PRIMA DDL & AOS Project

ARC
EPFL
ASTRON
MPIA Heidelberg
Observatoire de Genève
University of Leiden/NOVA

Astrometric Survey for Extra-Solar Planets with PRIMA

Requirements on Differential AT Mirror Surface Localizations

Doc. No.	VLT-TRE-AOS-15753-0004
Issue	0.2.281
Date	October 8, 2006

Prepared	Richard J. Mathar	October 8, 2006	Signature
Approved	Denis Mégevand	October 8, 2006	Signature
Released	Didier Queloz	October 8, 2006	Signature

Change Record

Issue	Date	Section/Parag. affected	Reason/Initiation/Documents/Remarks
0.1	07-Jul-2005	all	created
0.1.286	13-Oct-2005	all	presented during progress meeting of Oct 14
0.1.348	14-Dec-2005	all	updated for progress meeting of Dec 19
0.2.023	23-Jan-2006	Ref. [16]	added
0.2.185	4-Jul-2006	Ref. [17]	added
0.2.192	11-Jul-2006	Ref. [15]	added
0.2.281	8-Oct-2006	Ref. [8]	added

Contents

List of Figures

List of Tables

1 Abstract

Astrometry with PRIMA/VLTI puts high requirements on the knowledge of 4-way, dual-beam differential optical path differences for off-axis beams impinging on two Auxiliary Telescopes.

At a prototypical star separation of $\tau = 1'$, if an error in the differential OPD of 5 nm is allowed, M1, M2, and M5 must not be shifted (decentered) by more than 0.3 μm in the U-direction (away from the plane of the Coudé train, the case of the reference pointing), and M7 not by more than 0.15 μm. Displacements of other realy optics mirrors or into other directions are less critical.

These requirements are relaxed inversely proportional to the star separation τ. On the other hand, placing the stars asymmetrically across the STS edge increases the sensitivity of the DOPD to mirror placement.

This document is in fulfillment of the PDR AIs #2 and #3 [4]; this is its sole purpose. It paraphrases a subset of information that is discussed in detail in [21]. Any strategy to deal with these requirements on an observational basis ("calibration") will eventually be reformulated and moved over to the appropriate places in [18] and [7].

1.1 Documents

[1] Alenia SPAZIO 2003, Fringe Sensor Unit, Final Design Review, Tech. rep.

[2] Andolfato, L., & Karban, R. 2005, VLTI PRIMA Supervisor Software Interface Control Document. VLT-ICD-ESO-15736-3060

[3] Delabre, B. 1992, Specification for the optical layout of the VLT Auxiliary Telescopes. VLT-SPE-ESO-15100-0299

[4] Delplancke, F. 2005, Minutes of Meeting, PAOS Preliminary Design Review. TSD-05/42

[5] Glindemann, A. 2000, PRIMA, the Phase Referenced Imaging and Microarcsecond Astrometry facility: System Description. VLT-SPE-ESO-15700-2207

[6] Karban, R., & Wirenstrand, K. 2004, AT#1 Commissioning: Pointing, Test Report. VLT-TRE-ESO-15100-3464

[7] Launhardt, R. 2005, PRIMA Astrometry Calibration and Operation Plan. VLT-PLA-AOS-15759-0001

[8] Lévêque, S. 2000, in Interferometry in Optical Astronomy, edited by P. J. Lena, & A. Quirrenbach (Int. Soc. Optical Engineering), vol. 4006 of Proc. SPIE, 388

[9] Lévêque, S., Salvadé, Y., Wilhelm, R., & Rabeling, D. 2002, PRIMA Metrology Test Campaign 27/4/02 to 5/5/02. VLT-TRE-ESO-15730-2827

[10] Mathar, R. J. 2005, Astrometric Survey for Extra-Solar Planets with PRIMA, Requirements on Medium-Term Stability of Air Parameters in VLTI Ducts and Delay Lines. VLT-SPE-AOS-15753-0003

[11] Ménardi, S., & Gennai, A. 2001, Technical Specification for the PRIMA Fringe sensor unit. VLT-SPE-ESO-15740-2210

[12] Murakawa, K., & Mathar, R. J. 2005, Astrometric Survey for Extra-Solar Planets with PRIMA, Polarization Effects. AS-TRE-AOS-15753-0011

[13] Nijenhuis, J. R. 2003, PRIMA Star Separater (STS), Design and Analysis Report. VLT-TRE-TNO-15710-0001

[14] Pirnay, O. 2002, VLT The Auxiliary Telescope System, Telescope Structural Deflection Test Report. VLT-TRE-AMO-151100-265

[15] Porro, I. L. 1997, Ph.D. thesis, University of Padova. http://cisas.unipd.it/STS_course/thesis/tesi_IP.pdf

[16] Reffert, S. 2005, PRIMA astrometric standard stars

[17] Reffert, S., Launhardt, R., Heeker, S., Henning, T., Queloz, D., Quirrenbach, A., Segransan, D., & Setiawan, J. 2005, in Astrometry in the Age of the Next Generation of Large Telescopes, edited by P. K. Seidelmann, & A. K. B. Monet (Astron. Soc. Pacific), vol. 338 of ASP Conf. Ser., 81. http://www.aspbooks.org/custom/publications/table_of_contents/?book_id=48

[18] Reffert, S., Quirrenbach, A., Jaffe, W. J., & Mathar, R. J. 2005, Astrometric Survey for Extra-Solar Planets with PRIMA, Operation and Calibration Strategy. VLT-TRE-AOS-15754-0001

[19] Shao, M., & Colavita, M. M. 1992, Astron. Astrophys., 262, 353

[20] Stanghellini, S., & Michel, A. 1998, The Messenger, 94, 10

[21] Tubbs, R. N., & Mathar, R. J. 2006, Astrometric Survey for Extra-Solar Planets with PRIMA, Astrometric Error Budget. VLT-TRE-AOS-15753-0001

1.2 Acronyms

AI Action Item

AMOS Advanced Mechanical and Optical Systems http://www.amos.be/index.htm

ARC Ecole d'ingenieurs de l'arc Jurassie http://www.eiaj.ch/

ASTRON Stichting Astronomisch Onderzoek in Nederland http://www.astron.nl

AT Auxiliary Telescope (of the VLTI) http://www.eso.org/projects/vlti/AT/index_at.html

DAF Data Analysis Facility http://www.strw.leidenuniv.nl/~nevec/PRIMA/

DOPD differential OPD

DRS Data Reduction System

EPFL École Polytechnique Fédérale de Lausanne `http://www.epfl.ch`

ESO European Southern Observatory `http://www.eso.org`

FEM Finite Element Method

FOV field of view

FSM Field Selector Mirror (of the STS)

FSU Fringe Sensing Unit

GIS Ground Interface Structure

ICS Instrument Control Software

IOTA Infrared Optical Telescope Array `http://www.cfa.harvard.edu/cfa/oir/IOTA/`

IRIS Infrared Image Sensor `http://www.eso.org/projects/vlti/iris/`

ISS Interferometric Supervisor-Software

MIDI Mid-Infrared Interferometric Instrument `http://www.mpia.de/MIDI`

MPIA Max-Planck Institut für Astronomie, Heidelberg `http://www.mpia.de`

NOVA Nederlandse Onderzoekschool voor Astronomie `http://www.strw.leidenuniv.nl/nova/`

OPD optical path difference

OPL optical path length

PDR Preliminary Design Review

PRIMA Phase-Reference Imaging and Microarcsecond Astrometry `http://obswww.unige.ch/Instruments/PRIMA`

PRIMET PRIMA Metrology `http://www.eso.org/projects/vlti/instru/prima/description_lms_prima.html`

PS primary star

ROS Relay Optics Structure

SS secondary star

STRAP System for Tip-tilt removal with Avalanche Photodiodes

STS star separator

UT Unit Telescope (of the VLTI) `http://www.eso.org/projects/vlt/unit-tel/`

VIS visible (part of the electromagnetic spectrum)

VLTI Very Large Telescope Interferometer `http://www.eso.org/vlti`

WDS Washington Double Star (Catalog) `http://ad.usno.navy.mil/wds/`

2 Astrometric Mode

The dual-beam interferometer PRIMA at the VLTI aims at μas accuracy for the differential optical path difference DOPD between the two beams (two stars/sources). Standard trigonometry for template baselines of $\approx$ 100 m translates this to requirements on the accuracy of the delay difference between the two interferometers represented by both beams of typically $\approx$ 5 nm [5]. [1]

3 Error Budget

In rough terms, PRIMA interferometry measures a grand total phase of the wave packet by the FSUs. The difference between these is attributed to the "external" phase representing positions on the sky. As the AT mirrors M1–M8 (the de-rotator inclusive) are not monitored by PRIMET, any unforeseen (unknown) asymmetry in the optical path length of any of the two beams between the two telescopes becomes a signal sensed by the corresponding FSU, which is indistinguishable from and potentially misinterpreted as a signal originating from a modification in stellar position.[2]

In a straight forward manner this leads to the request that the OPL of the beam between some reference point on M1 of AT1 up to the M11/FSM of the STS and the OPL of the equivalent beam between the equivalent reference point on M1 of AT2 up to the other M11/FSM of the STS do not differ by more than $\approx$ 5 nm for off-axis angles up to an isoplanatic angle (star separation) of $\approx 20''$.[3].

If the asymmetry between the telescopes causes larger systematic deviations than 5 nm, the actual asymmetry must be made available to the DRS for off-line correction, typically via explicit single-shot online measurements of auxiliary parameters, measurements of the chopping/nodding/beam-swap type that have intrinsic capabilities of error subtraction, or measurements of the calibration type that assume stability of some opto-mechanical model.

4 AT Coudé Train Definition: Requirements

The sensitivity of the OPL to mirror translations and rotations depends on the off-axis angle, the telescope pointing direction, and the mirror (position, orientation, conic constants). Assuming that the two M11/FSM remove the static tip and tilt that may be left from these distortions, 5 nm of DOPD are equivalent to motions of the magnitude of 0.2 μm of M1, M2, M5 or M7 at a star separation of $\tau = 1'$, with requirements relaxed $\propto \tau$ at smaller separations.[4] This refers to the non-zero mean of the difference between both ATs averaged over the same time scale that is attached to the goal of 5 nm in DOPD, not to the vibrations of the structure.[5] The requirement is to know the "zero-sound" static difference between the bending of the two telescope structures and their mirror mounts to better than 0.2 μm for these particular optical surfaces. The requirements on the knowledge of axis tilts are typically $0.1''$ for M2–M5, $0.01''$ for M1 and M7–M8.[6]

[1] This transformation is detailed in Section 28.3.2 of [21], and not reviewed here.

[2] This is discussed in Section 11.4.2 of [21].

[3] See Section 26.3.3 of [21]. The value of this angle is not a subject of this memorandum, and it is to be regarded as a representative but not an exact value.

[4] This is the summary of Section 13.4 of [21] and may be compared with the requirements estimated for IOTA [15, §3.5.4]

[5] See Sect. 22.3 in [21].

[6] This is a summary of the $1'$ star separation columns in Table 5 in [21].

The answer to the question in how far the expected alignment of the relay and Coudé trains meets the requirements depends strongly on (i) which mirror is considered, (ii) which of the six parameters (rotational, translational) of this mirror, (iii) the star separation angle τ, and the split ratio of τ over the two faces of the M10/STS edge, (iv) the alignment of the field rotation as selected by the STS with the stiffer direction defined by the horizontal telescope axis, (v) the action of IRIS on M11/FSM as the common parameter set on both interferometric telescopes, plus a further set of parameters which generate differences in the mirror geometry between both telescopes. All these parameters play also roles in other aspects of the error budget [21] and [12]; to avoid an editorial nightmare we do not copy the various parameters, tables, discussions from the error budget to this document.

5 AT Coudé Train Definition: Expected Status Quo

The PRIMA consortium did neither specify the accuracy of the optical train, nor did it build the ATs nor did it perform any tests on the available telescopes: Theoretical and rather implicit estimates on the actual performance/compliance of the forefront optics are drawn from available AMOS test reports in Section 13.5 of [21].

In summary of the corresponding part in the error budget, the most violent apparent problem (in the sense that any of the aforementioned measurements allows to reduce data to the *differential* OPD) is a differential (in the sense of unpredictable) tilt of M1 along one optical axis—defined as the non-reproducible misalignment with the M2 axis—which may induce a DOPD 30 times larger than the 5 nm aim, at a star separation of $\tau = 20''$. Combined with a contribution of 8 times the error budget of 5 nm from M2, this is roughly 40 times the allowance, and would grow by another factor of three if $\tau = 1'$.

Axis runouts and over/undershooting of the altitude and azimuth axes will probably introduce a wiggle with a simple cosine-dependence on the azimuth direction in the narrow-angle baseline, at an amplitude of about the allocated prototypical error of 50 μm.[7] Compared to the compliance with the need for an accurate measurement of the DOPD this is a minor problem and not discussed any further. The axis runout contribution to the DOPD is estimated at less than 30 nm.[8]

6 Approaches to Improved Sensitivities

At this point, the Consortium is extending its task of providing an error budget for the instrument as being build by ESO and takes the role of a consultant to improve on the technology involved.

Subsequent mentioning of resources to gather precise information to meet the PRIMA criteria on the path length control does *not* indicate that any of these methods is recommended or endorsed by the consortium or the author, or that these means are a complete set of all options. The PRIMET extension is studied to fulfill AI#3 of [4]. Dead-end ideas like the one mentioned in Sect. 6.5 are included as well.

The author is not aware of any study of this problem beyond [9], which we therefore discuss first in Sect. 6.1. The baseline is always measurement, rather than active control, of the de-facto location of mirror surfaces. This may result in a direct output as a differential OPD, or in auxiliary surface

[7] Section 11.4.3 of [21].
[8] Section 13.5.5 of [21].

coordinates that need an additional synthetic beam model as the one used to derive all of the effects in the current error analysis.

6.1 PRIMET Extension to M2

Let us consider the idea to separate the differential delay caused by the mirror motions as described above from the differential delay caused by the star separation by measuring the mirror motions explicitly. The option of moving the PRIMET point of return such that the laser touches also these mirror surfaces comes obviously into mind [8].

The impact on PRIMET is considered supposed the laser point of return is moved from RR3 in the STS to the “blind spot” in the M2 center, adding a new retro-reflector there which we shall call M2R. The questions are (i) In how far would the two paths of the laser still represent the path lengths of the “science” light? (ii) Would the laser light suffer from back-coupling efficiencies associated with variable polarization as a function of pointing? (iii) Would the laser light suffer from a strong lateral expansion, which might reduce coupling efficiency and/or lead to spilling of the waist beyond the central core of the beams that match the FSU dichroics? (iv) Will the STS design be violated? (v) Is the formal decoupling from the narrow-angle baseline definition important?

6.1.1 Star Separator Design

If one wants to move the laser retro-reflector further up in the mirror train, the laser light is to be reflected from M9, whereas the current design [13] defines the laser path by the transmitted light.

- One can leave the mirrors RR1–RR3 in the ROS in place if somewhere between these a highly absorptive screen is added which attenuates this part of the 1.3 μm signal to avoid cross-talk with the laser light returning from the new M2R.
- The M9 dichroics would have to be changed from optimizing transmission at 1.3 μm to optimizing reflectance.

6.1.2 Common Path Definition

To image M10 on itself, M2R must be convex with a radius of curvature of ≈ 3.8 m.[9] This could only be achieved with a path length precision better than 100 μm if M2R also becomes a roof top mirror of two parts that intersect at an angle of $\approx 174°$, each matching one corresponding section of the split M10. This complicates the design because this ridge on M2R would have to be aligned with the motorized star rotator angle.[10] This need of moving also the PRIMET end point is disadvantageous compared to the current design where RR1–RR3 are fixed.

Note that, although the PRIMET diameter is only a fraction of the science beam diameter, this does not mean that the laser beam becomes very insensitive to the tilts by the $\propto \tau$ scaling of the DOPD:[11] The two PRIMET branches would trace the core of their associated science beams up to M2R and be fully sensitive to the first order of the effect. This is obviously what raises the need to model the M2R with two sections.

[9] This copies the role of the current RR3. The estimate is from Gaussian Optics assuming M3, M4, M6 and M8 are flat, and means the existing Nasmyth focus between M4 and M5 is one radius away from M2R.

[10] Other reflector solutions than this have not been investigated.

[11] See of Table 5 of [21].

Fig. 34 of [21] demonstrates that there is a structure in the OPL across the wave front for star separations of $\tau \geq 30''$ that is inherent to the AT and STS optics: For larger star separations, probing the optical path with PRIMET only at the beam center is no longer equivalent to building some "mean" as implemented by the FSU fiber hardware.

6.1.3 Polarization

With the Hagemann parametrization of the dielectric surfaces[12] we obtain the following degree of polarization for a round trip from M10 to M2R and return:

			p			s		
A / °	z / °	φ / °	P	ψ / °	$\tan\chi$	P	ψ / °	$\tan\chi$
0	0	0	1	0.	0.	1	0.	0.
20	10	0	0.970	4.1	0.10	0.973	3.9	0.10
30	10	15	0.244	0.8	0.78	0.188	9.9	0.82
30	10	30	0.369	33.5	0.17	0.364	33.4	0.20

Table 1: Degree of polarization P, tilt angle ψ of the principal axis of the polarization ellipsis versus the starting U, W frame, and axis ratio $\tan\chi$ of the polarization ellipsis as a function of azimuth A (starting from 0 if pointing along V), zenith angle z, and star rotator angle φ (also 0 if along V).

If the rotator mirrors stay aligned with the rest of the Coudé train optics, the case $\varphi = 0$ in the table, the effect of mirror polarization is small, but turning the star rotator around the W axis may drastically deteriorate the degree of polarization that remains on return.[13] There is no advantage from judiciously starting with an initially vertical or horizontal plane of polarization before first hitting M9: this has been the difference for the calculations grouped under the header p versus the results under the header s in Table 1.

This effect could not be seen with the 2002 measurements [9] because there is no such rotator between M8 and M9 for the UTs.[14]

6.1.4 Beam Expansion

The effect of pupil motion was summarized in [9] based on experience with UTs: *"By positioning the metrology retro-reflector at the center of the secondary mirror, the run-out of the telescope during azimuth rotation will introduce significant pupil motion..."* The change in fringe contrast has been tabulated in [9, Table 6-2].

The effect of adding 2×14 m to the total path length should be small compared to the total path length of the current design. The number of mirror/dichroic reflections is increased from $2 \times 28 = 56$ by $2 \times 9 = 18$ (M3 to M8 plus star rotator) with an accompanying reduction in reflected power. Simple geometric extrapolation of earlier measurements[15] yields an additional transmission factor of 0.45 (reduction by 55 %). If the laser power is doubled accordingly, the stray light which is directly moving towards the detector is also doubled in power.

[12] See Section 4 of [12]: $\epsilon = 0.303 - 9.61i$.

[13] Since M4–M7 are not co-rotated, nonzero φ means that the plane of incidence is redefined twice for each unidirectional passage through the star rotator.

[14] as shown in Fig. 4 of [12]

[15] 37 reflections are equivalent to a transmission of $< 19.4\%$ according to Table 4.6 of [9].

The ratio of the laser over the beam diameter is 2.5 mm / 18 mm $\approx$ 0.14 at the FSU.[16] Up-conversion to the M2 diameter of 0.138 m [3] yields an estimated laser beam diameter of 19 mm on M2R. We expect the central hole[17] in M2 to match the ratio of M2/M1, ie, to have a diameter of $0.138 \cdot 0.138/1.8$ m$\approx$ 10.5 mm. This would introduce a severe clipping of the laser beam, cutting the power returned by a factor $(1.05/1.9)^2 \approx 0.30$—the rest being lost into the night sky via M1. To avoid this, the PRIMET beam would have to be confined to a diameter of $\approx$ 1.3 mm at the FSU. In consequence, the pupil motions up to 0.3 mm reported with the 11 mm test beam [9] will become even more important to the variation of the overlap.

6.1.5 Baselines

The narrow-angle baseline is fixed by the centers of the four M11/FSM involved. It is relocatable, which means that the three components of the vector can be translated to another place.[18] For example, it could as well be defined by the *images* of these mirrors if the Coudé train would be substituted by one effective mirror. In summary, using PRIMET also as a monitor of baseline changes is not effected by moving its point of return from RR3 to M2.

6.1.6 Miscellaneous

It is clear that this type of reaching with PRIMET to M2 could only gather information on two out of four "critical" mirrors, M5 and M7 but not M1 and M2.[19]

MIDI chops with M6 at up to 5 Hz. The extended PRIMET may run into problems if used for an imaging mode in this scenario because all M6 vibrations are imprinted on the laser beam.[20]

6.2 Inverse Astrometry

6.2.1 Single Star

Are there any chances of mapping the OPL as a function of off-axis angle by moving the main telescope axis away from a single star with some kind of open-loop of STRAP and IRIS such that (one detector of) the FSU can build an OPL map as a function of off-axis angle? The signature of the (now non-differential) effect is a quadratic function of the off-axis angle.[21] One might envisage a single-star calibration mode—fundamentally different from the STS "split" mode—where the same star is judiciously placed on "opposite" sides of the two STSs of the two telescopes with varying distance to the main telescope axis, which would allow to find the center of this quadratic function in an off-line retro-fit.

The problems with this type of approach are

- Software: the ISS has no (public) mode of operation to run the telescopes in cross-eyed pointing.

[16] taken from [11, §3.4.26.3] and compatible with the mention of the factor 0.15 in [1].

[17] The author does not have information on whether the ATs have indeed an opening as do the UTs [20, Table 1] which would allow additional optics be placed on the rear-side of M2. At a diameter of 13 cm and the rear interface displayed in [14, Fig 4-2]—crowded with the focussing opto-mechanics—this seems unlikely.

[18] See Section 11.2.2 of [21]. This ignores small parallactic effects.

[19] see Table 5 in [21].

[20] Since the throw is of the order of $10''$, the metrology would stay on M2R without being nominally interrupted.

[21] Figure 29 in [21]

- Hardware: to map the two off-axis images of the same star in both telescopes on the same FSU for interferometry, the star rotator must rotate the FOV in one telescope by 180° (the star rotator axis rotate by 90°), which introduces a new potential source of error in form of imperfection of the rotator operation.

6.2.2 Double Star

A calibration method is to use the three fundamental variables (star separation vector projected on the projected baseline, differential OPD, baseline length) to calibrate each of them independently or in combination with astrometry on well-known objects. The major problem when applied to the mapping of the DOPD is that there are many other error sources in the Error Budget with similar signature (dependence on star separation, telescope pointing direction. . .) which are unlikely separable from the contribution of asymmetric telescope optics as discussed here.[22]

In a—definitely more complicated—double source version of the method of Section 6.2.1, one may use the predicted uniaxial dependence predicted by the theory, and the axis mixing introduced by placing the two stars not symmetrically across the STS edge[23] to build a 2D map of the off-axis positions as a function of edge distance and (deliberately tweaked) star rotator angle. The philosophy behind such a search for the "true zero" of the DOPD is that any error in the optical train can be transformed to a calibration method once there are controlled parameters (here: star placements within the 2D FOV) and a solid theoretical model (here: the ray tracing proposals) which can be joined. The intrinsic generic problem is whether the degrees of freedom in the controlled parameters (that would be four for both 2D maps if both telescopes are operated individually, using one fixed binary) is sufficient to cover the number of free parameters in the model (that would in some sense be only one, the leaky DOPD).

6.3 Calibration with Axis Flips

An experimental assessment of the OPD error associated with the non-ideal telescope structure could be attempted by using two equivalent telescope positions in succession for a single nominal star position: ideally, one can reach to a single sky position by rotating the azimuth axis by 180° and flipping over the altitude axis to the opposite side. In a pre-PRIMA test setup, with instruments like VINCI or even MIDI, piston differences on the 1 μm level (?) might be detectable (if this axis flip is done faster than the piston inherited from tunnel water vapor wandering [10]), although absence of the effect in the PRIMA error budget could not be proved because this still is 200 times coarser than the target of 5 nm.

During the regular operation, one may think in principle of successive axis flips on both telescopes to generate a "calibration" of the differential piston, building some poor statistical average across the four data points that emerge. The disadvantage of this type of operation might be that the telescope axis is forced through the zenith point which is worst affected by axis run-outs and de-centered mirrors.[24] However, if this is the method to re-settle axis bearings and mirror contacts, this way of averaging could be useful.

As a side benefit, this type of averaging could also eliminate to first order the (unimportant) effect

[22] to add a positive note here, this would provide a nice use case for the DAF.
[23] noted by the numbers in parenthesis in Table 5 in [21]
[24] see the references collected in Sect. 13.5 of [21]

of mutual over/undershooting of the two telescope axes.[25]

It is not known to the author whether some simple reasons in form of bolts or what is dubbed "cabling problems" disallow this kind of Alt-Az coordinate swap with the ATs.[26] The time overhead for this operation would be large (but within the 3 minutes specification for a completely new acquisition [6, §7.2]), since the flipped angular azimuth coordinate is far away from its value before the flip.

6.4 A Posteriori Software Filters

An "internal calibration" method to subtract the effect—comparable to the beam swap that exchanges beam paths *after* the star rotator—is not known. Methods like waiting until the sidereal motion has rotated the vector between the two stars by 180° and toggled the sign of the DOPD are likely to fail due to the long time intervals between such pairs of measurements: some phases of the DOPD are unavailable because the OPD is periodically switched off by the horizon and because both values are phase coupled.[27] With reference to [2, p 6] which argues "*Swap objects: In Astrometric mode the primary and secondary objects can be swapped in order to identify the bias introduced by the instrument*" we see that we actually cannot swap the objects, but have to wait until they've been swapped with a period close to 24 hours. Using the Earth rotation to swap the beams to eliminate the effect puts additional constraints on scheduling and is not promising since there is hardly any control on the alignment of the pair orientation with the (projected) baseline.

6.5 Pupil Diameter Reduction

Downsizing the effective M1 diameter with a mask to less than 1.82 m (or for simplicity an equivalent mask on a smaller mirror later on) has *no* effect on the induced "leaky" differential OPDs listed in Table 5 of [21], and does *not* help. The cause for this insensitivity is obvious from Figures 31 and 32 of [21]: the jitter in DOPD from mirror translations and tilts is a product of distances (focal lengths), per-beam off-axis angles (star separation) and mirror curvatures, all of which do not depend on the two beam's diameters.

6.6 Dedicated AT Structure Sensors

6.6.1 Another Local Laser Metrology

In principle, a further laser metrology system launched from somewhere within the GIS or ROS and reflected off the mirrors of the relay optics could serve the same purpose as the PRIMET extension of Sect. 6.1. The advantages are

- The freedom of choice of optical paths is larger. One could stay on the "rim" of the FOV for a particular launch point to increase sensitivity, and even chose an open loop path through the mirrors to avoid adding more dichroics to the path of the science beam. Supposed a FEM model of the structure is available, one could also perform a round trip through an additional set of flat mirrors attached to "pivot" points (Sect. 6.6.3) outside the standard beam diameter.

[25] Section 11.4.3 in [21].

[26] Although not documented, one might interpret the labels "+Alt" and "-Alt" found in many figures of [14] as if this two-sided sweep was a standard for the AT#3 tests.

[27] see Figure 45 of [21]

This may turn out to be a rather optimistic point of view, however, only applicable if the system is restricted to monitor M1–M4. The mirror train is generally not oversized to reach down to M7 or M8 by following any other path but the main axis within the standard FOV.

and the disadvantages

- Acquisition data rates ("stress" on the ICS) increases.
- Rather than being stationary, this system must be relocatable with the ATs, which may call for additional calibration.
- This type of ranging delivers total/integrated path lengths, one per mirror configuration, but does not take into account the different criticality of the six parameters of the mirror positions. This means one point on one of the mirror surfaces visited may potentially approach the laser source and another move away at the same time, and both "errors" may cancel to any degree in the laser interferometer's output.

  The PRIMET extension of Section 6.1 delivers a differential OPD in the PRIMA sense in hardware, whereas standard laser ranging needs to be backed up by a reduction software (similar to the dedicated C++ program and classes written by the author to generate the PRIMA error budget as summarized here).
- The path length being rather short, dispersion effects might be unimportant and a ranging with some more standard frequency in the VIS might suffice. For a beam path of < 30 m and an accuracy of ≈ 200 nm one needs the index of refraction accurate to $\approx 7 \cdot 10^{-9}$.

6.6.2 Tilt Sensors

Open questions:

- Would these provide the accuracy needed for a full range of pointing directions[28]
- Would these allow for any remote readout by electronics? Are there cabling problems?
- Would these find free spots on the mirror rears—with the disadvantage on adding weight to these—or need to be measuring the mounts only?

Disadvantages:

- Some tilt sensors refer to a local coordinate system, which means they do not measure the translational degrees of freedom that play an equally important role in producing DOPD. Others, like those that are capacitance based, provide a "mean distance" which mixes the directional dependencies. Generally speaking, both "tip" and "tilt," defined relative to the current alt-az-direction, are of comparable interest. A tilt sensor may measure only a single angle relative to the local direction of gravity, depending on the principle of measurement.

Advantages:

[28] Off the shelf electrolytic tilt sensors would reach resolutions of $1''$ in the narrow range of a few degrees, and $4''$ over a range of 60°, the former probably applicable to the static mirrors following M4, the later to M1–M3. This is *not* in any way a quote of the performances of the industry in this field, but meant to be compared with the numbers in Section 4. The author has not done a market review on this theme.

- Each point with a sensor attached is an independent input. This scaling is advantageous compared to the laser method of Section 6.6.1 which may be reflecting off an arbitrary number of surfaces and still yield one single path length. It might be possible to generate the "tip" information called missing in the previous bullet by some kind of subtraction of sensor distributed over the M1 surface. This, however, is a very ill-conditioned data reduction problem, and would only work for the big M1 to some degree, but unlikely for M7.

Accelerometers are a problematic option, and rather complementary to the query for a stable quasi-static definition of points in space. They would need additional calibration to define the reference point by some other auxiliary method each time after switch-off, and then yield the distance after double integration over the time elapsed since then. The absolute measure of the coordinate is continuously deteriorating due to linear accumulation of the internal errors over time.

6.6.3 Reference Structure

In combination with any kind of local measurement system like those mentioned above, a reference structure is either a cage that moves with the azimuth axis or a lever that moves with both axes but not attached to the telescope structure. The idea is to provide a mechanical reference frame that is stiffer and less vulnerable to wind and gravity than the system carrying M1 and M2. To have it rotating with one or two telescope axes is not a key principle but allows to fix the "gauges" (plane auxiliary mirrors for an optical system or the tilt meters that measure capacitance) to them such that the "center-of-mass" motion of the entire system—in which we are not interested—is already eliminated. An example of this principle is found with the measurements of the M1 motion *relative to* the tube with inductive sensors in [14].

The generic problem is that high stiffness and lean structure (wind cross section) are in essence opposite requirements. An additional request for low amplitudes in the frequency spectrum would not have priority; an accurate mean on slow timescales by "integrating" over vibrations would suffice here. The additional intrinsic problem is that this structure has the same expansion properties with temperature gradients as the telescope itself (unless built from some sort of carbon enforced plastic).

6.7 Star Selection

The sensitivity of the induced DOPD error proportional to the star separation means the sensitivity to mirror displacements is ten times smaller if the star separation is reduced from $1'$ to $6''$, for example. The knife edge effect sets a lower limit of $\approx 1''$ to the star separation for the ATs, see Sect. 6 of [21]. The problem can therefore be reduced but not be eliminated by selection of arbitrarily tight pairs of PS and SS.

This does not necessarily hamper the astrometric program given the skewed statistics of Figure 1. Supposed that an ample set of phase reference stars is available [16, 17][19, Fig. 5], one can roughly loose an additional factor of two (or even more) in sensitivity to the differential M1 tilt if the star pair orientation can be chosen "along" the more stable axis which would be a function of the azimuth; the star rotator then can select a favorable field angle such that the STS edge sees two fields that are more likely to be displaced along the STS edge than perpendicular to it.

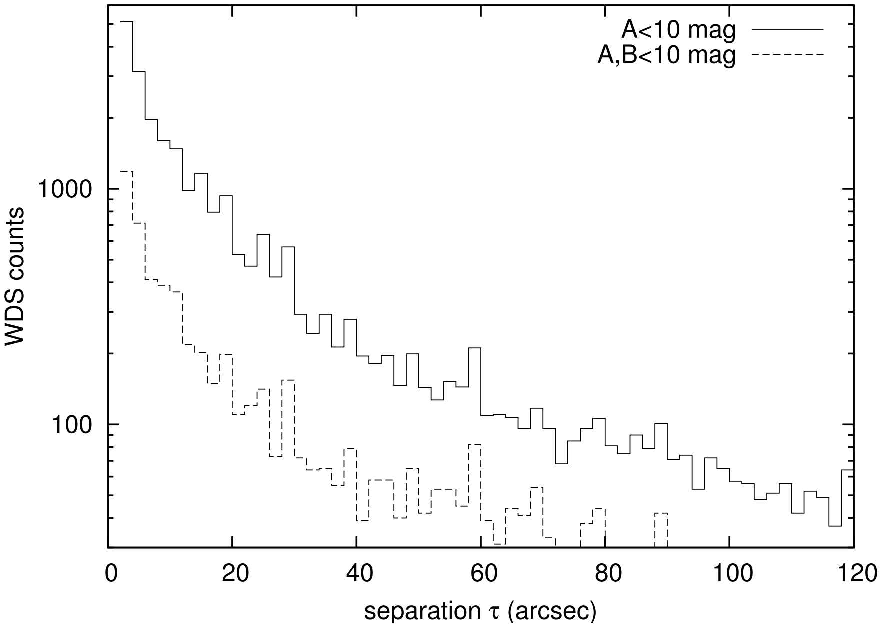

Figure 1: A bulk statistics on the star separations listed in the WDS Catalog over all 40,400 pairs with magnitude of the primary 10 or brighter (solid), or over all 13,300 pairs with both magnitudes 10 or brigher (dashed), in the PRIMA FOV of $2'$. Note that "bulk" refers to the fact that there has been no selection from any astronomical qualitative point of view. For comparison: the full solid angle of 4π is $47 \cdot 10^6$ times as large as a FOV of $2'$ in diameter.

7 Summary

The most critical positioning with respect to the differential OPD is M7 which must not move out of the Coudé plane by more than 380 nm to induce less than 5 nm in DOPD for a star separation of $20''$. The other powered optics (M1, M2, M5) is about half as sensitive. Requirements on the pointing (axis alignment) of M1 and M7 are ~ 30 mas for the same goal.

The static differential piston between the two ATs could be fourty times higher than required by the 5 nm specification of the DOPD at a star separation of $20''$, or 100 hundred times higher at a star separation of $1'$.

Some important aspects of extending the metrology point of return close to M2 have been pointed out during the 2002 tests. They are therefore well known to ESO and there is no good sense in paraphrasing them here. Passing twice by the star rotator is estimated to have a strong de-polarizing effect on the PRIMET beam. This may or may not be important depending on whether the PRIMET polarization is chosen to be linear or circular.

__oOo__