated fringe sensors or interferometric instruments, if the internal OPD is measured with a dedicated metrology, and if one accumulates information on a time long enough to average the atmospheric turbulence, one will have access to the two scientific observables: the angle vector between both stars projected on the baseline and the phase of the object complex visibility for one u-v plane point. If this measurement is repeated with many known baselines (at least 2 for astrometry and many others for phase-referenced imaging), the angle vector between both stars and the image of the object can be reconstructed (assuming that one of the object is centro-symmetric).

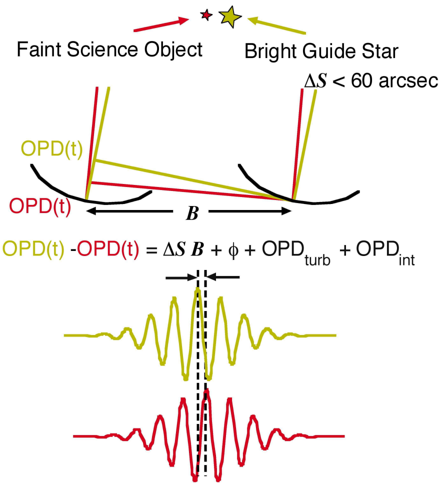

Fig. 1. Principle of dual-feed interferometry.

3 Scientific Goals

PRIMA has therefore 3 capabilities:

- faint object observation by fringe tracking on a close-by bright star. Both stars have to be within the same narrow-angle field (see section 5). The theoretical limits for fringe tracking is K∼13 on the UTs (Unit Telescopes, 8 meter diameter), and K∼10 on the ATs (Auxiliary Telescopes, 1.8 meter diameter). Due to various disturbances (see section 6), this is probably impossible to reach and the current PRIMA goal is a fringe tracking limiting magnitude of K∼10 on the UTs and K∼8 on the ATs. The limiting magnitude on the fainter object is then limited by the background and by the instrument systematics and could reach K∼18 on the UTs and K∼15 on the ATs.
- phase-referenced imaging with the instruments AMBER (J, H and K bands, $1 - 2.5\ \mu m$) and MIDI (N-band, $8 - 13\ \mu m$). A goal of 1% measurement accuracy on both the amplitude and the phase of the complex visibility is set. With 10% accuracy, good images can still be obtained if enough u-v points are measured. The image resolution is then fixed by the longest baseline used and can reach down to 2 mas in K-band and 10 mas in N-band.
- micro-arcsecond differential astrometry with a long term accuracy of 10 μas.

With these capabilities, PRIMA can encompass many science objectives, as long as a reference star is found close to the scientific target. The imaging capability of PRIMA will be used to observe accretion disk around nearby stars (see (Akeson), (Duchêne), (Wood), these proceedings). Figure 2 shows a theoretical model of a circumstellar disk with a planet, with typical sizes. Structures of 1AU scale (i.e. accretion disk) can be resolved with the VLTI up to distances of 1 kpc in K-band and up to 100 pc in N-band. Asymmetries in the disks and their dependence on the wavelength could be observed with the VLTI and with PRIMA in particular giving insights in the disk evolution (grain growth, sedimentation...), in the planet formation processes (mineralogy...) of young stellar objects, and in the mass losses, shock waves, dust envelopes, convection cells of evolved stars. Thanks to the higher limiting magnitude, a larger sample of objects will be within reach of the interferometer. The potential scientific applications of high angular resolution of the circumstellar environments are described in details in many other papers of these proceedings.

PRIMA will also give access to the observation with AMBER and MIDI of the cores of many Active Galactic Nuclei (AGNs). First observations with MIDI (Jaffe et al. 2004) and the Keck-I of the brightest AGNs gave indications that the Seyfert1 and Seyfert 2 types of AGNs belong to the same family but are viewed either pole-on or edge-on (unified scheme). It showed also that

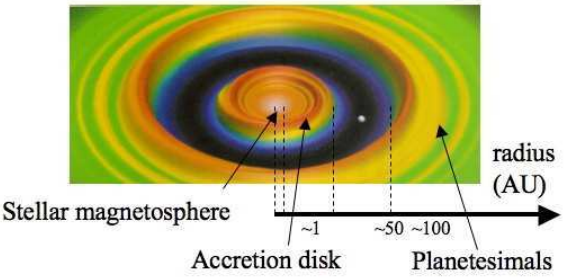

Fig. 2. Theoretical model of a circumstellar disk adapted from L. Allen and J. Alonso.

the structure of such AGNs is very complex. PRIMA would confirm/infirm the unified scheme by observing a larger sample of AGNs and give a better "face" to this complexity thanks to imaging: presence of jets, size, shape and clumpiness of the dust tori (Hönig et al.).

The astrometric accuracy goal (10 μas) is set by one of the main scientific goals of PRIMA: the detection and characterization of planets around nearby stars (Reffert et al. 2006). This is based on the measurement of the star reflex motion (wobble) due to the presence of a planet. Astrometry is a complementary method to radial velocity (see (Santos), these proceedings). Indeed, the astrometric signal is larger if the planet is more distant from the star; radial velocity is more sensitive to close-by planets (hot Jupiters). Moreover, the astrometric signal does not depend on the orbit inclination with the line of sight while radial velocity can only provide an estimate of the minimum mass of the planet. So for the planets that can be observed with both methods, astrometry will remove the uncertainty on the planet mass. Finally, astrometry can be applied to any star spectral type while radial velocity has some limitations in this domain. The very accurate study of binary stars will of course be also possible with the same technique.

Figure 3 shows that a Jupiter-like planet (same mass and same distance to host star) around a sun-like star (G-type) gives an astrometric signal of 50 μas up to a distance of 100 pc. To be able to characterize the orbit of such a planet, an accuracy of 10 μas is needed. This would also allow the detection of Uranus-like planets or of some hot Jupiters.

When trying to detect planets with astrometry, one has to pay a lot of attention to the correct data reduction. Indeed, close-by stars have a proper motion and parallax that are 1000 time larger than the planet-induced wobble. Other astrophysical effects like observer velocity aberration and angular perspective acceleration have also to be taken into account. Finally, one has to be sure that both observed stars are centro-symmetric or that their intrinsic complex visibility phases are known.

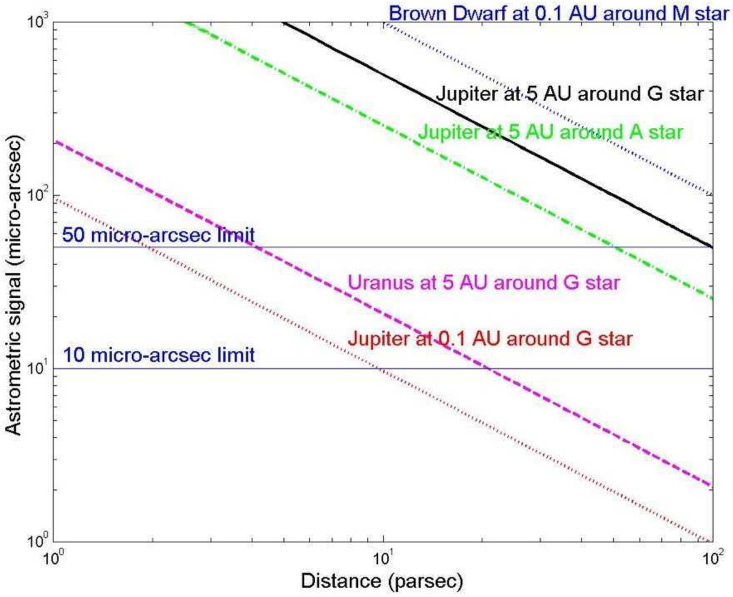

Fig. 3. Amplitude of the star reflex motion as a function of the distance to the star, for different planet planet types, star types and orbit diameter.

Planets can also be detected by another method: gravitational micro-lensing. If a faint star passes on the line of sight of a background brighter star (e.g. galactic bulge star), the light of the latter will be amplified. This can be detected by photometric survey programs like OGLE. At the same time, the image of the background star will be split in two and the separation on the images depends on the lens Einstein radius. If the lensing star is accompanied by a planet, a secondary photometric peak will be observed and the image will have a more complex structure (with 3 or 5 parts). The separation between the image components can be resolved with the VLTI but it requires PRIMA to reach the faint magnitudes (K$\sim$15-16 typically) of such events. Moreover the photo-center of the complex image moves with time and the amplitude is detectable by PRIMA.

4 High-level requirements

To reach an astrometric accuracy of 10 μas necessary to detect a Jupiter-like planet, when using a baseline of 200 m (longest VLTI baseline), Eq. (1) shows that all terms have to be measured or to be averaged out at better than 5 nm rms. The astrometric measurements have to be taken for 2 significantly different baseline orientations (ideally at 90° from each other) in order to get the two-dimensional angle vector on sky.

In order to get good reconstructed images of the object, one needs both accurate measurements and many points in the u-v plane (Haniff 2007a). So these measurements have to be repeated for many baseline orientations (super-synthesis thanks to the Earth rotation) and for several different baselines and it requires several nights of observation per object. The dynamic range of the reconstructed image (quantifying the quality of the reconstruction, it is the ratio of the peak intensity of a point source to the noise in the reconstructed image) is given by:

$$DR \sim \sqrt{\frac{M}{\frac{\delta V^2}{V^2} + \frac{\delta\phi^2}{\phi^2}}}. \tag{2}$$

where M is the number of independent measurements, V and δV are the visibility amplitude and its measurement error, ϕ and $\delta\phi$, the visibility phase and its error. So, for a dynamic range of better than 100 and when taking 100 independent observation points, the phase has to be known at $\delta\phi/\phi < 0.1$, i.e. $\sim$220 nm in K-band and 1000 nm in N-band. The quality of the reconstruction depends also on the extend of the u-v coverage.

So on the accuracy point of view, the planet detection scientific goal is driving

PRIMA: the measurement accuracy has to be of the order of 5 nm rms and all sub-systems have to be designed accordingly. The number of necessary baseline is driven by the imaging requirement: PRIMA has to be installed on all 4 Unit Telescopes of the VLTI and the Auxiliary Telescopes should be moved to many stations to increase the number of accessible baselines.

Of course, both scientific objectives need a limiting magnitude as high as possible both for the bright star (for fringe tracking) and for the faint nearby object in order to maximize the number of accessible targets. The limiting magnitude of the bright star is particularly important because it fixes the sky coverage of PRIMA. Unfortunately, as we cannot adjust the brightness of the stars with a button and as the VLTI is placed on the ground under the atmosphere, we have to take what nature is offering us with its physical limitations.

5 Physical Limitations

The main limitations of dual-field interferometry are linked to the atmospheric turbulence. Firstly, the coherence time τ_0 of the turbulence on the bright star determines at which frequency one has to measure the fringe phase in order to be able to stabilize them. In good nights, τ_0 is of the order of 20 to 30 ms in K-band. Thus a sampling frequency of 200 Hz is needed for a good stabilization. As fringes can be measured reliably with a 100 SNR (Signal to Noise Ratio), this imposes the minimum number of photons per 5 ms that has to reach the detector. Combined with the interferometer transmission, this constraint fixes the fringe tracking limiting magnitude. In theory, with the VLTI, with a perfectly stabilized beam (Strehl ratio larger than 50%) and with low noise detectors, one should be able to fringe track on stars of magnitude K=10 with the ATs and K=13 with the UTs. In practice (see section 6) it is very difficult to reach.

Secondly, as both stars are not in the same line of sight, their light does not pass exactly through the same turbulence. There is a so-called anisoplanatism. Even if the fringes were perfectly stabilized on the bright star (primary star), there would be an anisoplanatic fringe jitter on the secondary star. The standard deviation of this jitter for a typical Paranal atmosphere is given by (d'Arcio 1999):

$$\sigma_{dOPD} = 370.B^{-2/3}.\frac{\theta}{\sqrt{T_{obs}}}. \tag{3}$$

where B is the baseline length, θ is the star separation and T_{obs} is the total time during which one observes. It depends also slightly on the telescope diameter (lower residuals with bigger telescopes due to an averaging effect over the telescope aperture). The impact of the seeing quality (included in the factor 370) is very high.

The anisoplanatism influences the minimum observation time to reach a certain accuracy. Typically for a separation of 10”, a baseline of 200 m, the fringe jitter residuals average out to less than 10 μas in a total observation time of 30 min. The anisoplanatism determines also how separated the stars can be before losing the whole advantage of fringe stabilization: if the anisoplanatic fringe jitter gets bigger than $\lambda/6$ rms, fringe jumps on the secondary star will occur and the fringes will be washed out. The visibility of the fringes decrease with the OPD jitter as:

$$V = V_0.exp(-2.(\frac{\pi}{\lambda}.\sigma_{residualOPD})^2). \tag{4}$$

If one wants to measure the visibility amplitude with a good accuracy, the visibility loss induced by the anisoplanatic OPD jitter has to be calibrated and therefore limited to a reasonable amount. If one sets the limit for the visibility reduction to 50 to 90%, the maximum separation angle between both stars is 10 to 20” in K-band (AMBER and astrometry) and up to 2’ in N-band (MIDI).

As a consequence of this anisoplanatism and of the fringe tracking limiting magnitude, the sky coverage of PRIMA is limited on the same way as natural guide star adaptive optics: the probability to find a bright enough guide (fringe tracking) star close to the fainter target that one wants to observe (to image). With the Auxiliary Telescopes, the probability to find a 10th magnitude star within 10” of the target is non-null only close to the galactic center; within 60” it can reach as much as 90% toward the galactic center and 10% around the galactic plane. For a 13th magnitude star within 10” the situation is similar to the latter; within 60”, the probability is larger than 90% in the galactic plane and still larger than 30% toward the galactic poles. These estimations are made from a star distribution in the galaxy based on stellar population synthesis model from the university of Besançon (Robin 1994).

The case of the search for extra-solar planets is quite advantageous because we will be looking for planets around nearby stars that are usually bright enough for fringe tracking. The problem is then to find a faint (magnitude 13 to 15) astrometric reference star close to the target star (Reffert et al. 2005). The probability for such a configuration is relatively high. In any case, the number of available targets is highly dependent on the magnitude reachable for fringe tracking. And this one can be highly limited by technical problems.

6 Practical problems

6.1 Beam stability

Despite adaptive optics on the Unit Telescopes and tip-tilt stabilization on the Auxiliary Telescopes, the beam arriving at the fringe sensor in the laboratory are not perfectly stabilized: some tip-tilt or higher order residuals are still present and the internal air turbulence (inside the light ducts and tunnels of the interferometric complex) affects the beam stability as well. The problem is that one wants to inject the beams coming from the telescopes into monomode fibers. A slight error of pointing (e.g. on 20 milli-arcseconds with the UTs) induces a strong decrease of injected flux and a potential loss of the fringe signal if the SNR gets too low. So in practice, the feasibilit of fringe tracking does not depend on the average number of photons injected into the fibers but on the minimum one or, more exactly, how often and how long the number of injected photons gets below a certain threshold. These performance are highly dependent on the seeing and on the performance of the adaptive optics / tip-tilt stabilization. This is a domain still under study at ESO. To partially overcome this problem, at VLTI, a system of fast tip-tilt sensing in the infrared (IRIS Fast Guiding) similar to the angle tracker of the Keck interferometer (Crawford et al. 2006) has been implemented to stabilize as best as possible the beams on the fringe sensor entrance. Its performance is currently being optimized (decrease of read-out noise etc...) to improve its limiting magnitude from about 6 (in K) to 9 or 10 as achieved on the Keck. Moreover a dedicated method to optimize the centering of the beam PSF (point spread function) on the fiber core, base on circular modulation has also been developed.

6.2 Vibrations

The second practical problem encountered with the Unit Telescopes of the VLTI are the vibrations. Such big structures are subject to many vibrations sources: the wind, exciting their first eigenmodes, fans of electronic racks, rotating pumps for liquid coolant, pumps for the oil film on which the telescope is ”floating”, and, last but not least, closed-cyclo-coolers (cooling pumps to cool down some instruments to liquid helium temperature). These vibrations are propagated or amplified by the telescope structure and translate into variations of the OPD at many different frequencies. These OPD variations are in some cases as large as the OPD variations of the atmosphere but usually much faster: typical peaks (or forest of peaks) around 18, 48, and 96 Hz are dominating the OPD signal. These vibrations are particularly difficult to reduce using atmosphere-adapted fringe tracking . This forces also the fringe tracker to run much faster than normal, diminishing by as much the limiting magnitude. With PRIMA, these vibrations will be fought with 3 means: accelerometers placed on the first 4 mirrors, a fast laser metrology for the mirrors after the Coudé focus and dampers or active vibration compensations on the intermediate mirrors. It is an on-going project and the final performance cannot yet be evaluated. The goal is to reduce the OPD jitter on a bright star to less than 300 nm rms in order to avoid fringe jumps and to guarantee that, after averaging out this jitter over some minutes, the residuals are below the required accuracy (5nm for astrometry and 220nm for imaging).

6.3 Air dispersion

The VLTI is an interferometer with "air-filled" delay lines. That means that a scientific OPD in vacuum (outside of the atmosphere) is compensated by path in the air. And the air refractive index depends on the wavelength. It means that if one stabilizes the fringes at a certain wavelength (e.g. K-band), the fringes at another wavelength will drift progressively. When using PRIMA with AMBER in J and H-bands or with MIDI in N-band, this has to be taken into account: the differential OPD controller has to add a time-dependent offset between the beams going to the fringe tracker and to the instrument. Unfortunately, this offset depends on the OPD to compensate but also on the temperature and humidity of the air. Indeed, the variation of the air refractive index with the wavelength depends "strongly" on the temperature in the J, H and K-band and on the humidity between the K and N-band. As the air temperature and humidity above the telescopes and in the delay line tunnel vary with time on a non-predictive way, this effect has to be measured on the stellar signal itself (Mathar 2007).

It is done by dispersing the fringe sensing signal over several spectral channels: by measuring the phase delay (OPD) in each of the spectral channels, the group delay (of the white fringe) can be reconstructed and the phase delay at another wavelength can be extrapolated . The optimum number of spectral channels (a trade-off between group delay measurement accuracy and limiting magnitude) is still a matter of debate between experts. For PRIMA, it has been chosen to 5 spectral channels over the K-band. The compensation of the air dispersion can possibly be done in post-processing if the fringe real time stability requirement of the instrument is not too stringent.

---

[1] The phase delay is the position of highest maximum of the fringe pattern; the group delay is the position of the maximum of the fringe envelope. In vacuum both are equal but when the delay is compensated in air there is a shift between both delays, which depends on the compensated OPD, on the air refractive index and on the effective wavelength of the star as seen by the sensor.

6.4 Time evolving targets

PRIMA can only combine two telescopes at a time, providing measurement only along one baseline. Observing during a night, this provides only one trajectory in the u-v plane. To get a better u-v coverage for imaging, one has to move the telescopes to other stations. This cannot be done during the same night at the VLTI, and usually is done only every couple of weeks. Thus to reconstruct a good image of an object (with a minimum of 6 telescope stations, so 15 baselines), one needs to accumulate date over several weeks or months. This works only if the shape of the target is not evolving during this time. PRIMA cannot provide snapshot imaging (in opposition to phase closure techniques with more than 4 telescopes).

In case of astrometry, only 2 perpendicular baselines are needed. This can be provide by 2 different physical baselines or by observing the same object at 8 hours interval, using the Earth rotation. Moreover, if one wants to measure (imaging or astrometry) a periodically evolving target (planet reflex motion or Cepheid for instance) one can plan the observations as a function of time to observe the object with the various baselines always at the same phase of the periodic phenomenon. Observation preparation tools for the planet case will be provided to ease such a planning.

6.5 Good phase-reference stars

For imaging of faint targets, one has to find a bright star close by. Bright stars are usually giant stars in the close vicinity of the sun. Thus there is a high probability that these fringe tracking stars are resolved by the interferometer. PRIMA cannot disentangle between the complex visibility phase of the target and the one of the reference star: PRIMA measure the sum of both. So to make accurate measurements, the observer must be sure that the fringe tracking star is either a centro-symmetric star (i.e. its intrinsic phase is null for any baseline) or that its own phase is known by another method (e.g. observation of this star with a phase-closure instrument like AMBER). Preparation observations for PRIMA of the targets and of the potential guide stars are of prime importance to get valid scientific results (Reffert et al. 2005).

6.6 Other technical problems

There are several other technical problems that need to be solved to reach the $10\mu as$ astrometric accuracy. They are very complex and still under study. They will probably be solved only after accumulating real data so that we can verify the amplitude of these problems. Solving this issues can be done in data post-processing (long-term trend analysis). These problems include:

- Baseline calibration: to reach the $10\mu as$ differential accuracy, the baseline must be known to better than $50\mu m$. This needs dedicated observations of stars or binaries with well known coordinates. The problem is also to define what is the narrow-angle baseline: in the VLTI, it is not the distance between the pivot points of the mirrors but the distance between the images of the metrology retro-reflectors as "seen" by the star from space.
- Telescope flexures: the narrow-angle baseline is also affected by telescope flexures. These need to be modeled or measured to an accuracy that is still to be determined. It depends highly on the design of the telescopes. Unfortunately, the VLTI telescopes have not been optimized for astrometry and are suffering highly from this effect.
- Mirror irregularities and beam footprints: as the metrology measuring the internal OPD is propagating within the central obstruction of pupil, the beam footprint of the metrology and of the star light differ. If mirrors are irregular (e.g. have a bump), the metrology will not measure exactly the same internal path as the star light and this will result in a measurement error. So the mirror maps (especially of mirrors close to pupil planes) have to be known and taken into account in the data reduction.

7 PRIMA System Description

PRIMA main functions are the following:

- to select, pick up and track 2 stars in a 2' field of view at the Coudé focus of the telescopes (UT or AT). This is done by the so-called *Star Separators (STS).*
- to introduce the differential delay between the two stars. Indeed as both stars passing by the same delay lines, only one delay can be applied to both. This is the role of the *Differential Delay Lines (DDL).*
- to measure and track the fringes on the bright star (and on the faint object if possible). The fringe position measurement (in phase and group delay) is performed by the *Fringe Sensor Unit(s) (FSU)* (2 of them for astrometry) and by the instrument (AMBER or MIDI in imaging). The tracking is done by the *OPD Controller* and *dOPD Controller*.
- to measure the internal dOPD with nanometric accuracy. This is the role of the *PRIMA Metrology (PRIMET).*

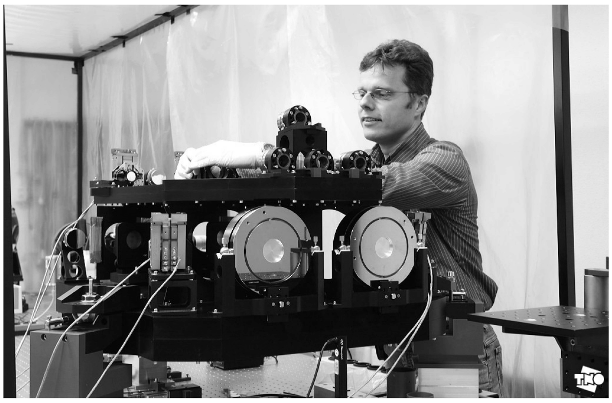

Fig. 4. Star Separator for the Auxiliary Telescopes.

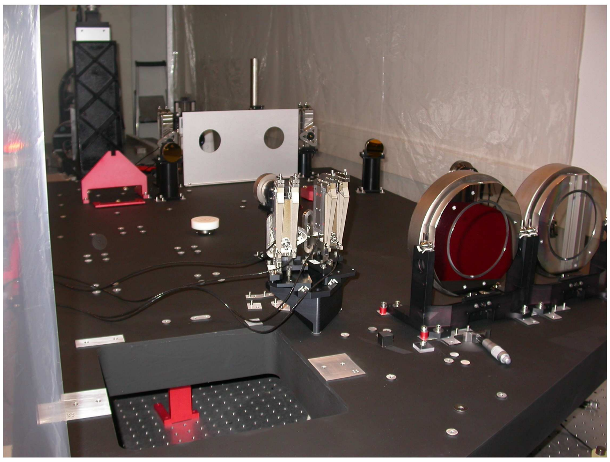

Fig. 5. Star Separator for the Unit Telescopes (the M9 dichroïc is not installed yet).

7.1 Star Separators

The STS are complex opto-mechanical systems placed at the focus of the telescopes (AT in Figure 4 or UT in Figure 5). They can pick up two sub-fields of 2” (UT) or 4 to 6” diameter each within the 2’ diameter Coudé field of view. In addition, the STS provide the following accessory functions: an independent tip-tilt actuator and an independent pupil lateral position actuator on each beam, all with an actuation frequency of up to 50 Hz, a pupil relay to the center of the tunnel (for any AT station position), an output beam of 80 mm diameter for both telescopes, the possibility to swap the two stars into the two beams without swapping the metrology (for calibration purposes.The STS on the ATs include a retro-reflector for the PRIMA metrology. The STS were developed and are produced by TNO in the Netherlands.

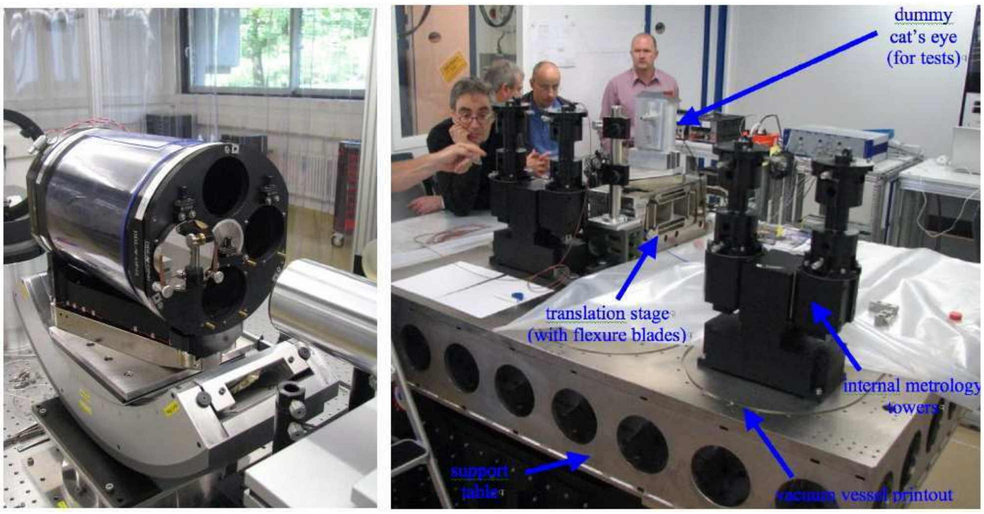

Fig. 6. Differential Delay Line cat's eye (left) and translation stage on its support table with the internal metrology tower (right).

7.2 *Differential Delay Lines*

The DDLs are cat's eye with 3 mirrors (5 reflections), a scaled down version of the main delay lines, mounted on a high accuracy translation stage (see Figure 6). Its range is 12 cm optical (6 cm mechanical) which corresponds to the maximum dOPD expected with PRIMA (120" star separation on the largest baseline of 200 m). The focal mirror of the cat's eye is mounted on a piezo and provides a larger bandwidth (>200 Hz) and shorter delay than the main delay lines, making the DDL more efficient for fringe and vibration tracking. An internal laser metrology is used for the position control. The requirements on the straightness of the movement are very stringent to insure that the pupil lateral motion during translation is smaller than $25\mu m$. The DDLs are placed in a vacuum vessel in order to avoid any dOPD bias due to air dispersion. The DDLs are designed and developed by the DDL consortium (Launhardt et al. 2007).

7.3 *Fringe Sensor Units*

The FSUs are the heart of PRIMA. They are twins (FSUA and FSUB) to be used for astrometry. In case of imaging with AMBER or MIDI, only FSUB will be used for fringe tracking. The FSUs are combining the light of 2 telescopes and are coding the fringes along a so-called *ABCD principle* (see Figure 7). The light of each telescope is divided in 4 parts. These parts are recombined with each other with a phase shift of 0, 90, 180 and 270°. This phase shift is produced spatially, as achromatically as possible, using a K-prism (three total internal reflections, inducing a phase shift of 90° between the two polar-

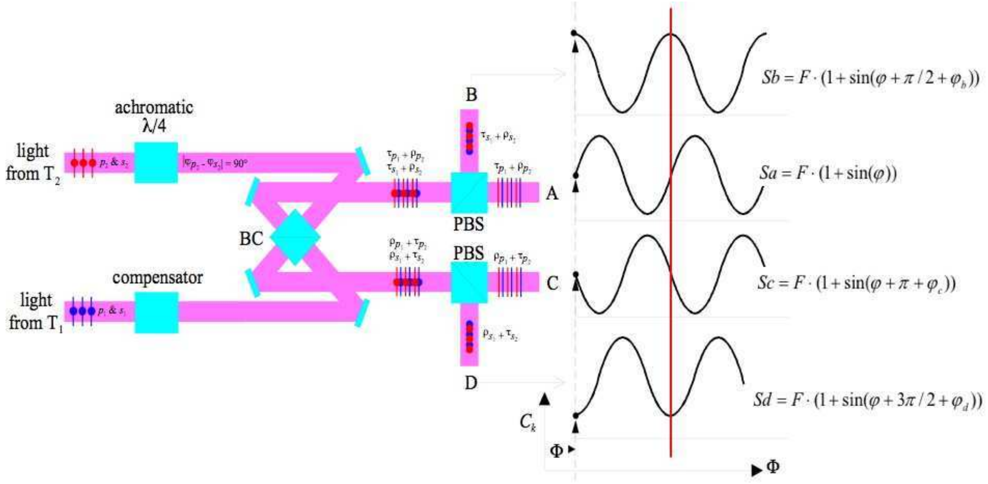

Fig. 7. Principle of the ABCD concept and how it is implemented in the FSU (p and s are the two polarization components of the light coming from both telescopes; T_1 and T_2 are the two telescopes; BC is the beam combiner; PBS are the polarizing beam splitters)

izations), a beam combiner (introducing a 90° phase shift) and polarization beam splitters. The 4 superimposed beams are then injected into monomode fibers for spatial filtering. These fibers are directed into a cryostat where the extremity of each fiber is reimgaed on an infrared detector (PICNIC from Rockwell) and slightly dispersed spectrally (the full K-band is dispersed over 5 pixels) to get the group delay and measure air dispersion effects. The expected performance are a resolution both on then phase and group delays of 1 nm, a measurement noise lower than 70 nm rms on bright stars (highly dependent on the star magnitude, the seeing characteristics and the detector read-out noise), a maximum measurement frequency of 8 kHz, a good linearity (to insure stable fringe tracking) and a very low bias (lower than 5 nm rms) on the phase and group delay. This last requirement is very stringent on the FSU temporal stability and on the quality of the FSU calibration (spectral transmissivity). This one is measured on an artificial source, MARCEL, using the technique of Fourier Transform Spectroscopy.

A view of both FSUs with their internal calibration source in a testbed (Abuter et al. 2006) is shown in Figure 8. As shown in section 6, the beam stability is essential to inject enough light into the fibers for reliable fringe detection. It is why the FSUs are integrating fast tip-tilt mirrors that will correct the tip-tilt residuals measured by the infrared camera, IRIS placed close to the FSUs. The FSUs and MARCEL have been designed and produced by Alcatel-Alenia Space Italy.

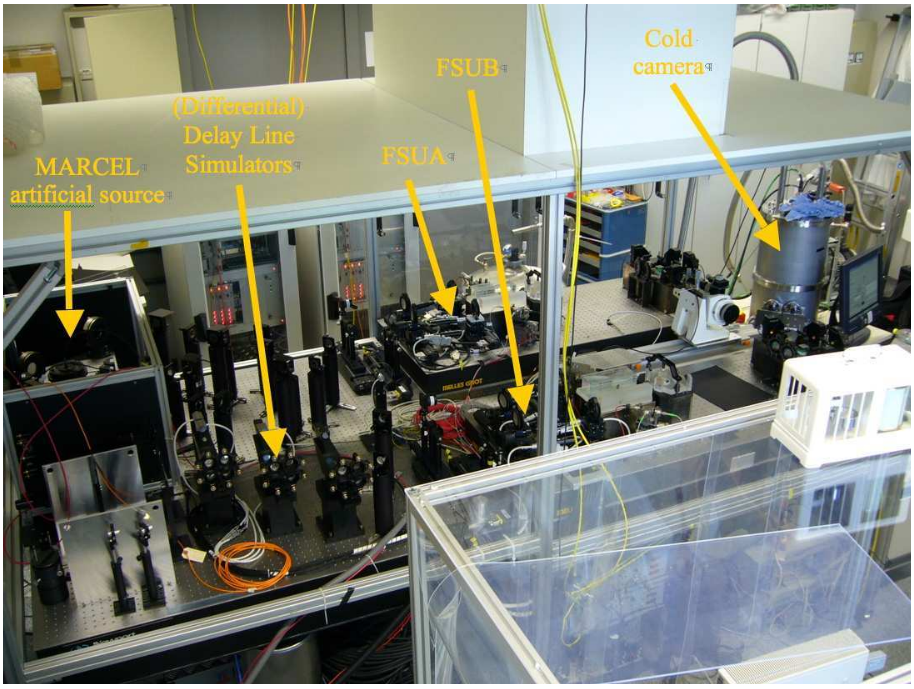

Fig. 8. The FSU testbed with the calibration source MARCEL; the simulator of delay lines and disturbances; FSUA and FSUB and the cryostat. In the foreground, the housing of the PRIMA metrology laser stabilization

7.4 PRIMA Metrology

PRIMA metrology is an incremental laser metrology, i.e. counting the number of fringes passing on its detector from a zero point. So it does not give an absolute distance. It is propagating inside the central obstruction of the telescope in order to limit the amount of straylight going to the instruments. It is generated in the laboratory close to the instrument (in the beam combiner of the FSUs), propagates backwards up to a retro-reflector placed at the level of the Star Separators, comes back through the same path and is detected close to the instrument. Its principle is based on super-heterodyne detection: the laser beam at wavelength of 1319 nm is divided into 4 parts (2 telescopes, 2 stars); each part is frequency shifted by acousto-optic modulators; after propagation, the various beams are combined together and the beat frequencies are detected. This give an resolution better than $\lambda/1000$, i.e. 1 nm rms at a frequency of 8 kHz. To transform it into an absolute accuracy, the laser wavelength needs to be known and stabilized at better than $\frac{\Delta\nu}{\nu} = 10^{-8}$. This is done thanks to a non-linear optics frequency doubler and an iodine cell stabilized in temperature as wavelength reference (see Figures 9 and 10). The absolute wavelength is calibrated using a laser comb. To work well, the metrology pupil has to be stabilized to better than $400\mu m$ rms, thanks to a quad-cell and the pupil actuators of the Star Separators. The PRIMA Metrology has been developed in collaboration with the Institute of Micro-technology of Neuchâtel (Switzerland).

As this metrology is incremental, it has to be zeroed. Two techniques can be used:

- if both stars are of similar brightness in imaging or in the astrometric case (using both FSUs), the two stars can be swapped between the instrument (AMBER, MIDI or FSUA) and the fringe tracker (FSUB) while the metrology beams are not swapped. When fringes have been found on both the instrument and the fringe tracker and in both swapped case, the internal biases and the zero point of the metrology can be removed by making the difference of both measurements.
- if the faint target (observed by MID or AMBER) cannot be used for fringe tracking, the swapping cannot be performed and the metrology will be zeroed by splitting the bright star in two at the Star Separator level and getting fringes on that same star both on the instrument and the fringe tracker. As the same star is observed, the dOPD is null by definition.

Of course, during these zeroing processes, the reliability of the metrology is essential: no glitches are allowed. The second zeroing method is also very time consuming. So a prototype for an absolute metrology (using 2 wavelengths) is being developed and could be implemented in a later stage. PRIMET has

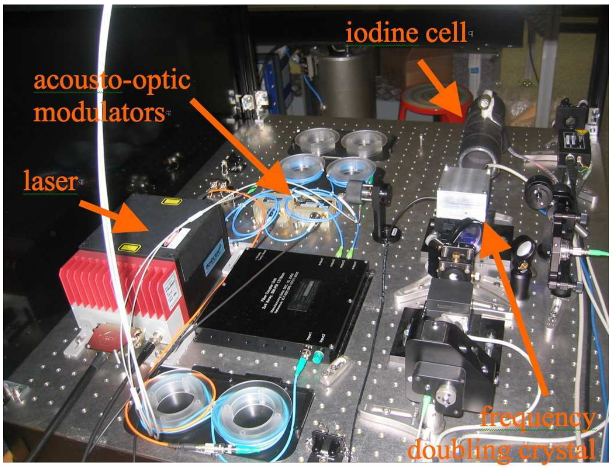

Fig. 9. PRIMA Metrology laser, laser stabilization and frequency shifting (left); frequency stabilization performance (right).

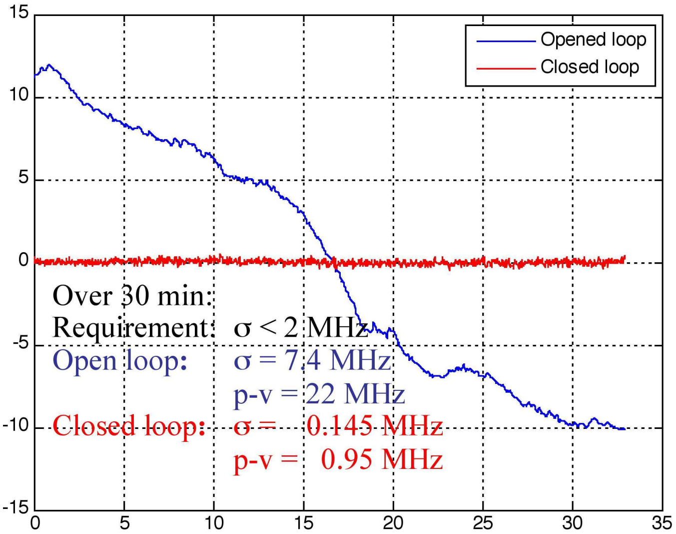

Fig. 10. PRIMA Metrology frequency stabilization performance.

also been adapted to measure the OPD between 2 telescopes (and not only the dOPD) in order to measure the vibrations up to the level of the retro-reflector. This will be used for a better vibration compensation.

7.5 PRIMA control and instrument software

All PRIMA sub-systems are controlled by dedicated control software and coordinated by the instrument software and the Interferometer Supervisor Software. The effort put in the development of this software is not to be neglected as, basically PRIMA is doubling the complexity of the VLTI software (in terms of number of sub-systems to be controlled and in terms of number of lines of code). The system has to be flexible enough to allow various operation modes (astrometry, imaging, single object, dual object, calibration etc...), paralleled enough to avoid high overhead times but reliable enough to limit technical downtime. For example, during a typical PRIMA astrometric observations, there will be 20 different real time control loops running in parallel: one adaptive optics / tip-tilt control loop at the Coudé focus of each telescope (2); a tip and tilt control loop between the laboratory and the Star Separators for each star and each telescope (2x2x2=8); a X and Y pupil lateral control between the PRIMA Metrology and the Star Separators for each star and each telescope (2x2x2=8); an OPD control and a dOPD control (2). All these loops are not always independent and off-loading of one to the other have to be handeled properly.

The instrument control software is in charge of implementing the operation and calibration strategy, of presetting and starting all required sub-systems and of recording the data. Therefore, a dedicated device has been developed to spy and record the real-time data placed on a reflective memory network by the FSU, PRIMET, OPD Controller, dOPD controller, tip-tilt commands etc...The fastest of these systems, PRIMET, running at 8 kHz, data have to be sampled at a higher rate in order not to miss data. The instrument control software is then producing FITS files containing the high rate data from all PRIMA sub-systems. These files are then processed by the pipeline, the ESO standard data reduction software (see section 8).

8 PRIMA Operation, Calibration and Data Reduction

The most stringent goal of PRIMA in terms of performance, is the $10\mu as$ narrow-angle astrometry for planet detection. Thus, this goal is driving the way we want to operate, calibrate and reduce the data. All the problems mentioned above have to be taken into account. Some of them are several order of magnitude larger than the signal that we want to measure. To get the final accuracy, PRIMA is based on multiple differential measurements that have to be done cleanly, and as much as possible at hardware level. PRIMA is so measuring the differences between: 2 telescopes of identical design (to limit differential behaviors), 2 stars in a narrow-angle (to reduce atmospheric effects), 2 swapped states (to remove the internal air dispersion effects in the light ducts and tunnels), 2 wavelengths (the metrology one and the star one), 2 moments in time (the evolution of the planet orbit is of interest). This should allow to measure the difference between 500-meter long optical paths with a nanometric accuracy. This requires i) a very good stability of the full instrument (the VLTI from M1 to the detector), ii) a careful calibration of what is not stable enough (e.g. baseline and FSU transmissivity), iii) an operation strategy that minimize the effects of what cannot be calibrated well enough (e.g. observing the same object always at the same telescope elevation) and iv) a data logging of most of the (environmental) parameters that cannot be controlled nor calibrated (e.g. air temperature and humidity inside the VLTI infrastructure). With the first three precautions, we hope to reach a $100\mu as$ accuracy of the measurements after one night of observations. The factor-10 gain i hoped to be reached thanks to a long-term trend analysis of the scientific data as a function of the logged environmental parameters.

The first three precautions are reflected in the observation and calibration strategy: PRIMA astrometric mode will require numerous careful and dedicated calibrations, like a precise baseline determination on specific calibration targets or the regular (daily) measurement of the FSU transmissivity. These calibrations will be taken into account in a specially designed off-line processing of the data at the end of each night: the baseline will be re-calibrated, the zero-point of the metrology will be accurately removed, the most recent FSU transmissivity and spectrum of the stars will be used, the daily trends in the injection or thermal evolution of the detector will be taken into account.

The long-term trend analysis will take care of the residual errors but can work only on a large amount of data distributed over a long time. It is planned to run it every 6 months on all data collected by PRIMA. Long term trends like the effect of telescope relocation, earthquakes and telescope flexures on the baseline, like the mirror irregularities and beam footprints, like the longitudinal dispersion of the air in the tunnel will be identified on the calibration data themselves. They will be modeled and their effect on the scientific data will be taken into account by running again the off-line processing using the long-term trend parameters. This means that the ultimate PRIMA astrometric accuracy will be reached only after several years of operation when the VLTI behavior will be better known. The long-term trend analysis and subsequent improvement of the data quality is a method that was applied for instance on Hipparcos data. The data reduction software and observation strategy (PAOS = PRIMA Astrometric Observation and Software) is developed by the PAOS Consortium.

Fortunately, astrometry is not the only objective of PRIMA and the other aims like faint object observation and phase-referenced imaging do not require (at all or at such a level) this long-term trend analysis. They will benefit of it but will produce interesting results from the start.

9 Conclusions

PRIMA is a very challenging project, especially in its ultimate goal of microacrsecond astrometry. It is also a complex system, interfering with the current VLTI infrastructure at many level and places. However it will significantly enhance the VLTI performance and capabilities by increasing the limiting magnitude and providing phase-referenced imaging and astrometric functionalities. This will make the VLTI a really unique facility in the world. Moreover, PRIMA sub-systems have been designed also to bring solutions to current VLTI problems like vibrations, beam stability, pupil stability and OPD control bandwidth. Only this should provide a significant improvement of the VLTI performance.

One should not hide that the original goals of $10\mu as$ astrometry and of fringe tracking on 10 magnitude stars on the ATs (13 on the UTs) will be very difficult (if not impossible) to reach routinely and will require a lot of efforts. But even with a performance of $100\mu as$ and fringe tracking on 8th magnitude stars (which seems feasible with a reasonable effort), many new fields and targets will be opened to the VLTI: imaging of circumstellar disks with MIDI, increase of the limiting magnitude of MIDI and AMBER, especially in the high spectral resolution modes, observation of Active Galactic Nuclei with AMBER, astrometry of binaries and characterization of the most massive planets, astrometry of stars around the Galactic Center with a gain of 10 in accuracy compared to current adaptive optics measurements... These scientific objectives are worth the efforts deployed for PRIMA. Pending any problem during the final tests of PRIMA sub-systems, they should be installed in Paranal during 2008 and the commissioning of the facility is expected to start in the third quarter of 2008.

ESO and the community are also developing the tools necessary to prepare observations with PRIMA and to reduce the data with the best accuracy possible. These tools will be made accessible to the community at large and should allow any interested astronomer, even without detailed knowledge on PRIMA, to use the facility. So do not be discouraged, plan to participate to the summerschool on PRIMA in June 2008 in Hungary, prepare your observation proposals ... and join the challenge !

10 Acknowledments

The development of PRIMA has been done by a large team at ESO and in the european interferometric community. Here is a non-exhausitive list of people / institutes who worked / are working specifically on PRIMA: R. Abuter, L. Andolfato, P. Ballester, J. de Jong, F. Derie, N. di Lieto, R. Frahm, S. Lévêque, S. Ménardi,, J-M. Moresmau, R. Palsa, T. Phan, D. Popovic, E. Pozna, F. Puech, J. Sahlmann, N. Schuhler, G. van Belle, G. Vasisht, the PAOS-DDL Consortium (Geneva Observatory, Max-Planck Institut für Astronomie - Heildelberg, Heidelberg Observatory, and formerly Leiden Observatory), the Max-Planck Institut für Extraterrestrische Physik, and many others.

References

[Abuter et al. 2006] Abuter, R., et al., VLTI-PRIMA fringe tracking testbed, 2006, Proceedings of the SPIE, 6268, pp. 62682Y

[Akeson] Akeson, R., Observations of circumstellar disks with infrared interferometry, these proceedings

[Booth 1985] Booth, R.S., High resolution in radio astronomy, 1985, in Saas-Fee Advanced Course 15 - High Resolution in Astronomy, pp. 65

[Crawford et al. 2006] Crawford, S.L., et al., Design and Performance of the Keck angle tracker, 2006, Proceedings of the SPIE, 6268, pp. 62683W

[d'Arcio 1999] d'Arcio, L., Selected aspects of wide-field stellar interferometry, 1999, PhD thesis, ASCI dissertation series number 64

[Duchêne] Duchêne, G., High-angular resolution imaging of disks and planets, these proceedings

[Jaffe et al. 2004] Jaffe, W., et al., The central dusty torus in the active nucleus of NGC 1068, 2004, Nature, 429, pp.47

[Haniff 2007a] Haniff, C., An introduction to the theory of interferometry, 2007, New AR, 51, Issue 8-9, pp. 565

[Haniff 2007b] Haniff, C., Ground-based optical interferometry: A practical primer, 2007, New AR, 51, Issue 8-9, pp. 583

[Hönig et al.] Hönig, S., et al., Radiative transfer modeling of three-dimensional clumpy AGN tori and its application to NGC 1068, 2006, A&A, 452, pp. 459

[Launhardt et al. 2007] Launhardt, R., et al., Towards High-Precision Astrometry: Differential Delay Lines for PRIMA@VLTI, 2007, in Exploring the Cosmic Frontier, ESO Astrophysics Symposia European Southern Observatory, pp. 265

[Mathar 2007] Marthar, R., The ABCD formula of phase definition in optical interferometry: combined effect of air dispersion and broad passband, 2007, Baltic Astronomy, 16, pp. 287

[Monnier 2000] Monnier, J.D., An introduction to closure phases, 2000, in Principles of Long Baseline Stellar Interferometry, course notes from 1999 Michelson Summer School

[Quirrenbach 2001] Quirrenbach, A., Optical Interferometry, 2001, Annu. Rev. Astron. Astrophys., 39, pp. 353

[Reffert et al. 2005] Reffert, S., et al., Choosing Suitable Target, Reference and Calibration Stars for the PRIMA Astrometric Planet Search, 2005, ASP Conference Series, 338, pp.81

[Reffert et al. 2006] Reffert, S., et al., The PRIMA astrometric planet search: goals and prospects, 2006, Proceedings of the SPIE, 6268, pp. 626846

[Robin 1994] Robin, A.C., Synthesis of galactic stellar populations and expected constraints from infrared surveys, 1994, Astrophysics and Space Science, 217, pp. 163

[Santos] Santos, N., Extra-solar planets: detection methods and results, these proceedings

[Shao & Colavita 1992a] Shao, M., & Colavita, M., Long-baseline optical and infrared stellar interferometry, 1992, Annu. Rev. Astron. Astrophys., 30, pp. 457

[Shao & Colavita 1992b] Shao, M., & Colavita, M., Potential of long-baseline infrared interferometry for narrow-angle astrometry 1992, A&A, 1, pp. 353

[Ulvestad 1999] Ulvestad, J.S., Capabilities of the Very Long Baseline Array, Bulletin of the American Astronomical Society, 31, pp. 921

[Wood] Wood, K., Infrared Signatures and Models of Circumstellar Dust Disks, these proceedings