The ESPRI project: Differential Delay Lines for PRIMA

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ABSTRACT

ESPRI is a project which aims at searching for and characterizing extra-solar planets by dual-beam astrometry with PRIMA@VLTI. Differential Delay Lines (DDL) are fundamental for achieving the micro-arcseconds accuracy required by the scientific objective. Our Consortium, consisting of the Geneva Observatory, the Max-Planck Institut for Astronomy Heidelberg, and the Landessternwarte Heidelberg, in collaboration with ESO, has built and tested these DDLs successfully and will install them in summer 2008 at the VLTI. These DDLs consist of high quality cat's eyes displaced on a parallel beam-mechanics and by means of a two-stage actuation with a repeatability of 5 nm over a stroke length of 70 mm. Over the full range, a bandwidth of 400 Hz is achieved. The DDLs are operated in vacuum. We shall present, in this paper, their design and their exceptional performances..

Keywords: Interferometry, near infrared, astrometry, extrasolar planets, delay lines

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1. INTRODUCTION

In only 13 years from the discovery of 51 Peg b [1], the search for extra-solar planets has yielded nearly 300 extra-solar planets candidates. Most of these planets have been unveiled by the Doppler technique (measuring stellar radial velocities), although transit-search programs started to deliver a bunch of new candidates as well. Each technique provides us with new understanding of the formation and evolution of planets and insight in very different aspects, such as kinematics, dynamics, internal structure and atmosphere of the planets. Multiplying the observation techniques is certainly of great interest for the further development of this field.

Astrometry has not been able, until present, to contribute much to the search and the characterization of extra-solar planets, mainly due to instrumental limitation in detecting the tiny astrometric signal induced by the planets on its host star. In fact, micro-arcseconds capabilities are required for this task. On the other hand, the astrometric technique promises new perspectives, since, for examples, *all* orbital parameters can be determined by the astrometric signature.

Also, this technique allows us to explore systems, which have been out of reach of the Doppler or the transit techniques, e. g. planets orbiting very young or active stars.

The ongoing developments by ESO on PRIMA, the instrument for Phase Referenced Imaging and Micro-arcsecond Astrometry at the VLTI [2,3], will provide us soon with the needed telescope infrastructure to carry out an astrometric search for planets. This will both complement some weakness inherent to the radial velocity method as well as open new discovery spaces. We refer to paper [4] in this same conference proceedings for a detailed the description of our project to contribute in making PRIMA an unique facility for detecting extra-solar planet by the astrometric method. A project overview as well as the description of the method and of our scientific goals is given therein.

In order to speed up the full implementation of the 10 µarcsec astrometric capability and to carry out a large astrometric planet search program, a consortium led by the Observatoire de Genève (Switzerland), Max Planck Institute for Astronomy, and Landessternwarte Heidelberg (both Germany), has built Differential Delay Lines (DDLs) for PRIMA in exchange of Guaranteed Observing Time. In section 2 we shall introduce to the need for such DDL for micro-arcsec astrometry and in section 3 recall the technical requirements which drive the system design. In section 4 we will describe the design of the DDLs, and in section 5 their laboratory performance.

2. THE NEED FOR DIFFERENTIAL DELAY LINES ON PRIMA

The ESO Very Large Telescope Interferometer (VLTI) consists of four stationary 8.2-m VLT "Unit Telescopes" (UTs), four movable 1.8-m "Auxiliary Telescopes" (ATs), and six long-stroke dual-beam delay lines (DLs). It provides baselines of up to 200m length and covers a wavelength range that extends from the near infrared (1 µm) up to 13 µm. PRIMA will implement the dual-feed capability for two UTs or ATs to enable simultaneous interferometric observations of two objects that are separated by up to 1 arcmin. PRIMA is designed to perform narrow-angle astrometry in K-band with two ATs as well as phase-referenced aperture synthesis imaging with instruments like Amber and Midi on the VLTI.

A two-telescope interferometer measures the delay between the wavefront sections from a star as they arrive at the telescopes. This delay is a function of the angle between the telescope baseline and the direction of wavefront propagation, i.e., the vector pointing toward the star on the sky. By means of the interferometer delay lines (DL), the internal delay of the interferometer is adjusted such that it is equal to the external delay, which means that the object light travels exactly the same distance through the two arms of the interferometer. In that case, fringes appear on the fringe detector. By measuring the internal delay with a metrology system, one can determine then the external delay, and thus the angle between the baseline vector and the star-pointing vector.

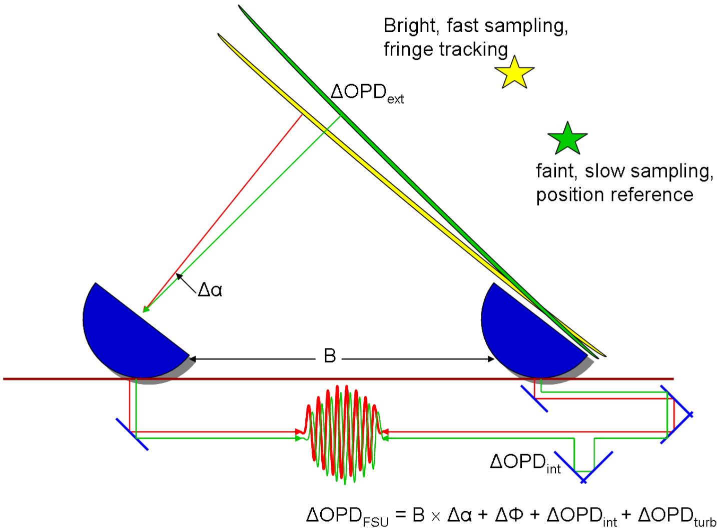

Figure 1: Measurement principle: narrow-angle astrometry with differential delay interferometry

However, atmospheric piston perturbations usually prohibit accurate measurements of this delay in absolute terms. Furthermore, it is impossible to determine the baseline vector to the accuracy needed for micro-arcsec astrometry (10 μarcsec would require an accuracy of nanometers on the 200-m baseline). In order to remove these huge systematic errors and possible effects due to atmospheric turbulences, a dual-star interferometer like PRIMA can observe two stars simultaneously. As if it was a second interferometer, one can measure, by using a second fringe sensor, the internal delay also for the second star. The difference of the internal delays of both stars, the so-called differential optical path difference dOPD, is the a measure of the differential path difference of the light before reaching the telescopes (difference of the external delay between the two stars from one telescope to the other), and thus a measure for the angular separation between the two stars (see Figure 1).

The issue is that if the DL is adjusted such to make appear the fringes of star A on the fringe detector A, one would not be able to detect any fringes of star B on detector B. The reasons for that is the slightly different external delay for star B compared to star A, since its angular position on the sky is different from that of star A. The internal delay produced by the DL does therefore not match exactly the external delay for star B, while it does for star A. This situation can be overcome by introducing an additional (differential) delay only on the internal optical path of star B, such that the interference condition is matched also for this star.

PRIMA is equipped with the dual-star capability, and does therefore integrate DDLs. In order to make the system fully symmetric, there will be actually for DDLs, i.e. one per telescope and per star. For the moment, PRIMA will be operated with two AT's, but on medium terms its capabilities might be expanded two 4 ATs, thus allowing to operate two independent interferometers simultaneously and possibly with perpendicular baseline vectors. For this reasons, the DDL system foresees the possibility to integrate 8 DDLs, although only four have been implemented for the moment.

3. TECHNICAL REQUIREMENTS

The DDLs have been designed to comply with technical requirements specified by ESO and foreseen in view of the integration of the DDLs into PRIMA. Hereafter, only the most relevant of these requirements shall be recalled:

Stroke: In order to compensate for a differential delay on two sky target separated by up to 2 arcmin and for a baseline of 200 m, a single DDL must be able to introduce an optical path difference of ±66 mm.

Retro-reflection: The input and output beam must be separated by 120 mm and be co-linear within 1.5 arcsec (tilt). Two beams within the field of 10 arcmin must not suffer differential tilt larger than ±0.75 arcsec.

Wavefront: Wavefront errors introduced by the DDL (two windows and 5 reflections) must not exceed 25 nm rms

Pupil transfer: The retro-reflector shall re-image the pupil at the same location at which it would be located if it was not inserted. The beam must not suffer lateral displacement (lateral pupil displacement) larger than 50 μm P-V.

Resolution: The position of the retro-reflector must be determined with a resolution of better than 2.5 nm

Transfer function: A 2nd order transfer function with a bandwith of larger that 200 Hz, a delay shorter than 125 μs shall be reproduced, the goal being to correct for possible vibrations in the VLTI or fast atmospheric piston.

Operation modes: The DDL must be able to correct for fast perturbations, e.g. atmospheric piston or vibrations, in closed loop on the fringe sensor or the PRIMA metrology PRIMET (active tracking mode). The DDL must also be able to track blind trajectories up to 200 μm/s, e.g. varying delay due to field rotation etc (blind tracking mode). Finally, the DDL may be operated in fast scanning to search for fringes (fringe scanning mode).

Vacuum operation: The DDLs must be operated in vacuum, in order to minimize differential OPD errors.

4. DESIGN OF THE DDLS

4.1 Overview

The design of the DDLs has been developed by the ESPRI consortium in close collaboration with ESO. The DDLs consist of Cassegerain-type, all-aluminum retro-reflector telescopes (cat's eyes) with ≈20 cm diameter that are mounted on stiff linear translation stages. A stepper actuator at the translation stage provides the long stroke of up to 69 mm. A piezo actuator at the M3 mirror in the cat's eye provides an additional fine stroke adjustment over ≈10 µm with an accuracy of 1 nm. Both actuators are driven by one control loop, such that the optical path can be smoothly adjusted within 120 mm (twice the stroke length) and with an accuracy of 2 nm. Together with an internal metrology system, the DDLs are mounted on a custom-made optical bench in non-cryogenic vacuum vessels. The actuators are controlled by the front-end electronics installed at only 1-m from the DDLs, while the VLT-standard control software runs on Local Control Units (LCU) mounted in electrical cabinets at about 40-m, outside the interferometric laboratory of the VLTI.

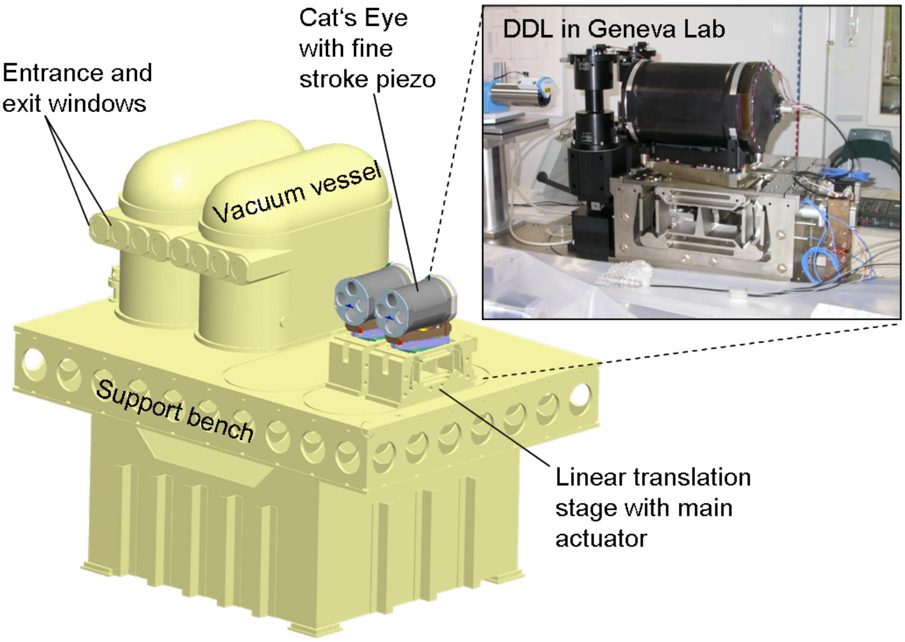

Figure 2: Schematic view of the Differential Delay Lines and photograph of one cat's eye telescope on the translation stage, set-up for acceptance tests in Geneva.

4.2 Cat's eye optics

The main purpose of the cat's eye is to retro-reflect the optical beam with a perfect 180° and a horizontal beam separation of 120 mm. Also, the entrance pupil has to be re-image at a given position, such that the instrument pupil stays always at the same location whether or not the DDLs are inserted in the optical path. The chosen DDL optical concept is a cat's eye retro-reflector with three mirrors and five reflections. Since the DDL is operated in vacuum, the windows are considered part of the optical design. In order to re-image the input pupils, which are at different positions for the four DDLs, the magnification is defined by a corresponding radius of the M3 mirror, which therefore varies. All other optical parameter are identical for all DDLs.

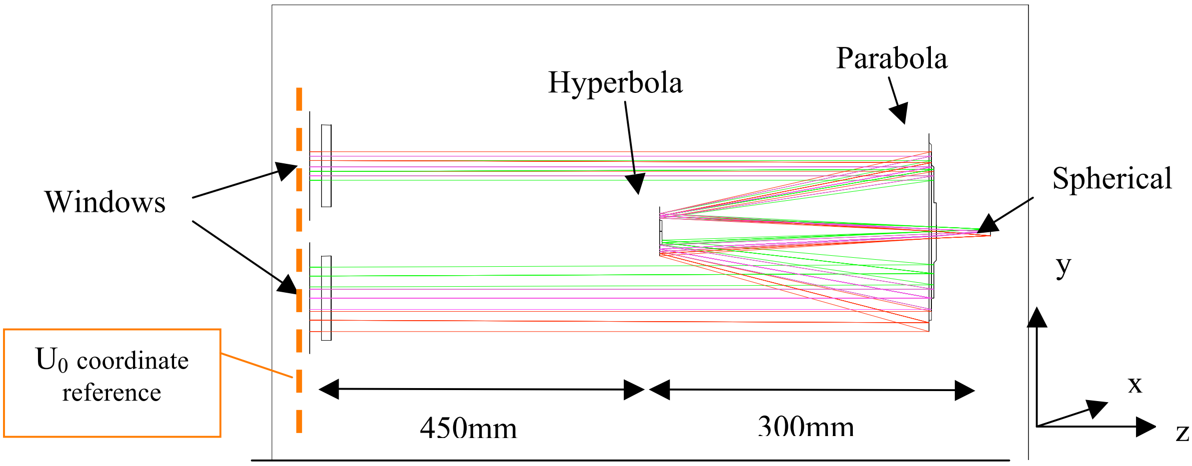

Figure 3: Layout of the cat's eye.

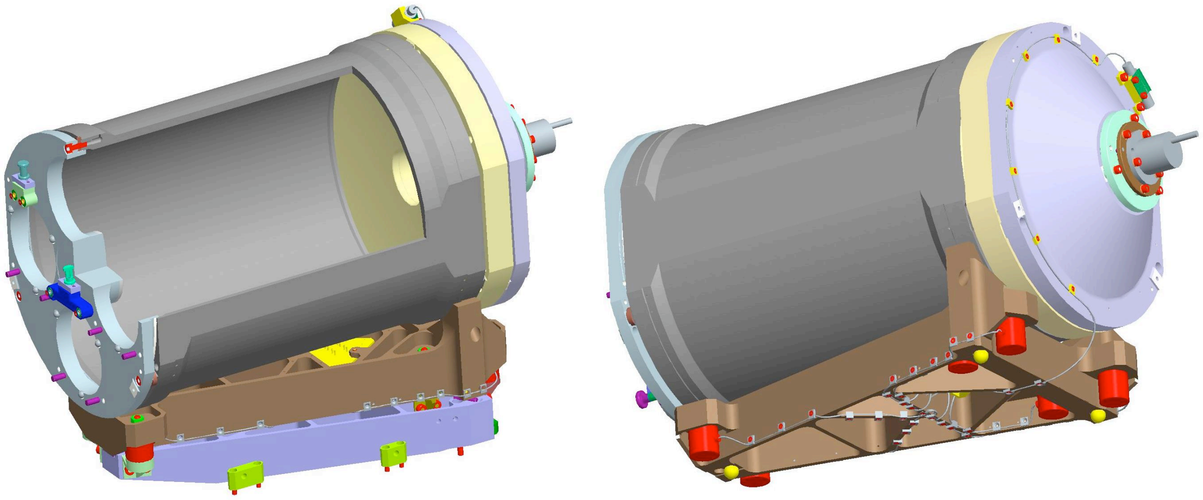

Figure 4: 3D CAD drawing of the cat's eye and adjustment plate assembly.

The cat's eye telescope assembly consists of the following main components:

- Primary Mirror M1 (parabola) with a central hole.
- Secondary Mirror M2 (hyperbola) with an extended base for mounting to the tube It consists of a round plate with the same diameter as M1 (200 mm), four holes of equal size for astronomy and internal metrology beams (in and out), and the actual mirror surface polished on the inner side of the central thicker part of the plate.
- M3 mirror unit, which consists of the piezo actuator (customized PI S-325 with three piezos which can shift and tilt the mounted mirror), a piezo interface plate, a shim plate and the actual spherical M3 mirror mounted to the piezo front side
- Tube, which separates M1 and M2.
- Piezo actuator mount.
- Support structure, which is mounted to the tube from below.
- Electrical permanent magnets KENDRION PEM 2020 A.
- Alignment target, dismounted before operation of the DDL optics.

The DDL opto-mechanical system consists of three major parts:

- Cat's eye
- Adjustment unit
- Vacuum windows

The cat's eye is mounted to an adjustment unit. This adjustment unit is the interface to the translation stage. The internal metrology is located in front of the cat's eye and has an interface to the optics. The vacuum windows, as part of the optics, are mounted to the vacuum vessel.

4.3 Translation assembly

The mechanical translation assembly subsystem is made of:

- A main translation stage provides the 70 mm stroke length with µm accuracy.
- A piezoelectric, high-precision actuator located on the mirror M3 provides the fine motion of the DDL Moreover, this 3-axis actuator performs a static compensation via a lookup table of possible Tilt/Tip errors introduced by the mechanical stage during the translation.

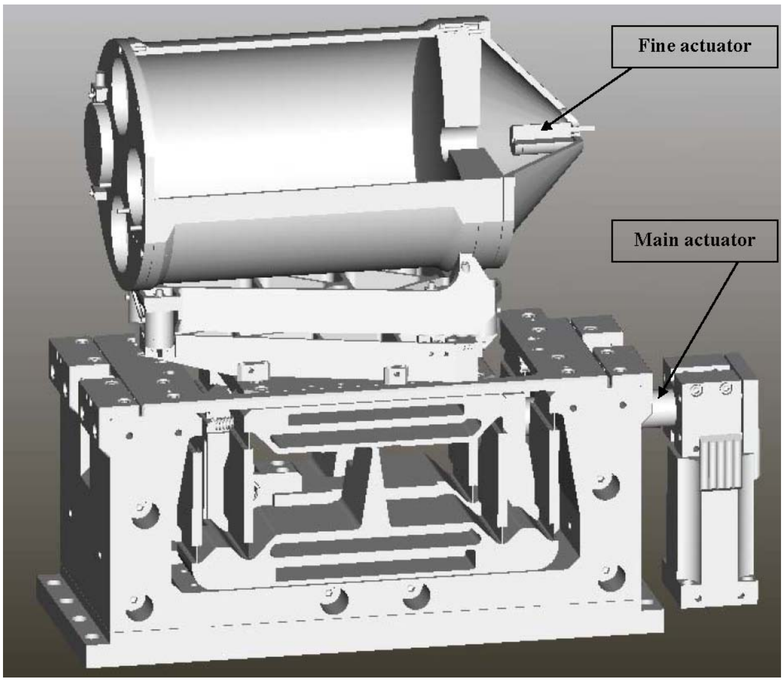

Figure 5: Translation assembly with cat's eye

The main translation stage is a guided mechanism composed of two arms where each arm is a compensated parallelogram constituted of 4 prismatic blades. The stroke and the parasitic eigenmodes are the parameters which determine the shape of these blades. The coupling of the movement of the intermediate block with the movement of the output stage is done by a **lever** placed within the structure, which constrains the movement of the intermediary stage under all circumstances, improves the translation accuracy and avoids uncontrolled vibrations.

The lever is one of the main design options which directly act on the global output performances of the translation stage. The final design of the lever presented here offers the best guiding performances for a very good reliability and is based on a rolling concept where the pivot point and the both contact with the intermediate block and the output stage are realized with ball-bearings.

The Main translation actuator is a *Digit* stepper motor from the company *Ultramotion* (www.ultramotion.com) which is an actuator with an in-line design where the motor shaft is directly coupled to an acme lead screw and then provides high accuracy and long life time. Moreover, this actuator is specified to be vacuum compatible.

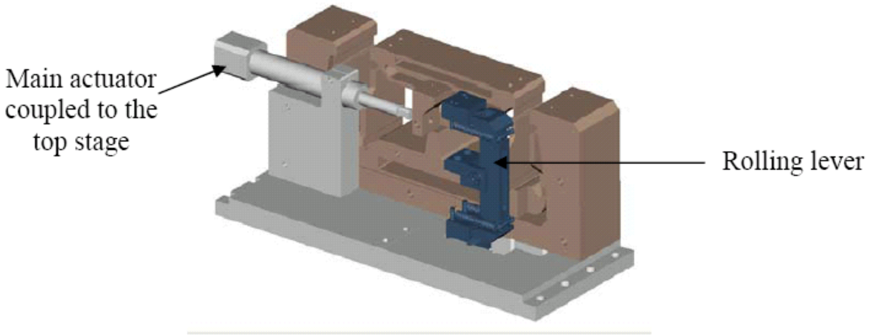

Figure 6: Mounting of the main actuator and the lever on the translation mechanics

Keeping in mind that the base line is to reach a very high accuracy in a piston movement but also to statically compensate for the tilt error of the main translation stage with this actuator, we have chosen a fast and very accurate S-325 multi-axis tip/tilt platform and Z-positioner piezo system from PI (www.physikinstrumente.de) which allows us to work with 3 degrees of freedom.

4.4 The internal metrology

The purpose of the internal metrology is to measure the actual (optical) position of the DDL, and thus the inferred optical delay on the scientific beam. The selected concept for the internal metrology is based on commercially available interferometer for displacement measurement. Agilent interferometer has been chosen for sake of compatibility with the internal metrology of the VLTI delay lines. Two Agilent metrology lasers are operated on up to four DDLs each. Each DDL has its own metrology receiver such that their position can thus be recorded independently.

A folding 45° mirror directs one metrology laser beam into two vacuum vessels and four DDLs. The beams are then splitted in several arms by means of the “Beam Directing Optics” composed of beamsplitters and beam benders Each beam feeds polarizing interferometers, in a Mach-Zehnder configuration, as sketched in Figure 7, left. The mechanical structures which holds the two polarizing beamsplitters PBS1 and PBS2, referred hereafter as the “Metrology Towers”, has been custom designed for this application (Figure 8) and for highest stability. The interference signals are detected on top of the metrology tower by means of Agilent receivers, as shown by Figure 7, right. The receiver head is linked to the main receiver electronics by an multimode optical fiber. The fibers pass through the vessels via a “Fiber Optic Vacuum feed-through”. The receiver electronics are located in a “Front End Electric Rack” in the Interferometric Lab. The electrical signals are then brought to the Computer Room and connected to a VME boards which allow to measure the interferometric phase with a resolution of 2π/256, corresponding to an OPD resolution of 2.47 nm.

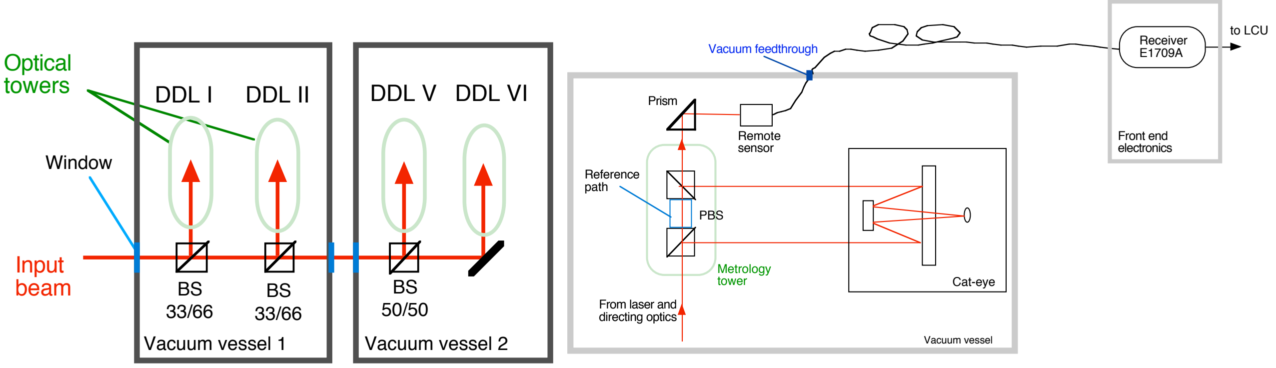

Figure 7: Schematic view of the beam directing optics and the measuring system

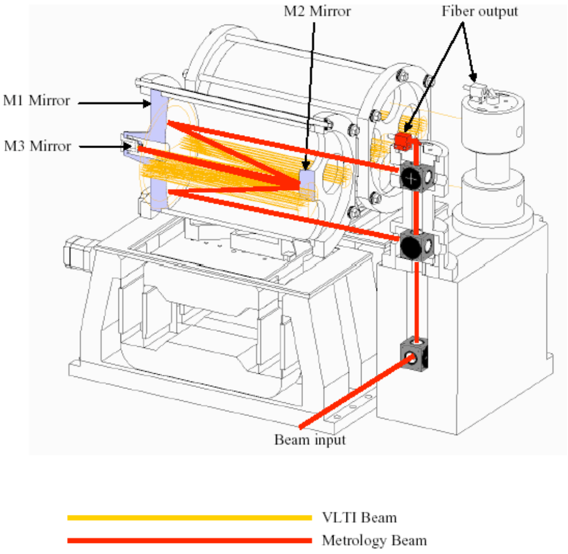

Figure 8: 3D CAD view of the metrology tower with the differential delay lines.

4.5 Vacuum system

The vacuum system represents more than only the vacuum vessel and includes actually the whole DDL infrastructure (Figure 9). It consists of a stiff optical table to support up to eight DDLs, the vacuum vessels (one vessel per two neighboring DDLs) and a pumping system for vacuum maintenance. It must be noted that only 4 DDLs will be installed, although the complete vacuum system is shown. In fact, only two vacuum vessels (first and third from left) will contain the DDLs VIII and VII, and IV and III, respectively, the other being empty for the moment.

A second but separated cabinet is installed just behind the DDL table; it is the front-end electronics. This electronics dissipates significantly more than the specified 5 W per DDL and must therefore be cooled by means of the laboratory cooling system. The metrology lasers is installed on steel pillars inside the cabinet because of its 25 W power dissipation. The cabinet has been separated from the rest of the system to avoid vibrations of the cooling system and the fans being transmitted to the DDL table.

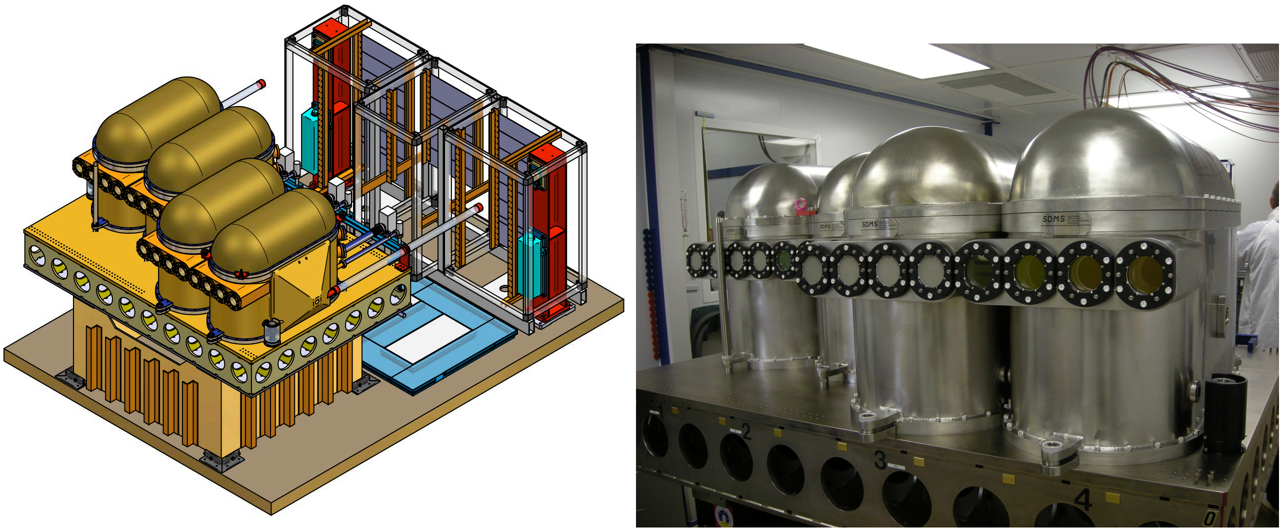

Figure 9, left: CAD of the DDL system infrastructure showing the tables, the vacuum vessels and the front-end electronic box. Right: Picture of the actual system during integration in Europe.

4.6 Instrument and translation control

Instrument control hardware is based on VLT's standard components list, and the software fully complies with VLT's common software package for instrumentation. The control algorithm is coded on ESO's realtime software architecture TAC.

The controller design is based on model matching a second order system specified in the ESO specifications. This leads to a choice of two controllers, one for the piezo actuator and one for the main actuator. Despite the two actuators to be controlled, there is only one position signal (the internal metrology) to be fed back in the control loop. The control algorithm presented in Figure 10 shows therefore our choice of using an 'observer' to solve the degeneracy.

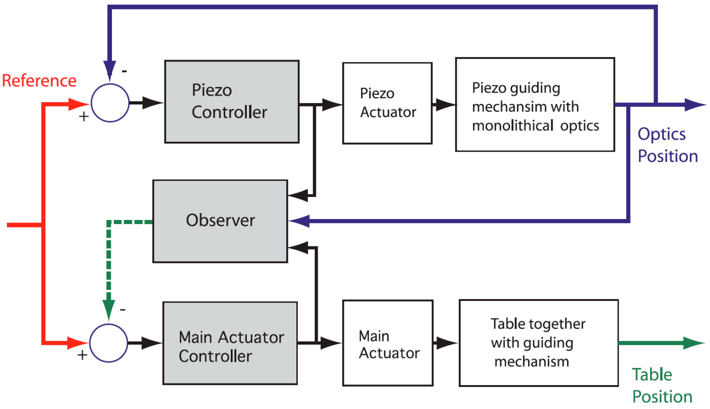

Figure 10: Concept of the translation control

The main actuator stepper motor is driven as a linear actuator (as a synchronous permanent magnet motor). The direct control of the phases enables a direct control of the stator magnetic field rotational position, which is driving the rotor position. A standard procedure of identification was applied, which produces a model with a resonant frequency of about 100 Hz. Because the coarse stage does not need to be very fast (the piezo handles the fast responses), we avoid excitation of this mode by limiting the bandwidth of the coarse stage to about < 10 Hz and also by low-pass filtering the reference fed to the coarse stage controller. The coarse stage thus off-loads the Piezo at low frequency. A double-integrator on the coarse stage ensures however that also fast ramps (up to 1 mm/s can be followed with it and that no delay is cumulated, which would drive the Piezo actuator out of its maximum stroke.

The fine stage actuator is a three piezo-electrical mechanically coupled stage to enable both the piston movement (for OPD control) and a tip/tilt angle (for compensating the flatness error of the translation table). The main properties of the selected piezoelectric stack actuator are:

- Stroke: 30µm mechanical stroke which corresponds to a differential stroke of ±15µm
- Resonant mode: the first unloaded resonant Eigenfrequency is estimated around 1kHz
- Tip/Tilt angle: the achievable angle is within ±4mrad with a resolution of 0.1µrad
- Input electrical capacitance: 3µF, the determinant factor to estimate the bandwidth

The most important characteristic of this fine stage is definitely its resolution and bandwidth. Because the flat mirror (which has to be moved by the piezo) is very light, the dedicated piezoelectric amplifier with respect to the input capacitance of the piezo itself, are determinant to estimate the real bandwidth. The well-known hysteresis of the piezoelectric actuator is limited by the use of the local controller of PI (E-509), which closes the loop locally (in the front-end electronic drivers) on internal strain gauges. Any residual hysteresis will be rejected by the position controller in the LCU by closing the loop on the internal metrology.

5. LABORATORY PERFORMANCES

5.1 Stroke and resolution

The blade spring system ensures a stroke length of a total of 70 mm while keeping the carrying top plate motion almost perfectly flat. The stepper motor ensures the full stroke length at low band width, while the piezo actuator ensures high band-width and precision. The internal laser metrology, a commercial Agilent system, offers 1.25 nm resolution at up to 100 kHz rate. In OPD the resolution becomes twice, i.e. 2.5 nm, due to the retro-reflection.

5.2 Optical performances

The maximum wavefront error for the specified field of view, which is indicated by the orange lines, is given in the following plot. The on-axis value is the average of the horizontal and vertical measurement.

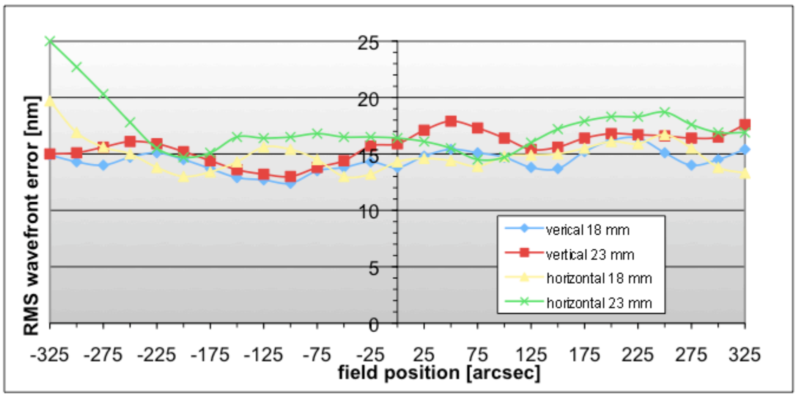

Figure 11: Wavefront error of DDL III as a function of field position, in vertical and horizontal direction.

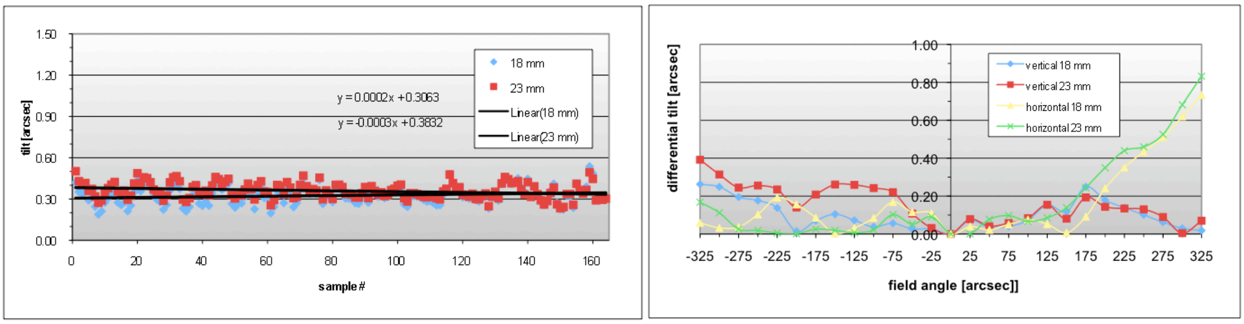

Figure 12, right: Measurements of the tilt angle of DDL III. Left: Differential tilt of DDL III for various field positions, in vertical and horizontal direction

The tilt angle measurements are done multiple times (more than 160 times in order to verify the stability of the measurement). The tilt was measured for a 18 mm and a 23 mm aperture centered to the input and output port of the cat's eye. The individual results are plotted in Figure 12. The differential tilt of a given field position with respect to the on-axis position was also measured in the laboratory at is shown in Figure 12. The total optical throughput of the DDL's optical system composed of cat's eyes and windows is shown in Table 1 and is fully compliant with the requirements.

Parameter Wavelength	Tranmittance (required)	Windows (two windows)	Cat's Eye (five reflections)	Total measured Transmittance
0.6 μm to 1.0 μm	> 0.80 (goal)	0.8574	0.8007	0.6865
1.0 μm to 2.0 μm	> 0.80	0.9308	0.9032	0.8407
2.0 μm to 2.5 μm	> 0.85	0.9289	0.9308	0.8647
2.5 μm to 28 μm (without windows)	> 0.90	n/a	0.9114	0.9114
1.319 μm	> 0.80	0.9926	0.8991	0.8924

Table 1: Total optical transmittance of the DDL system

5.3 Transfer function

The transfer function is shown in Figure 13. We have made a more ‘aggressive’ choice of parameters than required, in order to make the system more precise when working in blind-tracking mode and in order to speed-up the band width in view of unforeseen application, e.g. the correction of fast atmospheric piston.

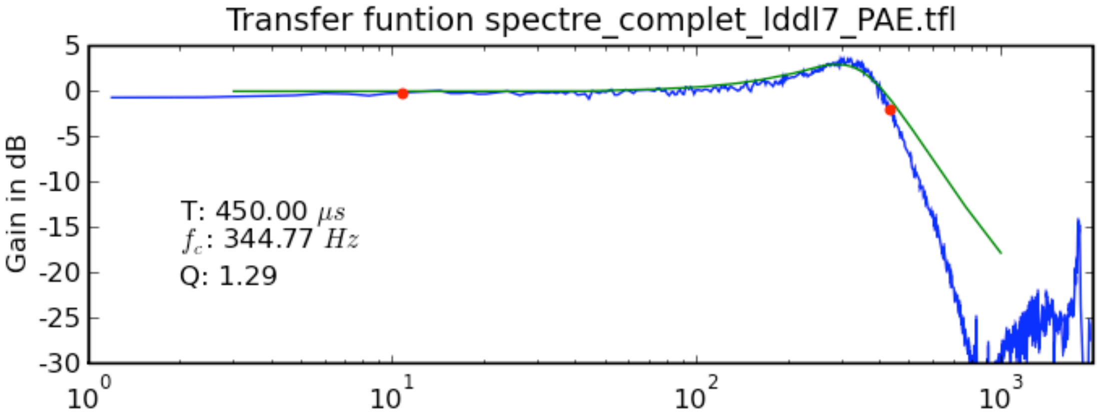

Figure 13: Transfer function for DDL IV as a function of the frequency [Hz].

5.4 Performances in tracking mode

The DDL have been tested in closed loop on a pessimistic Komolgorov-type atmospheric perturbation. The piston error has been fed on the set point of the DDL while the DDL tried to follow this perturbation function. Figure 14, left, shows a test run on one of the 4 DDLs over a time slot of 3 seconds. Although the injected amplitude is about 10 times that expected in real conditions, the observed rms is of about 50 nm, well below the specified value of 70 nm. In this plot the set point (blue) and the actual position (green) are completely superposed and cannot be distinguished. The figure shows also the estimated position of the mechanical stage driven by the motor, which is tolerated to be ‘misplaced’ by up to 2.5µm from the setpoint, but kept well within the piezo-actuator stroke.

Figure 14, right, shows also a blind tracking test in which a trajectory of 2 µm/s is followed. The difference between set and achieved optical position is always lower than 4 nm rms within any time-window of 8ms.

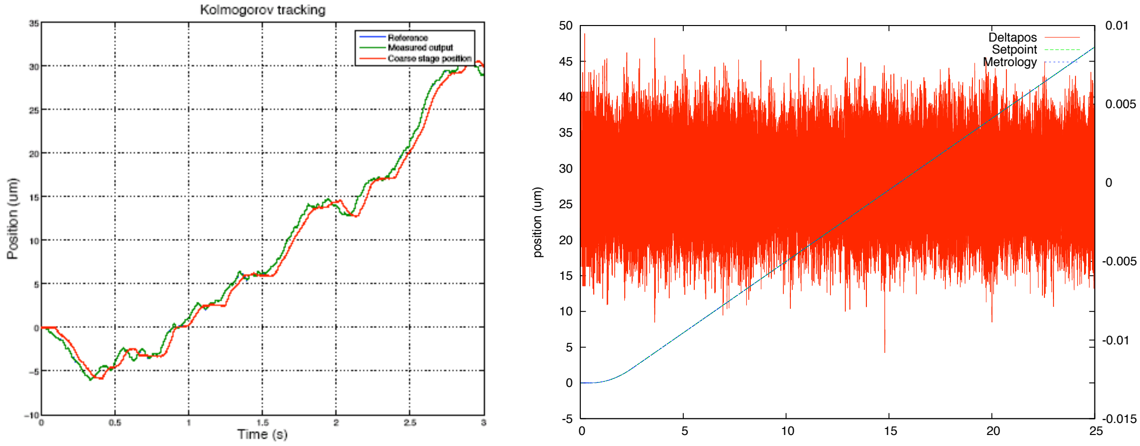

Figure 14: DDL in active tracking on a Komolgorov-type perturbation function.

5.5 Lateral Pupil displacement

In order to ensure coherence between the two beams of the same star, the pupil should not suffer major later displacement while moving the DDL. Because of mechanical imperfections, one cannot avoid, however, some tip, tilt or flatness error during motion, which will in turn produce a lateral displacement of the pupil. Therefore, we use the 3-axis M3 mirror to perform a correction of this residual pupil displacement.

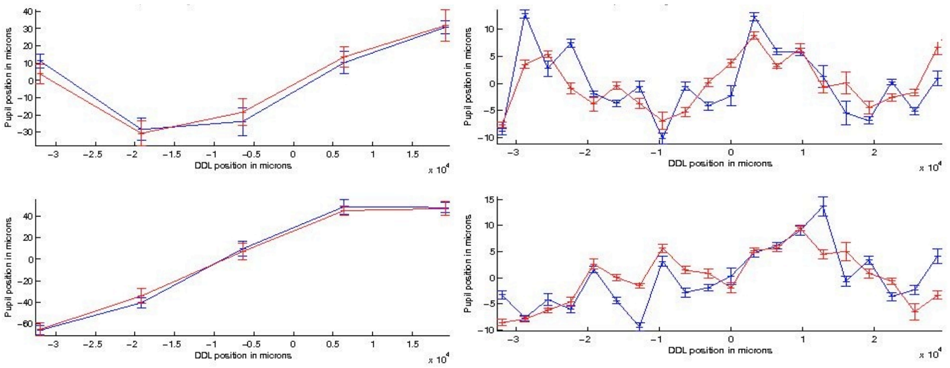

Figure 15: Lateral pupil displacement when scanning from one to the other end of the DDL stroke, before correction (left) and after correction with M3 (right), for tip (top) and tilt (bottom) directions

5.6 Summary of the achieved performances

A summary of the achieved performance is given in Table 2. A part from the fact that the control parameters have been tuned more aggressively than required, all the specifications have been met.

Requirement	Specification	Achieved performances
Field of view in pupil	> 10 arcmin	> 10 arcmin
Separation of input – output beam	120 mm	120 mm
dOPD range (maximum delay)	> 120 mm	> 124 mm
RMS wavefront error	< 25 nm	< 25 nm
Tilt	< 1.5 arcsec	< 1.5 arcsec
Differential tilt	< 0.75 arcsec	< 0.75 arcsec
Transmission range	See Table 2	See Table 2
Resolution	< 2.5 nm	2.5 nm at 100 kHz
Transfer function	2nd order, BW > 200 Hz, sampling = 8 kHz, delay < 100 µs, Q = 1/Sqrt(2)	2nd order, BW = 344 Hz, sampling = 8 kHz, delay ~400 µs Q = 1.3 (see plot)
Lateral pupil stability	< 50 µm P-V	< 30 µm PV

Table 2: Summary of the technical requirements and achieved performances

6. SUMMARY AND CONCLUSIONS

The ESPRI Consortium has successfully built and tested differential delay lines for the future micro-ascseconds facility PRIMA according to the technical requirements set by ESO. The DDLs, together with other subsystems like the star separators, the PRIMA metrology PRIMET, and the fringe sensor units (FSU), will be integrated in PRIMA at the VLTI during Summer 2008. The PRIMA facility is thus being finished and tested at the Paranal Observatory, and is foreseen to be commissioned during fall and winter 2008. If the performances are confirmed on site, ESO will have, starting on Spring 2009, a new powerful tool to search for and characterize extra-solar planets.

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