The VLTI PRIMA Facility

Gerard T. van Belle[1]
Johannes Sahlmann[1, 3]
Roberto Abuter[1]
Matteo Accardo[1]
Luigi Andolfato[1]
Stephane Brillant[1]
Jeroen de Jong[2]
Frédéric Derie[1]
Françoise Delplancke[1]
Thanh Phan Duc[1]
Christophe Dupuy[1]
Bruno Gilli[1]
Philippe Gitton[1]
Pierre Haguenauer[1]
Laurent Jocou[4]
Andreas Jost[1]
Nicola Di Lieto[1]
Robert Frahm[1]
Serge Ménardi[1]
Sebastien Morel[1]
Jean-Michel Moresmau[1]
Ralf Palsa[1]
Dan Popovic[1]
Ester Pozna[1]
Florence Puech[1]
Samuel Lévêque[1]
Andres Ramirez[1]
Nicolas Schuhler[1]
Fabio Somboli[1]
Stefan Wehner[1]
The ESPRI Consortium[5]

[1] ESO
[2] Max-Planck-Institut für extraterrestrische Physik (MPE), Garching, Germany
[3] Observatoire de Genève, Sauverny, Switzerland
[4] CNRS, Laboratoire d'Astrophysique de l'Observatoire de Grenoble, France
[5] ESPRI (Exoplanet Search with PRIma) Consortium: Observatoire de Genève, Sauverny, Switzerland; Max-Planck-Institut für Astronomie (MPIA) Heidelberg, Germany; and the Landessternwarte, Heidelberg, Germany

The Phase Referenced Imaging and Microarcsecond Astrometry (PRIMA) instrument was recently delivered to the summit of Cerro Paranal and installed as part of the Very Large Telescope Interferometer (VLTI) infrastructure. PRIMA is designed to (i) provide phase-referenced interferometric imaging at milliarcsecond scales, (ii) enable faint star science several magnitudes fainter than the current atmospheric limits of the VLTI, and (iii) provide astrometric measurements at the tens of micro-arcsecond level. PRIMA has successfully seen first fringes and is currently (as of late 2008) undergoing initial commissioning tests.

The PRIMA Big Bang and first fringes

The thirty-plus crates of optics, electronics, mechanics, and other assorted hardware and software of the Phase Referenced Imaging and Microarcsecond Astrometry (PRIMA) instrument arrived at Cerro Paranal in mid-July from ESO Garching, and the PRIMA Big Bang was underway. PRIMA's assembly, integration and verification phase — better known simply as "the Big Bang" — spanned the following seven weeks. Teams of engineers and scientists from ESO Garching and ESO Paranal split into multiple shifts and worked literally around the clock to assemble the complex instrument, carefully rationing out the limited resources of lab space, subsystem availability and sky time. Basically, we were just trying not to step on each other's toes. Two weeks after the first shipment, a further 18 crates arrived from our PRIMA partners at the Geneva Observatory, along with staff from Geneva and MPIA Heidelberg. In the end, over 30 individuals participated directly in a delicately choreographed dance of optical instrumentation in a space no larger than ESO Garching's lobby. An underlying sense of purpose and *esprit de corps* kept our efforts afloat as we worked long days and nights, playing out the endgame of more than eight years of PRIMA development.

As of the beginning of September 2008, individual subsystems had been unboxed, installed and taken through their paces, but the larger question of system integration was beginning to be considered. In the waning days of the PRIMA Big Bang, two of the VLTI's auxiliary telescopes (ATs) were trained skywards (Figure 1), and the 1.8 m apertures were used to thread light from a single star through the optical beam trains, delay lines, and into one of PRIMA's fringe sensor units (FSUs). On 3 September 2008 — a few days ahead of the ambitious Big Bang schedule — twin beams of starlight from HD 19349 (spectral type K0 III; $V = 5.2$; $K = 0.4$) were recombined in FSU A, and

Figure 1. Nicola Di Lieto (ESO) working to configure a PRIMA Star Separator out at AT4 during the PRIMA Big Bang.

the telltale wiggle of interfering light was seen as the delay lines swept through the position of equal path length for each aperture (Figure 2). Within a few days, this core element of the PRIMA system was not only sensing fringes on far dimmer stars, but achieving the more difficult task of locking onto the fringes and actively tracking them (Figure 3). Independently, the PRIMA laser metrology system was also successfully operated over an optical path of length 300 m, from the interferometry laboratory to two ATs and back.

What is PRIMA?

PRIMA is the last of the first generation of VLTI instruments, although its complexity and spot in the queue as the last of the first lend it a flavour of being VLTI generation 1.5; expanded technical details on PRIMA beyond the scope of this article can be found in Delplancke et al. (2008).

PRIMA is, put simply, two astronomical interferometers in one. It is able to collect starlight in each of two telescopes from not just one source but two, and simultaneously send these pairs of starlight beams to the interferometer backend. The *K*-band (2.2 μm) starlight from the first source is recombined in the VLTI laboratory to form interference fringes, while fringes are collected simultaneously on the second source.

However, PRIMA is also much more than two interferometers that just happen to cohabit the same lab. At the telescopes, star separator (STS) units take the field observed by each telescope and split it, sending one source down one PRIMA beam path and a second source down the parallel one. A secondary interferometric delay line, the differential delay line (DDL, built by the ESPRI consortium), accounts for small pathlength differences between the two sources due to their slightly different positions on the sky, and allows fringes to be obtained simultaneously from both sources. Each beam combiner contains a laser metrology gauge (PRIMET) that is injected at the point of combination, travels backwards through the system to the STSs, and is retroreflected back from that point, monitoring the pairs of telescope feeds and tying them together at the nanometre level. These additional subsystems take PRIMA out of the realm of simply achieving contemporaneous fringes and empowers it with three unique capabilities (see Figure 4).

The first of these capabilities is PRIMA's ability to measure astrometric angles between two sources. When using an astronomical interferometer, knowledge of the geometry of the separation between two telescopes (the "baseline") combined with a measurement of the

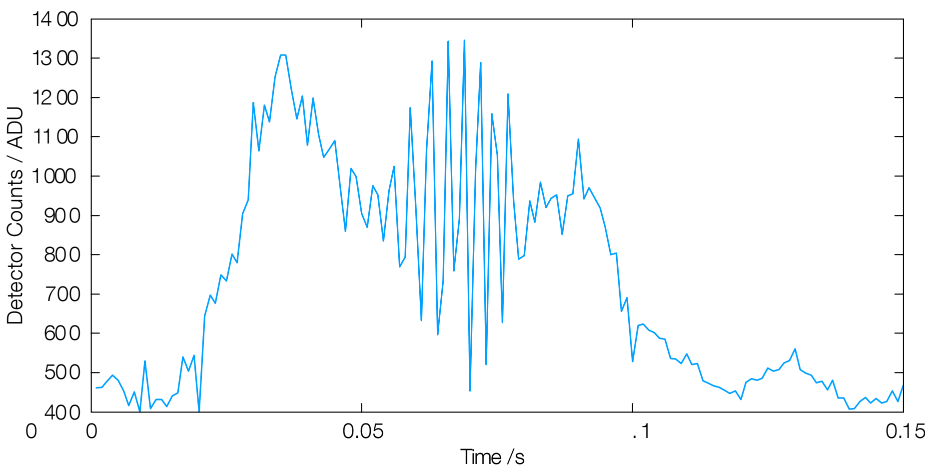

Figure 2. First fringes for PRIMA, obtained on Fringe Sensor Unit A on 3 September 2008, observing the star HD 19349 with two ATs separated by 32 m at VLTI stations G0 and G2.

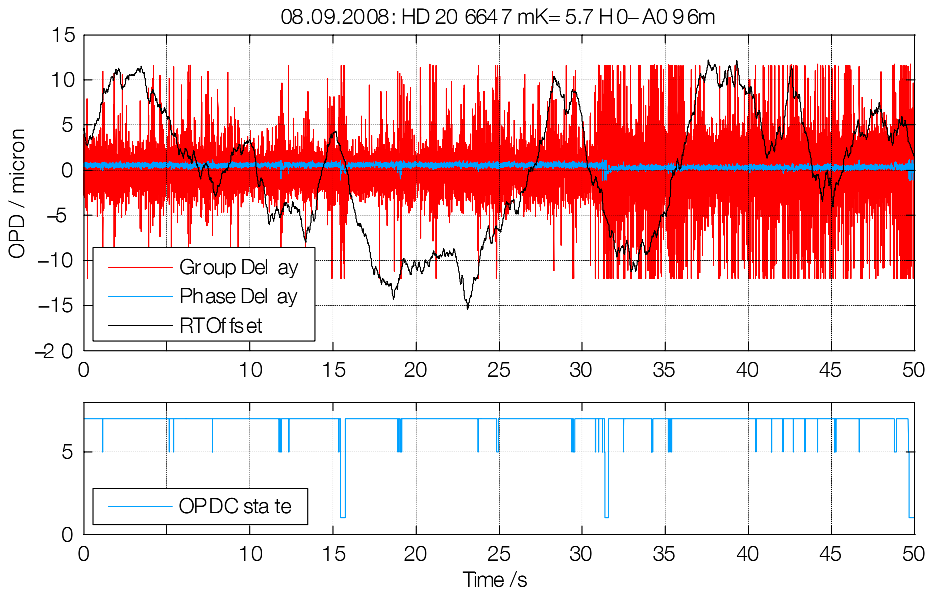

Figure 3. By the end of the PRIMA Big Bang, fringes from stars with *K* ~ 6 were not only being detected, but actively tracked. The upper panel shows the phase delay (blue), group delay (red) and delay line offset (black) in microns of optical path delay as a function of time for star HD 206647 with ATs at VLTI stations A0 and H0 for a separation of 96 m. The lower panel shows the optical path delay controller (OPDC) state during this time, with a high state (7) indicating fringe lock, low (1) a fringe search state, and a middle state (5) reflecting a minor loss being waited out.

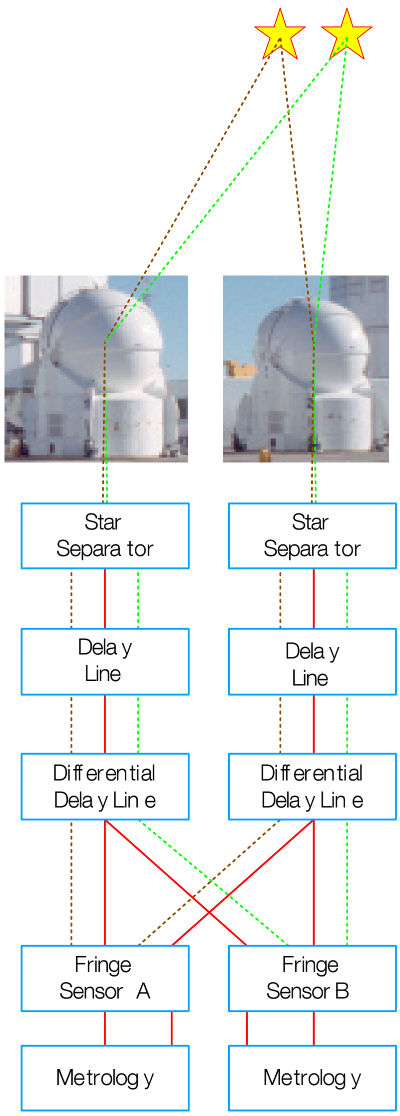

Figure 4. Schematic of the PRIMA system for the VLTI, highlighting the major subsystems along the optical paths of the facility.

delay line setting can be used to establish a position on the sky of the observed source. This is typically limited by the atmosphere and, more importantly, the instabilities of the optical system, which, for a widely distributed system like an interferometer, are considerable. However, by observing two sources simultaneously, and in particular, the instantaneous delay line settings for these two sources, this measurement may be done in a differential sense. Many of the dominant error terms become common mode and drop out when using this approach, allowing unprecedented levels of precision to be attained in measuring the astrometric angle between two sources. This technique was predicted to be useful by Shao & Colavita (1992) and demonstrated on an engineering basis by the Palomar Testbed Interferometer (PTI; Lane & Colavita, 2000); PRIMA will be the first instrument to offer this capability to the general astronomical community on a routine basis.

Secondly, PRIMA can leverage the twin-interferometer setup to observe sources significantly dimmer than previously possible with single-source interferometers. By observing a bright source in one of the two channels of the system, PRIMA can use this source not only to track the atmospheric disturbances for the bright source itself, but to feed-forward the error correction signals to the secondary channel. The secondary channel can then be steered off to a nearby, dim source, and interferometric observations can be carried out without the atmosphere obfuscating the interference fringes. In this fashion, PRIMA operates as an interferometric analogue to single-aperture natural guide star adaptive optics: the bright source in this case is not only being used to take out the "corrugations" in the wavefronts of the individual apertures, but is also used to remove pathlength errors that are introduced by the fluctuating atmosphere (commonly referred to as "piston" or "fringe jitter"). To track the fringes, the bright source is limited to observations no longer in duration than an atmospheric coherence time; however, the error signals from the bright source tracking can then be used to create a synthetic coherence time for the secondary source that is significantly longer. The second channel can then stare coherently at a significantly dimmer source and record useful data. Again, this was demonstrated by the PTI (Lane & Colavita, 2003) and again, PRIMA will be the first instrument to routinely offer this functionality to all. In addition to feeding one of the two FSUs with a dim source, PRIMA has been designed to provide off-axis dim source tracking to the existing VLTI instruments AMBER and MIDI.

Thirdly, the dual-object nature of the interferometer can be used to construct high resolution images of objects upon the sky using "phase referenced imaging". Atmospheric turbulence corrupts the phase information relevant to the Fourier transform of the object image — without such corruption, it would be possible for a single-object interferometer to construct, point by point, the full Fourier components of the object image, and allow full image reconstruction. PRIMA is able to make object image phase measurements by observing a science object simultaneously with a reference star; the reference star in this case being selected to have a null phase (i.e., be centro-symmetric). By making multiple observations over the course of a night, and with multiple baselines on different nights, many Fourier phase components for a science object can be built up, and an image can be reconstructed. This technique can be applied to faint targets as described in the previous paragraph.

These three capabilities make PRIMA extraordinarily special and an exciting development for astronomical interferometry with either the ATs or the Unit Telescopes (UTs). Its astrometric capability is a unique new tool, and its faint source capabilities will allow astronomers to reach past the barrier of sensitivity that has plagued interferometers and examine faint targets with high angular resolution.

Expected performance and limitations of PRIMA

As PRIMA operates, there are two major limitations familiar to all astronomers: the atmosphere, and the instrument itself. The atmosphere limits PRIMA in a number of ways. As mentioned above, the atmospheric coherence time is the maximum time span allowed for attempting to detect and track fringes on the brighter of the two sources. This value is typically about 10 ms for Paranal, which will limit the system (accounting for beam transmission losses, detector QE, and other system pitfalls) to sources of roughly $K = 8$ on the auxiliary telescopes (and correspondingly dimmer for UT observations, roughly $K = 11$).

For the second, fainter source, the tracking of PRIMA on the bright source allows a longer, synthetic coherence time to be provided, but only if the atmospheric corrections are common mode. This limits the second source to a sky location that is near the bright primary source — specifically within one isoplanatic angle. For Paranal, the size of this angle in the *K*-band for an evening of median seeing is roughly 10–20 arcseconds. As one might expect, as the primary–secondary on-sky angle decreases, the system performance improves, particularly in the area of determination of the astrometric angle. Astrometric precision also benefits from having a bright secondary source, but likelihood of finding a secondary source for use as an astrometric reference increases as one searches deeper. Unfortunately, it becomes increasingly difficult to find dim sources next to bright ones from existing surveys, due to saturation limitations. For example, sources at $K = 6$ in the 2MASS and DENIS surveys tend to wash out all dimmer sources out to 30 arcseconds, unfortunately making these surveys unsuited for selecting bright–dim pairs (although it is still quite useful for at least identifying the bright sources).

The instrumental limitations are many, which is unsurprising in an instrument of this complexity. Of these, one that is foremost in many people's minds is that of system vibration, which serves to smear out interference fringes by introducing variations in system pathlength that are too fast and/or large to be followed by the fringe tracker's observations of starlight fringes. The PRIMET metrology system will operate to mitigate these effects by monitoring the pathlengths through most the system, coherently preserving the precious starlight for the fringe tracker.

A second thorny instrumental issue is that of baseline knowledge. For astrometry at the 10–30 microarcsecond (µas) level, the geometry of the two telescopes relative to each other needs to be known to an accuracy of roughly 50 µm over separations of 100–200 metres. This problem separates out into two components: the wide-angle baseline, which is the average separation between the two telescopes during the observation, and the narrow-angle baseline, which is the differences in wide-angle baseline seen by the primary and secondary sources due to residual non-common paths and mechanical imperfections in the system. The wide-angle baseline can be established to the required accuracy by observations of stars with well known astrometric positions, such as Hipparcos targets. The narrow-angle baseline is determined through monitoring of the system mechanical structure, and is a primary motivation for the PRIMET subsystem. However, PRIMET is unable to monitor all of the beampath, in particular the telescope Coudé trains. Establishing a full solution for the narrow-angle baseline problem remains an outlying challenge for the PRIMA team. Fortunately, while this particular problem is an issue for PRIMA's astrometric performance, it does not impact the faint star science.

Working within these limitations, we expect to be able to reach magnitudes of $K = 8$ on the bright source in reasonable seeing conditions with the ATs, and push at least five magnitudes deeper with the companion faint source when a bright source is phasing up the system. Synthetic coherence times at the PTI experiment of 1–2 seconds — some 100–200 times longer than the atmospheric coherence time — bear this expectation out as a reasonable one. Anecdotal evidence from early FINITO operations that even longer synthetic coherence times are possible under excellent seeing conditions will be explored to establish the full sensitivity envelope of the system. Initial astrometric performance of the system, pending a solution to the narrow-angle baseline problem, will be limited to the 50–100 µas level (an expectation also supported by the previous work on the topic). The fully operational system will have an ultimate limit of 10–20 µas, although this will require not only near-perfect operations, but also almost unrealistically well-suited pairs of bright sources with almost similarly bright secondary astrometric reference sources situated well within an isoplanatic angle (of which there are no known examples in the southern hemisphere). Our expectation is that, for a reasonable science programme with a sample size of at least ten, the median performance limit of the system (accounting for instrument, good but not great atmospheric conditions, realistic source brightnesses, and realistic observing times) will be 30–40 µas.

Clearly, our goals are to push beyond these limits. However, even at these limits, the capabilities offered by PRIMA are exciting and enable unique science.

Science case for PRIMA

The general science case that motivated the development of PRIMA is discussed in Delplancke et al. (2003). A primary driver for the astrometric aspect of PRIMA's functionality is the detection and characterisation of extrasolar planets. At a distance of 10 parsecs, a star with spectral type G2 orbited by a Jupiter-mass object in a Jupiter-like orbit shows an astrometric signal of about 1000 µas (Figure 5) — clearly within the reach of even PRIMA's initial capabilities. These objects are, by design, particularly well suited for PRIMA, since the star of interest is nearby and will have a significant apparent brightness, providing PRIMA's bright channel with a strong signal upon which to fringe track.

Many of the extrasolar planets that are nearby have already been detected through the efforts of teams using the radial velocity (RV) technique. While this could be considered by some to be a "scoop" of PRIMA's opportunity to discover new worlds, it in fact greatly expedites PRIMA's ability to contribute significant astrophysical knowledge to the field. A major limitation of the RV technique is the uncertainty in planetary mass due to the lack of knowledge of orbital inclination: RV is essentially a one-dimensional technique and has this limitation built-in. PRIMA's astrometry, by contrast, is an inherently two-dimensional approach that has no such restrictions. As the field of extrasolar planetary science progresses from the discovery phase to the more detailed characterisation phase, specific knowledge of the planetary masses will help open up the considerations of planetary composition and structure that are now being pondered. The RV detections made to date provide a roadmap for PRIMA to provide contributions to the field rapidly, while it begins the more lengthy process of exploring its own unique discovery space (Launhardt et al., 2008).

It should be noted that recent results probing the limits of large single-aperture telescope astrometry are starting to push

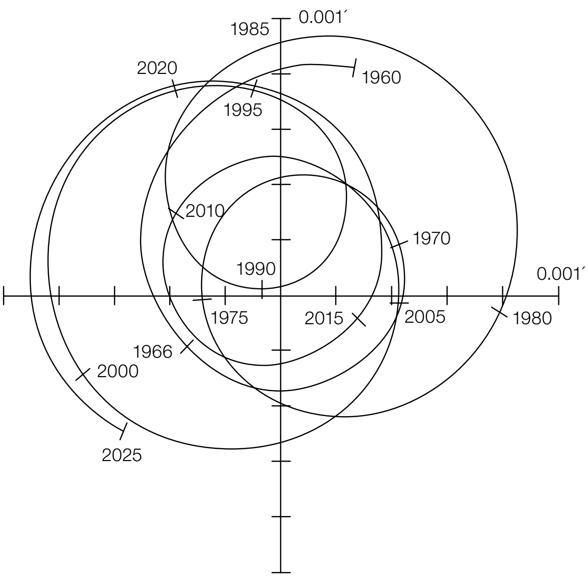

Figure 5. Apparent astrometric signature of our Sun as a function of time at a distance of 10 parsecs, exhibiting the astrometric reflex motion associated with all of the Solar System planets. Jupiter dominates, followed by Saturn and the other two gas giants. Earth's signature is masked by the plot line width at the ≤1 µas level.

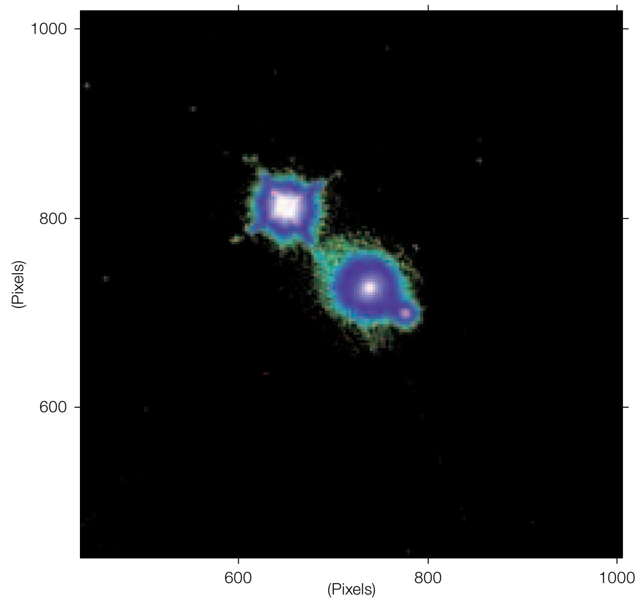

Figure 6. Example faint source for observation with PRIMA. NTT/SOFI image of ESO 548-81. The object is a Seyfert 1 galaxy, too dim for direct fringe tracking at $K \geq 10.5$, but nearby there is a bright source (HD23134, $K = 6.02$) that can be used to phase-up the interferometer.

into the slightly coarser 100–200 µas regime (Lazorenko et al., 2007). However, these experiments are limited to dense fields of stars of similar brightness, limiting their utility, particularly for extrasolar planetary investigations (although they are exciting new tools for exploring globular clusters and other sufficiently dense regions of the sky).

Many other astrometric applications exist for PRIMA beyond just extrasolar planets. Determination of parallax is possible with proper selection of the secondary reference star; deflection of starlight due to general relativistic effects could be explored (e.g., as Jupiter passes close to one of two stars being fed into PRIMA); orbits of small Solar System bodies could be tracked with unprecedented accuracy with PRIMA; dynamics of objects near the Galactic Centre could be tracked with accuracy beyond existing studies and additional applications surely exist that have not yet been considered.

For faint object and phased-referenced imaging science, PRIMA opens up a realm of phase space that, up until now, had been off-limits to optical interferometry. Galactic cores constitute an obvious class of objects that is of considerable interest for high resolution observations. Fringe-tracking limitations have, until now, limited such work to sources that could be self-referenced, serving as their own fringe tracking source, but PRIMA will be able to sidestep this limitation through use of its faint source channel. The need for a nearby bright soure for fringe tracking is its own limitation, but a quick survey of the appropriate catalogues shows it to be far less of a one than the previous limits (van Belle et al., 2008; see example in Figure 6). Other object classes include young stellar objects (especially those that are deeply embedded in dusty shells), asteroid shape mapping and density determination, imaging of evolved stars, and possibly brown dwarf angular diameters. As with the astrometric possibilities, many of the applications of PRIMA faint object mode await the creativity of the ESO community to exploit it in new and unexpected ways.

Description of the system

The PRIMA instrument has a sufficiently expansive footprint upon the VLTI infrastructure that we consider it to be more of a facility than merely an instrument. A significant component of PRIMA is the existing infrastructure, including the ATs, UTs, standard delay lines (DLs), telescope visible-light tip-tilt tracking system (STRAP), Multi-Application Curvature Adaptive Optics (MACAO) on the UTs, interferometer infrared tip-tilt tracking system (IRIS), variable curvature mirrors (VCMs) on the delay lines and now also part of the new star separator subsystem, the DL alignment subsystem, and when PRIMA is used with the UTs, vibration control.

Significant upgrades to the VLTI infrastructure that benefit the existing instruments are a new, improved alignment source MARCEL (which replaces the previous unit, Leonardo), and a new reflective memory network (RMN) that features improved throughput and reduced latency times.

PRIMA-specific subsystems that arrived *en masse* during and in advance of the PRIMA Big Bang began with the Star Separators (STSs). The STSs separate the light of two astronomical objects with separations 1–60 arcseconds and feed it into two parallel VLTI optical beam trains. The STS compensates for field rotation, stabilises the beam tip-tilt and adjusts the lateral and axial alignment of the pupil. Chopping and/or counter-chopping on the bright or faint source has also been implemented in the STS design; two units specific to the ATs and one for each of the UTs have been built (Nijenhuis et al., 2008).

The Differential Delay Lines (DDLs) were provided by the ESPRI Consortium and are responsible for providing slight delay offsets between the primary and secondary sources. The DDLs consist of high quality cat's eyes in vacuum, displaced on parallel beam-mechanics by means of two-stage actuation, with a precision of 5 nm over a stroke length of 70 mm. Over the full range, a bandwidth of about 400 Hz is achieved (Pepe et al., 2008).

The Fringe Sensor Units (FSUs) are designed to provide high precision fringe phase measurements with a goal of 1 nm rms (corresponding to $\lambda/2\,000$). To achieve this, careful calibration procedures were developed, with special attention given to the achieved measurement linearity and repeatability. The quality of the FSU calibration is crucial in order to achieve the ultimate astrometric accuracy (Sahlmann et al., 2008).

Central to successful FSU calibration is the PRIMA metrology subsystem (PRIMET, Leveque et al., 2003), designed by ESO and the Institute of Microtechnology of Neuchâtel (IMT). The PRIMET source, based upon a frequency-stabilised Nd–Yag laser, provided by IMT and calibrated with the help of the Max-Planck-Institut für Quantenoptik, allows nanometre-level pathlength measurements to be attempted with an imperfectly stable interferometer. The overall complexity of PRIMA is carefully being addressed from software standpoint with comprehensive operations software and astrometric data reduction software (Elias et al., 2008; Tubbs et al., 2008) as well.

A further significant effort in support of PRIMA that has now been retired, but bears special mention, is the Fringe Tracking Testbed that was employed extensively over the past two years to test the FSU and PRIMET subsystems and remove the risk associated with them (Sahlmann et al., 2008). This testbed facility was built at MPE laboratories in Garching with the aim of simulating the VLTI and included FSUs, an optical path delay controller, PRIMET and in-house-built delay lines.

Who is PRIMA?

More than the collection of hardware and software mentioned in the previous section, PRIMA is a partnership working towards the goal and rewards of dual-beam interferometry. PRIMA includes significant contributions from both ESO Garching and ESO Paranal, and ESPRI partners the Geneva Observatory, the Max-Planck-Institut für Astronomie in Heidelberg, and the Landessternwarte Heidelberg; PRIMA also includes contributions from Leiden University, the Ecole Polytechnique Fédérale de Lausanne, the Institute of Microtechnology of Neuchâtel and MPE Garching; industrial partners on the PRIMA project include TNO and Thales Alenia Space.

Schedule for PRIMA

Commissioning of PRIMA is scheduled to occur throughout Period 82, covering four runs of roughly ten days each; P82 observing will concentrate on simple system operations involving feeding only a single star into the system. Optimisation of fringe-tracking algorithms will lead to fundamental system characterisation, including night-to-night repeatability, absolute visibility amplitude tests and measurements of limiting magnitude. Period 83 will have a similar set of commissioning runs, but will expand testing to full dual-star operations, with initial tests of the astrometric observing mode. If successful, science verification observations will soon follow and PRIMA astrometry will be released to the community thereafter.

Future of PRIMA and phase-referenced imaging

Already there are plans to expand the scope of dual-beam interferometry at the VLTI. In particular, the second generation VLTI instrument GRAVITY (General Relativity Analysis via VLT InterferometrY; Eisenhauer et al., 2008) is specifically designed to operate in a PRIMA-like fashion, but using not just two, but all four UTs simultaneously to achieve 10 µas astrometry on six baselines on faint ($K \geq 15$) sources at the Galactic Centre. Such observations have the potential to probe highly relativistic motions of matter close to the event horizon of Sgr A*, the massive black hole at the centre of the Milky Way.

For PRIMA itself, exciting discoveries lie ahead in the more immediate future. The new capabilities it provides to the VLTI for both astrometry and faint object science open up wide new frontiers in astronomical interferometry. Experience has shown that in such circumstances, the most interesting results come from unexpected quarters.

Useful PRIMA Jargon

Term	Description
ADRS	Astrometric Data Reduction Software
DDL	Differential Delay Line
ESPRI	Exoplanet Search with PRIma
FSU	Fringe Sensor Unit
PRIMET	PRIMA Metrology
µas	micro-arcsecond
STS	Star Separator

References

Delplancke, F. 2008, New Astronomy Review, 52, 199
Delplancke, F. et al. 2003, Ap&SS, 286, 99
Eisenhauer, F. et al. 2008, SPIE Conference Series, 7013
Elias, N. M. et al. 2008, in IAU Symposium, Vol. 249, 119
Lane, B. F. & Colavita, M. M. 2003, AJ, 125, 1623
Lane, B. F. et al. 2000, SPIE Conference Series, 4006, 452
Launhardt, R. et al. 2008, in IAU Symposium, 248, 417
Lazorenko, P. F. et al. 2007, A&A, 471, 1057
Leveque, S. A. et al. Proc SPIE, 4838, 983
Nijenhuis, J. et al. 2008, in SPIE Conference Series, 7013
Pepe, F. et al. 2008, SPIE Conference Series, 7013
Sahlmann, J. et al. 2008a, in SPIE Conference Series, 7013
Sahlmann, J. et al. 2008b, in IAU Symposium, Vol. 248, 124
Shao, M. & Colavita, M. M. 1992, A&A, 262, 353
Tubbs, R. et al. 2008, in IAU Symposium, Vol. 248, 132
van Belle, G. T. et al. 2008, in SPIE Conference Series, Vol. 7013