

Assessment of an Active Optics system based on Phase Diversity and a Spatial Light Modulator for a Solar Space Instrument

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ABSTRACT

Solar spectropolarimeters operating on balloon-borne and space-based platforms are free from atmospheric turbulence, but their performance may still be degraded by quasi-static thermo-optical fluctuations and instrumental misalignments. Phase Diversity (PD) has been widely used for wavefront sensing and image restoration, such as in the Imaging Magnetograph eXperiment (IMaX), but its use within active aberration-correction schemes for solar instrumentation remains largely unexplored. In this work, we assess an active optics system implemented on a modified IMaX optical layout, combining PD with a Spatial Light Modulator (SLM) to enable both wavefront sensing and in situ aberration correction. Simulations show that direct compensation of aberrated solar scenes is feasible, leading to a significant reduction of the wavefront error and to improvements in image contrast. The study is further extended to diversity phases beyond defocus, including oblique astigmatism, vertical coma, and vertical trefoil, to evaluate the response of the PD algorithm under different diversity conditions. Preliminary results from a laboratory demonstrator provide an initial experimental validation of the concept under realistic conditions. The demonstrator is also used to test an iterative compensation strategy and to assess its potential for achieving complete aberration correction, approaching diffraction-limited image quality, and reducing, or potentially eliminating, the need for post-processing image reconstruction.

Keywords: astronomical instrumentation, active optics, Spatial Light Modulator, Phase Diversity, wavefront sensing, aberration correction, solar spectropolarimetry

1. INTRODUCTION

The Imaging Magnetograph eXperiment (IMaX) was a spectropolarimeter designed for solar observations and developed by the Spanish Space Solar Physics Consortium (S³PC). It successfully flew onboard the SUNRISE balloon-borne solar observatory. During two successful flights in 2009 and 2013, SUNRISE I and II demonstrated the potential of the observatory.^{1,2} Although these missions were not affected by atmospheric distortions, optical aberrations arose from quasi-static thermo-optical fluctuations. The wavefront error was periodically estimated during selected calibration windows employing the Phase Diversity (PD) method, and the retrieved aberrations were used to restore the closest images recorded by the instrument.

The PD method^{3,4} is a technique that retrieves the wavefront aberrations produced in an optical system. It usually employs a focused-defocused image pair to construct a merit function. The images vary only by a phase difference related to the amount of (known) defocus, which is the phase diversity. The optical transfer function is parameterized as a function of a set of Zernike coefficients, allowing scientific images to be restored a posteriori. The PD technique offers certain advantages when used for active optics (AO) applications. However, the use of PD in AO applications was historically not considered due to the prohibitive computational effort required.

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Recent algorithmic and computational advances have opened the possibility of using PD in AO applications on both ground-based and space-based platforms.⁵

To produce the diversity image, the PD system in IMaX required a mechanism that moved a transparent plate in and out of the optical path, thereby introducing an additional optical path difference of one wavelength. However, the use of thick plates has negative consequences for the instrument’s weight, dimensions, and optical quality. Another solar spectropolarimeter, the Tunable Magnetograph (TuMag), also developed by the S³PC, flew on board SUNRISE III and included new capabilities with respect to IMaX. In particular, and by means of narrow-bandpass filters located within a filter wheel, it was able to observe the sun at three absorption solar lines.

Alternatively, the PD technique can be implemented in combination with a refocusing mechanism. This approach is used in the Polarimetric and Helioseismic Imager instrument on board the ESA/NASA Solar Orbiter mission (SO/PHI).⁶ In SO/PHI, defocus is introduced mechanically by moving the refocusing lens. In all these cases, it is clear that a PD system requires a mechanism, with its inherent complexities and associated risk. Nevertheless, while PD is routinely employed for post-facto image reconstruction, its potential as a wavefront sensor for real-time aberration correction remains largely unexplored in solar instrumentation.

Within this framework, liquid-crystal-based spatial light modulators (SLMs) offer significant advantages for onboard instrumentation. Their compact size, low energy requirements, and electro-optic nature make them particularly suitable for balloon-borne and space-based spectropolarimeters. SLMs can act as phase-diversity mechanisms and function as both active optics elements and polarization modulators, making them a promising technology in this field. When illuminated, the phase of the reflected light is modulated according to the molecular alignment, which is controlled on a pixel-by-pixel basis through a CMOS backplane. This enables the introduction of tailored wavefront distortions in imaging systems, with SLMs operating as programmable phase masks.⁷ Consequently, they can function as high-precision tools for wavefront correction and Zernike-mode generation.⁸ The combination of high pixel density and the ability to introduce abrupt phase shifts further extends their versatility. These capabilities enable applications such as non-axial wavefront reflection in telescopes to emulate free-form optical elements,^{9,10} beam steering in free-space communication systems,¹¹ and digital adaptive coronagraphy.¹² Moreover, our group has demonstrated that SLM technology is robust and well suited for operation in the space environment,¹³ and its use as a phase-diversity generator for solar-observation instrumentation has been experimentally validated.¹⁴

In this work, we assess the performance of an active optics system implemented on a modified version of IMaX which combines the PD technique with an SLM to enable wavefront detection and correction using a single optical path, without the need for a separate mechanism. First, we describe an ideal simulation of the optical layout. Using this simulation, we evaluate the correlation among the Zernike phase maps displayed on the SLM and the coefficients retrieved by the PD algorithm. This approach allows us to define a wavefront-correction procedure from which compensated images are obtained. The analysis is further extended to PD image pairs in which the diversity phase is generated by representative aberrations other than defocus, such as oblique astigmatism, vertical coma, and vertical trefoil. The results provide an initial validation of the proposed compensation method and demonstrate its feasibility. Finally, we present preliminary experimental results obtained with a laboratory demonstrator, where an iterative compensation strategy is tested to reduce the residual aberrations and approach diffraction-limited performance.

2. SIMULATED OPTICAL SYSTEM

The modified optical layout of IMaX used in this work is shown in Fig. 1. It consists of a paraxial optical model designed using CODE V (Keysight Technologies). In this layout, a 4- f configuration is implemented, with the SLM located at the pupil plane. Ideal lenses with focal lengths $f_1 = 160$ mm and $f_2 = 361$ mm are used in both the simulation and the demonstrator. These values result in an $f/42$ system with magnification of 2.25, consistent with the IMaX design. It should be noted that these lenses are not identical to those used in IMaX. This difference arises because IMaX has a pupil diameter of 25.6 mm, whereas the shortest dimension of our SLM is 8.6 mm. Since the SLM acts as a pupil stop, the focal lengths must be adjusted to preserve the IMaX f -number and magnification. The SLM is modeled as a reflective surface, with Zernike phase maps implemented

as interferometric phase patterns. The object represents the focal plane that interfaces with the SUNRISE I and II telescopes. In addition, two folding mirrors are incorporated into the design to enable a double-pass optical path, which is required for the proper operation of the solid LiNbO_3 Fabry-Perot etalon. This etalon operates in a double-pass configuration as a spectrometer (i.e., an ultra-narrow tunable bandpass filter).^{15–17}

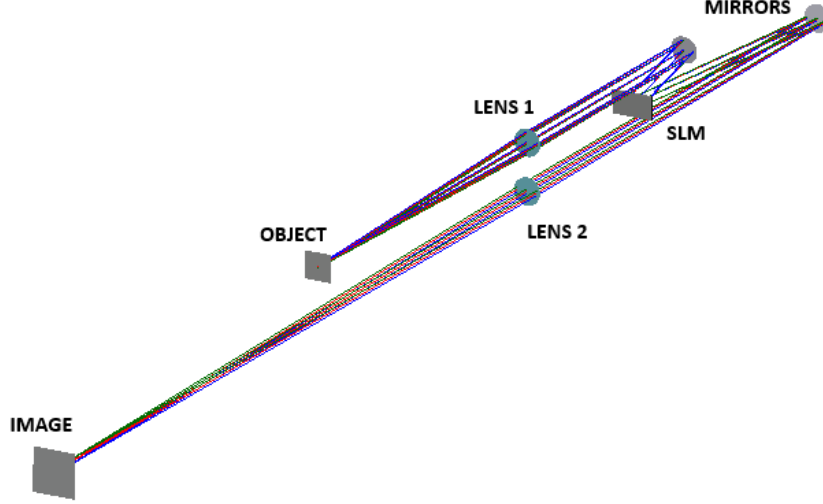


Figure 1: Optical layout based on a modified IMaX design with an SLM at pupil plane.

This simplified layout could be improved in the future by incorporating other critical IMaX subsystems that have not been included here, such as the liquid-crystal variable retarders in the polarization-modulation package or the etalon discussed above. Nevertheless, our analysis focuses on reproducing an optical relay system representative of the IMaX instrument.

3. SLM–PD CORRELATION ANALYSIS

We perform 2D image simulation in CODE V, a diffraction-based analysis tool that generates images from user-defined objects to evaluate optical system performance. The object used is a quiet-Sun image produced by a magnetohydrodynamic simulation. The CODE V simulation also takes into account the object size, camera pixel size, and wavelength. The resulting output images are shown in Fig. 2.

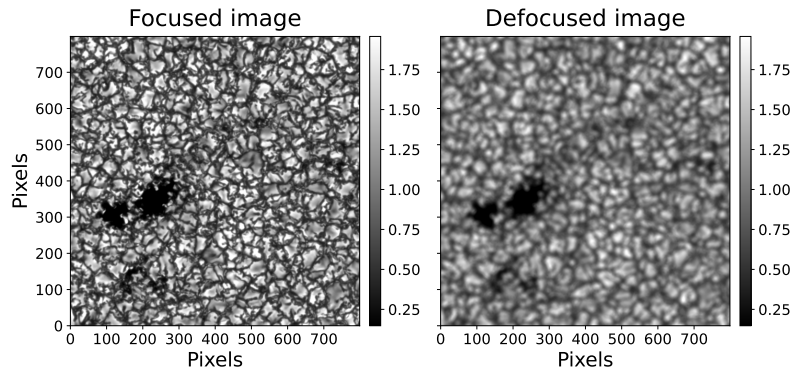


Figure 2: Left: focal-plane image of the modified IMaX optical system obtained from a 2D CODE V simulation. Right: corresponding image with an induced 1λ PV defocus at the pupil plane.

The left image shows the solar granulation at the nominal best-focus position. This image corresponds to the wavefront obtained without any phase modulation applied by the SLM ($\phi_1^{\text{SLM}} = 0$). The right image is produced by introducing, on the SLM surface, a phase map corresponding to the 4th Zernike coefficient (defocus), with a 1λ peak-to-valley (PV) amplitude ($\phi_2^{\text{SLM}} = c_4^{\text{SLM}} = 1\lambda$). This value was selected because a defocus diversity of 1λ PV is commonly used in solar-astronomy PD applications.¹⁸

From this pair of images, the PD algorithm retrieves the system's optical aberrations as a set of Zernike coefficients (c_j^{PD} with $j = 4, \dots, N$), excluding piston and tilt terms. In this work, we truncate the expansion at the fifth Zernike order, corresponding to $N = 21$. Our aim here is to determine how the PD algorithm retrieves aberrations deliberately induced on the SLM (c_j^{SLM}). In other words, we seek to establish the relationship between the coefficients of the Zernike phase map displayed on the SLM and those retrieved by the PD technique in an ideal paraxial optical system.

To explore these relationships, a pair of images was generated in CODE V. In this example, both images include an additional oblique astigmatism aberration corresponding to $c_5^{\text{SLM}} = -0.5\lambda$ PV. Their phase maps are therefore given by $\phi_1^{\text{SLM}} = c_5^{\text{SLM}}$ and $\phi_2^{\text{SLM}} = c_5^{\text{SLM}} + c_4^{\text{SLM}}$, respectively. The PD algorithm is subsequently applied to the image pair, and the retrieved Zernike aberration coefficients are presented in Fig. 3 as blue bars. Repeating the same procedure with an induced vertical astigmatism $c_6^{\text{SLM}} = -0.5\lambda$ produces the coefficients shown as orange bars. The horizontal axis shows the Zernike coefficient index listed in the Noll's expansion scheme.¹⁹ This figure shows a clear correlation between the coefficients induced on the SLM and those retrieved by the PD algorithm. It should be noted that the astigmatism terms recovered by the PD analysis are overestimated, and the reconstruction also shows a contribution from the defocus term and from other additional aberration components.

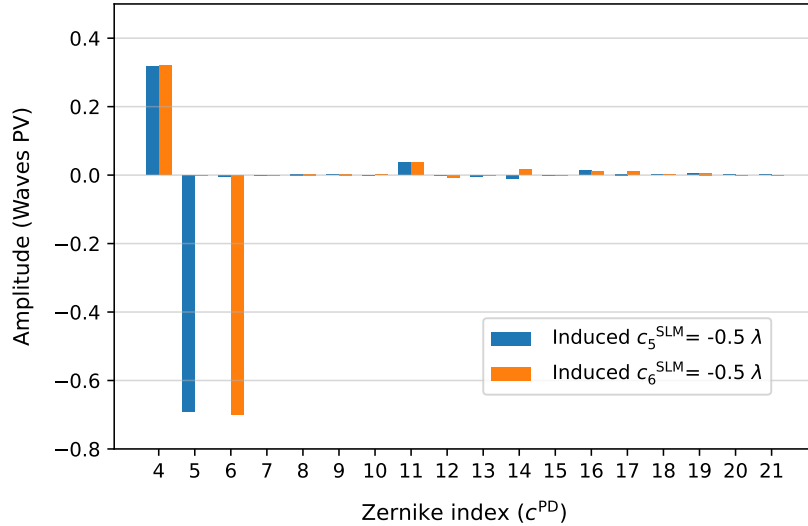


Figure 3: Zernike coefficients retrieved by the PD algorithm from simulated focused–defocused image pairs. Blue bars correspond to the image pair that includes an additional oblique astigmatism of -0.5λ PV, whereas orange bars correspond to the image pair that includes an additional vertical astigmatism of -0.5λ PV.

Finally, we repeated this simulation using focused–defocused image pairs with additional aberrations up to the 21st Zernike coefficient. The results are shown in Fig. 4a, where the second and third rows correspond to the data shown in Fig. 3. The graphs reveal a relationship between corresponding coefficients $c_j^{\text{SLM}} \Rightarrow c_j^{\text{PD}}$, which appears as a diagonal trend. However, part of the contribution is distributed among coefficients associated with other aberration modes or may even be lost in the PD reconstruction, thereby breaking the ideal diagonal behavior. The analysis was also performed using three representative diversity modes other than the commonly used defocus diversity, namely oblique astigmatism, vertical coma, and vertical trefoil, in order to explore the response of the PD algorithm in different cases. The results are shown in Figs. 4b, 4c, and 4d, respectively. The phase diversities generated by the defocus term c_4 and the oblique astigmatism term c_5 show a stronger direct

correlation than those generated by the vertical coma c_7 and vertical trefoil c_9 terms, where the correlation becomes noticeably weaker.

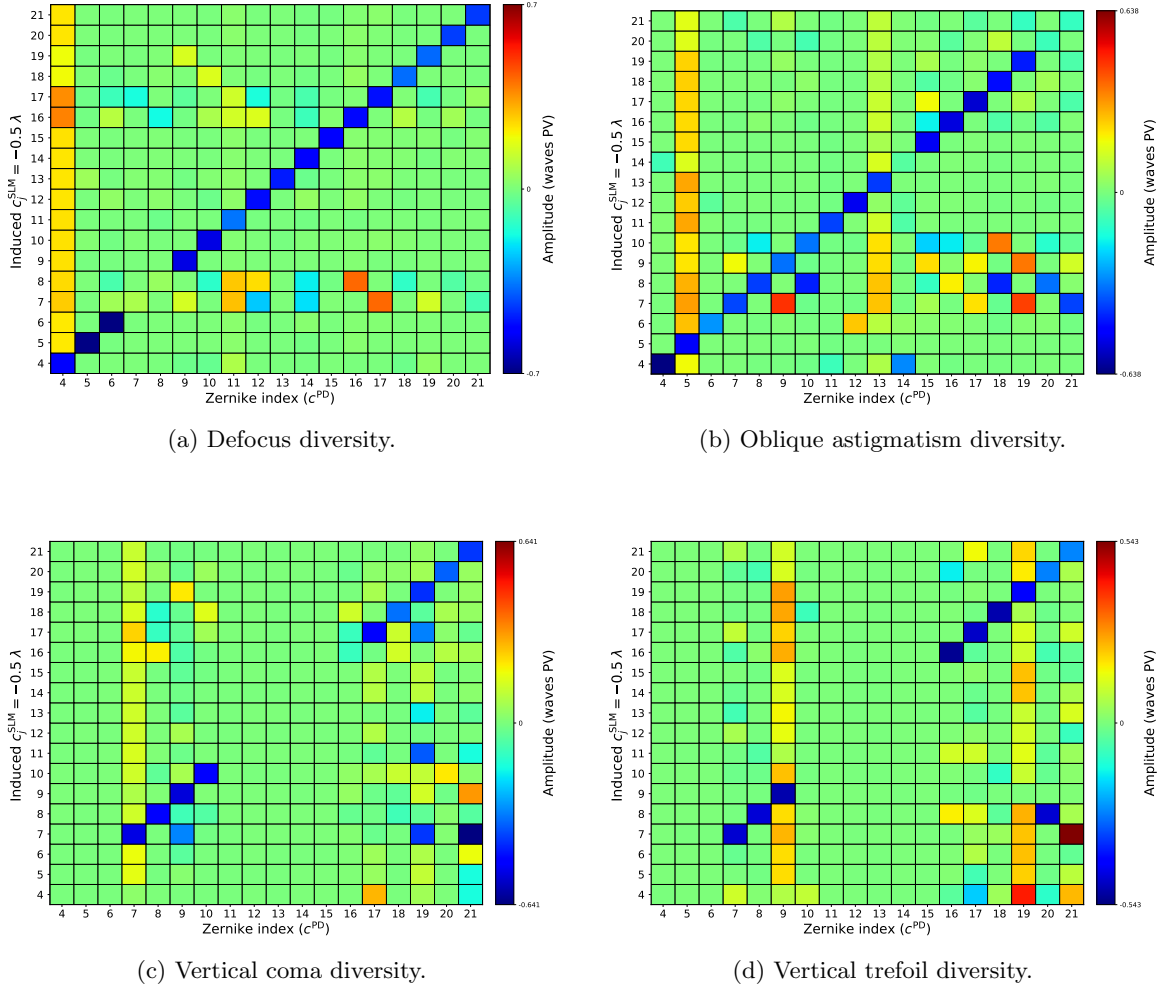


Figure 4: Zernike coefficients retrieved by the PD algorithm from simulated aberration-free/aberrated image pairs. For each induced aberration, the first image of the pair has a phase map of $\phi_1^{\text{SLM}} = c_j^{\text{SLM}} = -0.5 \lambda$ PV, whereas the second image has $\phi_2^{\text{SLM}} = c_j^{\text{SLM}} + \text{diversity}$. The applied diversity phases correspond to 1λ PV of (a) c_4^{SLM} , (b) c_5^{SLM} , (c) c_7^{SLM} , and (d) c_9^{SLM} , respectively. Each row corresponds to the retrieved PD coefficients, c^{PD} . The colormap encodes the coefficient amplitude in PV waves.

The behavior arises because the SLM imposes a prescribed phase distribution expressed in a given Zernike basis, whereas PD estimates the set of coefficients that best reproduces the focused and diversity image pair through an inverse optimization process. Therefore, the retrieved solution depends not only on the aberration introduced by the SLM, but also on the diversity phase used, the sensitivity of the image pair to each Zernike mode, and the conditioning of the minimization problem. As a result, a phase pattern applied as a single Zernike mode on the SLM may be reconstructed by PD as a linear combination of several modes, producing crosstalk between coefficients even in the absence of optical misalignments or non-paraxial effects.

In view of the observed correlations, better performance is expected when the diversity phase is generated using either the defocus term c_4 or the oblique astigmatism term c_5 , rather than the vertical coma term c_7 or the vertical trefoil term c_9 , since the coefficient correlations exhibit a more pronounced diagonal behavior. As will be shown below, even poorer correlations are expected under real experimental conditions.

4. COMPENSATION PROCEDURE

We now describe the procedure for wavefront compensation. In the simplest implementation, the diversity phase is introduced through a focused–defocused image pair, since this configuration is expected to provide better performance according to the correspondence relations discussed previously.

We first deliberately introduce a set of random aberrations, encoded as Zernike coefficients, by uploading the corresponding phase pattern onto the simulated SLM. This provides a controlled initial aberrated wavefront to be corrected. The first image is then acquired. For the second image, an additional phase map corresponding to the defocus term (diversity) is displayed on the SLM, with $c_4^{\text{SLM}} = 1\lambda$. The PD algorithm is subsequently applied to this image pair to estimate the set of coefficients c_j^{PD} associated with the aberrated optical system.

Wavefront compensation is performed by subtracting the coefficients c_j^{PD} from the initial SLM coefficients, $[c_j^{\text{SLM}}]^{\text{initial}}$, for $j = 4, \dots, N$. The final set of coefficients displayed on the SLM is therefore given by

$$[c_j^{\text{SLM}}]^{\text{final}} = [c_j^{\text{SLM}}]^{\text{initial}} - c_j^{\text{PD}}. \quad (1)$$

By applying this updated coefficient set to the SLM, the aberrated wavefront is compensated, leading to the corresponding corrected image. The same procedure is then repeated for the other phase diversities considered in this work: oblique astigmatism, vertical coma, and vertical trefoil. The performance of the resulting compensation for each diversity phase is evaluated in the following section.

5. SIMULATION RESULTS

Following the compensation procedure described in Sec. 4, the performance of the wavefront correction was evaluated for each of the four diversity phases considered in this work. Figure 5 shows the simulated solar images obtained before and after applying each individual correction, together with the relative RMS contrast computed from each image.

The initial aberrated image, obtained after introducing a set of random Zernike aberrations on the SLM, presents an RMS contrast of 26.9%. When compensation is carried out using a diversity phase generated by the defocus term c_4 , the RMS contrast increases markedly to 40.2%, indicating a recovery of fine-scale structure and a visibly sharper image. An equivalent improvement with the same RMS contrast of 40.2% is obtained when the oblique astigmatism term c_5 is used. Corrections performed using the vertical coma c_7 and vertical trefoil c_9 diversity phases yield RMS contrasts of 27.4% and 26.9%, respectively, values essentially indistinguishable from the initial aberrated image. This indicates that, for these two diversity modes, the compensation procedure fails to produce any appreciable improvement in image quality.

These results are fully consistent with the SLM–PD correlation analysis presented in Sec. 3. As shown in Fig. 4, the diversity phases generated by c_4 and c_5 exhibit a well-defined diagonal trend in the correlation matrices, with limited crosstalk toward other Zernike coefficients. This allows the PD algorithm to retrieve an accurate estimate of the induced aberration and, in turn, to achieve effective compensation via Eq. (1). Conversely, the c_7 and c_9 diversity phases show a considerably weaker diagonal correspondence, with a significant fraction of the retrieved contribution distributed among other coefficients or lost in the PD reconstruction. As a consequence, the wavefront estimate obtained with these diversities is not representative of the actual aberration present in the system, and the resulting compensation does not translate into a measurable gain in image contrast. Overall, these simulation results confirm that the choice of diversity phase has a direct impact on the achievable compensation performance.

Although the results in Fig. 5 demonstrate a significant recovery of image quality when employing the c_4 and c_5 diversity phases, diffraction-limited performance is not reached. This limitation can be explained by the crosstalk analysis presented in Sec. 3. As discussed there, the relationship between the phase map imposed on the SLM and the set of coefficients retrieved by the PD algorithm is not strictly diagonal. Consequently, the direct application of Eq. (1) cannot fully cancel the aberrations, leaving residuals that prevent the system from reaching its maximum performance.

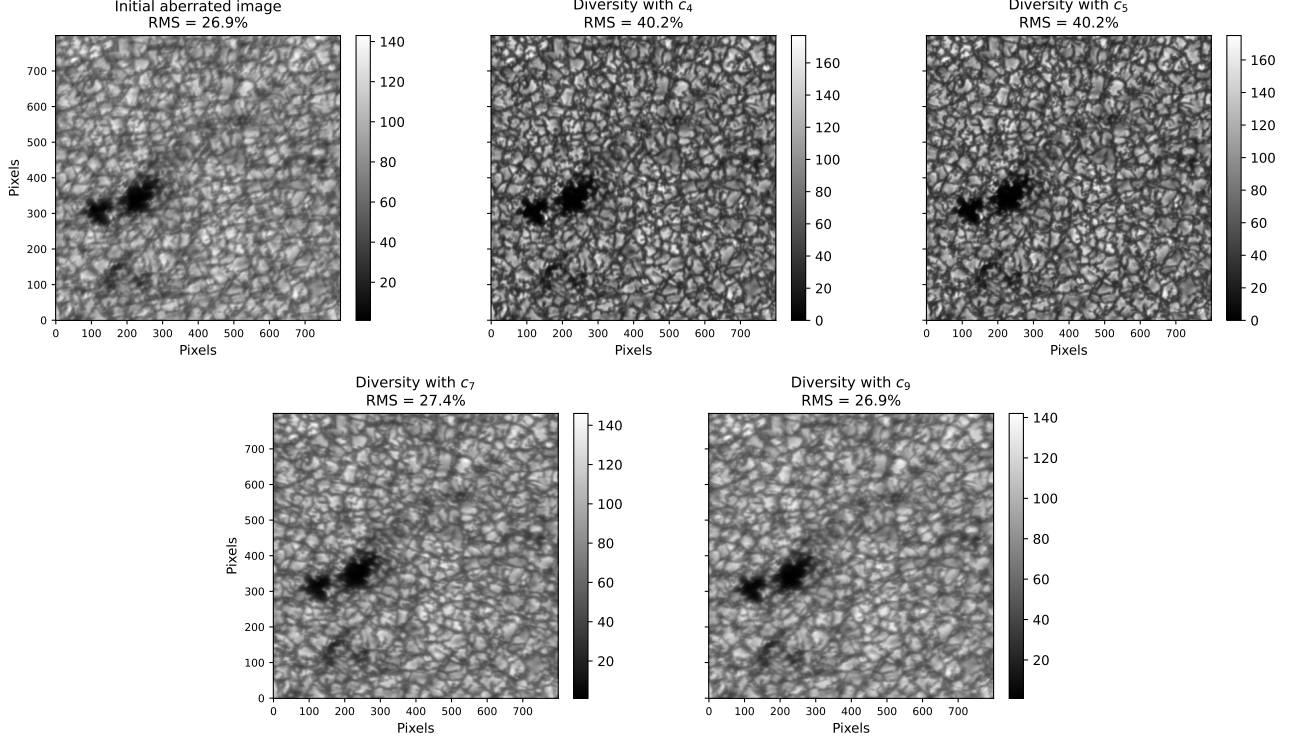


Figure 5: Simulated solar images before and after applying individual wavefront corrections. Top row, from left to right: initial aberrated image, correction using the c_4 diversity phase, and correction using the c_5 diversity phase. Bottom row, from left to right: corrections using the c_7 and c_9 diversity phases. The value shown above each panel corresponds to the relative RMS contrast.

This behavior is even more critical under real experimental conditions, as shown in Sec. 6, where the laboratory demonstrator exhibits a weaker correspondence between the imposed and retrieved coefficients. This finding has a key implication for the design of the active optics system: the compensation strategy cannot rely on a single correction step, but must instead be implemented as an iterative scheme. An iterative correction process would allow residual crosstalk and experimental errors to be gradually mitigated, thus providing the most plausible path toward diffraction-limited performance in a solar space instrument.

6. PRELIMINARY EXPERIMENTAL RESULTS

To provide an initial experimental validation of the compensation approach described in Sec. 4, we implemented a laboratory demonstrator that reproduces the modified IMaX optical layout presented in Sec. 2. The setup follows the same $4\text{-}f$ configuration considered in the simulations, with the SLM located at a pupil plane and used as a programmable phase element. This experimental arrangement allows controlled Zernike phase maps to be displayed on the SLM, the corresponding focused-diversity image pairs to be acquired, and the data to be processed with the same PD algorithm used in the simulation analysis. As a first step, we repeated the SLM-PD correlation analysis under laboratory conditions. In this preliminary experiment, only the defocus term was used as the diversity phase ($c_4^{\text{SLM}} = 1 \lambda \text{ PV}$). Additional aberrations were then sequentially induced up to the 21st Zernike coefficient, and for each case a focused-diversity image pair was acquired and processed. The retrieved Zernike coefficients are shown in Fig. 6. The experimental matrix preserves, to some extent, the diagonal trend observed in the simulated case for defocus diversity. However, the diagonal behavior is significantly less clear than in the ideal simulation shown in Fig. 4a, and a larger fraction of the retrieved signal is distributed among other Zernike coefficients. This degradation of the diagonal correlation with respect to the simulated case is expected, since the laboratory demonstrator includes effects that were not present in the ideal CODE V model.

These include residual optical misalignments, imperfect pupil matching, calibration uncertainties in the SLM phase response, camera noise, finite sampling effects, and possible deviations from the ideal paraxial propagation assumed in the simulations. As a consequence, the experimental PD retrieval exhibits stronger crosstalk among Zernike modes, meaning that an aberration displayed as a single Zernike coefficient on the SLM may be reconstructed as a combination of several coefficients.

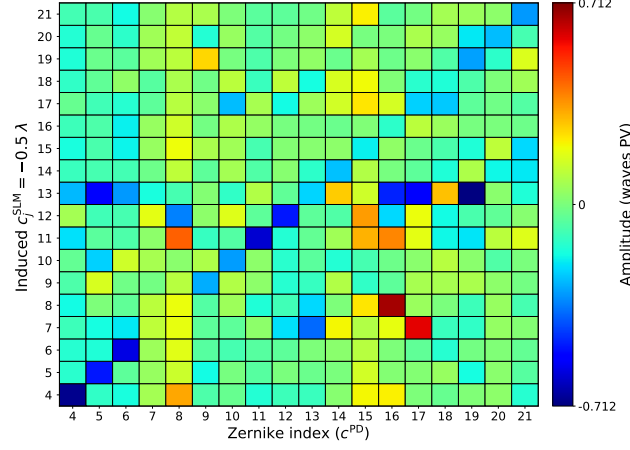


Figure 6: Zernike coefficients retrieved by the PD algorithm from experimental focused–defocused image pairs. For each induced aberration, the first image of the pair has a phase map of $\phi_1^{\text{SLM}} = c_j^{\text{SLM}} = -0.5 \lambda$ PV, while the second image has $\phi_2^{\text{SLM}} = c_j^{\text{SLM}} + \text{diversity}$. The applied diversity phase corresponds to 1λ PV of c_4^{SLM} . Each row corresponds to the retrieved PD coefficients, c^{PD} . The colormap encodes the coefficient amplitude in PV waves.

These results confirm that, under experimental conditions, the nearly direct relationship between the aberration introduced on the SLM and the coefficients retrieved by the PD algorithm enables the implementation of the compensation strategy discussed in Sec. 4. However, the stronger crosstalk observed in the experimental correlation matrix indicates that a single direct correction based on Eq. (1) is not expected to fully cancel the wavefront error. This result is consistent with the ideal simulation analysis presented in Sec. 5, where residual aberrations remained after one compensation step. Therefore, the compensation process must be implemented as an iterative procedure, in which the residual wavefront error is repeatedly estimated by PD and corrected by updating the phase map displayed on the SLM.

To assess this approach, we performed a preliminary iterative compensation experiment with the laboratory demonstrator. At each iteration, a focused–diversity image pair was acquired, the residual Zernike coefficients were retrieved by the PD algorithm, and the corresponding corrective phase map was applied to the SLM following the compensation principle described by Eq. (1). The evolution of the retrieved coefficients during this process is shown in Fig. 7. The horizontal axis represents the Zernike index, whereas the vertical axis indicates the iteration number. The progressive reduction of the coefficient amplitudes over the successive iterations shows that the iterative compensation scheme is able to mitigate a significant part of the residual aberration left after the first correction step, eliminating almost all aberration contributions and bringing the system close to diffraction-limited performance after five or more iterations. Although these results are still preliminary, they provide an experimental validation of the proposed SLM-based active optics concept. The demonstrator confirms that the combination of PD and an SLM can be used not only to sense wavefront aberrations, but also to apply in situ corrective phase maps.

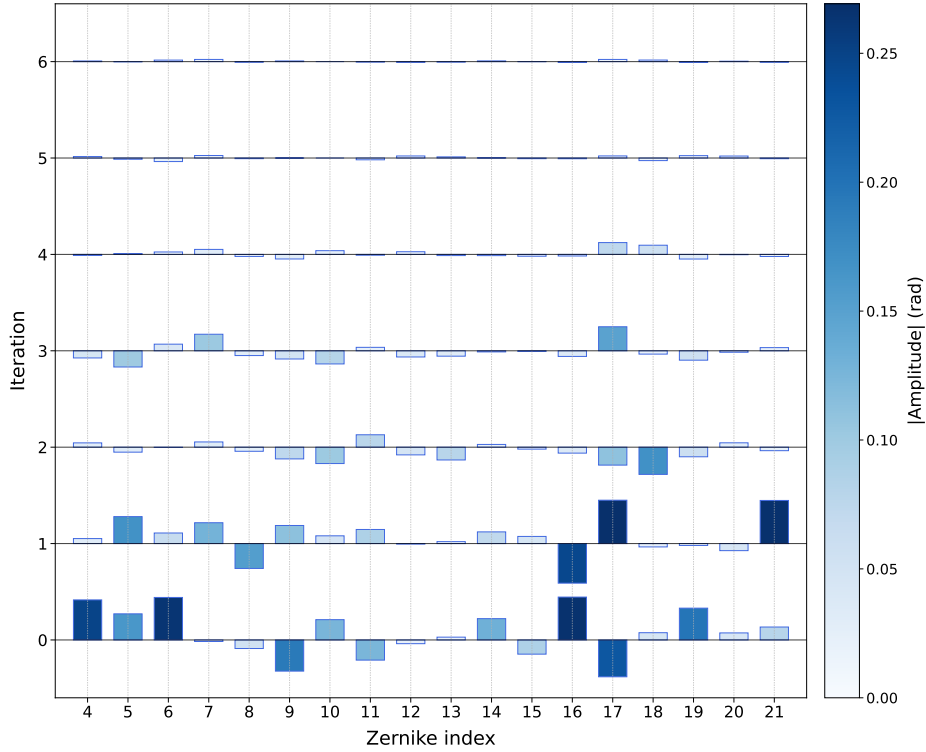


Figure 7: Zernike coefficients retrieved by the PD algorithm during each iteration of the laboratory compensation procedure. The horizontal axis represents the Zernike index, whereas the vertical axis indicates the compensation iteration. For each iteration, the bars show the amplitude of the retrieved coefficients in radians, with positive and negative values plotted with respect to the zero-amplitude baseline of each iteration step. The colorbar encodes the absolute value of the coefficient amplitude in radians.

7. CONCLUSIONS

In this work, we assessed the performance of an active optics system based on the combination of Phase Diversity and a Spatial Light Modulator for a solar spectropolarimetric instrument. The proposed approach was evaluated using a modified IMaX optical layout, first through a CODE V simulation and subsequently with a preliminary laboratory demonstrator. The SLM was used as a programmable phase element both to generate the diversity phase required by the PD algorithm and to introduce corrective phase maps for wavefront compensation.

The SLM–PD correlation analysis showed that the relationship between the Zernike coefficients displayed on the SLM and those retrieved by the PD algorithm is not perfectly diagonal. Even in the ideal simulated system, part of the imposed aberration is redistributed among different Zernike modes or lost in the inverse reconstruction process. This effect depends strongly on the diversity phase used. Among the diversity modes considered in this work, the defocus term c_4 and the oblique astigmatism term c_5 provided the strongest direct correlation, whereas vertical coma c_7 and vertical trefoil c_9 showed a weaker correspondence and a larger crosstalk.

The simulated compensation results confirmed that a direct correction strategy can significantly improve the quality of aberrated solar scenes when suitable diversity phases are used. In particular, corrections based on the c_4 and c_5 diversity modes produced a clear recovery of image contrast and sharpness. However, the compensated images did not reach diffraction-limited performance. This limitation is attributed to the non-ideal correspondence between the SLM coefficients and the PD-retrieved coefficients, which prevents complete cancellation of the aberrated wavefront through a single compensation step. Preliminary experimental results obtained with the laboratory demonstrator further support these conclusions. The experimental SLM–PD correlation matrix obtained with defocus diversity preserves a nearly direct relationship between the induced and retrieved

coefficients, confirming that the compensation strategy can be implemented experimentally. Nevertheless, the diagonal behavior is weaker than in the simulation, and stronger crosstalk among Zernike modes is observed. This is expected due to experimental effects such as misalignments, SLM calibration uncertainties, and other deviations from the ideal paraxial model.

These results indicate that, under realistic experimental conditions, wavefront compensation should not rely on a single correction step. Instead, an iterative scheme is proposed, in which the residual aberration is estimated after each correction and the phase map displayed on the SLM is updated accordingly. The preliminary iterative experiment performed with the demonstrator shows that this approach can progressively reduce the retrieved residual coefficients, providing a promising path toward more complete aberration correction and diffraction-limited image quality. The implementation of a closed-loop iterative compensation scheme, together with the extension of the analysis to other diversity phases and aberration amplitudes, represents an interesting topic for future work. In particular, the combination of several diversity modes within the same compensation process may provide additional information to the PD algorithm and help reduce modal crosstalk. Such a multi-diversity approach could enhance the robustness and accuracy of the compensation strategy. Overall, the results presented here demonstrate the potential of SLM-PD-based active optics as a compact and flexible solution for future balloon-borne and space-based solar spectropolarimeters.

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