Phase ambiguity solution with the Pyramid Phasing Sensor

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ABSTRACT

In the technological development for the ELTs, one of the key activities is the phasing and alignment of the primary mirror segments. To achieve the phasing accuracy of a small fraction of the wavelength, an optical sensor is required. In 2005 has been demonstrated that the Pyramid Wavefront Sensor can be employed in closed loop to correct simultaneously piston, tip and tilt errors of segmented mirror. The Pyramid Phasing Sensor (PYPS) is based on the sensing of phase step on the segment edges; this kind of phasing sensors have the common limitation of the signal ambiguity induced by the phase periodicity of $\pi\delta/\lambda$ on the mirror surface step $\delta$, when the wavelength $\lambda$ is used for the sensing.

In this paper we briefly describe three different techniques that allow to solve the phase ambiguity with PYPS. As first we present experimental results on the two wavelengths closed loop procedure proposed by Esposito in 2001; in the laboratory test the multi-wavelength procedure allowed to exceed the sensor capture range of $\pm \lambda/2$ and simultaneously retrieve the differential piston of the 32 mirror segments starting from random positions in a $3.2\lambda$ wavefront range, the maximum allowed by the mirror stroke. Then we propose two new techniques based respectively on the segment and wavelength sweep. The Segment Sweep Technique (SST) has been successfully applied during the experimental tests of PYPS at the William Herschel Telescope, when 13 segments of the NAOMI DM has been phased starting from a random position in a $15\lambda$ range. The Wavelength Sweep Technique (WST) has been subject of preliminary tests in the Arcetri laboratories in order to prove the concept.

Each technique has different capture range, accuracy and operation time, so that each can solve different tasks required to an optical phasing sensor in the ELT application. More in detail the WST and SST could be used combined for the first mirror phasing when the calibration required for the closed loop operations are not yet available. Then the closed loop capture range can be extended from $\pm \lambda/2$ to $\pm 10\lambda$ with the multi-wavelength closed loop technique.

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Keywords: cophasing, ELT, segmented mirror

1. INTRODUCTION

The main task for an optical phasing sensor, employed on an ELT segmented primary mirror, is to keep phased the segments during the observation\textsuperscript{123}. In previous works has been demonstrated that PYPS can simultaneously correct piston, tip and tilt errors of mirror segments.\textsuperscript{4} This has been done operating PYPS in closed loop with a broadband (i.e. 600 – 900 nm) source. To operate PYPS in closed loop mode some calibration has to be done before: the signal pattern of the reference position has to be acquired and the interaction matrix between PYPS and the mirror segments has to be recorded. These calibrations require that at least one time the best phased mirror position has to be reached. Another requirement to operate this mode is to have all the segment differential pistons in the capture range. In this paper we propose three different techniques that are aimed to provide these two requirement with PYPS itself.

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The PYPS open loop measurement range and the closed loop capture range in single wavelength are defined by the sine dependence of the PYPS signal. On a sub-aperture corresponding to a physical mirror step $\delta$ the PYPS signal is:

$$S = C + A \sin \left[ 2\pi \frac{2\delta}{\lambda} \right],$$

where $\lambda$ is the working wavelength supposed monochromatic, $C$ and $A$ are constants. Therefore the open loop measurement range is equal to the non ambiguous range of the sine function ($\pm \pi/2$ in phase, centered on a sine function zero), while the closed loop capture range is extended to $\pm \pi$ around a sinus zero; that is because in the two ranges $[0, +\pi]$ and $[-\pi, 0]$ the function sign is respectively preserved and the closed loop operation is able to drive the actuator to the same position.

2. THE TWO WAVELENGTH CLOSED LOOP TECHNIQUE

This phase ambiguity solution technique has been proposed in 2001 by Esposito,\textsuperscript{5} in this section the working principle and the first experimental results are exposed.

2.1. WORKING PRINCIPLE

This technique is based on the iteration of two step: a closed loop correction operated at the wavelength $\lambda_{CL}$ and an open loop measurement at $\lambda_{OL} = \lambda_{CL} + \Delta \lambda$. After a first closed loop run at the wavelength $\lambda_{CL}$, all the segment differential pistons ideally reach the value $\Delta \phi(i) = 2k(i)\pi = 2\pi [2\delta(i)]/\lambda_{CL}$, where $\delta(i)$ is the physical differential piston on the mirror surface and $i$ is the segment index. Then the operating wavelength is switched to $\lambda_{OL} = \lambda_{CL} + \Delta \lambda$ and a single open loop measurement is done. The physical differential pistons are still $\delta(i) = k(i) \lambda_{CL}/2$, so that the signal detected with $\lambda_{OL}$, on a sub-aperture on the segment edge, is:

$$S^M_{OL}(i) = C + A \sin \left[ 2\pi \frac{2\delta(i)}{\lambda_{OL}} \right] = C + A \sin \left[ 2\pi k(i) \frac{\lambda_{CL}}{\lambda_{CL} + \Delta \lambda} \right];$$

$C$ is an additive constant due to statical aberation and can be removed subtracting $S^R_{OL}(i)$ the signal of the same sub-aperture measured when $\delta(i) = 0$. Choosing $\lambda_{OL}$ so that $\Delta \lambda > 0$ and $\Delta \lambda/\lambda_{CL} \ll 1$, the sign of

$$S_{OL}(i) = S^M_{OL}(i) - S^R_{OL}(i) = A \sin \left[ 2\pi k(i) \frac{\lambda_{CL}}{\lambda_{CL} + \Delta \lambda} \right]$$

is opposite to the sign of $k(i)$ as shown if fig.1. That is because $\lambda_{CL}/[\lambda_{CL} + \Delta \lambda] = 1/[1 + (\Delta \lambda/\lambda_{CL})]$ is always positive and $\ll 1$, while $k(i)$ is integer by definition. This relationship remains true while the phase difference between $S_{OL}$ and $S_{CL}$ is less then $\pi$: $[2\pi 2\delta/\lambda_{OL}] - [2\pi 2\delta/\lambda_{CL}] < \pi$. Taking in to account that $k(i) = 2\delta(i)/\lambda_{CL}$ and $\Delta \lambda = \lambda_{OL} - \lambda_{CL}$ we found:

$$k(i) < \frac{\lambda_{OL}}{2\Delta \lambda}$$

Once the sign of $S_{OL}(i)$ is known, $\Delta \phi(i)$ can be corrected of $\pm \lambda_{CL}$, according to the measured sign. The procedure closed loop, open loop measurement and piston correction is then iterated until $S_{OL}(i)$ is null for all the segments. The capture range of this technique is derivable directly from eq. (4) obtaining:

$$\delta(i) = \pm \frac{\lambda_{CL}\lambda_{OL}}{4\Delta \lambda}$$

Typical wavelengths in this application are $\lambda_{CL} = 850\text{nm}$ and $\lambda_{OL} = 900\text{nm}$; for these values we find a capture range $\delta = \pm 3.8\mu$m.

The signal $S_{OL}(i)$ is the signal on a single sensor sub-aperture, but usually\textsuperscript{*} several sub-apertures are involved by the piston signal of a single segment. Is it possible to take into account all these sub-apertures using the reconstruction multiplication in the open loop measurement too. This approach requires a interaction matrix

\textsuperscript{*}The sampling values used in the closed loop operation for tip, till and piston correction are 4 sub-aperture per segment or higher.
Figure 1. In the graph is represented the PYPS signal of a sub-aperture corresponding to a segment edge as function of the wavefront step. The bold and the thin lines represent the signals at $\lambda_{CL} = 800nm$ and $\lambda_{OL} = 900nm$ respectively. The stars and the triangles represent the signal values at $\lambda_{OL}$, when the edge step is $\delta = k\pi/\lambda$, with $k$ integer. The sign of this signal reveal if the phase ambiguity is on the positive or negative side of the physical step zero. This is true while the phase difference between the two signals is in the range $[-\pi; +\pi]$ (circles in the graph); when this range is exceeded the signal signs are inverted and the $\lambda$ correction is done in the wrong direction. The values $\pm T$ (points and dashed lines) represent the threshold used to determinate the success of the closed loop operation and the minimum amplitude of the open loop measurement to detect the phase ambiguity. In this example the value of $T$ corresponds to a physical step of $\sim 20nm$ that a larger than the expected accuracy achieved by the closed loop operation.

acquisition and inversion exactly as for the closed loop operation. The signal-reconstructor multiplication is a linear operation that preserve the sign of each sub-aperture signal for the differential piston estimation; so that the consideration done on $S_{OL}(i)$ remains valid for the piston correction computed by the signal-reconstructor multiplication.

The main advantages offered by this technique are the parallel correction, so that the operational time is not dependent on the number of segments, and the accuracy reached, that is the same of the single wavelength closed loop. The main limitations are the finite capture range, that is basically dependent on the single closed loop accuracy, and the need of calibration. The last limitation prevents the use of the technique for the mirror first phasing.

2.2. EXPERIMENTAL PROCEDURE AND RESULTS

In the experimental application the first closed loop is considered achieved when all the differential piston are estimated under a predetermined threshold $T$. The estimation of the residual piston error for all the segments is directly given at each step by the differential command computation. The value of $T$ has to be chosen greater than the accuracy achieved by the phasing closed loop at $\lambda_{CL}$. When all the differential piston results simultaneously lower then $T$ the loop is opened. After this step, all the segment pistons are phased with the accuracy $T$ around values of $k\lambda_{CL}$, where $k$ is an integer number. Keeping the mirror in the same status, the sensing wavelength is switched to $\lambda_{OL}$ and a single measurement is done. This single measurement gives, through the signal-reconstructor multiplication, an estimation of all the differential piston measured at $\lambda_{OL}$. All the piston values lower than $T$ are considered as properly phased. The differential pistons estimated bigger than $+T$ or lower than $-T$ are corrected of $+\lambda$ or $-\lambda$ respectively. After this correction the entire procedure is iterated starting again from the closed loop. The procedure stops when all the differential pistons measured at $\lambda_{OL}$ results in the range $[-T; +T]$. 

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Figure 2. In the picture are represented the simulated PYPS signals for a pure piston error of a square mirror segment (square dotted lines). The dotted circle shows the pupil position on the PYPS x and y signals on the left and right side respectively. When the signal on a single sub-aperture is considered (little circles on the segment contour), the differential piston estimation relies only on a single edge measurement is done. When the piston error is estimated with the signal-reconstructor multiplication, the signals of all the sub-apertures in the pupil are taken into account and then all the segment edges are considered.

Figure 3. In the plots are reported the piston commands for all the 32 MEMS controlled segments. The top plot represents the starting position; the bottom left the mirror configuration after the first multi-wavelength correction; the bottom right after the second one. In the bottom plots the dotted lines represent the multiple values of $\lambda_{CL}$, where the single wavelength closed loop drives the actuators. We can notice out that the accuracy of the phasing around these three levels are not dominated by the minimum step of the deformable mirror (22nm wavefront), that is because of the tilt introduced on the segments while a piston is applied. This tilt can not be corrected by the MEMS and injects an error in the closed loop. In the presented experiment that error is dominating the closed loop accuracy.
This technique has been tested in the Arcetri laboratories with the PYPS prototype in development for the APE project. A commercial PC has been used as wavefront computer (WFC) and a MEMS segmented mirror purchased by Boston Micromachines as deformable mirror. This MEMS is composed by a 12X12 array of square plane mirrors with a single side of 300µm; each segment has only the differential piston as degree of freedom and is adjustable by physical steps of round 10µm. The pupil of the optical system is arranged on this mirror covering a diameter of 5 segments and the reflected beam is analyzed by PYPS; the signals so generated are sent to the WFC that calculates the differential piston commands to be sent to the MEMS electronics. An optical fiber, feeded by an incandescence lamp, has been used as light source. The two working wavelength so obtain has been 625nm and 675nm both with 50nm of bandwidth. The segment differential pistons has been initially scrambled in the range 0 – 2000nm and, after three iterations of multi-wavelength procedure, all the segments have been phased in the closed loop accuracy removing all the phase ambiguity. Some significant step of the described run is reported in fig.3.

3. THE WAVELENGTH SWEEP TECHNIQUE

3.1. WORKING PRINCIPLE

The WST is based on the piston signal dependence on the wavelength λ. Taking into account a physical step δ on a segment edge, the signal on the corresponding sub-aperture is done by eq.(1): \( S = C + A \sin \left[ \frac{2\pi A}{\lambda} \right] \); so that the piston signal has a sine dependence on 1/λ. The period of this sine is simply 2δ; then measuring the signal for several values of λ we can fit \( S(1/\lambda) \) with the function \( S_f(1/\lambda) = C_f + A_f \sin[2\pi T_f(1/\lambda) + P_f] \), obtaining \( C_f, A_f, T_f, P_f \), with \( T_f = 2\delta \). This measurement gives an estimation of the physical step that lies on the considered sensor sub-aperture. Supposing negligible the segment tip&tilt error, this is a differential piston measurement.

The working limits of this technique are the minimum and the maximum detectable step. The minimum physical step \( \delta_m \) that can be measured using the WST is defined by the extreme values of the wavelength \( \lambda_s \) and \( \lambda_c \) applicable in the sweep. That is because, in order to fit the period of the sine function, a minimum phase variation \( \Delta \phi_m \) is required. Sweeping from \( \lambda_s \) to \( \lambda_c \) we obtain \( \Delta \phi = 2\pi 2\delta (\lambda_c - \lambda_s)/(\lambda_c \lambda_s) \) and \( \delta_m \) is defined as the minimum step that induces the phase variation \( \Delta \phi_m \):

\[
\delta_m = \frac{\Delta \phi_m}{4\pi} \frac{\lambda_c \lambda_s}{\lambda_c - \lambda_s}.
\]

Requiring \( \Delta \phi_m = \pi \) we obtain \( \delta_m = \lambda_c \lambda_s / 4(\lambda_c - \lambda_s) \).

The other WST limit is the maximum detectable step \( \delta_M \). This value is defined by the finest wavelength variation \( \Delta \lambda_m = \lambda_{i+1} - \lambda_i \) applicable between two consecutive sweep steps. In order to properly fit the period of the sine function, we have to impose a maximum phase variation \( \Delta \phi_M \) due to the wavelength variation \( \Delta \lambda_m \). Then we find:

\[
\delta_M = \frac{\Delta \phi_M \lambda_{i+1} \lambda_i}{4\pi \Delta \lambda_m}.
\]

In order to avoid aliasing in the period estimation, we can require \( \Delta \phi_M = \pi/4 \), obtaining \( \delta_M = \lambda_{i+1} \lambda_i / (8\Delta \lambda_m) \).

The generic step \( \delta \) can be seen by PYPS as positive or negative according to the sensor signal definition. Fitting the signal \( S(1/\lambda) \) with the function \( S_f(x) = C_f + A_f \sin[2\pi T_f x + P_f] \), the sign of \( T_f \) is supposed to be positive, so \( \delta = T_f/2 \) is supposed positive too, and the information on sign of \( \delta \) is lost. Practically we can better say that \( T_f = 2|\delta| \). When the \( \delta \) is negative, the eq.(1) becomes: \( S = C + A \sin \left[ -2\pi 2|\delta|/\lambda \right] = C + A \sin \left[ \pi + 2\pi 2|\delta|/\lambda \right] \), so that we will find \( P_f = \pi \). Therefore the sign of \( \delta \) is determinable through the \( P_f \) value: 0 for \( \delta > 0 \) and \( \pi \) for \( \delta < 0 \).
The main advantage afforded by this technique is the simultaneous estimation of all the mirror steps with a single wavelength sweep\(^\dagger\), measurement that does not require any segment movement. Having the values of all the steps, the mean piston error of each segment can be estimated with an off-line algorithm. It is important to notice that it is not required any kind of system calibration, as for example in all the closed loop techniques where an interaction matrix and a reference position acquisitions are required. For commercial liquid crystal tunable filters in the visible-NIR range\(^\ddagger\), typical values are \(\lambda_s = 650\,\text{nm}\), \(\lambda_e = 950\) and \(\Delta\lambda_m = 7\,\text{nm}\). So that the order of magnitude of the \(\delta_m\) and \(\delta_M\) are respectively \(500\,\text{nm}\) and \(11\,\mu\text{m}\). This working range, together with the fastness, suggests to use this technique to quickly reduce several micron piston errors to the capture range of other phasing techniques that allow the finest phasing accuracy. The no calibration need suggests also that the WST can be used in the mirror first phasing, when the mirror has never been phased and the closed loop calibrations are not yet available.

### 3.2. PRELIMINARY EXPERIMENTAL RESULTS

A preliminary experimental test has been done in the Arcetri laboratories in order to prove the technique concept. This experiment has been performed using the opto-mechanical set-up described in sect.2.2. The only modification has been the substitution of the filter wheel with the liquid crystal tunable filter mod. VIS-07-20-STD purchased by Lot-Oriel Group.

\(^\dagger\)That is assuming at least one sub-aperture per edge, but this sampling is lower than the one required by the closed loop correction of piston, tip and tilt.

\(^\ddagger\)These data are referred to tunable filter mod.SNIR-10-20-STD produced by Lot Oriel Group.
Table 1. In the table below the fitted values for the plots in fig.4 are reported. From top to bottom the values are referred to the top left, top right, bottom left and bottom right plots respectively. In this measurements all step estimations are consistent with the nominal value in the expected 500nm accuracy. The \( P_f \) values are not only around 0 and \( \pi \) as expected, that is because of an error on the \( T_f \) value induce an equal indetermination in \( P_f \); so that with a 20% error on \( T_f \) the sign of the step can not be evaluated through \( P_f \). In this experiment the step measured has been limited by the deformable mirror stroke. For bigger steps, when more than one sine period is measured during the sweep, the error on \( T_f \) is supposed to be significatively reduced.

<table>
<thead>
<tr>
<th>Nominal step wf/Fitting res.</th>
<th>( T_f \text{ (nm)} )</th>
<th>( P_f \text{ (rad)} )</th>
<th>( C_f )</th>
<th>( A_f )</th>
</tr>
</thead>
<tbody>
<tr>
<td>+2200nm</td>
<td>2730nm</td>
<td>0.1( \pi )</td>
<td>0.1</td>
<td>0.25</td>
</tr>
<tr>
<td>-2200nm</td>
<td>2400nm</td>
<td>1.9( \pi )</td>
<td>0.1</td>
<td>0.25</td>
</tr>
<tr>
<td>+2200nm</td>
<td>2320nm</td>
<td>-0.4( \pi )</td>
<td>0.1</td>
<td>0.27</td>
</tr>
<tr>
<td>-2200nm</td>
<td>2030nm</td>
<td>0.9( \pi )</td>
<td>0.05</td>
<td>0.21</td>
</tr>
</tbody>
</table>

The MEMS segments has been positioned at the same nominal value except a single segment actuated at +100 nm mirror steps over the others (each mirror step introduces a mean differential piston of 22nm on the wavefront). Then, leaving the mirror in the same position, the PYPS signal has been acquired for wavelength values between 500nm and 700nm at steps of 5nm. The sub-apertures corresponding to the edges of the un-phased segments has been easily identified considering the signal amplitude variations. In fig.4 some typical edge signal is reported. In table 1 the corresponding fitted values are shown.

4. THE SEGMENT SWEEP TECHNIQUE

The SST (Segment Sweep Technique) allows to solve the phase ambiguity without any system pre-calibration and can provide a fine first phasing of the mirror with a non limited capture range. The time required to phase the mirror using the SST depends on the the number of the mirror segments \( N \) and on the maximum differential piston expected.

4.1. WORKING PRINCIPLE

This technique is based on the phase step PYPS signal behavior when the system is feeded by a finite bandwidth source. In the monochromatic case the PYPS signal is, as said, (eq.1): 

\[ S = C + A \sin \left[ 2\pi \frac{2\lambda}{\lambda_2} \right]. \]

When the light has a finite bandwidth \( \Delta \lambda = \lambda_2 - \lambda_1 \), we have to consider the contribution of any infinitesimal \( d\lambda \) to the overall signal that results (taking for simplicity \( C = 0 \) and \( A = 1 \)):

\[ S(\delta) = \int_{\lambda_1}^{\lambda_2} \sin \left[ 4\pi \delta \lambda \right] d\lambda = 4\pi\delta \int_{4\pi\delta/\lambda_1}^{4\pi\delta/\lambda_2} \sin[t^2] \frac{dt}{t^2} = 4\pi\delta \left[ Ci(t) - \frac{\sin[t]}{t} \right]_{4\pi\delta/\lambda_2}^{4\pi\delta/\lambda_1} \]

where \( Ci(t) \) is the Cosintegral (\( S(\delta) \) is plotted in fig.5). Each monochromatic component \( d\lambda \) of \( \Delta \lambda \) is contributing with a sinusoidal signal with the phase \( \phi = 4\pi\delta/\lambda \). When \( \delta = 0 \) all the \( \phi \) are equal and all the signal contributions are directly summed. When \( \delta \neq 0 \) the sine phases of each \( d\lambda \) are different because \( \phi = \phi(\lambda) \); e.g., when \( \delta = \lambda_1\lambda_2/4(\lambda_2 - \lambda_1) \) we obtain \( \phi(\lambda_2) - \phi(\lambda_1) = \pi \) and the contribution of the signal due to \( \lambda_1 \) and \( \lambda_2 \) are equal in amplitude and opposite in sign. Following these considerations, the signal phase ambiguity is resolved by the amplitude modulation that identifies \( \delta = 0 \) as the function zero between the signal absolute maximum and minimum. In order to effectively remove the ambiguity, the bandwidth \( \Delta \lambda \) has to be taken large enough to introduce a signal amplitude depression between two consecutive maxima larger than the signal indetermination.

This phase ambiguity solution can be used to phase the mirror segments taking one segment as reference and sweeping the neighbors, as better explained in the next section.
Figure 5. The theoretical broadband PYPS signal (eq.8) in arbitrary units as function of the mirror step reported in nm. The considered $\lambda_1$ and $\lambda_2$ are respectively 600 and 900nm as the source used in the experiment described in sect.4.2. This plot can be compared with the measured signals reported in fig.6.

Figure 6. A screen-shot of the SST software tool during the operation. In the left upper corner the PYPS frame and real time signals are shown. In the left bottom corner there is a schematic representation of the mirror segment status (phased, un-phased, or sweeping), these status can be changed by the user. On the extreme right column the selected edge sub-apertures are shown, while the graphs show the corresponding signal plot during the segment sweep. The phased edge position is estimated looking to the absolute maximum and minimum positions.
4.2. EXPERIMENTAL RESULTS

The SST has been tested during the experimental runs at the William Herschel Telescope. The PYPS prototype has been optically coupled with the NAOMI Defomable Mirror on a Nasmyth platform of the WHT; this mirror is composed by square plane segments controllable in piston, tip and tilt with a nominal 0.7 nm accuracy on the physical surface. The system has been feeded by the NAOMI incandescence calibration source. The SST has been tested phasing 13 segments of the deformable mirror, starting from an unknown position in the whole mirror actuator range (±3 μm physical). A semi-automatic software tool has been developed for the SST use (a screenshot is reported in fig.6). This procedure is taking one segment as reference and then sweeping the neighbors through a 2 μm range. A sub-aperture is found on the edge between the reference segment and the sweeping one. The signal of this sub-aperture is then plotted and the phased position determined as the middle between the main maximum and minimum. The segment is moved to the estimated position and considered as phased. In the next step the segments adjacent to a phased one can be sweep. Iterating this procedure, 13 segments of the NAOMI DM has been phased allowing to acquire the mirror reference position and the interaction matrix for the closed loop phasing techniques.

The SST can provide a first accurate phasing starting from any differential piston errors, but the operational time is dependent on the segment number and the initial phasing errors. In principle the SST could be parallelized sweeping the half of the segment at the same time, recording the signals and reconstructing the differential piston as proposed for the WST.

5. CONCLUSION

Table 2. In the table are resumed the main pro and cons of the three techniques presented in the paper. The accuracy and capture range values are expressed in physical differential pistons on the surface. As fast we mean that the technique allows differential piston measurement in parallel mode, so that the time required is not dependent on the number of segments.

<table>
<thead>
<tr>
<th>Technique</th>
<th>PRO</th>
<th>CONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength Sweep</td>
<td>Calibrations not required</td>
<td>Low accuracy ±200 nm</td>
</tr>
<tr>
<td></td>
<td>Capture range ±13 μm</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fast</td>
<td></td>
</tr>
<tr>
<td>Segment Sweep</td>
<td>Calibration not required</td>
<td>Slow</td>
</tr>
<tr>
<td></td>
<td>Capture range infinite</td>
<td></td>
</tr>
<tr>
<td></td>
<td>High accuracy</td>
<td></td>
</tr>
<tr>
<td>2 Wavelengths c-loop</td>
<td>Fast</td>
<td>Calibrations required</td>
</tr>
<tr>
<td></td>
<td>High accuracy</td>
<td>Capture range ±3.8 μm</td>
</tr>
</tbody>
</table>

We presented three techniques to solve the phase ambiguity with PYPS. The different characteristics of each one (see tab.2) suggest the best use for the ELT co-phasing. The absolute first phasing can not be done with any closed loop procedure because the calibrations required need the phased mirror. The WST can provide a fast reduction of the differential piston error, but can not reach an high accuracy. After that, the SST can be run in order to obtain the best accuracy for the first mirror phasing. The advantage to run the SST after the WST correction is to start from a small differential piston error; so that the segment sweep can be done only in this range, with a large reduction of operational time. Once the first phasing is achieved all the closed loop calibrations can be acquired and the on-sky phasing is ready to start. The two wavelength closed loop technique can be usefully applied to recover the phased mirror position starting from few microns piston errors, avoiding the WST+SST procedure after the first phasing. The advantage offered by this technique is the parallel phasing together with a best accuracy, while keeping a large capture range.
APE experiment and William Herschel activities will provide the right environments to provide test and further developments of the cophasing techniques proposed in this paper.

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