

Experimental Validation of a Pyramid Piston Sensor for Segment Co-Phasing in a Laser Guide Star Adaptive Optics System

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ABSTRACT

The increasing adoption of segmented primary mirrors in next-generation large-aperture telescopes imposes stringent requirements on segment co-phasing, which must be controlled to well below the observing wavelength to preserve diffraction-limited performance. Residual differential piston, tip, and tilt between adjacent segments introduce phase discontinuities at segment boundaries, degrading the point-spread function (PSF) and overall image quality. Accurate detection and characterisation of these discontinuities are therefore essential for the alignment and maintenance of segmented optical systems. Building on an initial demonstration of discontinuous phase-step detection, this work advances toward the full calibration of a Pyramid Piston Sensor (PPS) within a representative adaptive optics (AO) environment.

The experiments are conducted using the CaNaPy facility, a laser guide star adaptive optics (LGS-AO) platform at the Optical Ground Station (OGS), Tenerife, developed for on-sky validation of high-performance AO techniques at visible wavelengths. Operated in collaboration with ESA, CaNaPy enables the investigation of advanced AO concepts under realistic observing conditions, including strong atmospheric turbulence, daytime LGS-AO operation, and monostatic configurations with co-aligned uplink and downlink paths. The system supports flexible AO architectures, including closed-loop operation using either a natural guide star Shack–Hartmann wavefront sensor (NGS SH-WFS) or an LGS-driven pyramid wavefront sensor. Within this framework, the present study targets the direct detection of phase discontinuities from LGS-based wavefront measurements under adverse seeing conditions.

Segmented mirror behaviour is emulated using a set of discontinuous phase masks introducing controlled piston steps across sub-aperture boundaries. Wavefront sensing is performed with a pyramid wavefront sensor configured for piston sensitivity, and calibration is carried out in a monostatic uplink/downlink configuration representative of operational LGS systems. Measurements are acquired over a range of turbulence conditions and flux regimes, both in open loop and closed-loop AO operation.

The PPS response is evaluated in terms of differential piston sensitivity, and noise propagation, demonstrating sub-wavelength sensitivity under representative conditions. Robustness to LGS-specific effects, including return flux variability, is assessed, together with calibration stability across varying observing conditions and the impact of AO correction on phase-step detectability. The results provide experimental validation of pyramid-based piston sensing in an LGS-AO context and inform the development of co-phasing strategies and visible-wavelength AO architectures for future segmented-aperture telescopes.

Keywords: Discontinued phase, Segmented mirrors, Wavefront, CaNaPy, Laser Guide Star

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1. INTRODUCTION

The PPS test bench was developed to evaluate and validate techniques for measuring discontinuous wavefront phases, such as those arising from piston errors between misaligned segments of a segmented mirror. The system employs a Pyramid Wavefront Sensor (PyWFS) similar to that implemented in the CaNaPy LGS-AO facility. CaNaPy, presented by Bonaccini et al.^{1,2} and Pedreros et al.,³ provides a platform for investigating novel visible-wavelength adaptive optics correction techniques.

For small residual phase errors ($\Delta\phi < \pi/2$), the differential piston can be measured using a single-wavelength PyWFS. However, larger phase discontinuities require alternative approaches, such as multi-wavelength sensing techniques.⁴ In this context, a PyWFS can complement conventional segmented-mirror edge sensors by providing an independent measurement of differential piston errors, as written by Esposito et al.⁵ Such an independent measurement is particularly valuable during the initial alignment of a segmented mirror, for example, following the replacement or realignment of an individual segment.

A PyWFS does not directly measure the phase difference between adjacent mirror segments. Instead, the wavefront discontinuity at the segment boundary produces a characteristic tent-shaped feature in the measured slope response, centred on the inter-segment gap.⁴ For a modulated pyramid sensor, the amplitude of this feature varies sinusoidally with the differential piston. As a result, the measurement becomes ambiguous when the phase difference exceeds $\pm\lambda/2$, since multiple piston values can produce the same sensor response, as described by Pinna et al.⁶

This ambiguity can be resolved by combining measurements acquired at multiple wavelengths, allowing the most probable differential piston value to be determined. Holzlöhner et al.⁴ demonstrated that this approach can provide an accurate estimate of the true phase difference. Nevertheless, for small phase discontinuities ($\Delta\phi < \pi/2$), single-wavelength measurements remain an effective and practical solution, offering a simpler measurement scheme and avoiding the additional complexity associated with multi-wavelength operation.

Motivated by the first positive on-sky results reported in,⁷ a measurement campaign was conducted on Tenerife island at the end of July 2026. The campaign investigated the PPS approach under a sequence of increasingly realistic measurement conditions. First, a set of measurements was performed using an internal LED source on the optical bench, providing a controlled reference and baseline for subsequent experiments. This configuration was then extended by introducing simulated atmospheric turbulence using a deformable mirror. The second measurement regime employed a laser guide star (LGS) source, reproducing conditions relevant to the CaNaPy LGS-AO system. Finally, measurements were performed using an Natural Guide Source (NGS), providing additional validation of the technique under on-sky observing conditions. The results of this measurement campaign are presented and discussed in the following sections.

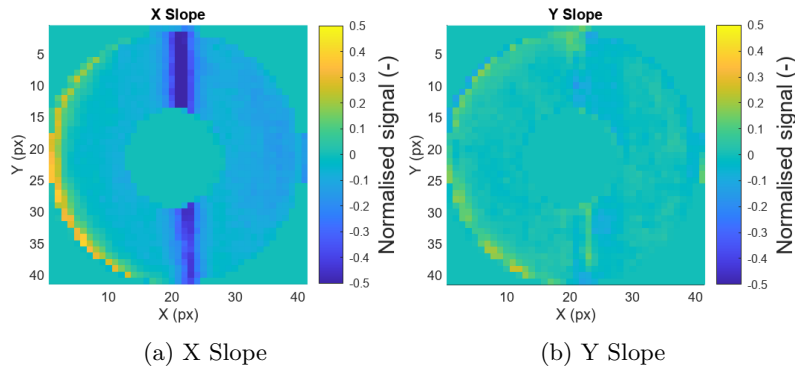


Figure 1: Example of the corresponding X- and Y-slope responses for 146 nm high phase step. A clear and pronounced response is observed at the edge of the phase plate, demonstrating the sensitivity of the PyWFS to the wavefront discontinuity introduced by the physical phase step.

2. ON BENCH VALIDATION AND ON-SKY EXPERIMENTS

Following the successful campaign conducted in April 2026, an expanded set of on-sky experiments was planned for the subsequent observing run. The experiments were conducted using the CaNaPy facility, described by Pedreros et al.,³ during a second observing campaign in July 2026.

The observing conditions varied throughout the campaign, with seeing ranging from approximately 0.6 to 2.4 arcsec. The observations also experienced varying levels of Calima, i.e., atmospheric dust transported over the Canary Islands. While these changing conditions introduced additional variability into the observations, they were beneficial for the present study, as they allowed the performance of the measurement approach to be evaluated under a range of atmospheric conditions.

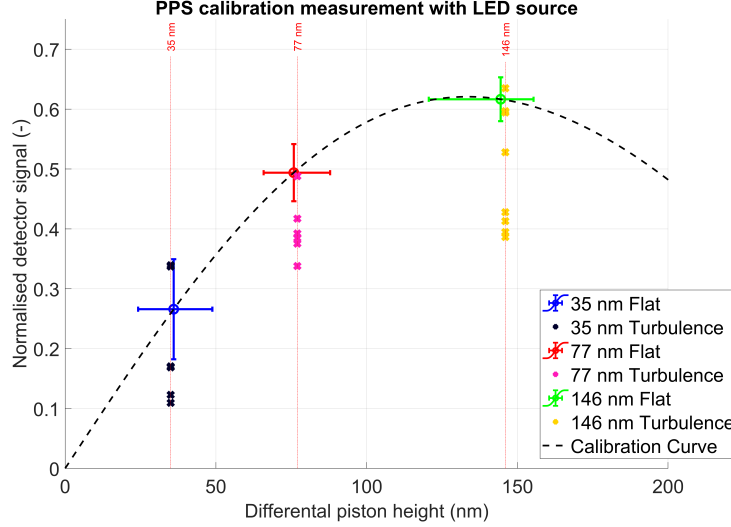


Figure 2: The calibration curve was calculated from the data points obtained from measuring the 35, 77 and 146 nm phase plates with a flattened wavefront, i.e. corrected residual optical aberrations of the CaNaPy bench. The vertical error bars correspond to the standard deviation of the measurements. The black, magenta and yellow points illustrate the measurements with introduced atmospheric turbulence.

For the first measurement series, three physical phase steps with nominal values of 35, 77, and 146 nm were mounted in rotational holders and attached to a rotating wheel similar to a standard filter wheel. This configuration allowed the phase-step edges to be rotated to an orientation that avoided overlap with the telescope spider. In addition, the motorized wheel enabled the phase steps to be selected remotely during the observations.

The initial measurements were performed using a 594 nm LED source to acquire the PyWFS signal under controlled laboratory conditions. The deformable mirror (DM) was used to flatten the wavefront incident on the physical phase mask, thereby minimizing the contribution of common-path aberrations and providing a reference measurement under near-aberration-free conditions. An example of the corresponding X- and Y-slope responses is shown in Fig. 1. A clear and pronounced response is observed at the edge of the phase plate, demonstrating the sensitivity of the PyWFS to the wavefront discontinuity introduced by the physical phase step.

The resulting calibration curve, together with the measured values corresponding to the three physical phase steps, is shown in Fig. 2 and summarized in 1. The blue cross denotes the measurement obtained for the 35 nm phase step, the red cross corresponds to 77 nm, and the green cross indicates the measurement for the 146 nm phase step. The error bars represent the uncertainty associated with the estimated phase-step amplitudes.

As a second stage of the internal calibration, the DM was used to introduce simulated atmospheric turbulence. Since both wavefront sensors observed the same point-like LED source, the Shack–Hartmann wavefront sensor (SH-WFS) was used to close the AO loop while the PyWFS simultaneously measured the response to the physical phase step. The AO loop therefore compensated the simulated turbulence while the PPS measurement was performed in the presence of dynamically varying aberrations.

The corresponding measurements are also shown in Fig. 2 and are labelled “Turbulence”. The measured phase-step values are systematically lower than those obtained in the flattened-wavefront configuration used for the aberration-free calibration. Nevertheless, the measurements affected by the simulated turbulence follow the same overall sinusoidal trend as the calibration curve. For clarity, the turbulence measurements were not fitted to the calibration curve. Instead, they are plotted directly at the known differential piston values of the physical phase steps. This representation highlights the deviation of the turbulence-affected measurements from the mean response obtained under flattened-wavefront conditions.

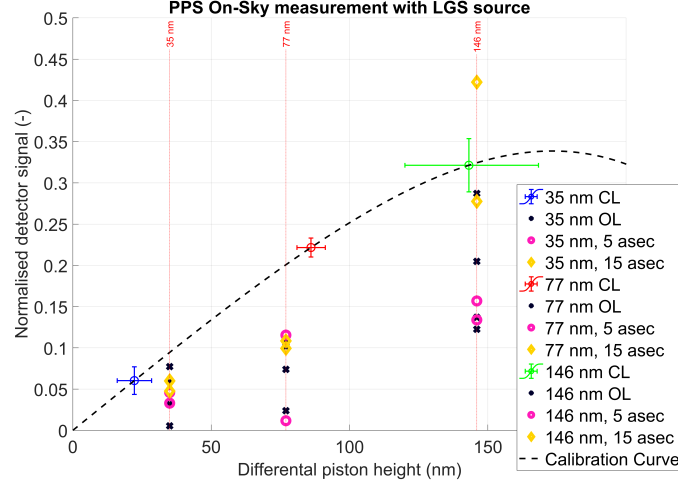


Figure 3: PPS measurements obtained with the LGS source. The calibration curve was derived from measurements of the 35, 77, and 146 nm phase steps with the AO loop closed using an NGS, while the LGS provided the source observed by the PyWFS. The black, magenta, and yellow points show measurements obtained with AO open-loop operation and with 5- and 15-arcsec FoVs, respectively. Vertical error bars indicate the uncertainty in the measured signal, while horizontal error bars denote the corresponding uncertainty in the phase-step estimate obtained from the calibration curve.

2.1 Laser Guide Star Measurements

Following the on-bench calibration and validation, the PPS was evaluated under on-sky conditions using an LGS source. Several data sets were acquired over three observing nights with good seeing varying between 1 and 1.2 arcsec. The LGS was operated in a monostatic configuration, resulting in a non-elongated laser guide star image. To investigate the influence of atmospheric turbulence on the PPS performance, measurements were obtained with the AO system operating in both closed-loop and open-loop configurations.

For the closed-loop measurements, the SH-WFS was used to control the AO loop using natural guide stars. The selected targets were Alpheratz (magnitude 2), HIP 101769A (magnitude 4), and HIP 86032 (magnitude 2). The selection of the natural guide star was primarily determined by the availability of a clear line of sight and the ability to propagate the laser in the corresponding direction. The performance of the CaNaPy SH-WFS has previously been characterized by Martinez et al.⁸ The resulting LGS signal was simultaneously recorded by the PyWFS, allowing the response of the PPS to be evaluated under different atmospheric correction conditions.⁹

Four data sets were acquired for each of the three available physical phase steps during the observing run. Datasets were processed using the PPS reduction pipeline described by Janout et al.⁹ As a baseline, the calibration curve and corresponding mean phase-step values were derived from the closed-loop measurements obtained with a 10-arcsec field of view (FoV). The resulting mean values are shown in Fig. 3 as blue, red, and green crosses, corresponding to the three physical phase steps. The values can be found in Table 2. The standard deviation of the individual measurements was used to characterize the uncertainty of the retrieved phase-step amplitude. The resulting calibration curve exhibits a lower overall response amplitude than the corresponding on-bench calibration shown in Fig. 2. This difference is consistent with the reduced signal quality under on-sky conditions, where

atmospheric turbulence, residual tip-tilt, field-alignment errors, and additional instrumental effects contribute to the measured response. The on-sky measurements therefore exhibit a lower signal-to-noise ratio than the controlled LED measurements.

The remaining measurements, including the open-loop data and the measurements obtained with 5- and 15-arcsec FoVs, were compared with this baseline calibration. As in the internal calibration, these measurements were not fitted to the calibration curve. Instead, the retrieved phase-step amplitudes were plotted directly at the corresponding known differential piston values of the physical phase steps. As shown in Fig. 3, the closed-loop configuration provides the strongest and most consistent response among the tested configurations.

An important limitation during the LGS measurements was the alignment of the field on the PyWFS. In all three on-sky measurement sets, residual tip-tilt and imperfect field positioning were present and affected the measured PPS response. These observations highlight the importance of accurate field alignment and tip-tilt control for reliable differential piston measurements with the PyWFS. The effect is particularly relevant for on-sky operation, where atmospheric disturbances and variations in the AO correction can make maintaining the optimal field position more challenging.

Although the absolute estimates show deviations from the nominal phase-step values, the three phase-step levels remain clearly distinguishable. This result is particularly relevant for the LGS measurements, where the purpose of the experiment was to demonstrate the applicability of PPS sensing rather than to optimize the absolute phase reconstruction accuracy.

2.2 Natural Guide Star Measurements

For the final set of measurements, Vega was used as both the reference source for closing the AO loop with the SH-WFS and as the source observed directly by the PyWFS. Since the broadband emission of the star is not suitable for precise determination of the phase steps, the spectral bandwidth was restricted using an Alluxa narrowband filter with a bandwidth of 0.5 nm centred at 589 nm. This configuration was used to investigate whether a natural guide star alone can provide a sufficiently strong and stable signal for differential piston measurements with the PPS.

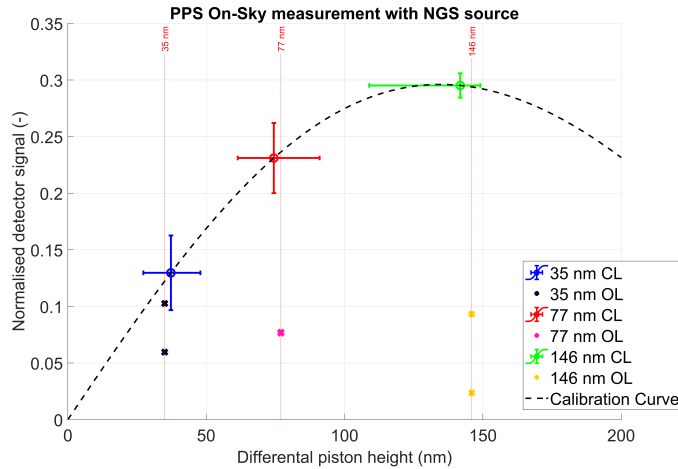


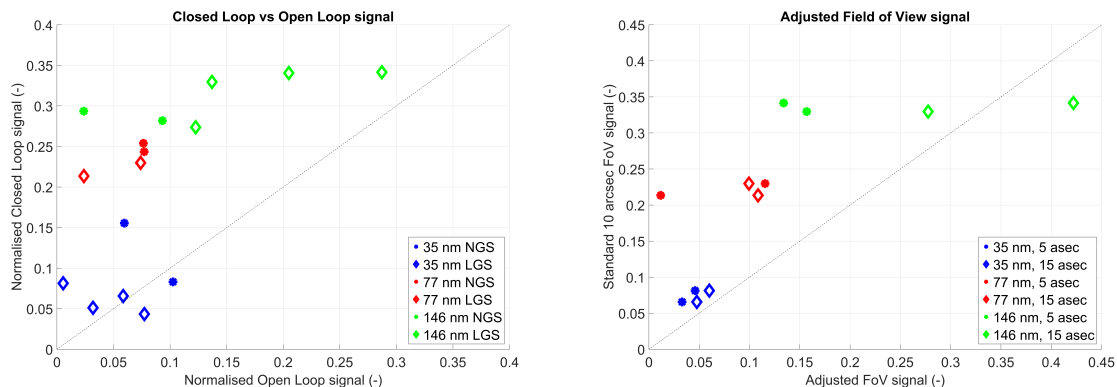
Figure 4: The calibration curve was calculated from the data points obtained from measuring the 35, 77 and 146 nm phase plates with AO closed loop on NGS. The black, magenta and yellow points illustrate the measurements in AO open loop. Vertical error bars indicate the uncertainty in the measured signal, while horizontal error bars denote the corresponding uncertainty in the phase-step estimate obtained from the calibration curve.

As shown in Fig. 4, the measured PyWFS response was sufficiently strong to distinguish the three phase-step levels from one another. Particular attention was paid to the field alignment during these observations, following the experience gained during the LGS measurements. The improved alignment resulted in a well-resolved calibration curve for the closed-loop measurements, demonstrating the importance of accurate field positioning for reliable PPS measurements. The values are listed in 3.

In contrast, the open-loop (OL) measurements exhibit a substantially weaker response. Nevertheless, they remain consistent with the general trend observed in the closed-loop data and provide further evidence that closed-loop AO correction is an important component for robust PPS measurements under on-sky conditions. As for the previous measurements, the open-loop data were not fitted to the calibration curve; instead, the retrieved values were plotted directly at the known differential piston values of the corresponding physical phase steps.

2.3 Comparison

The measurements presented in the previous sections already reveal several consistent trends. In particular, the open-loop measurements generally exhibit a weaker PPS response than the corresponding closed-loop measurements. The results also indicate that the choice of the PyWFS FoV has a significant influence on the measured signal and, consequently, on the achievable signal-to-noise ratio.



(a) Closed vs Open AO loop

(b) 10 arcsec FoV vs 5 and 15 arcsec FoV

Figure 5: Comparison of the PPS response for different measurement configurations. The left plot compares the AO closed-loop and open-loop measurements, while the right plot compares measurements obtained with 10-, 5-, and 15-arcsec FoVs. Most measurements lie above the diagonal, indicating a stronger PPS response for the 10-arcsec closed-loop configuration.

To facilitate a more direct comparison, the results are summarized in the two plots shown in Fig. 5. Figure 5a compares the closed-loop measurements obtained with a 10-arcsec FoV with the corresponding open-loop measurements. Most of the measured points for all three phase steps lie above the diagonal, indicating that the closed-loop configuration generally produces a stronger and more clearly resolved PPS response than the corresponding open-loop configuration.

Table 1: Estimated phase-step amplitudes derived from the PPS on bench measurement with the LED source. The upper and lower limits correspond to the extrema of the phase-step values obtained by propagating the measurement uncertainty through the calibration curve.

Phase Step (nm)	35	77	146
Mean Signal (-)	0.2659 ± 0.0836	0.4938 ± 0.0477	0.6165 ± 0.0366
Results of phase estimates			
Est. Phase (nm)	36.0010	75.8307	144.4690
Upper Limit (nm)	48.7951	87.8768	168.3303
Lower Limit (nm)	24.1928	65.8317	133.5819

A similar comparison can be made for the different FoV settings, see 5b. All the measurements used in the FoV comparison were acquired in AO closed loop. The results indicate that a 10-arcsec FoV provides a favourable balance between signal strength and noise for the CaNaPy configuration. It therefore represents a suitable choice

for PPS measurements on this particular bench. This value should not, however, be considered a universal optimum. The appropriate FoV depends on the optical configuration, PyWFS characteristics, and observing conditions of the individual facility and should therefore be independently validated for each implementation.

Table 2: Estimated phase-step amplitudes derived from the PPS on-sky measurement with the LGS source. The upper and lower limits correspond to the extrema of the phase-step values obtained by propagating the measurement uncertainty through the calibration curve.

Step (nm)	35	77	146
Mean Signal (-)	0.0604 ± 0.0167	0.2217 ± 0.0115	0.3214 ± 0.0322
Results of phase estimates			
Est. Phase (nm)	22.2308	86.0765	143.1309
Upper Limit (nm)	28.4535	91.2775	168.2857
Lower Limit (nm)	16.0436	81.0233	120.0072

Table 3: Estimated phase-step amplitudes derived from the PPS on-sky measurement with the NGS source. The upper and lower limits correspond to the extrema of the phase-step values obtained by propagating the measurement uncertainty through the calibration curve.

Step (nm)	35	77	146
Mean Signal (-)	0.1296 ± 0.0330	0.2311 ± 0.0310	0.2957 ± 0.0108
Results of phase estimates			
Est. Phase (nm)	37.2530	74.4554	141.8468
Upper Limit (nm)	47.9170	91.0085	134.5975
Lower Limit (nm)	27.2863	61.4106	108.9152

These results demonstrate the sensitivity of PPS measurements to atmospheric turbulence and the importance of AO correction for obtaining a clear and reproducible response. While the closed-loop measurements provide well-resolved phase-step signals, the presence of uncorrected turbulence degrades the measurement response, resulting in increased uncertainty and a systematic reduction in the retrieved phase-step amplitude.

The objective of this experiment is not to determine the most accurate absolute value of each phase step, but rather to demonstrate the ability of the PPS to distinguish between different differential piston values. In this respect, the measurements demonstrate that the three phase steps can be clearly separated despite the presence of residual atmospheric and instrumental effects.

3. CONCLUSION

The July 2026 PPS measurement campaign demonstrated the feasibility of detecting and distinguishing known discontinuous phase steps with a Pyramid Piston Sensor under different observing conditions and with different illumination sources. The measurements progressed from on-bench calibration, through simulated atmospheric turbulence, to on-sky observations using both LGS and NGS sources. In all configurations, the PPS provided a measurable response to the introduced differential piston, and the three physical phase steps of 35, 77, and 146 nm could be distinguished from one another.

The measurements further demonstrated the importance of adaptive optics correction and accurate PyWFS field alignment for reliable PPS operation. The AO closed-loop measurements generally provided a stronger and more clearly resolved response than the corresponding open-loop measurements, while residual tip-tilt and imperfect field positioning were found to degrade the measured signal. The comparison of different PyWFS fields of view also showed that a 10-arcsec FoV provides a favourable balance between signal strength and measurement noise for the CaNaPy configuration.

The primary objective of the campaign was not to achieve the most accurate absolute reconstruction of the physical phase-step amplitudes, but rather to demonstrate the ability of the PPS to discriminate between different

differential piston values under realistic observing conditions. The results confirm the applicability of the single-wavelength PPS approach within the investigated measurement regime. For larger phase discontinuities outside the unambiguous single-wavelength measurement range, the periodic response of the PyWFS leads to ambiguity between different piston values. Such cases require complementary approaches, such as multi-wavelength sensing, to extend the measurable piston range. Within the investigated single-wavelength regime, the successful on-sky detection of the phase steps using a laser guide star demonstrates the applicability of PPS measurements to an LGS-based adaptive optics system. Together with the NGS measurements, these results represent an important step toward the use of pyramid-based differential piston sensing for segmented-mirror alignment and discontinuous wavefront sensing in adaptive optics systems.

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