PRIMA — Study for a Dual-Beam Instrument for the VLT Interferometer

A. Quirrenbach[a], V. Coudé du Foresto[b], G. Daigne[c], K.-H. Hofmann[d], R. Hofmann[e], M. Lattanzi[f], R. Osterbart[d], R. le Poole[g], D. Queloz[h], and F. Vakili[i]

[a]University of California, San Diego; Physics Dept., Center for Astrophysics and Space Sciences; Mail Code 0424; La Jolla, CA 92093-0424; USA

[b]DESPA / Observatoire de Paris; 5 Place Jules Janssen; F-92195 Meudon; France

[c]Observatoire de Bordeaux; BP 89; Avenue P. Semirot; F-33270 Floriac; France

[d]Max-Planck-Institut für Radioastronomie; Auf dem Hügel 69; D-53121 Bonn; Germany

[e]Max-Planck-Institut für Extraterrestrische Physik; Giessenbachstr.; Postfach 1603; D-85470 Garching; Germany

[f]Osservatorio Astronomico di Torino; Strada Osservatorio 20; I-10025 Pino Torinese; Italy

[g]Sterrewacht Leiden; University of Leiden; P.O. Box 9513; 2300 RA Leiden; The Netherlands

[h]Observatoire de Genève; CH-1290 Sauverny; Switzerland
and
Jet Propulsion Lab; Mail Stop 306-473; 4800 Oak Grove Drive; Pasadena, CA 91109; USA

[i]Observatoire de la Côte d'Azur; Departement Fresnel; CNRS UMR 6528; 2130 Route de l'Observatoire; Caussols; F-06460 St Vallier de Thiey; France

ABSTRACT

PRIMA (instrument for Phase-Referenced Imaging and Microarcsecond Astrometry) is a conceptual study for a single-baseline dual-feed instrument for the Very Large Telescope Interferometer (VLTI), which is under construction by the European Southern Observatory on Cerro Paranal in Chile. The goals of PRIMA include narrow-angle astrometry with a precision of $10\,\mu$as over an arc of $10''$, and imaging of faint sources with the full sensitivity of the 8 m telescopes in the VLT array. Key scientific programs that can be carried out with PRIMA in imaging mode include observations of active galactic nuclei, the Galactic Center, stars, and circumstellar matter. Scientific drivers for the astrometry are searches for planets and low-mass stellar companions, binary stars, dynamics of clusters, and (relative) parallaxes. We list the main performance requirements for PRIMA, present system architectures for the dual-beam system, and discuss limitations of the interferometric field-of-view.

Keywords: Interferometry, Interferometric Instrumentation, Interferometric Field-of-View, Astrometry, Phase Referencing, VLT, VLTI

1. INSTRUMENTATION FOR THE VLT INTERFEROMETER

The Very Large Telescope Interferometer (VLTI) is part of the European Southern Observatory's VLT project. It will combine the light from the four 8 m telescopes and three 1.8 m auxiliary telescopes, which provide baselines of up to 200 m. The original plan for the VLTI included only imaging capabilities, but it was pointed out by Quirrenbach (1995) and von der Lühe, Quirrenbach & Koehler (1995) that narrow-angle astrometry could also be implemented within the VLTI concept. Subsequently the delay line architecture was changed from an $8''$ diameter unvignetted field-of-view to a dual-beam concept with two separate fields of $2''$ diameter; this change in architecture is very favorable

Other author information: (Send correspondence to A. Quirrenbach)
A. Quirrenbach: E-mail: aquirrenbach@ucsd.edu

for astrometry and phase-referenced imaging. The VLTI will initially operate in the infrared, at wavelengths between 1.2 and 20 μm. Three instruments are foreseen to form the initial instrument complement: a near-infrared closure-phase instrument (AMBER), a mid-infrared instrument (MIDI), and a near-infrared instrument for Phase-Referenced Imaging and Microarcsecond Astrometry (PRIMA). Together, they will provide a suite of capabilities which cover the requirements of a wide range of observing programs.

This instrumentation plan is based on the rationale that each instrument development team should address one major technical challenge. For MIDI, this is control of the thermal background, which has to be kept to a minimum for optimum sensitivity. AMBER will deal with the simultaneous combination of multiple large telescopes and closure-phase measurements. PRIMA will use a dual-star feed to perform precise narrow-angle astrometry and phase-referenced imaging of faint sources; this requires accurate measurement of the differential delay (equivalent to the phase difference) between the two stars. In this context it is important to note that the split between closure-phase imaging on one hand, and astrometry and phase-referenced imaging on the other hand, is a natural one. In many ways, phase-referenced imaging is very similar to narrow-angle astrometry: both rely on an accurate measurement of the phase difference between two stars observed simultaneously, and both — unlike closure-phase imaging — can be performed with a single-baseline instrument. (Adequate coverage of the uv plane is important for phase-referenced imaging, but the individual baselines can be measured sequentially, because the object phase is a "good" observable.) Building separate dual-beam – single-baseline and single-beam – multiple-baseline instruments is therefore a way to reduce their technical complexity and to minimize risk.

Here we report on the results of an initial conceptual design study for PRIMA. We list some of the science drivers for this instrument, give the derived high-level requirements, and discuss some salient features of possible system architectures.

2. KEY SCIENCE PROJECTS FOR PRIMA

The most important scientific goals for the VLT Interferometer have been summarized by Paresce et al. (1996) and by Quirrenbach & Mariotti (1997). A more complete overview is provided by the conference proceedings edited by Paresce (1997). Many of these programs require astrometric measurements or imaging of faint objects, and therefore rely on the capabilities provided by PRIMA.

2.1. Imaging Mode

PRIMA will be the most sensitive instrument for imaging with the VLTI, because it provides the ability to integrate the fringes coherently for a long time. The main limitation is the requirement of having a sufficiently bright guide star ($K \lesssim 12$) within the isoplanatic field.

Active galactic nuclei: Among the fundamental issues regarding the nature of active galactic nuclei (AGN) is the question about the relative contributions of a circumnuclear starburst and a compact nuclear source to the energy output. In one extreme case, if the emission comes completely from a starburst, the 2 μm continuum emission should be completely resolved on VLTI baselines. Observations with PRIMA can therefore be used to carry out a critical test of this scenario, and will provide a constraint on the flux from an extremely compact source. Another important source of infrared radiation in AGN is a dust torus. According to unified theories of AGN, it is absorption by this torus which causes the apparent differences between Seyfert 1 and Seyfert 2 galaxies through orientation effects. The size of this torus is not well-constrained to date; it may be possible to measure it with PRIMA in a few objects. These observations would at the same time provide constraints on the geometrical thickness and inclination of the torus, which are important parameters for tests of unified schemes. The broad line region (BLR) of AGNs and quasars will not be resolved in the near-IR on the VLTI baselines. It should be possible, however, to detect the phase shift between the red and blue wings of lines such as Br γ. This would also provide a measurement of the BLR size, and give valuable information about the velocity field.

Galactic Center: The Galactic Center will be an important target for imaging observations with PRIMA. First of all, it will be possible to search for a counterpart of the radio source Sgr A*, the very center of our Galaxy. Sgr A* is probably a massive black hole, but its emission is surprisingly weak. A detection of this source in the near-infrared spectral region would help us solve this puzzle; it would thus considerably enhance our understanding of "quiescent" black holes in the centers of nearby galaxies. This search requires interferometric imaging, it would be difficult at lower spatial resolution because of severe crowding. Imaging with PRIMA employing moderate spectral resolution can also be used to classify the stars in the Galactic Center cluster, which is necessary to determine the mass function, age distribution, and the star formation history in this highly peculiar environment. At higher spectral resolution ($R \sim 2000$), radial velocities can be determined. Again, because of the crowding, interferometric measurements are an essential addition to observations with single telescopes.

Stellar Astronomy: Interferometric imaging is a powerful tool which can address a large number of questions in stellar astrophysics. With a resolution of a few milliarcseconds, it is possible to test stellar model atmospheres by measuring angular diameters and limb darkening. These data are also needed for calibrating effective temperatures. In the case of pulsating stars, temporal changes of the stellar diameter can be used to determine the pulsation mode, and to derive the distance to the star. Further information about stellar atmospheres can be gleaned from the observation of surface features such as starspots. Many stars — in particular those which have evolved off the main sequence — possess circumstellar shells or disks, which can be observed directly by interferometry. These topics can all be addressed by PRIMA. In many cases, there is an overlap with the capabilities of AMBER, and it will depend on the details of the design of the two instruments which one will be better suited for a particular observation. In any case, having two independent instruments which can perform a core science program and which can be used to cross-check each other will boost the confidence in the results from the VLTI.

2.2. Astrometric Mode

The atmospheric limit for narrow-angle astrometry with PRIMA over a $10''$ arc is $\sim 10\,\mu$as (Shao & Colavita 1992, von der Lühe, Quirrenbach, & Koehler 1995). It is the ultimate goal for PRIMA to reach this limit, but many very interesting observations are possible even at an accuracy of $\sim 50\,\mu$as. If the object of interest is relatively bright ($K \lesssim 12$), it can be used to phase the interferometer, and a fairly faint star ($K \lesssim 17$) is sufficient as astrometric reference. Otherwise a bright nearby guide star is required.

Extrasolar planets and brown dwarfs: During the last two years, the situation in the area of searches for extrasolar planets and brown-dwarf companions has drastically changed with the discovery of more than a dozen of substellar objects, mostly with radial-velocity techniques. The sensitivity of radial-velocity surveys are nevertheless limited when the separations are greater than 2 AU. Moreover they provide us only with a measurement of the minimum mass of the companion, yielding uncertainties on the real nature of detected companions. The determination of the mass for the very low mass companions is a key issue to understand if there is any critical mass separating giant planets from brown dwarfs. This can be accomplished with measurements of the orbital inclination of known extrasolar planets with PRIMA. Jupiter- and Saturn-like planets can easily be detected with astrometric measurements at $\sim 50\,\mu$as accuracy. The sensitivity regime of astrometry is complementary to that of the radial velocity technique, and the precision of astrometric measurements is independent of the spectral type of the target star. Observations with PRIMA should therefore dramatically increase the number of giant planet detections and should allow a census of planetary systems for a large range of parent star masses.

Binary stars: The determination of binary frequency and of binary orbit characteristics has a thorough impact on the scenarios of star formation and the evolution of stellar systems. For example, competing binary formation scenarios either by capture or by fragmentation predict a very different behavior of the binary mass fraction depending on the mass of the primary. For the 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, mostly because of the difficulty to measure the radial velocity for these stars. A better knowledge of the duplicity of massive stars will have a profound impact on our understanding of star formation and binary 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 with PRIMA.

Globular clusters: The globular clusters are very important systems to understand fundamental dynamical processes such as relaxation, mass segregation, core collapse, and tidal effects. Their mass, which is intermediate between open clusters and dwarf galaxies, makes them unique because all dynamical processes take place on time scales shorter than the Hubble time. So far the information on their internal dynamics has been mostly restricted to 1-dimensional data, namely radial velocities. Measurements of proper motions would give access to the 3-dimensional space velocities. With the merging of radial velocity data and astrometric measurements, a substantial improvement in our understanding of the internal dynamics of such objects can therefore be expected. The measurements of the differential proper motions between stars of such systems permit the investigation of their internal motion and rotation at a very high accuracy. The measurement of transverse velocities of the clusters as a whole needs an absolute position reference, which quasars could perhaps provide for some objects. The internal motions in globular clusters are of the order of 5 to 10 km s^{-1}. Therefore an accuracy better than 1 km s^{-1} in the proper motion measurement is crucial. At a distance of 10 kpc, an accuracy of 10 μas / yr corresponds to a tangential velocity of 0.5 km s^{-1}. Such an accuracy would give access to nearly all galactic globular clusters.

Galactic Center: Measurements of radial velocities and proper motions of individual stars in the Galactic Center cluster provide a strong argument for the presence of a massive black hole in the center of our Galaxy. With improved astrometric accuracy, it will be possible to determine real orbits for these stars, which will give a much better picture of the dynamics in the central 0.1 pc. In addition to further constraining the mass distribution, these measurements will also provide clues about the history of the Galactic Center cluster.

Parallaxes: In principle, trigonometric parallaxes with 10 % errors can be derived with PRIMA for targets out to a distance of 10 kpc. There are two 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). For example, the absolute parallax of stars close to quasars can be determined in this way.

3. REQUIREMENTS AND INSTRUMENTAL CAPABILITIES

The requirements on PRIMA are defined by the different operating modes for this instrument: astrometry with the 1.8 m auxiliary telescopes (ATs), phase-referenced imaging with the 8 m unit telescopes (UTs) or with the 1.8 m ATs, and dual-wavelength operation. In the last operating mode, PRIMA will use a bright guide object to provide a coherent signal to a separate instrument (e.g. MIDI), which can then integrate the fringes coherently for an extended time. This is particularly useful for objects that are compact at 2 μm but extended at 10 μm; in this case PRIMA is essentially used as a standard on-axis fringe tracker working in the near-IR. However, with the dual-beam design it is possible to provide a coherent signal anywhere within the isoplanatic field of a suitable guide star.

For a long-baseline interferometer, the astrometric error σ scales with $\sigma \propto B^{-2/3} \cdot \theta$, where B is the baseline length, and θ the angle between the target and the reference star (Shao and Colavita 1992, Colavita 1994). Based on measured turbulence and wind profiles at Paranal, the atmospheric limit for the VLTI is $\sim 10\,\mu$as for $\theta = 10''$ with an integration time of 1800 s (von der Lühe, Quirrenbach, & Koehler 1995). The goal for PRIMA is to reach this limit with the 1.8 m ATs. (The heavy time demand of any astrometric program probably precludes the use of the 8 m UTs for this purpose.) This translates into a total error budget on the optical path difference (OPD) between the target and reference stars of 5 nm; the baseline vector has to be known to within 50 μm. The OPD precision requirement implies that an internal metrology system is needed; the layout of this system depends on the architecture of the dual-beam system (see Section 4). The baseline vector can be determined directly from the astrometric data, provided that imperfections in the telescopes (flexure, non-intersecting axes, irregularities in the telescope bearings) can be calibrated to the same level. This appears possible without much difficulty at least for the ATs.

The 5 nm OPD precision translates into a $0.^\circ 8$ phase error at 2.2 μm, which is sufficient for phase-referenced imaging with a dynamic range of at least 70. (In most cases, the dynamic range will be limited by the incomplete coverage of the uv plane or atmospheric phase noise, not by instrumental phase errors. However, systematic phase errors could limit the detectability of faint companions.) To fully exploit this capability, it is also necessary to measure and calibrate the fringe amplitude to a level of ~ 1.5 %, which can be achieved with spatial filtering using single-mode fibers.

The optimum wavelength band for narrow-angle astrometry is the K band (2.2 μm) because in the infrared fewer stars are resolved than at optical wavelengths. Furthermore, the isoplanatic angle is larger, which means that the visibility of the faint star is higher, which gives a better SNR. PRIMA will therefore be optimized for the K band, but it will also operate at J and H. A variety of beam combination schemes are possible in principle; co-axial beam combination seems to be the simplest and most sensitive solution. The architecture for the bright star beam combiner is described in more detail below (see Section 5). The beam combiner for the faint star will be a "standard" co-axial combiner with dispersed-fringe capability; the spectral resolution R will be variable with a goal to achieve a maximum $R \sim 2000$. The sensitivity of the faint star beam combiner will be close to the single-telescope sensitivity limit, because it operates with essentially coherent light.

In view of the considerable technical challenges imposed mainly by the precision requirement on the differential OPD, it is foreseen to implement the capabilities of PRIMA in a phased approach. Initially, the metrology will be designed to measure the differential OPD to within $\sim 25\,\mathrm{nm}$, which is sufficient for most imaging applications, and for astrometry with $50\,\mu$as precision. Operational experience with this instrument will then allow the identification of the major sources of residual OPD error, and thus provide input for the design of the "final" system capable of $10\,\mu$as astrometry.

4. DUAL-BEAM SYSTEM ARCHITECTURE

Two different architectures are considered for the dual-beam system: propagation of the light from the two stars on separate paths through the delay lines (see Figure 1), and multiplexing of the two fields (see Figure 2).

In the "separate paths" architecture (which has been implemented in the Palomar Testbed Interferometer and is the "default option" also for PRIMA) a field selector separates the light from the reference star and from the target object, and sends the two beams to separate entry ports of the delay line. After compensation of the overall delay for the reference field, and compensation of the differential delay between the fields, the light from the two interferometer arms is combined and detected separately for each of the two stars. An end-to-end metrology system is required to measure the internal delay difference between the two fields in this layout. In contrast, the "multiplex" architecture uses only one path through the delay lines and a single beam combiner. Here the differential delay line is located directly behind the field selector. A multiplexer feeds a fraction of the light from both stars into the same entry port of the delay line. The multiplexing can be done either in wavelength or in polarization (i.e., use orthogonal polarization states of the two stars). After beam combination, the two stars are separated again in a demultiplexer. A local metrology system monitors the internal delay in that part of the system where the light from the two stars travels on separate paths, i.e., through the field selector, differential delay line, and multiplexer.

The main disadvantage of the "separate paths" architecture is the long non-common path between the beams from the two stars, and the consequent stringent requirements on the accuracy of the end-to-end laser metrology. For example, any systematic temperature difference between the two beams leads to a metrology error because of dispersion in the air-filled delay line tunnel between the operating wavelength of the interferometer (in the near-IR) and the metrology laser wavelength (e.g., at 633 nm). The 5 nm OPD tolerance implies that any such temperature difference has to be kept at $\lesssim 0.01\,\mathrm{K}$.

The "multiplex" architecture alleviates this problem, since it needs only a local metrology of the field selector, differential delay line, and multiplexer. However, this layout suffers from crosstalk between the two stars, depending on the way the multiplexing is done. For example, if polarization multiplexing is used, crosstalk will be due to imperfections in the polarizers. This limits the magnitude difference between the two stars, which is a severe problem both for astrometry, where at least 5 magnitudes are required, and for phase-referenced imaging, where up to 10 magnitudes are desirable.

Some of the advantages of the two architectures can be combined in a hybrid scheme (see Figure 3). A small fraction ($\sim 1\,\%$) of the light from the bright guide star is split off, multiplexed with the faint star, and sent through one port of the delay line. Most of the light from the guide star is sent through the other port, and used for fringe tracking. The multiplexer is switched in regular intervals between the two polarization states (star 1 pol 1, star 2 pol 2 $\longleftrightarrow$ star 1 pol 2, star 2 pol 1) to compensate for systematic effects. The phase difference between the two stars is then measured between the two multiplexed signals, which have traveled through most of the delay line on a common path. This leads to a substantial reduction of the systematic errors over the "separate paths" architecture at the cost of using only half of the photons of the faint star.

5. BRIGHT STAR BEAM COMBINER

The bright star beam combiner and fringe detector are critical components of the instrument, because their design determines the fringe tracking sensitivity and thus the sky coverage. In the near-IR, and for the short exposure times imposed by the coherence time of the atmosphere, the sensitivity is limited by the read noise of the detector. It is therefore mandatory to use as few pixel readouts per atmospheric coherence time as possible. This argues for white-light fringe tracking, which can be done with four pixel readouts per integration time. (The integration time should be a small fraction ($\sim 10\,\%$) of the atmospheric coherence time, in order to achieve a stable delay control loop with sufficient bandwidth.) However, it is difficult with a white-light fringe tracker to identify the central fringe; this is more easily done with dispersed fringes. The proposed architecture for PRIMA therefore combines both approaches: the light from one output of the bright star beam combiner feeds a white-light fringe tracker; the light from the other output is dispersed and can be used to identify the central fringe (see Figure 4).

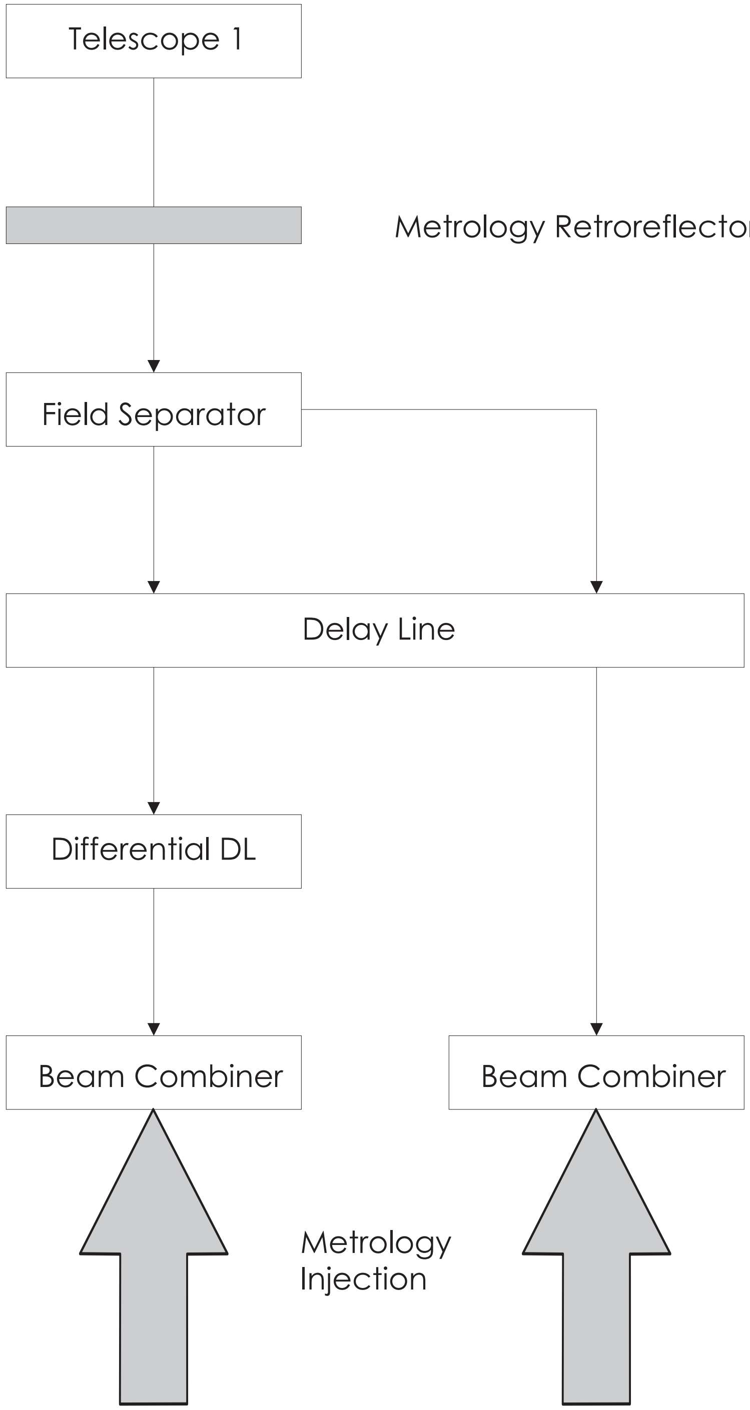

Figure 1. Dual-beam architecture with end-to-end metrology. The light from the two stars is propagated on different paths through the delay lines. (Only one of the two interferometer arms is shown.)

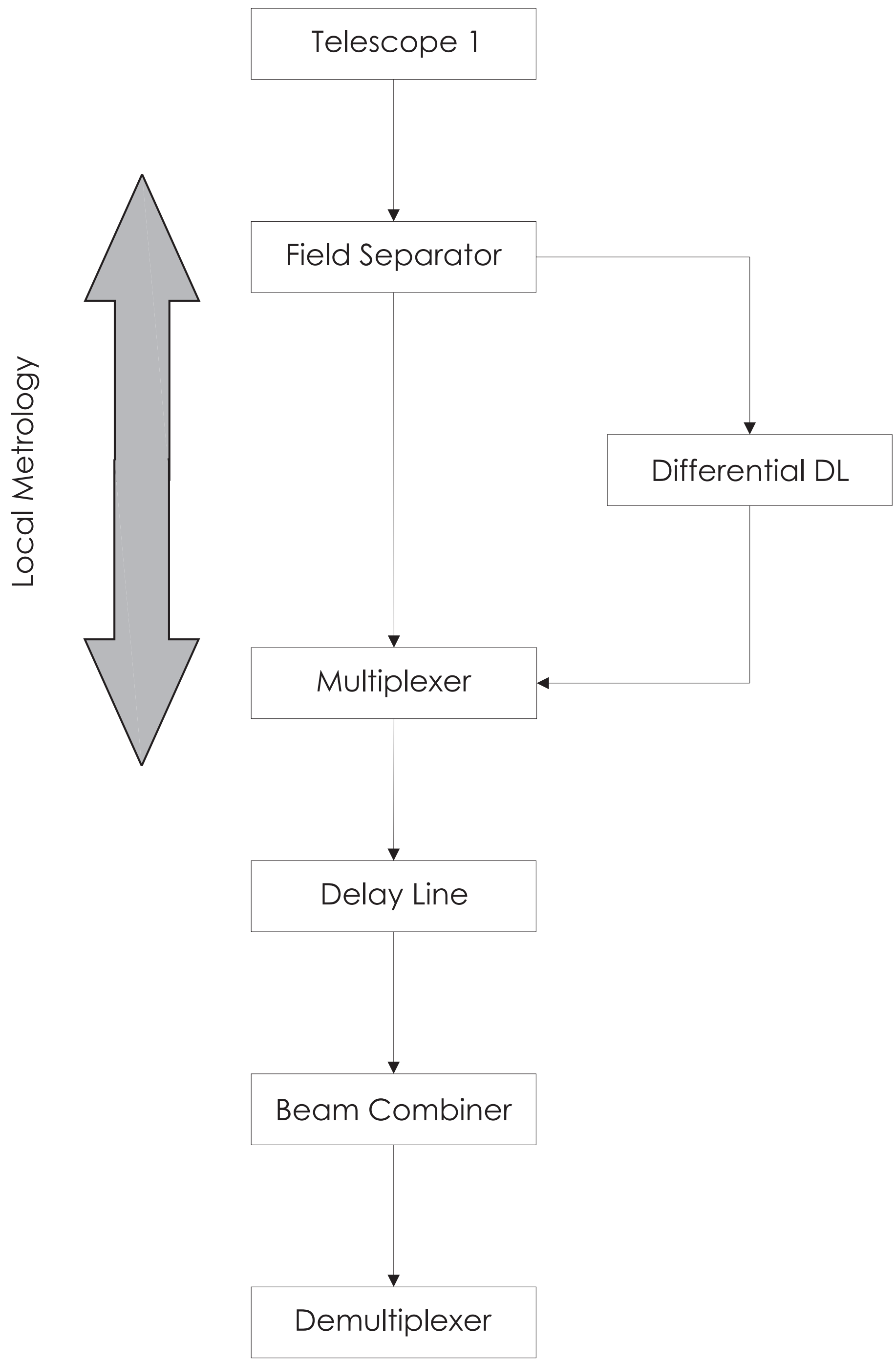

Figure 2. Dual-beam architecture with multiplexing. Part of the light (e.g. one polarization state) from each star is propagated on the same path through the delay lines. A local metrology system monitors the pathlength through the field separator, differential delay line, and multiplexer. (Only one of the two interferometer arms is shown.)

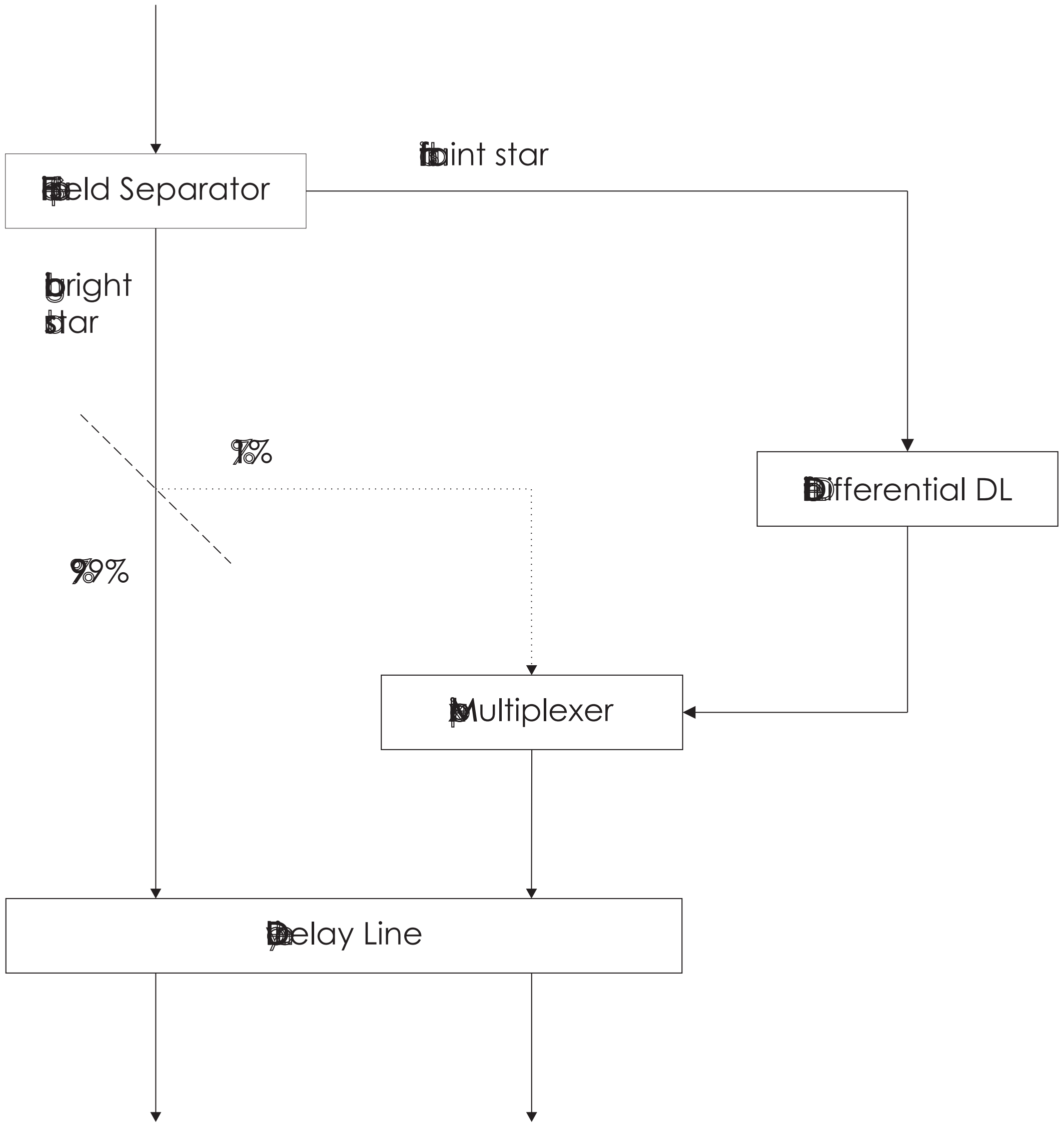

Figure 3. Multiplexing in the hybrid architecture. 99 % of the light from the bright star is used for fringe tracking, 1 % is multiplexed with the faint star for precise measurement of the differential delay.

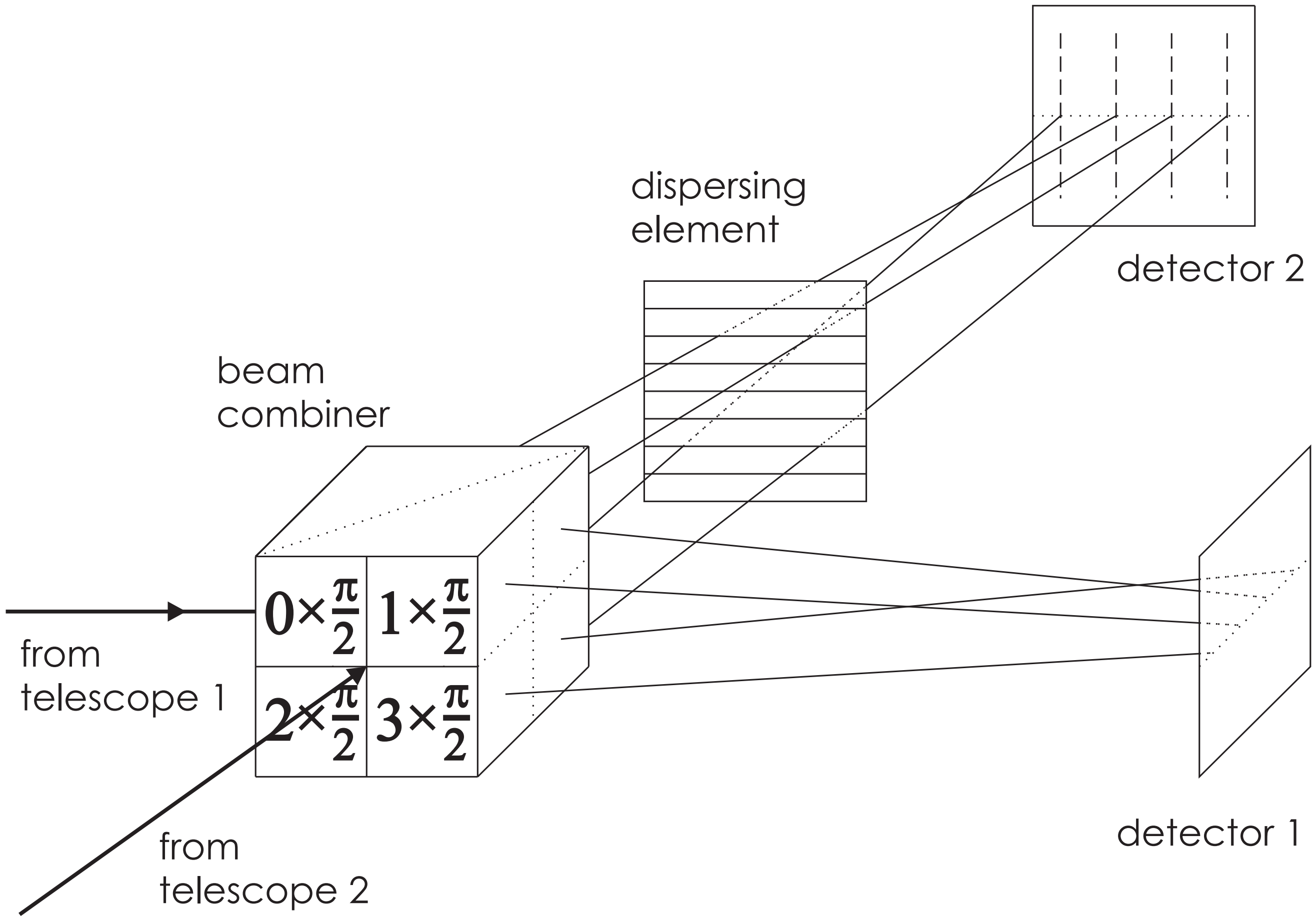

Figure 4. Sketch of co-axial beam combiner for the bright guide star. The aperture is divided into four subapertures; the four pathlength differences required for measurements of the fringe sine and cosine are introduced in these subapertures. The white-light output from one side of the beam combiner is imaged on four pixels on detector 1. The light from the other side is dispersed; the spectra are imaged on detector 2. This arrangement allows reading the two detectors at different rates. (Optical elements that image the four subapertures on four spots on the detectors are not shown.)

Measurement of the fringe sine and cosine requires data at four different pathlength differences, corresponding to phase shifts of 0, $\pi/2$, π, and $3\pi/2$. In most interferometers employing this principle of fringe detection, these phase shifts are introduced by a temporal dither of the delay with a piezo mirror. However, this delay dither then sets the read rate, which has to be the same for all detectors. In contrast, in the PRIMA architecture the aperture is divided into four subapertures, and the four phase shifts are introduced in these subapertures. The four subapertures are imaged onto separate points on the detectors, thus creating four spots on the white-light detector and four spectra on the other detector (see Figure 4). For the white-light fringe detector, the number of pixel readouts per integration time is the same as with temporal delay dithering (namely four), but now the dispersed-fringe detector can be read at a slower rate, to compensate for the smaller signal per pixel. The fringe servo will thus be implemented with two nested loops: the fast loop is used to stabilize the fringes on the output of the white-light detector, whereas a slower loop uses the output of the dispersed-fringe detector to detect and correct fringe jumps. A signal-to-noise estimate based on realistic assumptions of the system efficiency and system visibility indicates that a fringe-tracking sensitivity of $K \sim 12$ should be achievable with the 1.8 m ATs and currently available infrared detectors under median seeing conditions on Paranal. The performance with the 8 m UTs will be correspondingly better provided that the individual wavefronts of the two telescopes are adequately corrected with adaptive optics.

Fringe detection without temporal delay dither has additional operational advantages when PRIMA is used as a fringe tracker for another instrument, because the second instrument receives an unmodulated signal. Furthermore, MIDI has an operation mode that includes synchronized chopping of the telescope secondaries, which is necessary for an accurate calibration of the fringe amplitude in the thermal infrared. Synchronization of the fringe tracker with the chopping is somewhat easier when no temporal delay dither is required.

6. INTERFEROMETRIC FIELD-OF-VIEW

Several of the astrometric programs described above, including the search for extrasolar planets, can be carried out with a dual "zero" field, i.e., with two fields that are much smaller than the Airy disk of a single telescope. However, the programs aimed at measuring proper motions and orbits in clusters could be carried out much more efficiently with an interferometric field-of-view of about $1''$ in one of the two fields, which would allow the *simultaneous* measurement of many stars (either with respect to one another, or referenced to the guide star in the other field). This option appears attractive from the scientific point of view, but it places stringent requirements on many of the instrumental tolerances, and it makes the design of the focal plane and the data reduction procedures much more complicated.

Observations with a non-zero field-of-view require accurate mapping of the telescope pupil to the beam combiner. With a beam compression factor of 1/100, the tolerance for lateral pupil alignment is only $5\,\mu$m for a $1''$ field; the requirements on pupil rotation and magnification are similarly stringent. However, the main problem with a non-zero field-of-view are imperfections of optical surfaces located close to an image plane. A 5 nm goal on the OPD accuracy implies that these imperfections have to be calibrated to that same level over the "footprint" of a $1''$ field on each relevant surface. In this context, the critical component in the VLTI design is the variable curvature mirror (VCM), which is located in the focal position of the delay line trolley's Cassegrain telescope. The VCM consists of a thin membrane, which forms the front surface of a pressure cell and whose curvature can be controlled by changing the pressure in the cell. It is the VCM which allows for proper pupil relay in the VLTI, but any slight deviations from its nominal shape cause field distortions which spoil the astrometry. More testing of this crucial component is needed for a reliable assessment of the field-dependent effects. (Note that this is also relevant for some applications that are normally not considered "astrometry", e.g., the determination of orbits of binaries with separations of order $0.''1$.) At the moment these errors seem prohibitively large, but implementing simultaneous astrometry over a "wide" ($\sim 1''$) field would certainly be an attractive option for future upgrades of PRIMA.

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