Phase-referenced imaging and micro-arcsecond astrometry with the VLTI

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ABSTRACT

An update of the current status and schedule of PRIMA (*Phase-Referenced Imaging and Mirco-arcsecond Astrometry*) developed for the Very Large Telescope Inteferometer (VLTI) is given, with emphasis on the astrometric objectives, performances and technological challenges.
PRIMA will allow to observe simultaneously two fields separated by 2 to 60 arcsec, to detect and track the fringes on the brightest object, to detect the fringes on the faintest, and to measure the phase of the secondary set of fringes relative to the primary one, with an accuracy of $\lambda/1000$ at 2 μm.
PRIMA facility will allow VLTI instruments like MIDI and AMBER to observe objects up to 5 magnitudes fainter than in single field mode. Combined with the high modularity of VLTI baseline frame, it will enable 1 mas high resolution imaging on objects as faint as $22nd$ magnitude. PRIMA high accuracy metrology and astrometric camera will also allow to measure relative angular positions of stars with a 10 μas accuracy. Detection of Jupiter like planets as far as 240 pc and characterization of gravitational micro-lensing events on the galactic center and on the Magellanic Clouds will then be possible.

Keywords: Interferometry, VLTI, phase-referenced imaging, astrometry

1. INTRODUCTION

The Very Large Telescope (VLT) of the European Southern Observatory (ESO) was designed from the very beginning to provide high resolution and interferometric capabilities. The main elements of the VLT interferometer (VLTI) are now on the verge to be completed and its first instruments are in the end of the design phase.[1]
The VLTI will combine, ultimately, the four 8-m Unit Telescopes (UT), and at least three 1.8-m Auxilliary Telescopes (AT) in a variable geometry array. Baseline lengths range from 8 to 202 m with a very dense u-v coverage for the ATs, and from 57 to 130 m for the UTs, with a total of 328 different baselines. This high modularity gives a particular advantage to the VLTI for interferometric imaging. The long baselines are requested for high resolution and micro-arcsecond astrometry. Interferometric imaging can be performed on two ways : by phase-closure, using 3 telescopes or more, and by phase-referencing. Both capabilities will be implemented in the VLTI.

Thus ESO is currently designing the Phase-Referenced Imaging and Micro-arcsecond Astrometry (PRIMA) facility. This system will pick up two stars in the telescope field-of-view, allow to observe the fringes simultaneously on both stars and measure the differential delay between their optical path differences, with a very high accuracy. One of the advantages of such a dual-feed system is to give access to the telescope field (2') without propagating this large field throughout the whole interferometer, which would give rise to very large optics and very stringent specifications on magnification and field rotation.
The aim of the PRIMA facility is triple :

- tracking the fringes on a bright guide star to stabilize the fringes on a nearby faint object and to measure their visibility with the instruments like MIDI and AMBER. This pushes the limiting magnitude of the VLTI to fainter objects (typically K=20).

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- phase-referenced imaging, where the differential delay between the bright and faint star fringes is measured with a dedicated metrology. The bright star serves as a fringe tracking source and as a reference for the object fringe phase. This phase measurement combined with the visibility measurement, for a number of different baselines, enables object image reconstruction with a very high resolution (1 mas at 2.2 μm) on fainter objects than phase-closure techniques.

- micro-arcsecond astrometry, where the differential delay is measured with a very high accuracy (5 nm rms) and is related to the angle between the two observed stars. The 200 m baseline would give a figure of merit of 10 μas for a 10" separation angle, in only 30 min integration time.

The first two modes will be used in combination with the VLTI instruments : MIDI, a mid-infrared (10 μm) imager, and AMBER, a near-infrared (1 to 2.5 μm) imager and spectrometer capable of multi-telescope phase closure. The astrometric mode will use a dedicated high accuracy, high sensitivity astrometric camera. The micro-arcsecond accuracy can be reached thanks to the narrow-angle properties of the atmospheric turbulence at long baselines[2] which relax the stability and measurement accuracy by a factor depending on the baseline length.

This paper describes the main PRIMA scientific objectives in section 2 in imaging and astrometric modes. PRIMA principle, sub-systems, required characteristics and expected performances are given in section 3. The most critical mode in PRIMA is the micro-arcsecond astrometry because it requires a very high, long term (several years) instrument stability, a high accuracy differential delay metrology and rigourous, cautious calibration and observation procedures. The technical challenges raised by astrometry and the calibration strategies are discussed in section 4.

2. PRIMA SCIENTIFIC OBJECTIVES

The most important scientific goals for the VLTI have been summarized by Paresce *et al.*[3] and Quirrenbach *et al.*,[4] and extensively developed in the conference proceedings edited by F. Paresce.[5] However, since then, new fields of applications have raised, especially in the astrometric mode.

2.1. Phase-referenced imaging

2.1.1. Extra-galactic astrophysics

- **quasars and active galactic nuclei**. Their light distribution is very well suited for interferometric observations, with a high flux small source surrounded by a not too faint environment. PRIMA could be able to determine relative contributions of circumnuclear starburst and compact nuclear source to the nature of AGNs, to measure the size and inclination of the dust torus, and to give indications about the velocity field. For quasars, PRIMA could discern detains like starburst knots in their host galaxies and resolve emission cones and reflection nebulae.

- **Magellanic clouds**. PRIMA could observe a wide variety of objects in these clouds : bright variable stars, small planetary nebulae, clusters ... on the same way as these objects will be observed in our galaxy.

- **nearby galaxies**. The closest satellite galiaxies of the Milky Way are very small compared even to the Magellanic clouds. Their study is comparable to the study of globular clusters or very dense open clusters. The imaging of their core, probably containing a black hole, is very interesting and would be accessible to the VLTI ATs.

2.1.2. Stellar astrophysics

- **globular and open clusters**. Both astrometry and imaging modes of PRIMA could be used to study the cluster dynamics.

- **galactic center**. It will be an important target for both imaging and astrometric modes of PRIMA. It will be possible to search for a counterpart of the radio source Sgr A*, usually difficult due to severe field crowding. Spectral classification of the galactic center cluster stars would help to determine its mass function, age distribution, and star formation history. At higher spectral resolution (R≈2000), radial velocities can be determined.

- **late type stars**. The VLTI milli-arcsecond resolution will allow to study the immediate vicinity of far-evolved stars and of their surfaces. This concerns giants on the asymptotic giant branch, long period variables, proto planetary-nebulae phase stars, and supergiants. PRIMA is necessary to track the fringes on a nearby star, the visibility of late type being too low to track on. One can expect at least about 2000 stars with apparent diameters larger than 1 mas and declination of less than 40 degrees ; roughly 400 of them have diameters larger than 10 mas. Star diameters, limb darkening, pulsation, mass loss and dust-shell properties could be measured with PRIMA. The planetary nebulae surronding low mass evolved stars are also easy targets for PRIMA thanks to their compactness and luminosity.
- **stellar surface features**. Surface inhomogeneities, or "hot spots", have been observed on late type supergiants. They could be observed on Red Giants or main sequence stars with PRIMA.
- **interacting binary systems**. PRIMA imaging will make it possible to observe the shape of the individual inetracting stars, and to build a precise 3-D model of their shapes. This will give important clues about the atmospheres and internal structures of the stars.
- **compact stellar objects** (white dwarfs, pulsars, black holes in binary systems). Interferometry is currently the only technique which can make observations of the surface of these stars and measure their extremely small angular diameters. The observation of their environment, influenced by the large magnetic and gravitational fields, is also of great interest.

2.1.3. Stellar environment

- **circumstellar disks**. Circumstellar dust disk and ejecta represent an essential step in the formation of planetary systems. But the high contrast between themselves and their host star, and their size, lerger than the Airy disk makes them very difficult targets, even with phase referencing.
- **extrasolar planetary systems**. Planets could be detected in the imaging mode by observing the star at two wavelengths, outside and inside molecular absorption bands (2 and 10 μm). One should observe a very small displacement of the photocenter due to the oresence of a planet. This is a challenging application of PRIMA with respect to the phase measurement accuracy, instrument stability, and bias calibration.

2.1.4. Special targets

- **cataclysmic variable stars** (novae, supernovae). The field of interest for imaging with PRIMA would be the imaging of the binary system during the outburst and the evolution of the ejected material with time.
- **solar system** (asteroids, occultations, Pluto and Charon, comets). PRIMA could image asteroids and comets, time precisely occultations and easily resolve the Pluto-Charon couple.
- **gravitational microlensing** (MACHOs, galactic center black holes). Gravitational microlensing splits a background star into 2 images, separated by up to some milli-arcseconds and with large intensity magnifications. The VLTI will be able to resolve this splitting. However, the lensed stars are faint, so PRIMA is needed to reach the required magnitude. The measurement of the phase is not required. The micro-lensing problem could be solved only with measurement of the visibilities as a function of the spatial resolution. The VLTI is a unique tool for such a study thanks to its modular baseline structure and high sensitivity. The critical point is to make several baseline measurements in a short time (some days).

2.2. Micro-arcsecond astrometry

2.2.1. Extrasolar planets and brown dwarfs

Interferometric astrometry is a complementary method to radial velocity techniques for extrasolar planet detection and characterization. Firstly, the radial velocity gives only an evaluation of the planet *maximum* mass. combined with astrometry, it gives its exact mass. Secondly, the applicability domains of both methods are complementary, astrometry being limited to nearby stars but being able to detect Jupiter-like planets far from the star while radial-velocity is not limited by the distance to the system but can only detect planets close to the star.

An astrometric measurement accuracy of 10 μas would allow the detection of Jupiters arouns pre-main-sequence stars up to a distance of 240 pc, Uranuses up to 44 pc and 10 Earth-mass planets up to 1.5 pc. But a 50 μas accuracy provides already very interesting science with Jupiters around pre-main-sequence stars up to 48 pc, brown dwarfs around all M dwarfs to VLTI sensitivity limit and Uranuses up to 9 pc.

2.2.2. Gravitational micro-lensing events

Gravitational micro-lensing events splits the background star image into two spot separated by some mas with large intensity differences. The image photocenter moves as a function of the relative position of the lensing body and the background star. The amplitude of the photocenter movement depends mainly on the lensing body distance from the observer and on its mass. Thus astrometry can be used to discriminate between micro-lensing due to Magellanic cloud faint stars or to MACHOs, in our own galactic halo. There is indeed a factor 30 between the astrometric effects of both bodies, reaching several hundreds of μas, for the MACHOs and only some tens of μas in the case of Magellanic cloud lensing body. Astrometry can also be used to determine the mass and Einstein's radius of lensing objects when looking toward the galactic center and to discriminate them as stellar mass black hole or ordinary stars.

Both programs need only 100 μas astrometric accuracy to bring first results. The critical point is the limiting magnitude. Toward the galactic center, the sky coverage will already be good with a limiting magnitude of 16 for the faint object and 10 for the fringe tracking one, a level that can be reached easily by the ATs. Toward the Magellanic Clouds, the sky coverage will not be good at this level but will anyway bring some events per year. If the faint object magnitude can be increased to 18, the sky coverage would be much better.

The VLTI has a large advantage relative to other astrometric interferometers : it is located in the southern hemisphere, with the galactic center passing by the zenith and with access to the Magellanic clouds during most of the year.

2.2.3. Binary stars and open clusters

Full orbits of spectroscopic binaries can be used to determine the masses of the two components and the precise distance to the system. There are a number of astrophysical applications of such measurements, including tests of stellar evolutionary tracks, and the role of convective overshoot. Astrometry, combined with single-lined spectrosopic observations, will give a full solution of this problem for a large number of stars.

In open clusters, the determination of binary frequency and their orbital characteristics has a thorough impact on the scenarios of star formation and the evolution of stellar systems. For stars with masses ranging from solar-type stars to early M dwarfs extensive work has been carried out using radial velocity measurements. However, almost no data are available for massive stars, whose duplicity statistics knowledge would certainly have an impact on our understanding of star formation. Many young open clusters up to a distance of about 1 to 2 kpc can be selected as potential targets to look for binarity in massive stars. This kind of work will need the ultimate accuracy of PRIMA.

2.2.4. Globular clusters and the galactic center

The globular clusters are very important systems to understand fundamental dynamical processes such as relaxation, mass segregation, core collaps, tidal effects and so on. Measurement of proper motions, combined with radial velocities, would give access to 3-D space velocities. A strong improvement of our understanding of internal dynamics of such objects can therefore be expected. The internal motions in globular clusters are of the order of 5 to 10 km/s. So we need to reach a 1 km/s measurement accuracy, *i.e.* a 10 μas/yr accuracy at 10 kpc, giving access to all galactic globular clusters.

In the same order of ideas, 3-D space velocities in the central 0.1 pc of our galaxy would give a much better picture of its dynamic and would provide a strong argument for the presence of a massive black hole in its center. In addition to further constraining the mass distribution, these measurements would also provide clues about the history of the galactic center cluster.

2.2.5. Parallaxes

In principle, trigonometric parallaxes with 10 % errors can be derived with PRIMA for targets out to a distance of 10 kpc. There are 2 major difficulties, however : the need to find a bright star for phasing the interferometer, and the relative nature of parallaxes measured over small fields. The first issue is not a problem for intrinsically bright objects (*e.g.* Mira variables). The conversion of relative parallaxes into absolute parallaxes may in some cases be accomplished through the careful choice of the reference object(s).

2.2.6. Extra galactic astrometry

The astrometric mode of PRIMA will also provide a unique possibility to determine the so-called AGN Dance-centroid due to SN explosion predicted by the Starburst model, events occuring roughly once per year. The AGN centroid would appear to move by a few tens of μas, within the nominal sensitivity of PRIMA, as long as a reference bright star can be found in the isoplanatic patch.

3. PRIMA PRINCIPLE AND REQUIRED PERFORMANCES

3.1. General scheme

PRIMA facility will be installed on the UTs and on the ATs. It will be optimized for phase-referenced imaging on faint objects, from 1 to 10 μm, on the UTs and for micro-arcsecond astrometry, between 1.5 and 2.2 μm, on the ATs. However, phase-referenced imaging *and* astrometric capabilities will be garanteed on both telescopes. In a first phase, PRIMA will work with 2 telescopes but could be later extended to the co-phasing of up to 4 telescopes at the same time.

PRIMA system should fulfill the following general requirements :

- pick up 2 stars at the Coudé focus and follow them accurately,
- redirect both collimated beams, parallel to each other, through the VLTI light ducts and delay lines, down to the interferometric laboratory,
- introduce an accurate and variable differential delay between both star light,
- track the fringes on the brightest star in order to co-phase the telescopes, and measure the fringe phase residuals,
- detect and measure the faint star fringes on the second feed,
- measure the total differential delay between both star light paths in the interferometer.

To perform this task, PRIMA needs 4 sub-systems, distributed all over the VLTI : star separators at the Coudé foci, differential delay lines in the lab, two fringe sensors/trackers (one of which used as the astrometric camera) and a dedicated, high accuracy, long range metrology coupled with adequately placed retro-reflectors. PRIMA principle scheme is given in figure 1.

A feasibility study was made, in 1999, by the *ONERA* (France) for the fringe sensor and by *Dornier Satellitensysteme GmbH* (Germany) for the other sub-systems. Moreover, a rider study on specific metrology issues was performed by the *Institute of Microtechnology* of Neuchâtel (Switzerland). These studies pointed out PRIMA critical points and proposed technical solutions. They helped us to revise our technical requirements and refine our system design choices, which are described here below.

The main delay lines were designed, from the beginning, to be compatible with a dual feed.[6] The capability of the delay lines to re-image the pupil at a fixed location in the interferometric laboratory, whatever their position, has enormous benefits for PRIMA by canceling diffraction effects linked to the long propagation lengths (Fraunhoffer's diffraction). The Variable Curvature Mirror (VCM[7]) performing this task, maximizes the VLTI optical throughput, stabilizes the star wavefront phases, removes diffraction effects, maintains the available field-of-view of each feed down to the lab, and allows to optimize the fringe sensor design. The VLTI instruments work also better with a fixed entrance pupil.

3.2. Star separator

The star separator shall be able to pick up 2 stars, each with its 2" field-of-view, within the 2' diameter field-of-view at the telescope Coudé focus, and to follow them in their movement due to field rotation, with a 10 mas accuracy. The light will then be collimated into two 80 mm diameter beams, propagating horizontally, parallel to each other.

Moreover, the system shall implement several degrees of freedom to allow slow pupil alignment and tilt adjustments during operation. The pupils shall also be reimaged at given appropriate locations in the VLTI light ducts, in order to stay compatible with the VCM use.

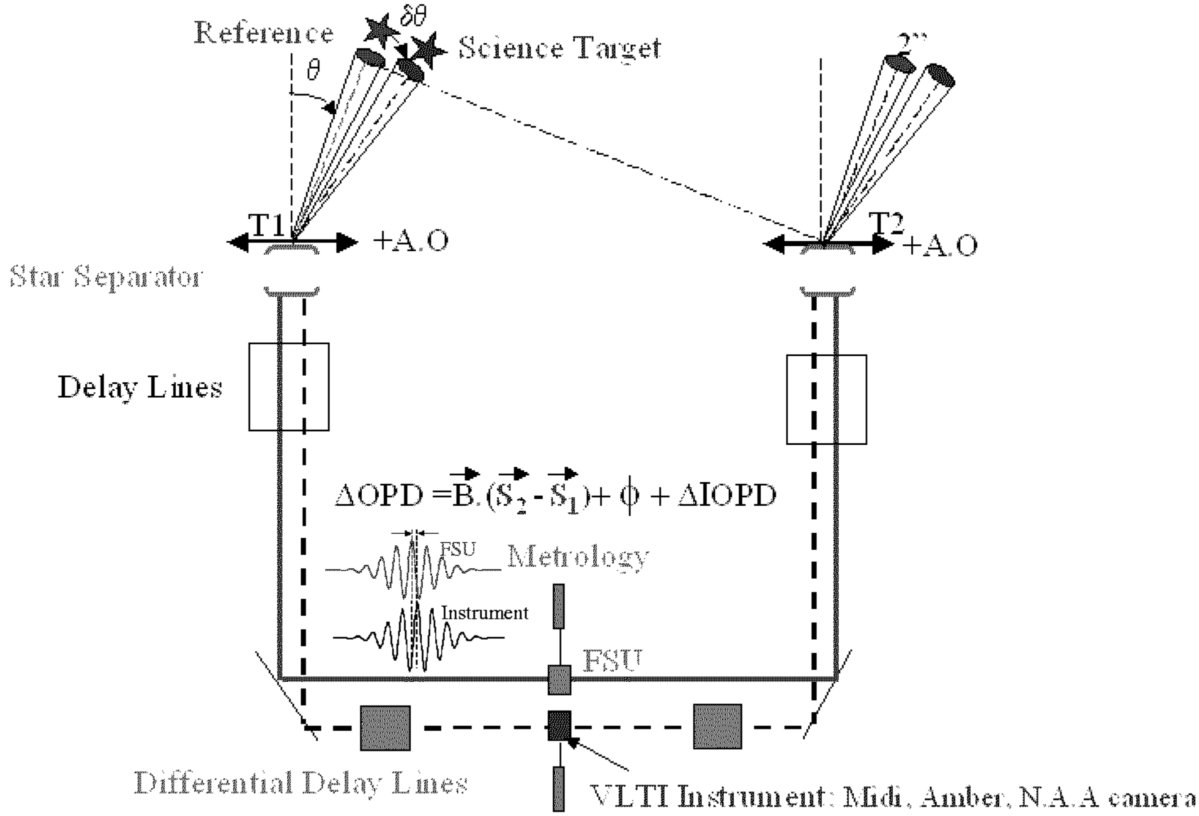

Figure 1. PRIMA principle scheme with its 4 sub-systems

The stringest requirements for the star separator are linked to its capability to perform phase-referenced calibration. Indeed, the constant term of the interferometer - or its zero point (where the optical path lengths from the star separator to the fringe sensors are equal for both feeds) - has to be calibrated very regularly with a high accuracy (see section 4). The usual way to do it is to split the light of the bright star into both feeds and to set the zero point when fringes are measured on the fringe sensor and on the scientific instrument. The frequency at which the calibration must be made is a function of the interferometer stability.

Finally, the star separator shall avoid any transmissive optics part and rely on reflective optics in order to maximize the throughput at 10 μm, especially on the UTs.

3.3. Differential delay lines

The differential delay lines (DDL) shall compensate the small (0 to 65 mm) optical delay between both star optical path differences (OPD) and follow the evolution of this differential delay with earth rotation in real time. They will probably feature a cat's eye design, mounted on straight and stiff air bearings with a small piezo-actuator on the cat's eye secondary mirror for fine adjustments. The DDL design could also be combined with a beam compressor capability in order to gain reflections. Indeed, the beams coming from the telescopes are 80 mm in diameter while most of the instruments accept only 18 mm beams. A compression is so needed and could be performed independantly from or combined with the differential delay. A local metrology system shall continuously monitor their position for servo control.

The DDL technical critical points are the required high stability in tilt (yawn and pitch), low heat dissipation and compatibility with a possible vacuum environment.

3.4. Fringe sensor / fringe tracker unit

The fringe sensor unit (FSU) shall allow fringe tracking with low residuals on bright stars ($K \leq 10$ for the ATs, $K \leq 13$ for the UTs) as well as accurate fringe detection and measurement on fainter stars ($K \leq 18$ on the ATs and $K \leq 22$ on the UTs). The FSU shall perform the tasks of a general purpose fringe tracker and of a dedicated astrometric camera, switching quickly from one task to the other with no configuration modifications before beam combination. This dual capability will allow to permute the two observed stars in the astrometric mode between the feeds in order to calibrate for biases not measured by the metrology. The FSU design shall also be integrated and optimized with the metrology injection optics in order to reduce the non-common optical paths to the minimum and to stabilize them in a controlled environment.

The FSU concept shall probably be based on co-axial beam combination, with spatial achromatic discrete phase modulation and chromatically dispersed fringes.[8] An interferometric ABCD-like algorithm shall be implemented. This concept has the advantages that no temporal OPD modulation is introduced in the metrology path and that the spectral dispersion makes the simultaneous measurement of phase and group delay possible, for coherencing and co-phasing. An even more sensitive AC algorithm is under study.

The FSU critical points are in the throughput and efficiency optimization to co-phase the inteferometer on the faintest star possible, in the required high speed detection to track the fringes, and in the optimization of its interface with the metrology.

3.5. Metrology

A highly accurate metrology system is required to monitor the PRIMA instrumental optical path errors to possibly reach a final instrumental phase accuracy limited by atmospheric piston anisoplanetism. The metrology system shall measure the internal differential delay, ΔL, between both stars with a 5 nm accuracy goal (or $\lambda/200$ for $\lambda = 1\mu m$), over typically 30 min. The accuracy requirement is driven by the astrometric mode, but can be relaxed by a factor 50 to 100 in the imaging mode, and depending on the observing parameters. In addition to an ambitious accuracy objectives, the metrology system has to cope in particular with long, air-filled path.

In observing conditions, the amplitude of DL can reach about 65 mm. However, the metrology system must monitor the entire internal path of the VLTI, i.e along hundred of meters, to obtain an accurate estimation of ΔL by eliminating equivalent dead path error.

Driven by the accuracy requirements, implementation constraints, and metrology state of the art, the baseline of the PRIMA metrology system is a heterodyne laser interferometer, as identified during the PRIMA feasibility study. It consists in a telescope pair-wise configuration: the internal optical path difference is monitored for each celestial object from its beam combiner to reference points located in both telescopes. Therefore, it involves two similar heterodyne laser interferometers and ΔL is obtained by monitoring the difference between the 2 interferometers based on a super-heterodyne detection technique as detailed in Lévêque's paper, in these proceedings.[9]

4. MICRO-ARCSECOND ASTROMETRY CHALLENGES

In ground based interferometry, one wants to get performances limited only by the atmospheric perturbations. In phase-referenced imaging and astrometry, the critical measurement is the phase measurement. In the very narrow angle regime, where PRIMA will always be working, the variance of the differential angle measurement is given by[2] :

$$\sigma_\delta^2(T) \simeq 5.25 B^{-4/3} \theta^2 T^{-1} \int_0^{+\infty} dh C_n^2(h) h^2 V^{-1}(h) \,, \tag{1}$$

where T is the total integration time in seconds, B the baseline in meters, θ the angle between the stars in radians, $V(h)$ the wind velocity in meters per second of a layer at height h, in the Taylor hypothesis, and $C_n^2(h)$ the weight of the turbulence at that layer. Using Paranal model of the atmosphere, we can estimate that the possible figure of merit of the VLTI should be 10 μas for a 10" angle, 30 min integration time and 200 m baseline.

This ultimate performance requires an accuracy on the OPD measurement of 5 nm rms and an accuracy on the baseline knowledge of ≈ 50 μm. To reach this, accurate calibrations will be necessary. And the frequency at which calibration shall be made - and so the scientific production rate - will depend strongly on the instrument stability. Moreover, at low light flux, the noise on the fringe detection must be taken into account to check if the 5 nm accuracy on the fringe measurement is met.

4.1. Baseline calibration and instrument stability

Position of the telescope stations and Alt/Az axes intersection will be known, using geodesic measurements and telescope specifications, with an accuracy of 2.2 mm and the Az axis runout will be less than 0.1 mm. It is not yet good enough for astrometric measurements. So the baseline must be calibrated on stars whose absolute positions are known. This is done using the VLTI in single field and measuring the position of the delay lines as a function of the pointed star coordinates. The global, final baseline knowledge accuracy will depend on :

- the accuracy at which the star positions are known,
- the number of calibration stars used,
- the stability of the baseline during the calibration, when pointing to stars at large angular distances from each other (several degrees),
- the stability of the baseline during the observations, after calibration.

To reach a 50 μm accuracy on the baseline at calibration, a properly selected set of calibration stars must be chosen. Lévêque proposed a genetic algorithm to perform this selection.[10] This reduces the number of calibration stars and the effect of calibration noise on the accuracy of the estimated parameters. So a set of 4 stars, properly located within a 30° radius from the scientific target, with positions known at a 10 mas level are required. If more stars are used, the requirement on their individual position accuracy knowledge is reduced by a proportional factor.

This was assuming that the baseline was not changing during calibration. In practice, 1.8 m telescopes suffer from flexures under gravity load and the baseline could depend on the pointing direction. For the ATs, a computer modeling of the mechanical system showed relative displacements of mirrors M1, M2 (limiting the pupil) and M3 (on which the Alt-Az axes are crossing) reaching several tens of micrometers, as a function of the zenital angle. The position of the azimut axis will not change by more than 100 μm. Fortunately, these deformations will be similar for both ATs used in the interferometer because they will point to the same object. The differential movements will then be reduced by, at least, a factor of 10. Moreover, the accuracy of the telescope pointing model will be enhanced, by independent calibration, once the telescopes will be installed on Paranal. The residual, non-calibrated baseline variations will then be reduced to the micrometer level, during the astrometrical calibration and during the observations.

The last effect on the baseline length is linked to telluric phenomenons : earth tides, which can be modeled to the required level, and earthquakes. Weak earthquakes will just interrupt observations but larger ones could result in permanent modifications of the telescope reference positions or of the telescope structure, requesting a new calibration of the baseline and new pointing models. For instance, the 1995 earthquake (magnitude 7.2) induced a general displacement of the whole observatory of 50 cm.

4.2. Zero OPD calibration and air propagation effects

The differential OPD offsets between the reference object and the science beam must be measured. Relatively frequent calibration will be needed if the interferometer *constant term*, or more relevant the difference between the *constant terms* for the two beams tends to vary with time. The zero OPD calibration allows to determine at which setting of the differential delay lines the optical path lengths in both PRIMA feeds are equal, with an accuracy of a few nanometers. This setting is taken to be the PRIMA zero point. The measurement is achieved by setting up the PRIMA system with a nominal zero OPD difference between the two beams, and then feeding both beams from a single source. Then, resetting PRIMA (differential delay lines, star separator etc....) to the science target observation setting and monitoring the path length changes with the metrology while doing so, one measures accurately the differential path length between the reference and science objects, enabling imaging and/or astrometry.

This zero OPD calibration can be made on two ways : i) using the star separator to feed the same reference star into both feeds and defining the zero point on the basis of the fringes detected in both beam pairs, ii) using a white light (infra-red, broad band) metrology propagating into both feeds of each of the telescopes, observing the central fringe between both beams for each telescope, and deriving the PRIMA zero point through the equal path lengths so defined. This last method is equivalent to generate an artificial reference star split into both feeds. This could be accomodated to PRIMA currently planned sub-systems without significant design modifications. The implementation of the first calibration procedure (i) has important effects on the star separator design and requirements. The star separator should be able to split the reference star into both feeds and to switch back to the normal dual field mode while metrology continues to monitor the full system. The weakness of this method is that the calibration and the measurement are not made with quite the same optical settings. So if parameters affecting the differential OPD, but not monitored by the metrology are differentially changing in between, it will affect the measurement as an additional optical path length difference. Mechanical systematic effects of such a kind can be calibrated by measuring some given pairs of stars during a whole night and fitting a dual-feed ΔOPD model to the measurements.

Both zeroing calibration processes as well as the whole night systematic calibration will be performed with PRIMA.

There remain one last source of error linked to the propagation of the star and metrology beams in air. A mishap could possibly occur when, with monochromatic metrology, temperatures can change between zero OPD calibration and science measurement. Indeed, the metrology measures an optical path difference depending on the air pressure and temperature. This measurement must then be combined with the fringe sensor measurements to retrieve the vacuum differential delay which is linked to the astrometric value. Temporal environmental variations between the calibration and measurement steps can compromise the 5 nm accuracy target for micro-arcsecond astrometry. Such problems might be solved alternating measurement and zero OPD calibration often enough but the cycle *calibration-measurement-calibration* cannot be done more than once in a minute. If the changes are quicker than that, one has to find another solution. Measuring the air temperature and pressure is neither a good solution because the 5 nm level accuracy is lower than the accuracy of the formula giving the air refractive index as a function of the temperature and pressure. The problem could be solved using a multi-wavelength absolute metrology or implementing a simultaneous calibration scheme. The multi-wavelength metrology is difficult to implement and not yet available with the required accuracy. This solution will be studied for possible future implementation.[11] The concept of a simultaneous calibration was studied and led to a partial multiplexing calibration scheme. The principle of this method is to send (a small) part of the reference star light into the science beam (and possibly vice-versa) using wavelength or polarization multiplexing. Then, on the science object fringe sensor unit (or the astrometric camera), one can observe simultaneously the reference star and science object fringes, while they are frozen using the main part of reference star light on the PRIMA fringe tracker. In the science feed, both lights have followed the same path at the same moment and any temporal environment modifications are part of both measurements. The partial multiplexing calibration may not always be needed, and hopefully only for the most demanding astrometric purposes (so primarily on the ATs). It will not be easy to implement on the system as it implies a multiplexing system at the star separator level and a de-multiplexing system in front of the differential delay lines, both requiring local metrologies. For very faint science target observations it will almost certainly have to be removed altogether, as limits to the suppression of the multiplexed flux will cause a limit to the maximum intensity ratio between science target and reference star. Thus the partial multiplexing concept will not be integrated in the first phase of PRIMA but the system will be compatible with a later implementation of multiplexing if this calibration method shows to be necessary for high accuracy astrometry.

4.3. Integration time : snap shots versus long exposures

With a noise-free or background limited detector, a dual-feed fringe tracking system like PRIMA increases the observation limiting magnitude by increasing the characteristic time τ_0 of the differential OPD turbulence. So, one has no interest to increase the individual exposure time, over the one needed to get enough photons for fringe detection. Post-processing of such fringe snap-shots will perform as well and even better than long exposures. Indeed with snap-shots, the fringes will not be blurred and their contrast will be better.

With practical detectors with read-out noise, two phenomenons compete when having to choose the number and duration of short exposures to be made (supposing a constant total integration time fixed by the astrometric accuracy limit to be reached, linked to the atmospheric residual). The presence of read-out noise pushes toward a few exposures of long duration while the anisoplanatic OPD, which blurrs the fringes and diminishes their visibility, pushes toward a large number of snap-shots. A trade-off must be found, depending on the faint star magnitude, on the off-axis angle, on the read-out noise, on the baseline, and on the telescope diameter.

The optimum single exposure duration was computed by minimizing the measured phase variance supposing a classical dispersed ABCD algorithm. The “white” channels were supposed to be detected by 4 pixels each, the 8

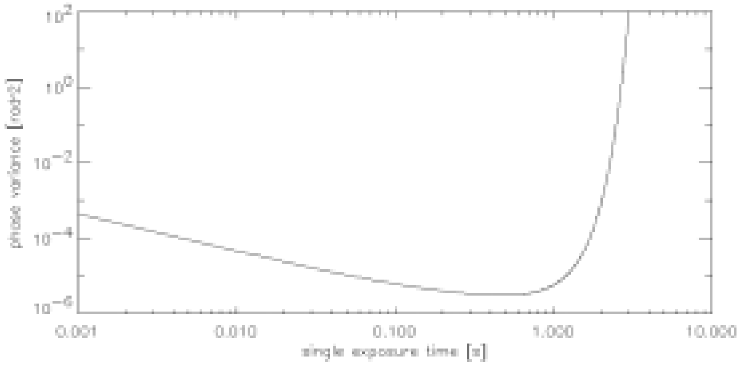

Figure 2. Phase measurement error as a function of the individual exposure time, for the ATs, a baseline of 200 m, a 10" off-axis angle, a 30 min integration time, a star K-magnitude of 16, a read-out noise of 10 e^- rms, and a fringe detector reading 20 pixels (4 for the white light, 8 spectral channels and 2 pixels per channel).

spectroscopic channels (for each phase point) by 2 pixels each. The obtained 20 pixels were supposed to be rebinned to get the final A, B, C and D measurements. The fringe visibility loss, affecting the phase measurement accuracy, was computed using the expression of the differential anisoplanatic OPD variance over an integration time t given by d'Arcio.[12] Atmospheric turbulence profiles obtained at Paranal during the PARCSA balloon campain in March 1992 were used. The bright star fringe tracking (co-phasing) was assumed to let a residual OPD variance of 70 nm.

In figure 2, one can see that the phase measurement variance presents a minimum as a function of the single exposure time, for a constant maximum integration time. This minimum corresponds to the optimum single exposure time. One can also compute the maximum single exposure time at which the measured phase variance, over the total integration time, goes over a certain limit. This limit can be fixed as the atmospheric accuracy limit. With a larger single exposure time, one cannot reach the target accuracy anymore. These optimum and maximum single exposure time depend on the star separation and on the faint object magnitude. The optimum and maximum times for the ATs and the UTs are shown in figures 3.

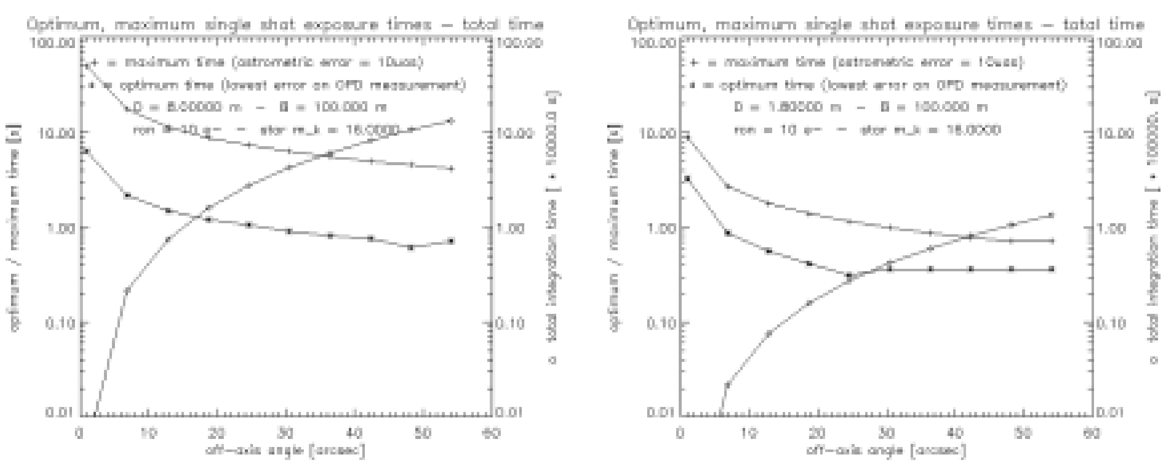

Figure 3. Examples of optimum (+) and maximum (*) single exposure times as a function of the off-axis angle, for the UTs (left) and for the ATs (right), for a star K-magnitude of 16, a read-out noise of 10 e^- rms, 20 pixels per fringe detection, a 100 m baseline, and an astrometric error of 10 μas. The total integration time to reach this accuracy as a function of the off-axis angle is also shown, with the scale at right (note the factor, on the total integration time scale, of 10000 for the UTs and of 100000 for the ATs).

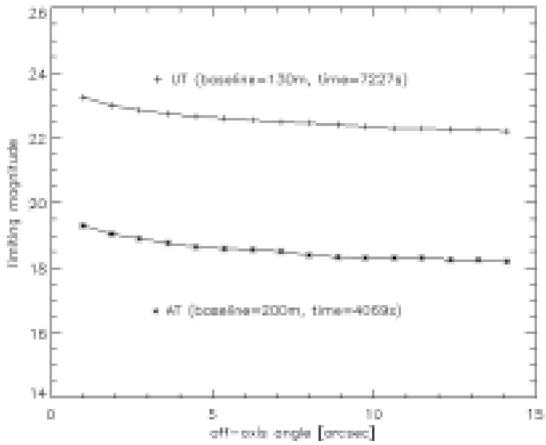

Figure 4. UT and AT limiting magnitudes, as a function of the off-axis angle, for a total integration time leading to an astrometric accuracy of 10 μas with a star separation of 15".

If the measured phase variance never goes lower than the atmospheric limit value, the limiting magnitude of the system has been reached. The limiting magnitude for the UTs and for the ATs, as a function of the star separation, for a given total integration time, were computed and are shown in figures 4. The total integration time was chosen such that a 10 μas astrometric accuracy at a separation of 15" was reached with a 200 m baseline on the ATs and 130 m baseline with the UTs. It led to total integration times of 68 min on the ATs and 2 hours on the UTs. At separation angles larger than 15", the total integration time required to reach the astrometric accuracy becomes prohibitive and was not considered here, even if limiting magnitudes can still be computed.

5. CONCLUSIONS

The Phase-Referenced Imaging and Micro-arcsecond Astrometry facility for the VLTI is necessary to i) increase the interferometer sensitivity limit, ii) provide high resolution (1 mas) imaging, and iii) do micro-arcsecond astrometry. It will be built starting from the end of this year and should be operational on Paranal observatory by the end of 2003. It includes 4 sub-systems, distributed over the inteferometer structure : star separators at the telescope Coudé foci, differential delay lines and fringe sensor units in the interferometric laboratory, differential delay and white light metrology whose light sources will be in the laboratory and retro-reflectors in the telescope structure, as close to the entrance pupil as possible.

The realization of PRIMA implies several technical challenges linked to the accuracy at which such opto-mechanical sub-systems must work. The micro-arcsecond capability is particularly stringent. It requires a very high overal stability of the interferometer, especially on the mechanical and thermal points of view. At long term (hours or days), any ground based structure of the size of the VLTI is not stable enough to keep 10 μas atrometric accuracy. So regular and - more or less - frequent calibrations of the interferometer baseline and of its *constant term* will be required.

PRIMA could use a genetic algorithm to choose the right star set for baseline calibration in order to get the baseline requested accuracy (50 μm) as fast as possible. For the *constant term* measurement, PRIMA will implement 3 calibration strategies : i) splitting of the reference star into both feeds, ii) creation of an *artificial* calibration star in the laboratory by use of a white light metrology, and iii) global, whole night calibration (similar to the one used in radio-astronomy) to calibrate for systematic effects not calibratable by the previous methods.

If the interferometer reveals, at term, not to be stable enough to reach the astrometric accuracy, due for instance to evolving thermal gradients in the air filled light ducts and delay lines, other calibration or measurement procedures could be implemented like an absolute metrology or partial multiplexing in the dual-feed.

We showed that ultimate measurement accuracy depends also on the duration of the individual exposures which will be combined, in post-processing, to get the fringe position. For each star magnitude, detector read-out noise and off-axis angle, one can compute an optimum single exposure time. The PRIMA-VLTI limiting magnitudes with the UTs and ATs, to reach the 10 μas accuracy were computed. For a star separation of 10", they reach 22 for the UTs and 18 for the ATs, in K-band.

PRIMA will so provide a very high improvement in the VLTI capacities.

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