PHASE REFERENCED IMAGING AND MICRO-ARCSEC ASTROMETRY (PRIMA) TECHNICAL DESCRIPTION AND IMPLEMENTATION

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1.Scope

After a brief introduction of the key scientific objectives of PRIMA, this paper will summarize the preliminary system engineering study and will introduce the technical baseline and implementation of the system. Mutual benefit of GENIE and PRIMA development, in particular on the Fringe Sensor and the Metrology, will be also discussed.

2.Introduction

PRIMA will be designed to make use of the Dual feed capability of the Very Large Telescope Interferometer for both Unit and Auxiliary Telescopes. With PRIMA the global limiting magnitude of the VLTI will gain about six magnitudes in H, K and N. The system is designed to perform high accuracy (10 µas) narrow angle astrometry in band H or K, aperture synthesis (phase reference imaging) and model constrained imaging in bands J, H, K and N (depending on the instrument: VINCI, AMBER, MIDI).

In the astrometric mode, the prime observable is the differential optical delay between the object and a reference. In Imaging mode, the observable are phase and amplitude of the object visibility. Both will require observation on a number of baselines (minimum two for Astrometry, more for Imaging).

PRIMA will be composed of four major sub-systems: Star separator, Differential Delay Lines, Metrology, Fringe Sensor Units and one overall control system including software.

3.Science Objectives

The first objective is the detection and characterization of extra-solar planets and their birth environment. This objective requires application of both the astrometric and the imaging capability of PRIMA. The astrometric capability will determine the main physical parameters of planets orbiting around nearby stars already found by radial velocity (RV) techniques including their precise mass, orbital inclination and a low resolution spectrum.

In addition and most importantly, astrometry will allow VLTI to extend the search for planets to stars that cannot be properly covered by the RV technique, in particular pre-main sequence (PMS) stars. The crucial exploration of the initial conditions for planetary formation in the stellar accretion disk as a function of age and composition will be finally possible. The reach of the VLTI in the local star forming regions is shown in Figure 1 where the expected magnitude of the reflex motion of the object specified is plotted as a function of distance. The VLTI then will be able to reach all the way out to Orion to study planets in a wide variety of environments.

The simultaneous image at mas resolution or better of the accretion disk from which any particular planet is born will add a new and exciting dimension to our understanding of both planetary and stellar formation mechanisms since the complex accretion disk is expected to be the cradle of these objects. The expected disk structure open to VLTI with PRIMA might look something like that shown in Figure 2.

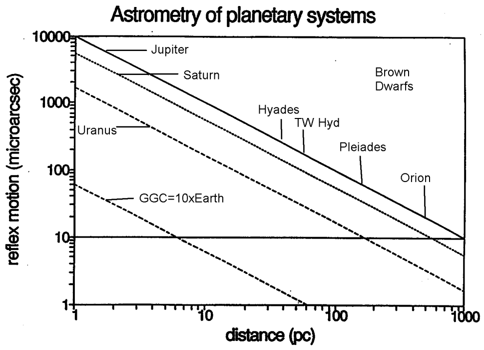


Figure 1. The expected astrometric reflex motion of objects of different masses as a function of distance. The VLTI is expected to measure reflex motions > 10 μas (horizontal line).

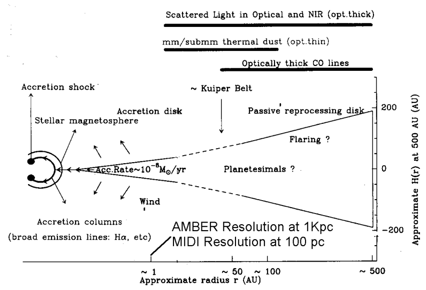


Figure 2. Schematic diagram of the outer regions of the accretion disk around a PMS star adapted from Lopez. Expected VLTI linear resolutions at 2 and 10μ are shown.

Another key objective for VLTI with PRIMA will be the exploration of the nuclear regions of galaxies including our own. The resolution of the VLTI at 2μm corresponds to 15AU at the galactic center or about 1500 times the Schwarzschild radius of a 10^6 $M_\odot$ black hole (BH). The first and most important goal will be to test for the presence of a central massive BH by measuring the three-dimensional velocity field of the star cluster centered on IRS16. The VLTI will be able to probe the 3D space motions of stars in the nuclear cluster down to 10^{-4} pc of the central source or approximately two orders of magnitude better than currently. This data will certainly provide very precise information on the central mass without the a-priori assumption of isotropic motions. High precision astrometry with PRIMA might even go so far as to probe the central BH to a few times its Schwarzschild radius ($2.5*10^{-7}$ pc).

As is quite apparent from Figure 3, high resolution imaging with the VLTI of the nearest AGN (Cen-A is at ~ 3.5Mpc) has a crucial role to play in this area especially with MIDI at 10 and 20μ. At these wavelengths, the view towards the heart of the galaxy is not hampered by extinction of dust in the galaxy and is not confused by stellar emission. The VLTI should, therefore, allow the unambiguous detection of dust torii and constrain their inner and outer radius and density and temperature structure. A number of models and geometries for obscuring torii have been proposed. The models range from extended 100 pc scale torii having moderate optical depths to much more compact ones with very high optical depths and, possibly, some with warped disks. All of these models can be severely constrained or eliminated easily by VLTI observations.

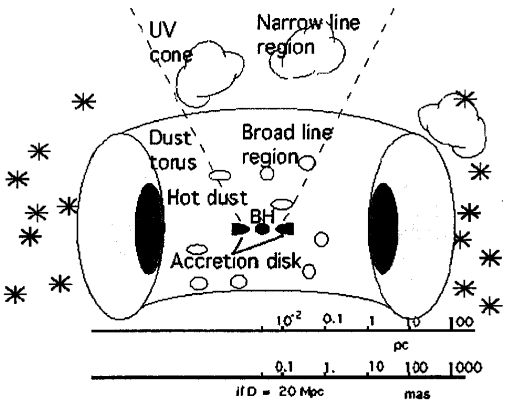


Figure 3. Drawing of the possible structure of the core of an AGN at 20 Mpc distance indicating several of the main components

4.Overall Description and Principle

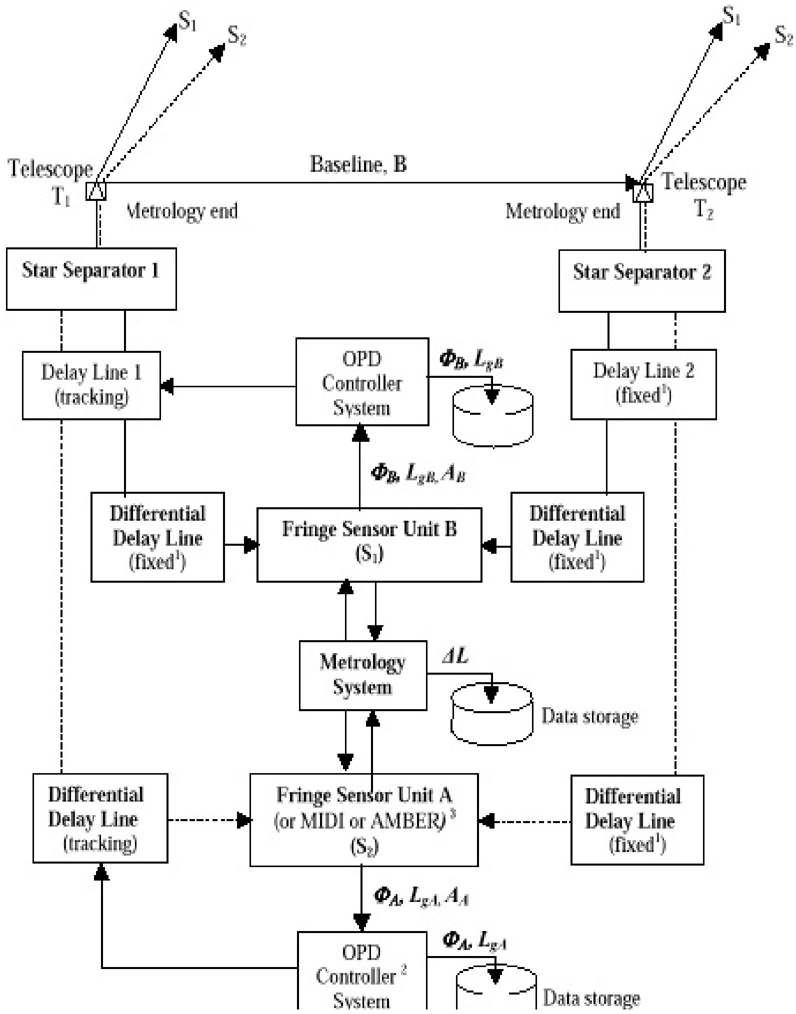
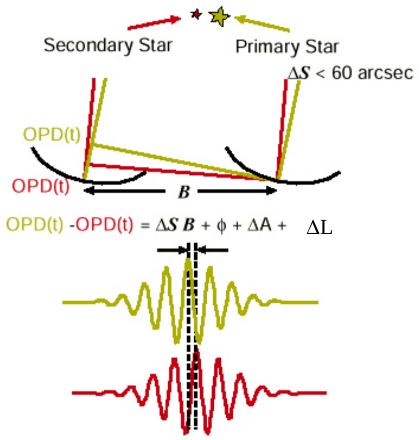


Figure 4. General Principle of PRIMA

The general principle of an observation with PRIMA is illustrated in Figure 4.

The selected object and reference star are observed by a pair of telescopes (either UT-8m or AT-1.8m). The selection of the reference star is made within the anisoplanetic angle at the selected wavelength. For Paranal the anisoplanetic angle varies between 10 arcsec in H band and 60 arcsec in N band. The two field separation will be performed by the Star Separator System (STS) located at Coudé focus of each telescope. The STS will collimate the two beams and send them to the delay lines tunnel. The main Delay Lines will compensate for both beams the optical path difference introduced by Earth rotation. They will also transfer the pupil from the telescope to the selected instrument. Before the instruments, both beams will be directed to the Differential Delay Lines. Those DDL have for function to compensate the relative Optical

Path Difference introduced between both beams coming from the same telescope. This optical path difference is related to the angular separation between the object and the reference. There will be one DDL per beam and per telescope for a total of 4 systems to keep the optical symmetry. After the DDL, the reference beams will be directed to the Fringe Sensor Unit B. The FSU –B- will generate the interference and analyse the fringe pattern in order to determine the Optical Path Difference to be compensated by the main DL and the DDL. The FSU B is used as a fringe tracker for both reference and object. The two beams coming from the scientific object will be directed either to the instruments (VINCI, MIDI, or AMBER) in imaging mode or to the Fringe Sensor Unit A in case of astrometry mode. At the level of the FSU A/B and Instrument, the metrology will be introduced in the optical path. The metrology will measure in real time the relative optical path difference between the reference and the object beams. The fringe patterns of both objects combined with metrology measurement will be analysed to determine either the angular separation of both objects in the sky (astrometry) or the complex visibility of the science object (imaging Mode).



The recorded distance between white fringes of the reference and the object is given by the sum of four terms:

(? S . B) the Angular separation (< 1 arcmin) times Baseline;

+ (?) the Phase of Visibility of Object observed for given baseline;

+ (? A) the Optical Path Difference caused by Turbulence (supposed to average towards zero in case of long integration time);

+ (? L) the Optical Path Difference measured by Laser Metrology inside the VLTI.

n.b. For astrometry both Objects are supposed to have the Phase of their complex visibility = zero (point source or circularly symmetric object)

5. PRIMA Physical Limitations and Ultimate Performance

PRIMA is designed for three observation modes: Faint object, Model independent imaging and astrometry.

5.1. Limiting Magnitude

PRIMA will allow observation of objects having about 6 magnitudes fainter than in the present configuration. Limiting Magnitudes of AMBER, MIDI or VINCI with fringe tracking in K band with FSU B are summarised in the following table.

	UT	AT
Object in H or K Band	19	16
Object in N Band	11.5 (no IR counterpart)	8.3
Reference in K Band	13/15	10/12

5.2. Phase and Astrometric Accuracy

In Model Independent Imaging (Aperture Synthesis), the complex visibility of faint objects observed with AMBER, MIDI, VINCI will be measured within an accuracy better than 1%.

In micro-arcsec Astrometry mode, the Phase and Group Delay measured with FSU A and with the Metrology will allow angular measurements up to 10 µarcsec resolution. This corresponds to 5 nm accuracy for the metrology and an accuracy of ?/2000 for the FSU.

5.3. U-V Coverage

As already designed, VLTI allows interferometric observation with Baselines from 8 to 200m. The number of independent baselines is given in the following table.

	2 UT	3 UT	4 UT	2 AT/29 stations
Range	45, 56, 60, 86, 99, 130m	idem	idem	8 to 200 m
Independent Baselines	1	3	6	259 (with 8 DL or 4DDL) 232 (with 6 DL and no DDL)

5.4. Sky Coverage

The Sky Coverage of PRIMA is limited by the probability to find within the anisoplanetic angle a reference star. First simulation of the probability to find, in the galactic plane, at least a star of a given magnitude in K (FSU B is designed for K Band only) is shown in figure 5.

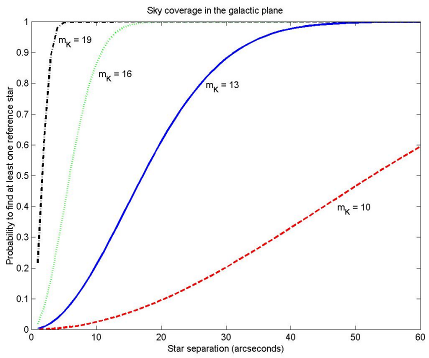


Figure 5. Probability to find a reference star of a given magnitude in K within a certain field angle in the Galactic plane

Taken the assumption that the FSU B will be able to track on stars having M_K = 13, same simulation of the probability to find reference star within a certain angle is given for the galactic plane (figure 6) and out of it (figure 7).

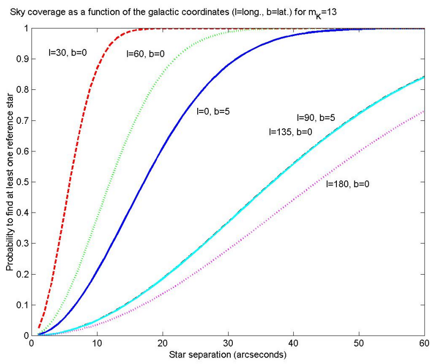


Figure 6. Probability of presence M_K 13 star in galactic plane

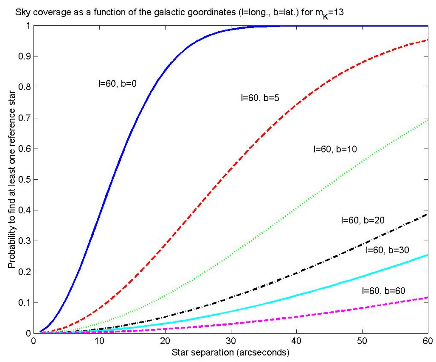


Figure 7. Probability of presence M_K 13 star out of galactic plane

5.5. Visibility Loss and Measurement accuracy

Fringe visibility attenuation is related to off-axis observation. The visibility loss is function of the Anisoplanatic optical path difference (figure8). This visibility loss (figure 9) has two effects on the observation of the faint object: it reduces the limiting magnitude on the faint object and it reduces the accuracy with which the visibility of the object is measured. However, the visibility loss can be calibrated on reference stars.

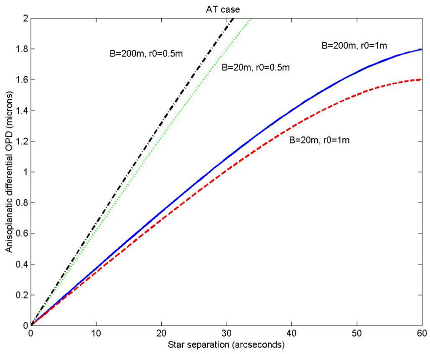


Figure 8. Anisoplanatic OPD noise as a function of the angle between the stars for the AT (left) for a wavelength of 2.2µm.).

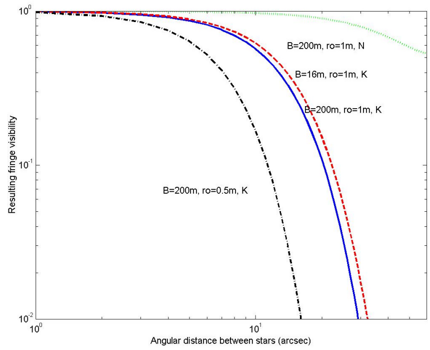


Figure 9. Fringe visibility (normalized to V_0=1) as a function of the off-axis angle for the AT at 2.2µm (K-band) and 10µm (N-band

The Optical Path Difference Tracking Residual are another important factor for the perfromance evaluation. OPD noise is dominated by Fringe tracking noises (sensor and loop noises) and is linked to band pass and atmospheric turbulance. Current OPL tracking loop (OPD controler and main Dealy Lines) at Paranal has 44.6 Hz Band Pass. OPD residual is estimated at about 100 nm. For small angular separation the DDL with high sampling rate can optimise the OPD residual but only for separation < 3" in K and bright stars. A first simulation of the normalised fringe visibility versus FSU noise (OPL in nm) expected for different close loop residuals is given in figure 10.

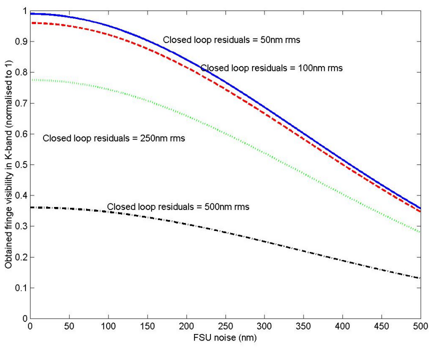


Figure 10. Fringe visibility in K band function of FSU noise
for different close loop residuals

5.6. Observation Time

Last factor to be considered for the main performance of PRIMA is the total Observation Time. If short exposure visibility and phase measurements are supposed averaged incoherently, for Paranal typical atmospheric condition 18µas/hr$^{1/2,}$ baseline 200m and 10" separation between the object and its reference (typical for K band), the 10µas astrometry accuracy requests about 3 hr observation time in total per baseline and 1% accuracy in imaging will request about 40 min per baseline.

Single Exposure Time will be selected according to desired OPD residual and fringe visibility loss as shown in figures 11 and 12.

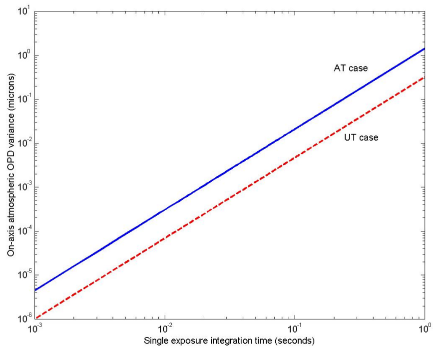


Figure 11. Variation of the residual OPD as a function of the integration time, for the AT (*D*=1.8m, *B*=200m) and UT (*D*=8m, *B*=120m) cases.

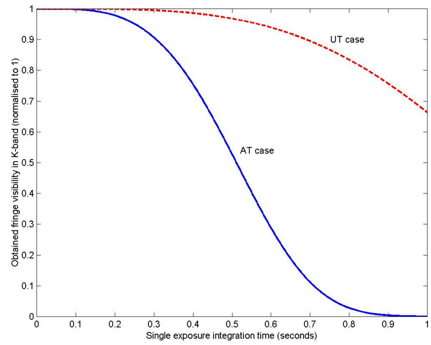


Figure 12. Resulting fringe visibility at 2.2µm, same condition as Figure 11.

6.GENIE with PRIMA

The joint ESA-ESO project GENIE (Ground-based European Nulling Interferometer Experiment) could benefit from both fringe tracking and metrology technologies implemented for PRIMA.

The measurement principle of GENIE imposes stringent requirements on the OPD control accuracy. Estimates for the maximum tolerable residual [1] closed-loop OPD error (rms) are as follows:

- < 20 nm for nulling beam combination in the N band (around 10.2 µm)
- < 5–7 nm for nulling beam combination in the L band (around 3.4 µm)

Because of the limitation imposed by the infrared background level and its fluctuations in the N band (which are still to be evaluated), the L band becomes of high interest for GENIE. However, requirements on the residual OPD error, especially in L-band, cannot be met by the already implemented VLTI fringe tracking control loop consisting of FSU, OPD controller and main DL. This raises the need for a very fast OPD compensation system.

As a solution, a *two-stage fringe tracking concept* could be envisaged: the classical VLTI fringe tracking loop will be enhanced by a fast “GENIE fringe tracking loop”. For both loops the measurement of the OPD fluctuation shall be performed by a PRIMA FSU. The FSU will use the K-band spectrum of the stellar beams to deliver measurements of the OPD error at a rate of 8 kHz (estimated measurement accuracy <= 5 nm rms for stellar magnitude $m_K = 5$). While the classical VLTI loop will employ the main DL working at a sampling rate of 2 kHz as actuator, for the fast GENIE loop two possibilities for the actuator can be considered: (1) implementation of fast GENIE-internal delay line (e.g., based on a Piezo-electric actuator), or (2) usage of PRIMA’s Differential Delay Lines (DDLs) which are specified for 8 kHz sampling rate. The second option shows mutual benefit for both projects, PRIMA and GENIE. However, it assumes a DDL design in accordance with GENIE performance specifications (sampling rate and closed-loop bandwidth).

In addition, the PRIMA laser metrology could be also used to monitor the following fluctuations of the optical path whose measurement would be added to the FSU measurement in closed loop:

- Fluctuation of the optical path between the location of fringe sensing (PRIMA FSU) and the location of nulling beam combination (GENIE) (induced by air turbulence)
- Residual fluctuation of the optical path due to mechanical vibrations of the telescopes

7.Sub-System Description and main Performance

PRIMA will be composed of four sub-systems: Star separator, Differential Delay Lines, Metrology and Fringe Sensor Units

- Star Separator

The Star Separator is an optical system for the UTs and ATs located at the Coudé foci feeding two arbitrary objects from the Coudé field of view into the Delay Lines of the VLTI. The Star Separator will allow the transmission of two fields up to 1 arcmin apart in the sky and 2 (for the UTs) resp. 9 (for the ATs) arcsec in diameter towards the Delay Lines. The two beams will be collimated and will have a pupil transfer. The pupil will be 80 mm in diameter (same for both UT and AT). The STS will compensate for field rotation, will stabilize the beam tip tilt and adjust the lateral alignment of the pupil. The possibility of counter-chopping will be foreseen for operation at 10 µm. Tracking accuracy requirement is 10 mas with 2 mas resolution.

- Differential Delay Lines

The difference of the white light fringe position of the primary and of the secondary star can be expressed as a differential OPD (maximum 65mm) that has to be adjusted with the differential Delay Lines with a precision of 5 nm. The differential Delay Lines will be installed in the beam combination laboratory. OPL stability performance is 14 nm RMS over 8 ms. The DDL will also transfer the pupil.

- Fringe Sensor Unit

This unit consists of an infrared camera measuring the position of the white light fringe of the primary star (and a second unit for the secondary star in astrometric mode), thus providing the error signal for the fringe tracking system (and the OPD difference between primary and secondary star). The fringe sensor unit has to be able to provide the error signal on a K = 13 star (on the UTs) with a measurement noise of 70 nm rms at a 500Hz rate. The FSU maximum output data rate is 8 KHz. It is highly desirable to be able to use a very faint reference star even with a reduced performance (lower data rate). The fringe sensor unit is located in the beam combination laboratory. Both FSU channels (FSU A and B) can be used as the sensor for the fringe tracking system and on both stars to do astrometry.

In imaging mode, FSU B is operated to stabilise the fringe motion induced by atmospheric turbulence (fringe tracking) *for both objects*, by feeding-back its measurements to the main DL. The secondary object can be observed by MIDI or AMBER with long integration times and its phase measured, for several interferometric baselines, with respect to the "constant point" provided by FSU B, thanks to the PRIMA Metrology System.

In astrometric mode, both FSU channels are operated and one OPD control loop is closed for each object, at a frequency which depends on the object magnitude. The FSU records the residual group delay for each object, which is processed off-line to derive the astrometric data.

The selected instrument concept uses co-axial beam combination, which consists of adding the incident beams amplitudes at a semi-reflective surface, close to a pupil plane. The beam combiner provides simultaneously four interferometric outputs (optical beams resulting from the superimposed incident beams), with $\pi/2$, π and $3\pi/2$ relative phase shifts (FSU2 concept in [2]). This enables using the so-called ABCD algorithm to derive the phase delay, without introducing any temporal OPD modulation.

PRIMA metrology beams are inserted in (and extracted from) the stellar path after the FSU beam combiner. Therefore the OPD is monitored by the metrology system over the whole FSU internal path.

General concept proposed by the selected contractor is given in the figure13.

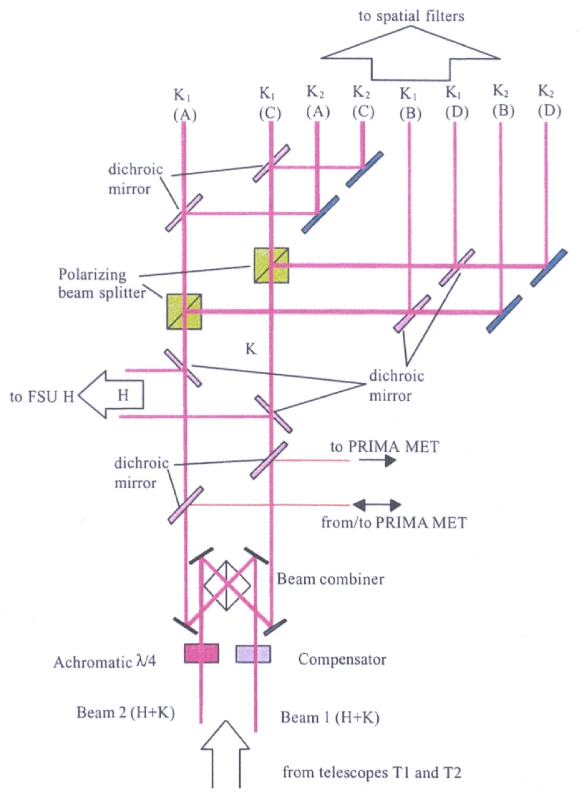


Figure 13. PRIMA FSU beams combination, as proposed by Alenia Spazio.

- Metrology System

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 anisoplanatism. The metrology system must measure the internal differential delay, ΔL, between both stars in both interferometer arms with a 5 nm accuracy requirement over typically about 30 min. This accuracy requirement is driven by the PRIMA astrometric mode. Each interferometer arm can reach up to 552 m (return way), with an optical path difference of 120m varying at a maximum speed of about 25 $mm.s^{-1}$.

The concept of the PRIMA metrology system developed by ESO in collaboration with the Institute of Microtechnology of Neuchatel (IMT) is based on super-heterodyne laser interferometry, where two heterodyne Michelson interferometers are operating simultaneously and have a common optical path with both observed stars through the VLTI optical train [4,5]. The two interferometers use different heterodyne frequencies (650 kHz and 450 kHz) generated using four fiber coupled acousto-optics modulators connected to a single Nd-YAG laser emitting at 1319 nm. After photodetection and filtering, the individual heterodyne signals are mixed such that the disturbance to be monitored is directly coded in the phase of a 200 kHz carrier signal (i.e. 650 kHz -450 kHz). Finally, the phase of the 200 kHz carrier is measured based on the principle of time interval measurement using a 200 MHz clock signal. A prototype of the photodetectors and of the phase meter has been manufactured by IMT as shown in the two pictures of figure 14.

The Laser Metrology has been tested at Paranal in April 2002. The tests focused on characterization of the performance of the prototype hardware under representative operating conditions. This included the characterisation of Internal OPD fluctuations, polarisation measurements and an assessment of the interfaces with VLTI.

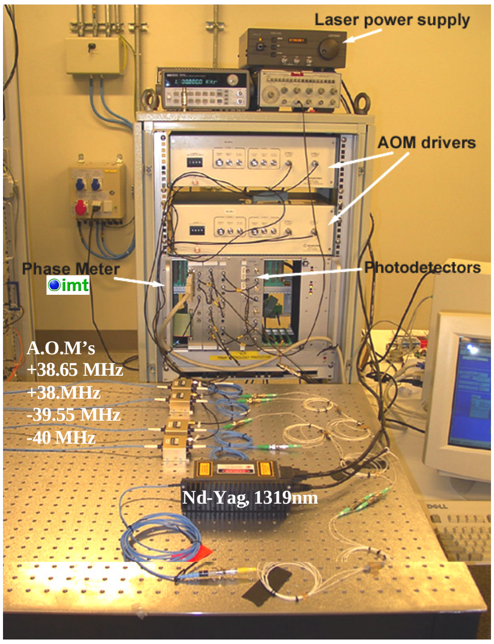
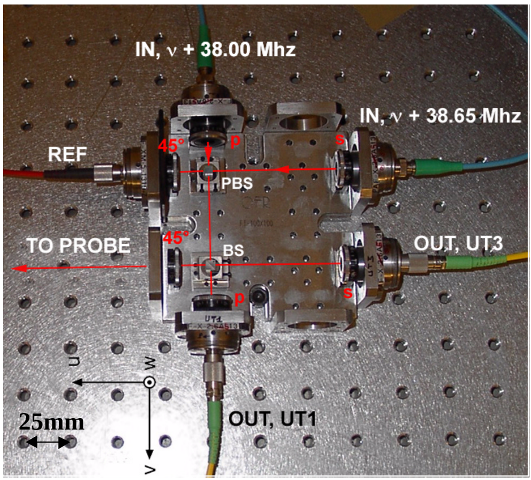


Figure 14.
View of the heterodyne assembly, and of the Photodetectors/Phase meter electronics



View of one Beam Launcher/Combiner of the metrology system tested at Paranal

The performance of the *photo-detection and phase measurement chain* was first evaluated. The fiber pigtailed photodetectors offer a 10MHz bandwidth and a Noise Equivalent Power of 0.2 pW/√Hz, which is very close to the Johnson noise limit. The resolution of the digital board: is $2\pi/1024$ (or 0.64 nm in double pass) with a maximum sampling frequency of 200 kHz. The standard deviation of the phase noise is less than $2\pi/1024$, for an optical power higher than 100 nW per interferometric arm and a fringe contrast of 70%. For the same fringe contrast, the measured accuracy is $2\pi/800$ (or 0.8 nm in double pass) for a 50 kHz bandwidth and a photodetected power of 20 nW per interferometric arm.

Internal OPD fluctuations have been reliably measured at Paranal between UT1 and UT3, using the PRIMA metrology prototype. The metrology beams were retro-reflected on a flat mirror located in the folded Nasmyth focal plane of each UT. The maximum interferometer arm length was 520m (return way) when the delay lines were set to an OPD stroke of 100m. An example of the recorded OPD fluctuations is shown in figure 15. The measurements were made during day-time and without laser frequency stabilization.

The metrology beams were launched in the VLTI optical train using fiber pigtailed collimators based on a polarizing heterodyne configuration. The frequency shifted “s” and “p” components were sent separately in both arm of the interferometer. The polarization state of the metrology beams “s” and “p” was analyzed after a round trip to a UT. The angles of ellipticity are all smaller than 7.5°. The transmission factor (after a return trip) is Tp=19% and Ts=17% for respectively the “s” and “p” polarization states. Furthermore, the phase shift between these two polarization states is $\phi_p - \phi_s$ =10.5 deg.

Metrology tests at Paranal between UT1 and UT3.

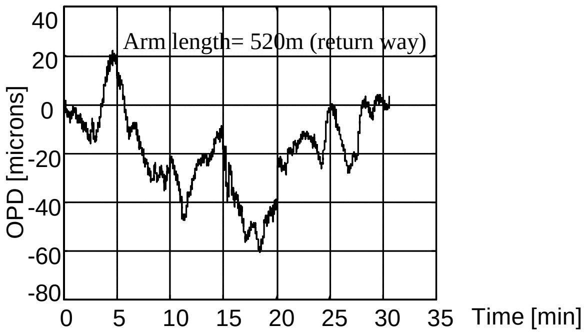
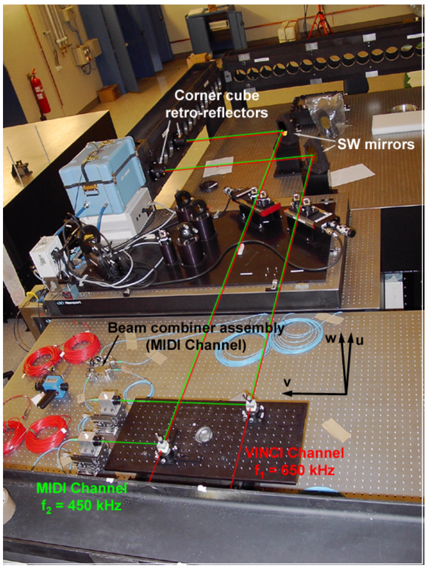


Figure 15

Example of Measured OPD fluctuations between UT1 and UT3 (520m arm length return way), duringg day time and without laser frequency stabilisation



View of part of the metrology injection optics used in the VLTI laboratory. The metrology beams are shown in red and green.

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8.Main Development and Schedule

Driven by the science objectives defined by the implementation committee [3], ESO will implement PRIMA in three phases. Each phase will have dedicated key objectives. At the end of the project the full capability of PRIMA will be achieved. Each phase is defined in such way that it can be realized in no more than 3 years.

<u>Phase 1 (2002-2004)</u>: Micro-arcsec Astrometry with 2 AT's

The first phase of PRIMA is clearly defined by scientific objective of 10 µas astrometry for extrasolar planet studies at about the same time as Keck, and well ahead of the launch of SIM.
The hardware configuration of phase 1 will also allow phase-referenced imaging with the ATs. Some selected AGN can thus be studied with key goals such as the detection of the long sought after circum-nuclear gas/dust torus, measuring the size of broad line regions and jet physics. The observations of the Galactic Center region can also begin in this phase.

To satisfy these objectives, ESO will implement two STS in the AT, the dual FSU (A/B), the MET with 5 nm resolution (as design goal) and the control system (hardware and software). The DDL will not be implemented in this phase due to programmatic constraints. However, the DDL function will be performed by the main DL. Optical layout of the VLTI will be modified accordingly. About 232 baselines from 8 to 200m will be accessible. For Auxiliary Telescope, working in high accuracy and highly dispersed modes, the limiting magnitude will be M_K 16 on the secondary Object (science target) and about M_K 10 to 12 on the Guide Star. In N Band the limiting magnitude will be about 8.3 and there will be no need of near IR counterpart.

<u>Phase 2 (2005-2008)</u>: Faint Object imagery with 2 UTs

The main thrust of this phase are the extragalactic observations described above. The large collecting area of the UTs will give access to fainter, more distant targets, and it will enable the use of fainter reference stars for off-axis fringe tracking. It is the combination of these two factors that will dramatically increase the scope of extragalactic programs.

In additional to the phase 1, ESO will implement two STS in the UT (choice of UT still to be decided), the MET with 10nm resolution (as design goal inside the UT) and additional control system related to the UT. Only one baseline (45, 56, 60, 86, 99 or 130 m) will be accessible. Ultimate UT limiting magnitude in K Band will be about 19 on the secondary Object (science target) and between 13 and 15 on the Guide star, in N Band the expected magnitude will be 11 without the need of near IR counterpart.

<u>Phase 3</u>: in addition of Phase 1 and 2, VLTI with PRIMA will be able to perform in 2010 with 4 UTs

The main and final objectives of the third phase are:

Model Independent Imaging with 2 or 3 of 4 UT with 6 baselines (45 or 130m);
Astrometry with 2/4 UTs within an accuracy of about 10 µas;
Ultimate UT limiting magnitude $K \approx 19$ on secondary Object (science target), $N \approx 11$ no need of near IR counterpart and $K \approx 13$ to 15 on Guide Star;
Fringe tracking in different bands.

In additional to the phases 1 and 2, ESO will implement two additional STS in the UT, the full MET, the upgrade of FSU A/B in band H, the 4 DDL and the final control system.

9.Conclusion

PRIMA will enable VLTI to perform high precision narrow-angle astrometry down to the atmospheric limit of 10 µas, real imaging of objects fainter than K~14 and nulling at contrast levels of ~10^{-4}. These capabilities will, in turn, enable VLTI to address directly a number of extremely important scientific issues that are currently at the top of the list of challenges for future astronomical high resolution instrumentation.

Based on the scientific priorities, the first goal is to implement 10 µas astrometry in 2004, in order to search for exoplanets. In parallel, ESO should make sure that the first images of extragalactic objects can be obtained and that the necessary actions be taken to get to faint objects in 2006.

This phasing of PRIMA is driven by the scientific objectives and competitive situation, but it also provides for the most logical sequence of technical developments. Letting the astrometry drive the first phase of PRIMA will ensure that stringent requirements on OPD measurement and control are met. Experience with existing interferometers demonstrates that all aspects of the performance of the facility will benefit from a rigorous implementation of an astrometric mode. It should be stressed that the scientific goals of PRIMA require fringe-sensing units that are as sensitive as possible.

GENIE will benefit on PRIMA development in particular on the Fringe Sensor and the Metrology. However, GENIE will request very high OPD accuracy that imposes a redefinition of VLTI OPL control loop in term of bandwidth and precision.

10. References

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