THE ACTIVE PHASING EXPERIMENT
PART I: CONCEPT AND OBJECTIVES


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ABSTRACT

In a framework of ELT design study our group is building an Active Phasing Experiment (APE), the main goals of which is to demonstrate the non-adaptive wavefront control scheme and technology for Extremely Large Telescope (ELT). The experiment includes verification and test of different phasing sensors and integration of a phasing wavefront sensor into a global scheme of segmented telescope active control. After a sufficient number of tests in the laboratory APE will be mounted and tested on sky at a Nasmyth focus of a VLT unit telescope. The paper presents APE as a demonstrator of particular aspects of ELT and provides a general understanding concerning the strategy of segmented mirrors active control.

Keywords: ELT, segmentation, phasing, wavefront sensor

1. INTRODUCTION

Each segment of a segmented telescope is a solid body having 6 degrees of freedom exposed to the gravitation force, wind blowing, and other mechanical forces. If the position of each segment is not controlled, the resolution of the whole telescope will be the same as if telescope had the diameter equal to the size of one segment. To achieve a resolution commensurable with that of a monolithic telescope of the same diameter the segmented surface must be controlled with a precision better than $\lambda/40$ wavefront RMS. Phasing is a part of an active control responsible for three degrees of freedom of each individual segment: translation along the optical axis (piston) and rotation about two axes perpendicular to the optical axis (tip-tilt).

Three principal hardware systems are required for phasing:1 positioning edge sensors which provide real time information about relative segment displacements, segment actuators which compensate for these displacements, and a phasing camera. The inner loop: edge sensor – actuators is the fast correction for the segment displacements. It runs all the time during telescope operation. The measurable entity of edge sensor is relative capacity or inductance. The reference for the edge sensors reading is provided by independent optical measurement of the segmented surface. This method is referred to as optical phasing or on sky calibration.2 The optical phasing is realized in closed loop phasing camera - edge sensor, which runs much slower than the inner loop. As an opposite of inner loop, the loop phasing camera - edge sensor we call the outer loop.

There are two regimes of optical phasing: during segment integration (initial reference for the edge sensors) and periodically to follow up the drift of edge sensors reference. For the second phase (periodical calibration) the periodicity is a tentative value. The current baseline is that the optical phasing is performed only in the beginning of the night before the observations. In the following we call this option a technical run. On top of it the optical phasing can run also automatically during the observation as well (automatic run). The second way becomes feasible once it is proven that the sufficient precision can be achieved with a relatively dim reference star. If the technical run is required anyway to set the telescope in a working condition, the automatic run is optional.
2. CONCEPT

APE is a demonstrator of particular functionalities of ELT related to optical phasing. As any simulator it describes a telescope only within a frame of a model, and only following a definite baseline of ELT design. In this section we present the main elements of APE breadboard emphasizing their functions related to a modeling of a real telescope. More technical description of APE breadboard can be found in a subsequent paper.3

2.1 Segmented mirror

The central part of the breadboard is an active segmented mirror (ASM, Figure 1). It simulates the segmentation of primary mirror. The size of ASM is 15 cm in diameter (projected VLT pupil diameter is 13 cm), the number of segments is 61. The shape of a segment was chosen hexagonal, which is the most popular design of the segmentation of a primary mirror. The size of a segment (projected onto VLT 8 m pupil) is 1.6 m flat to flat with the intersegment gap of 6 mm. That corresponds to physical values of 17 mm for a segment and 100 microns for a gap in average.

The segment’s optical surface is flat, so is the ASM nominal position. The model is closer to a spherical primary design rather than to an aspheric primary: the rotation of the segments in the nominal plane is not included in the model. The segments are controllable in three degrees of freedom, piston, tip and tilt, by means of three piezo-actuators with a mechanical stroke of ±7.5 micron. The more detailed description of ASM design and manufacturing is presented elsewhere at this conference.4

2.2 Phasing sensors

Optical phasing includes phasing wavefront sensor (PWFS) to measure the segment error (piston plus tip-tilt). The measurement of the segment error can be implemented in different optical ways. For APE we test four different PWFS:

- DIPSI – the modification of the curvature sensor5
- PYPS – based on the pyramid sensor6
- ZEUS – the conceptual descendant of the Mach-Zehnder interferometer7
- SHAPS – based on a Shack - Hartmann method8

Shack-Hartmann and curvature sensors are implemented in Keck phasing camera.9

The basic principle for all four techniques is a modification of the wavefront reflected by the mirror surface in such a way that the amplitude of the outgoing wave conveys the information about the phase discontinuities created by segmentation error. In SHAPS the selection of the area of the beam containing the information is achieved mechanically by placing the lens which selects the vicinity of the intersegment border. In three other sensors the selection of the intersegment area occurs not mechanically, but optically: each of them represents an optical modulator which transfers derivatives of the phase to the amplitude variation. In DIPSI this amplitude coding is achieved by defocusing of the beam. PYPS is the modified Foucault test: beam in the focal plane is split into four parts by means of a prism (pyramid). In ZEUS the phase recording is achieved by a center symmetric spatial filtering. Each of the last three sensors is design to be extremely sensitive to the phase discontinuities: the light intensity at the output of the optical train of a sensor is proportional to the derivative of
the phase (depending on the sensor, first or second, derivative). Each of the sensors is presented at this conference.

Any of PWFS acts on the border between segments to be phased. That sets some requirements for the segment optical quality and segments packing. The most important factors are gaps between segments, segment edges (rolled down/up borders), and optical distortion of segment’s surface.

2.3 Inner loop

To control the shape of the ASM the piston and tip-tilt aberrations of the segments are measured with the Internal Metrology (IM), which is the 2 wavelengths interferometer. The IM controls the segments’ aberration in a closed loop with ASM actuators (sampling frequency 8Hz). The measurement from the PWFS is a reference for the loop IM - actuators. This reference is provided each 40 sec.

The internal metrology is playing in APE a multiple role. First, it measures independently the position of the ASM segments and therefore can be used for the verification of the phasing sensor performance. Second, it keeps the segments stable during the image acquisition with the PWFS: small segments of ASM do not have the same dynamical behavior as the segments of ELT. Third, it helps to verify the concept of interaction between inner and outer loops. The IM is not meant to simulate the edge sensors themselves: it has different temporal bandwidth and a digital controller. The noise of this system has also different physical origin. For example, we do not study the wind rejection in this experiment. The wind rejection in segmented mirror control is being studied by our colleagues. Nevertheless one can model the spatial behavior of the edge sensors with IM, translating its absolute phase readings in differential ones, which the edge sensors will provide.

2.4 Atmosphere and adaptive optics

The wavefront which arrives to the PWFS contains not only steps due to segmentation; it is distorted by an atmosphere. In the focal plane the level of atmospheric turbulence is characterized by the full width half maximum (FWHM) of the PSF (size of a seeing disk). The PWFS signal should be least sensitive to the atmospheric part of the wavefront. As each PWFS is design to measure the derivative of the wavefront, one can expect that the output signal recorded in an amplitude variation contains mostly the phase jumps and least sensitive to the smooth variations of the wavefront coursed by the atmosphere. On top of it, the atmospheric perturbations are filtered out also temporally by long integration of the PWFS image (30sec).

The future ELT is thought to be an adaptive telescope. That means that at least one adaptive mirror (DM) conjugated to the ground layer of the atmosphere is embedded into telescope optics. Therefore, the PWFS receives the wavefront reflected by the DM. With respect to the aberration introduce by a DM onto PWFS we can consider two different regimes:
1. Adaptive optics loop is off. The aberrations come from the deviation of the DM shape from an assumed perfect surface, driven to give the best possible flat. Depending on the technology of the large adaptive mirror, this might have significant or negligible effect on the performance of the phasing sensor. In APE there is possibility to test this effect by placing a glass phase plate with static aberrations simulating the initial position of the DM in the optical train.
2. Adaptive optics loop is on. If we assume that the wavefront sensor of AO does not see the segmentation of M1 or it is filtered out in AO closed loop control, the influence of the AO on phasing sensor can be considered as “improved” or “worsened” seeing. The latter depends on the separation between the guide star of AO and the reference star of the phasing sensor. This separation can be up to 6 arcmin (telescope technical field of view). The angular boundary between “improved” and “worsened” seeing depends on the number of modes corrected by AO. To test different seeing conditions in the lab APE will use the Multi Atmospheric Phase screens and Stars (MAPS) Turbulence generator. The atmospheric turbulence at VLT is granted.
2.5 Telescope aberrations and active optics

The continuous global optical aberrations are induced by a residual misalignment of telescope optics and residual deformations on large thin meniscus mirrors. The value of the global aberrations is defined by the performance of the active system and location of the reference star used for active optics: the further from the main axis the severe distortions.

The presence of the global aberration may degrade the performance of the phasing sensor. For example, the global tilt shifts the focal point in lateral direction, while the global defocus shifts it in axial direction, therefore the phasing wavefront sensor which working principle is based on the focal filtering or defocusing can be affected. The global astigmatism induced the non-symmetry of the focal spot, therefore the measurements in x and y directions might be unequal.

The segmented mirror eigenmodes is a set of segments error configurations, possessing certain symmetry. This set is calculated in a pseudo inverse of interaction matrix (section 4.3) and presents a basis in the command space. Any configuration of the segment errors can be expressed uniquely as a linear combination of those eigenmodes. As eigenmodes differ in smoothness (have different amount of phase “jumps”), the PWFS sees them differently.

The low order global modes and the low order segmented mirror eigenmodes have similar shapes (Figure 2) and are sensed by the sensor of active optics equivalently. Due to their equal spatial and temporal bandwidths they might even cancel each other, leaving the scalloped residual wavefront (Figure 3). This type of the wavefront is analyzed by active optics and phasing camera. The strategy for modes disentangling depends on the number of available Shack-Hartmann sensors in the telescope active optics. If there are more than one such sensor, the measurement of the global aberrations can be performed in different directions in FoV.

The Shack Hartman sensor (SHAPS) in APE due to a chosen lenslet configuration (Figure 4) is both, the phasing sensor and the sensor of continuous aberrations. For the first role the lenses covering the intersegment border are used for segment piston measurement and lenses in the center – for segments tip-tilt. Other lenses serve for reconstruction of the continuous aberrations. The global aberration for the test in the laboratory can be introduced either by a slight misalignment of the optical system or by setting a glass plate with etched profiles in the optical train. The telescope aberrations in VLT are residuals of its active optics.

2.6 Double segmentation

The design of ELT might include a secondary segmented mirror. Two mirrors have to be phased in parallel. The latter implies that the signal image contains the information of mirror configuration for both, secondary and primary, mirrors. The signal image has to be treated in a way to extract the information about configuration of
primary and secondary mirrors independently in order to send the related commands for two control loops. Two approaches are possible. First is to measure configurations in M1 and M2 with only one sensor. Second is to have in phasing camera two sensors: one is tuned for M1 and another for M2. In both cases the signal from another mirror is considered as an additional noise. The level of disturbance is defined by three main factors:

1) difference in spatial scales or/and geometry of two segmented patterns (in the plane of measurement)
2) RMS of segmentation error from another mirror configuration
3) the relative angular orientation of two segmented pattern

The segmented secondary is modeled in APE by a glass plate with etched phase steps shaped in petals - secondary mirror piston plate (SMPP, Figure 5). These phase steps are static and the presence of the segmented M2 is considered in the experiment only as an external factor disturbing the measurement of ASM.

3. KEY PARAMETERS

The performance of the PWFS can be described in terms of four key parameters: capture range, final accuracy, operational time, and limiting star magnitude. Each of these parameters can be improved at the expense of another. To find a good compromise between these four characteristics is a general goal of APE. In finding the trade-off we have to bear in mind that the requirements can be different for different phasing regimes, mentioned in introduction: segment integration, technical run and automatic run.

3.1 Final accuracy

Final accuracy is a residual segmentation error. It is characterized by the wavefront RMS and by the distribution of the residual wavefront over the segmented mirror eigenmodes. The 98% Strehl ratio corresponds to $\sim \lambda/40$ wavefront RMS, which corresponds to 16nm for 650nm wavelength. The degradation of the Strehl ratio due to the segmentation errors is shown in Figure 6 (Gaussian distribution of the errors over the segments).

The distribution of the final error over the modes is an important aspect. First, the final image changes in dependence on a dominating mode (Figure 7), and, second, the further compensation of the residual low order segmented mirror modes is possible by means of active and adaptive optics (see above).
3.2 Capture range

Capture range is a maximum segment error which can be measured by the phasing sensor. For the segment integration regime the required capture range is related to the precision to which an initial segment position can be defined by the edge sensor. In Keck a segment can be integrated in a telescope with precision of ±60 micron wavefront.\(^9\) Option of using spherometers for initial phasing might help to reduce this value to a few microns.\(^5\) The maximal capture range which can be tested in APE is defined by the stroke of ASM actuators. It is 30 microns wavefront. The optical measurements using one narrow band filter is limited to the ±λ/2 (the full APE bandwidth is from 500nm to 900nm). For increasing the capture range the measurement on the several narrowband filters must be combined (see section 4.4). The mirror configuration to be tested is one segment off.

For the technical run the requirements on a capture range comes from the averaged diurnal drift of the edge sensor readings. The measurand of the edge sensors is relative change of the capacity (inductance) due to the relative shift of the segments. The reference value of the edge sensor readings may be affected by the change of dielectric/ magnetic constant due to temperature and humidity, thermal deformation of the bodies of edge sensors and relative motion between two parts of the sensor due to the mechanical expansion/contraction of the segment support units when the telescope moves in elevation. The averaged diurnal drift is expected to be less than 1 micron. For the automatic run option the requirements on capture range can be much milder, because in this case the phasing camera traces the slow drift of the sensors with higher periodicity. The initial mirror configuration to be tested is random position of all segments with different RMS and the configuration in which one or another segmented mirror mode dominates.

3.3 Operational time

Another important parameter to be established is the operational time. It includes the time required to calibrate the phasing sensor and to close the loop on the segments actuators. The calibration is required to establish two
parameters: responses of the phasing sensor on unit and zero phase steps (see section 4.3). It is the most time consuming operation. Major part of it has to be done as a part of segment integration.

The time required to close the loop with a phasing sensor is time of iteration multiply by a number of iterations. The latter depends on the controller, but typically in 5-10 iterations system achieves the reference value. The time of iteration depends on integration time for one image, the number of images needed for the iteration and the computational time (limitations come mostly from image analysis) and the time required to change a hardware.

For developed so far algorithms, the computation time increases linearly with a number of borders. Therefore, the found computation time for 61-segmented ASM has to be multiplied by a factor ~11 to estimate the computation time in a case of 700-segmented mirror.

For the technical run the limitation the operational time should be as short as possible, though without big lost in performance. The upper limitations are set by the requirements on telescope calibration time at the beginning of the night and should be of order of 10-15 minutes. For the second automatic run option the duration of operational time is not critical, because it consumes no observational time.

3.4 Limiting star magnitude

The determination of the limiting star magnitude necessary to achieve the required precision is an important point of the experiment. That value will define the regime of the phasing for the future ELT. The limiting star magnitude defined with UT telescope is comparable with the expectations for ELT due to the identical size of the CCD pixel projected onto pupil.

The definition of a limiting star magnitude is not critical for the segment integration and in a technical run. In this case the telescope can be pointed to any bright star on sky to perform the optical phasing. The question concerning appears for the automatic run option. The reference star must be available in the technical field of view (~6 arcmin) of the telescope for an arbitrary alt-azimuth position. The probability to find the reference star in a given field of view of the telescope depends on the star magnitude and spectral bandwidth. The determination of the limiting star magnitude for phasing wavefront sensor comes from two factors: (1) ability to close the loop with this star and (2) final precision (RMS of final mirror configuration). These results together with the statistical star counts will define the star coverage for the phasing wavefront sensor.

4. PHASING CONTROL ALGORITHM

Optical phasing includes phasing wavefront sensor to measure the segment error and segmented mirror control algorithms. Phasing of a segmented mirror is an iterative process, similar to the closed loop in adaptive optics. Phasing control algorithm is a list of conceptual tasks to be solved in order to phase a segmented mirror with any phasing sensor. The list is general for all PWFS and includes following tasks:

1. Pre-calibration
2. Pupil registration
3. Signal analysis
4. Piston, tip, tilt disentangling
5. Two segmented patterns disentangling
6. Signal vector computation
7. Zero signal vector computation
8. Interaction matrix acquisition
9. Reconstruction matrix computation
10. Command vector computation
11. Closed loop colour set sequence

In this section we describe the most critical of them
4.1 Signal analysis

The information about segment error is recorded in intensity variation revealed in a signal shape. This signal is concentrated near the border of two neighboring segments where the derivative of the wavefront is maximal. The signal shape is different for each PWFS. Figure 8 shows the signal from all four PWFS for the phase step of \(-\pi/2\) obtained in simulations.

Several methods can be used to convert intensity variation in a phase step. Each sensor can utilize several methods, some of them also applicable for other sensors. As the result of analysis several possible signal attributes, containing the sufficient information about piston, tip and tilt, are calculated: e.g. signal integral over different areas of the CCD image, peak to valley or amplitude of a fitting curve.

Different signal attributes contain different amount of information related to a segment error, therefore the ultimate precision for segment error determination can be different. Also analysis related to different signal attributes can have different level of computation complexity. The more profound and more precise signal analysis might be at the expense of the operational time.

The arbitrary segment error is a combination of piston, tip and tilt. These degrees of freedom are controlled independently. The method of disentangling utilizes properties of signal shape, for example using anti-symmetrical properties of the signal with respect to the axes parallel and perpendicular to the border. Using different lenses of the Shack-Hartmann array is another example of disentangling.

If in the Shack-Hartmann method the lenslet has to be aligned with a high accuracy with respect to segments borders, in the pupil imaging techniques (DIPSI, PYPS and ZEUS) this difficulty becomes a requirement for the accurate edge detection on the CCD image. As the signal is concentrate on a segment border, the location of this border has to be known with a sub-pixel precision. The detection is done in image processing software using two methods: Hough transform technique and the correlation technique.

![Figure 8. Intensity profiles created by different sensors as a response to a phase step. Signals’ intensities are given in relative units and not comparable.](image-url)
4.2 Zero signals

Typically, any attribute is related to the phase step $\Delta \phi$ as $S(\Delta \phi) = a \sin(\Delta \phi) + b$, where parameters $a$ is defined during interaction matrix acquisition process. It depends on a number of factors: the chosen signal attribute, light intensity, atmospheric seeing. Parameter $b$ is a random value, changing from one border to another. It originates from the diffraction effect on the segment border caused by segment edge imperfections (cuts, turn-off edge, gap etc.) It is a value of a signal attribute in a case of zero phase step. It cannot be defined during interaction matrix acquisition. The determination of signals zeros is necessary because otherwise the close loop will drive the segment piston step to the value $\Delta \phi = -\arcsin(b/a)$ instead of zero. For example in ZEUS, when the signal anti-symmetry is chosen as an attribute, the difference of 10mm in length of segment edge mis-figure lead to 12nm residual error. The acquisition of the zero flat requires the initial first phasing loop, which can be done once during M1 assembly and each time after segment integration. The techniques, which can be used for the first phasing, are segment swiping or wavelength swiping.

4.3 Interaction matrix acquisition

The command vector of actuators' movements ($s$) is related to the signal vector containing the signal attributes for each borders ($s$) by a matrix multiplication $A \cdot s = c$. The interaction matrix $A$ has to be found during calibration (interaction matrix acquisition). There exist 4 principally different ways to construct the iteration matrix: with the stellar source, with the artificial source, pseudo-synthetic and synthetic.

4.3.1 With the stellar source

Illuminated by the stellar source each segment is pushed at unit value in piston, tip and tilt consequently. For each of these three positions of each segment the unit signal vector is recorded. The unit value has to be small enough to provide a linearity of sensor response. As signals are localized, it is possible to push segments simultaneously by groups as it is shown in Figure 9. For hexagonal geometry there are three groups of segments without common borders (for ASM there are 21, 21, and 19 segments in each group). Therefore to calibrate the sensor 9 exposures are required; and this number is the same for any number of segments. The advantage of this method is that pixelization is not critical, because the change in the signal shape due to the location of the signal with respect to CCD pixels is taken into account automatically. The main disadvantage is that it requires moving the segments, also the photon noise as well as changeable seeing might affect the precision of the calibration.

4.3.2 With the artificial source

It is the same as the previous method but using the artificial light source. Compare to the previous case the additional advantage is in lower photon noise. Disadvantage is that the mounting the additional light source at the telescope might be not feasible. In the laboratory APE is tested first with the fiber source.

4.3.3 Pseudo-synthetic

The signal attribute answering a unit piston step is the similar for each border. The structure of the interaction matrix is predictable from mirror geometry. For construction of pseudo-synthetic iteration matrix only one segment is pushed in piston, tip and tilt. The calculated from these three measurements signal attributes are replicated then in a matrix maintaining the geometrical structure. In a pseudo-synthetic one can use a stellar
source or artificial source. Advantage: method does not require moving all segments; disadvantage: the individual segment features and pixelization are not taken into account.

4.3.4 Fully-synthetic
The construction of the matrix is the same as pseudo-synthetic, but without measurement. The value is chosen a priori from simulations or analytical estimations. Advantages: no segment movement is required; disadvantages: the same as in the pseudo-synthetic method, plus probability of having a wrong model for estimation.

4.4 Colour set sequence
As it was described in section 3.1 to enlarge the capture range and to increase the final precision, the measurements has to be performed at several different wavelengths and several filter with different bandwidth. There are several strategies to do the combined (multi wavelength) measurements. These different approaches can be expressed in terms of colour set sequences. Colour set is a combination of filters used to perform an iteration of the outer loop. Number of filters varies from 1 to a maximal number of filters available at the breadboard. During the outer loop the colour set may change according to the current position of the ASM. The change of colours set is necessary to drive the ASM from the initial range to the nominal position. Typically, the loop starts when segments are out of phase by several microns. Therefore, the first iterations are done with several narrow band filters. The first colour set is the set of narrow band filters. The measurements are not accurate because the small number of photons passing through each filter. After several iterations the position of the segments is within a capture range of one of the filters. At this point the change of the colour set happens. The loop continues using one filter. After several iterations the residual phase RMS reaches the value of measurement error. The final tuning phasing is done with the broad band filter or even with the white light. This is the third colour set of this example. For each filter its own interaction and control matrices has to be defined.

5. CONCLUSION
The APE experiment consists in a number of tests to be performed in the laboratory (planned for the beginning and mid 2007) and at the VLT (fall 2007). These tests are dedicated to verify certain aspects of ELT wavefront control, described in this paper. The tests will be done in an order of increased complexity, starting from the base ASM - PWFS, first for small initial segment error, then up to full 30 micron. Afterwards the additional elements are included: atmospheric phase screens, phase plates, spider mask. The tests with different phasing sensors can be run consequently, as well as in parallel. At the APE platform there is place to mount all four sensors. In the last case one of the sensor is a master which drives ASM, while other provide passively the measurements at every iteration of the loop. In such a way the performance of the sensors can be compared.

The results and the breadboard of APE can be used beyond the scope of APE experiment, for example for PSF characterization task, adaptive optics and high contrast imaging (coronagraphy).

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