A low-cost and high-performance technique for adaptive optics static wave-front correction

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\begin{abstract}
Non-Common Path Error (NCPE) is one of the factors that limit an Adaptive Optics (AO) system to deliver ultra-high performance. To correct the NCPE associated static aberration, we propose a simple but robust and high-performance pupil-plane based wavefront measurement and correction technique, which can copy a single-mode fiber generated perfect wavefront to the AO system via an iteration optimization process, and the NCPE can be effectively corrected by directly commanding the Deformable Mirror (DM) of the AO system. Compared with the previous focal-plane based approach that uses focal plane based Point Spread Function (PSF) for correction evaluation, the pupil-plane based approach can be reliably and rapidly converged to a global optimization result and provides better performance, in particular for an AO system with a large initial static wavefront error. This technique we proposed can be used for astronomical AO systems where extremely high performance is required.

\textbf{Key words:} astronomical instrumentation:adaptive optics — astronomical instrumentation:high angular resolution — astronomical techniques:high angular resolution
\end{abstract}

\section{1 INTRODUCTION}

To correct atmospheric turbulence perturbation induced wavefront errors and to achieve diffraction-limited imaging performance, AO systems are being used for ground-based observations. Recently, extreme adaptive optics (ExAO) is proposed for the high-contrast exoplanet imaging. The ExAO systems were optimized for extremely high performance, which will be able to deliver a SR better than 0.9 and a contrast up to $10^{-7}$ for coronagraphic imaging within a few $\lambda/D$ to the host star. For such a challenging task, studies show that one of the performance limitations is the NCPE that is introduced by the physical separation between the AO wavefront sensor (WFS) path and the science camera path (Ellerbroek \textit{et al.} 2010), which cannot be measured by the AO WFS and thus cannot be corrected by the AO closed loop system. Therefore, this static optical error must be effectively removed, before the ExAO can be used for the high-contrast exoplanet imaging.

The previous approaches adopted by the ExAO for the NCPE correction are complicated and time-consuming, since dedicated hardware system will be needed to achieve ultra-high performance. They
adopted a two-step approach that involves two independent procedures for the measurement and the correction, respectively. In the first step, only the wavefront error is measured, such as by using the phase diversity (PD) algorithm (Gonsalves 1982) or a dedicated interferometer (Wallace et al. 2011; Bauman et al. 1999), in which no wave front error correction is applied and the measured results are output as Zernike polynomial. For example, the traditional PD algorithm uses a couple of focused and defocused images to measure wavefront errors only (Blanc et al. 2003; Jean-Francois et al. 2007). In the second step, the measured wavefront error of the Zernike polynomial is imported to an AO system. Since the first step measurement is relied on traditional general wavefront measurement techniques such as the PD and interferometer that only provide the wavefront measurement expressed by the Zernike polynomial, one needs to consider how to input this result into an existing AO system to correct this wavefront error. In principle, in the second step of the wavefront correction, one can manually input the measured Zernike polynomial to an existing AO system and then command its DM to correct this error measured in the first step. Of course, one can also modify an existing AO code to accommodate the Zernike polynomial generated in the first step. Even though, there are still some potential issues for this 2-step measurement-correction approach. The measurement accuracy of PD technique is limited by the number of the Zernike polynomial orders used. For example, the phase diversity for the VLT measured 15 orders of Zernike polynomials only (Hartung et al. 2003), and high frequency wavefront message is missed because of the use of the polynomial. The order of the measured Zernike polynomial may not exactly match what the DM can correct. In addition, because the separation of the wavefront measurement and the AO correction, the alignment of the measured wavefront with the AO system such as the wavefront orientation is also an issue, which further limits the final performance that the AO can deliver. Although the dedicated interferometers can deliver high accuracy wavefront measurement (Wallace et al. 2010, 2011; Hinkley et al. 2011), an interferometer is sensitive to the vibration, stray light, and temperature change in the measurement environment, which may degrade its actual performance. Because of the inherent nature of the two-step approach, the errors introduced in the measurement process will be eventually added into the correction process (Jean-Francois et al. 2007; Blanc et al. 2003; Wallace et al. 2011), which limits the final correction performance.

In our previous work, based on a multi-core personal computer and LabVIEW software programming, we had developed a portable AO system (Ren et al. 2010; Ren & Dong 2012). This portable system uses off-the-shelf commercial components, and is further developed for the high-contrast exoplanet imaging with 4-meter class telescopes, including the ARC 3.5-meter telescope located at the Apache Point Observatory, USA and the 3.58-meter Telescopio Nazionale Galileo (TNG) located at the Roque de los Muchachos Observatory on the island of La Palma, Spain. As a visiting instrument, the NCPE must be corrected rapidly in an efficient way before any AO observation can be conducted on the same day. As such, we proposed a focal-plane based wavefront sensing and correction approach, in which both the wavefront error measurement and correction are integrated in a single step and optimized in our SPDG algorithm until good performance is achieved. Since it uses the AO system’s DM to directly correct the wavefront and avoids the use of the intermedium wave reconstructed by the Zernike polynomial, the correction fully matches the DM correction capability (Ren et al. 2012). This approach uses the focal plane science camera to evaluate the PSF image, and directly commands the DM to correct the wavefront error. However, since the measurement is done with the PSF on the focus plane where the PSF intensity in the area outside the Airy disk is weak and is rapidly dominated by the WFS camera’s readout noise as well as the camera’s limited dynamic range, the focal-plane based approach needs a large amount of time to optimize to achieve acceptable performance, and in the worst case it may deliver a local optimization result, instead of a global one, which further limits this approach’s performance.

In this article, we propose a novel pupil-plane based measurement and correction technique to measure and correct the NCPE simultaneously in a single step. By using an iteration optimization algorithm such as the stochastic parallel gradient descent (SPGD) approach, a perfect reference wavefront, which is free of optical aberration, is used to provide an effective guide for the optimization in the correction process, and thus it can significantly speed the correction process and achieve a global optimization for the NCPE correction. Since the measurement is done on the pupil plane, the previous weaknesses associated with the PSF measurement on the focus image plane are avoided. The hardware setup is
relatively simple, and this approach is robust and can deliver excellent performance at different circumstances with different initial wavefront errors. This article is organized as follows. In Section 2, we will describe the general principle of our pupil-plane based approach dedicated to the AO NCPE correction. In Section 3 and 4, we present our laboratory experimental test and result, in which we describe our pupil-plane based wavefront optimization result. In Section 5, we compare different approach for the NCPE correction. Finally, we discuss our conclusion in Section 6.

2 WORK PRINCIPLE

Fig. 1 shows the schematic diagram of the AO system we used for the NCPE correction. The light from a single-mode fiber (SF1) is collimated by lens L1 and reflected by a tip-tilt mirror (TTM) and a deformable mirror (DM), which can be commanded to correct possible NCPE aberration. A non-polarized beam-splitter (BS) directs part of the incoming light to the AO wavefront sensor (WFS) path and science image path, respectively. The AO WFS path consists of lenses L2 and L3, a microlens array (MLA), and a high-speed camera (C1) for real-time AO wavefront sensing. At the science image path, the science camera (not shown), which is located on the AO output focal plane immediately after the science image lens L4, is replaced by an assembly that consists of a lens L5 and a Shack-Hartman wavefront sensor (SH-WFS) during the period of the NCPE measurement and correction. Please note that the SH-WFS is used for the NCPE measurement and correction only, and it is not a part of the AO closed-loop system for the AO real-time wavefront correction, for which the AO has its own WFS shown in the AO WFS path in this figure. The L5 is used to generate an exit pupil image on the surface of the MLA in the SH-WFS, where the measured wavefront is sampled and imaged. A second single-mode fiber (SF2), which only allows the fundamental wavefront mode going through and thus is free of optical aberration, can be inserted into the focal point of the lens L5 to generate a perfect reference wavefront for the NCPE wavefront measurement and correction. Each time, either the reference light (SF2) or the AO light source (SF1) will be located in the optical path to be imaged by the system. After the completion of the NCPE wavefront measurement and correction, the SF2, L5 and the SH-WFS assembly in the AO image path will be removed from the optical path, and the science camera can be switched back to the optical path for regular AO closed-loop imaging.

Table 1 lists the extra hardware required to construct our pupil-based SPGD measurement-correction system. The single-mode-fiber assembly, including both a HeNe cylindric laser light source, a single-mode fiber patch (SF2) and the associated mount, was purchased from Thorlabs Inc. The output end of the single-mode fiber and its mount are installed on a standard pedestal-style post holder (purchased from Thorlab Inc), which allows the manual alignment in the XYZ directions. The collimator lens is a standard mounted lens (purchased from Thorlab Inc), and it has a focal length of 50mm. In our actual field observations, we use a microlens array (purchase from Thorlab Inc) and a standard C-mount video camera to reconstruct the SH-WFS assembly. The microlens array is glued on a small aluminum tube that is directly screwed into the C-mount camera. The extra total physical size required for the NCPE correction is 150mm immediately after the AO science image focus, which is used to accommodate the collimator lens and the small SH-WFS assembly. Since all components are commercially available, the cost of the NCPE correction system is not expensive. When implementing the NCPE correction, the AO science camera is moved out of the optical path to provide the necessary physical space, and it is removed back after such a correction is completed. Since large amount of off-the-self components are used, the cost required for the hardware for the NCPE system is much low. Please note that in this experiment, we used a standard SH-WFS assembly previously purchased from the Thorlab Inc, which includes its software for the characterization of the corrected wavefront error by measuring the Zernike polynomials, and such a characterization is not necessary for our actual field observations.

The following alignment procedure is involved to take data that will be used for the measurement and correction of the NCPE. First, the AO SF1 image is recorded by the SH-WFS camera in the science image path, which includes all of the static wavefront information, as shown in Fig. 2(a). This standard SH-WFS focal plane image consists of an array of spots, in which each microlens sub-aperture forms a
Fig. 1: The schematic diagram of the AO NCPE measurement and correction system.

Table 1: Hardware required for the construction of the pupil-based SPGD measurement-correction system.

<table>
<thead>
<tr>
<th>Method</th>
<th>Hardware</th>
</tr>
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<tbody>
<tr>
<td>SPGD pupil-plane method</td>
<td>Single-mode-fiber assembly (SF2), collimator lens, SH-WFS, C-mount camera.</td>
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</table>

Fig. 2: (a) Recorded SH-WFS image on the AO science image path. (b) The original image taken before the alignment of the 2 fiber images. (c) The final image taken after the well alignment of the 2 fiber images.

Point Spread Function (PSF) spot of the image. Thus, any deviation from the perfect spot position will be an indication of associated wavefront aberrations that need to be corrected.

Secondly, the AO SF1 light source is blocked and the single-mode fiber SF2 is inserted into the SH-WFS focus to replace the AO SF1 light source. The image of the SF2 is served as the perfect wavefront and thus its spot array is used to define the perfect spot position in each sub-aperture that has no wavefront error. During this process, the previously recorded AO SF1 spot array is shown as a background image in an output display window, as shown in Fig. 2(b). The SF2 is installed on an XYZ translation stage, and is moved as close as possible to overlap with the spot array previously generated by the SF1. An overall image shift between SF1 and SF2 corresponding to a tip-tilt error between these 2 wavefronts, and thus a small shift will be preferred to reduce the correction burden applied to the DM. Fig. 2(b) shows the initial image before these 2 fiber images are aligned, and Fig. 2(c) shows the final image after the 2 fiber images are well aligned, by carefully moving the SF2 single-mode fiber via the XYZ translation stage. Now, since the AO system has some NCPE, the spots between these 2 images generated by these 2 fibers cannot be exactly overlapped, as shown in Fig. 2(c), which must be corrected by the AO DM until all spots are exactly overlapped. Please note that in principle the quality of lens L5 in Fig. 1 will not affect the correction results of the NCPE, since the both the AO image and the SF2 reference optical paths go through the same portion of this lens, and any potential wavefront
error induced by the lens L5 will be removed by the subtraction of the spot centroid in each sub-aperture between these two beams, in our NCPE measurement and correction.

Once the above alignment is done, we can command the AO DM to change the DM’s shape to correct the NCPE, until all spots generated by SF1 and SF2 are exactly overlapped. To achieve this goal, we can use an iterative optimization approach. For our NCPE correction, we use the well-known SPGD algorithm (Vorontsov et al. 1997; Vorontsov & Sivokon 1998; Vorontsov & Yu 2004). It applies small random perturbations to all control parameters (i.e. the voltages of DM actuators) simultaneously and then evaluates the gradient variation of a metric function $J$. The control signals are updated in an iterative process using the following rule,

$$ u^{k+1} = u^k - \gamma \delta J^k \delta u^k $$

where $k$ is the iteration number; $u = u_1, u_2, ..., u_n$ is the voltages of DM actuators, $n$ is the number of effective actuators; $\gamma$ is a constant gain coefficient which is positive for minimizing and negative for maximizing the metric function $J$; It is in the range $0 < \gamma < 0.01$, and in our test a value of 0.002 was used. $\delta u$ denotes small random perturbations that all elements of the $\delta u$ have identical amplitudes and but pseudorandom signs (Bernoulli distribution). An initial 0 value for all elements of $\delta u$ was used in our test. $\delta J$ is the variation of the system’s performance metric function,

$$ \delta J = J(u + \delta u) - J(u) = J(u_1 + \delta u_1, ..., u_n + \delta u_n) - J(u_1, ..., u_n) $$

To improve the estimation accuracy of $\delta J$, a two-sided perturbation is used as follow,

$$ \delta J = J_+ - J_- = J(u + \delta u/2) - J(u - \delta u/2) $$

Even though a constant gain coefficient $\gamma$ was used for our test, a variable constant can also be used to accelerate the convergence,

$$ \gamma^{k+1} = \gamma^k J^k $$

Considering the correction system with a goal to remove the NCPE and achieve a perfect plane wavefront on the exit pupil of the AO system image path, the SF2 generated wavefront is viewed as a prefect wavefront to provide an explicit guide for the optimization direction in each iteration in the correction process. The metric function $J$ is used to evaluate the wavefront difference between the perfect reference and AO actual waves. For the SH-WFS with $m$ effective sub-apertures, we define the metric function $J$ to be optimized as

$$ J = \sum_{i=1}^{m} (x_i - x'_i)^2 + (y_i - y'_i)^2 $$

where $(x_i, y_i)$ and $(x'_i, y'_i)$ are the centroid coordinates of AO (generated by SF1) and the reference (generated by SF2) light sources in each microlens sub-aperture $i$ of the SH-WFS, respectively. As the above equation indicates, the metric function $J$ will have a minimum value after the optimization, which corresponds to a wavefront difference minimum between the reference and AO paths. In perfect case, $(x_i, y_i)$ and $(x'_i, y'_i)$ are overlapped at every microlens of the WFS, so that we have $(x_i, y_i) = (x'_i, y'_i)$ and thus $J$ is equal to 0 and a minimum is achieved. In a real operation, because of the measurement noise, the $J$ cannot be optimized to be 0, and a small value will be an indication of good performance for the optimization. Please note that SPGD Equations (1) to (4) were used previously by other researchers for the closed loop operation of an AO system in which no WFS is needed (Vorontsov et al. 1997; Vorontsov & Sivokon 1998; Vorontsov & Yu 2004). For our metric function Equation (5), as we will see in our laboratory test in next section, it will deliver a excellent PSF correction with a Strehl ratio of 0.995, and both the $(x_i, y_i)$ and $(x'_i, y'_i)$ are overlapped at every microlens after our SPGD optimization (see Fig. 6), which indicates a global optimization is achieved. Please note that the metric function is not only simple overlap between two independent light sources. It used an SH-WFS to record the image position of all
the effective sub-aperture, i.e. the wave-front phase information. Then, the recorded perfect reference wave-front is copied to the AO system by SPGD algorithm. Therefore, after the correction, the NCPE is effectively corrected.

Once the above SPGD correction is done, the DM voltages are locked and are used as the DM reference voltages for the AO system. The DM reference voltages correspond to a perfect wave-front that the AO will correct for. Therefore, by simply replacing the DM reference voltages in our AO system, the single-mode fiber SF2 generated reference wavefront is copied to our AO system for real-time closed-loop operation. Also, by directly commanding the DM in the wavefront measurement and correction in each of our SPGD optimization iteration and without the need of the intermediate wavefront reconstruction, we are able to integrate both the wavefront measurement and correction in a single step.

3 LABORATORY TEST

Fig. 3 shows the experimental setup in the laboratory. A HeNe laser light source of $\lambda=632.8$ nm wavelength is used for this test via the single-mode fiber SF1. According to the waveguide theory a single-mode fiber only allows the fundamental wave mode to go through and thus can provide a perfect wavefront. The TTM is a fast-tilting platform provided by PI Corporation. The DM is purchased from the ALPAO Corporation with 97 actuators (in 11 × 11 configuration, excluding those actuators in the four corners). The SH-WFS is purchased from the Thorlabs Inc (WFS150-5C). Thorlabs SH-WFS provides a function of user reference pupil, which allows users to define a reference wavefront that has zero wavefront. Only 90% of the beam with a 3-mm diameter is used to measure the wavefront and PSF images. To measure and correct the NCPE, we wrote a dedicated LabVIEW code to grab images from the SH-WFS and command the DM with the SPGD algorithm discussed previously. Zernike polynomial are measured by using the software provided by the Thorlabs, for performance evaluation purpose only, although this is not necessary for our NCPE measurement and correction.

The AO NCPE measurement and correction consist of these procedures for the system alignment and measurement-correction, respectively:

1. Recording the reference wavefront.

Close shutter S1 and insert the SF2. This only allows the reference wavefront to be measured. The SH-WFS will record the reference wavefront’s centroid coordinates of all effective microlenses. The corresponding centroid coordinates are recorded and used to serve as the reference wavefront. Since the quality of the reference wavefront directly affects the final correction result, we therefore use a single-mode fiber SF2 as the light source, which is free of optical aberration. Each reference centroid coordinate in each sub-aperture will provide a guide direction during the NCPE correction. Any AO wavefront error is measured relative to these centroid coordinates of this reference wavefront. Please note that reference image can be recorded in advance before the correction.

2. NCPE correction.
Open the shutter S1 and remove the SF2 out of the optical path. This only allows the AO NCPE measured and corrected. A dedicated LabVIEW code was developed to control the DM according to the SPGD algorithm that optimizes all DM actuators’ voltages by evaluating the metric function $J$, according to Eq. 1 and Eq. 5. Fig. 4 shows our LabVIEW graphical user interface (GUI) in the SPGD optimization process for the evaluation of the metric function $J$ as a function of the correction iteration number. When the metric function $J$ has no significant reduction, the correction can be stopped and the DM voltages are automatically saved. Please note that the final metric function $J$ and the residual wavefront error is not in a linear relationship. In fact, an iteration value of 40,000 in Fig. 4 has almost no difference with a value of 60,000, in term of the residual wavefront error or the final Strehl ratio. With a commercial computer, the correction process takes about 45 minutes, which is a good value for a system with a large NCPE. The required SPGD optimization time is a function of the magnitude of the aberration to be corrected. For a smaller NCPE, 5 minutes will be enough to deliver a good correction result. Please note that here the AO system is optimized for high-contrast exoplanet imaging, where ultra AO performance is required. For the case if a low SR such as a SR of 0.8 is required for other general applications (Burke et al. 2015), the required optimization can be significantly reduced. Once the best wavefront is achieved, the DM voltages are saved and applied to the AO system by replacing the existing AO DM reference voltages so that high Strehl ratios (SRs) are achievable for the AO closed-loop operation. Please note that such an NCPE correction only needs to be done once for an AO system, if the system is installed in a stable platform.

4 EXPERIMENTAL RESULTS AND ANALYSIS

Fig. 5 (a) shows the focal plane PSF image, before the NCPE correction. As shown, the initial focal plane PSF has a large initial wavefront error, with a PV and an RMS of 766-nm and 110-nm, respectively, most contributed by the DM’s residual wavefront error, since the ALPAO DM we used generally has a large initial wavefront error. After the NCPE correction, the wavefront error is dramatically reduced. Fig. 5 (b) and Fig. 5 (c) show the AO focal plane PSF images with different exposures time, after the NCPE correction. Fig. 5 (b) shows the PSF image with a proper exposure, while Fig. 5 (c) shows the PSF with a 10-time overexposure, which provides more details to see the diffraction pattern. As shown, the wavefront error is greatly reduced after the NCPE correction. The PV and RMS wavefront errors are reduced to 45-nm and 7-nm, respectively. The metric function decreases from the original value of 2.6 to that of the 0.4 after the SPGD optimization by commanding the AO DM. Fig. 6 shows the SH-WFS spot image generated by both the AO image and the reference fiber optical paths after the SPGD optimization and the NCPE correction. Now, compared with Fig. 2 (c) before the correction, the spots generated by these 2 fibers after the correction are exactly overlapped, which indicates that the reference wavefront is effectively copied to the AO system.
Table 2: AO system wavefront error expressed by the Zernike polynomial coefficients.

<table>
<thead>
<tr>
<th>Zernike coefficient</th>
<th>Initial error</th>
<th>Corrected error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Astigmatism y</td>
<td>-0.020</td>
<td>0.002</td>
</tr>
<tr>
<td>Astigmatism x</td>
<td>0.091</td>
<td>0.003</td>
</tr>
<tr>
<td>Trefoil y</td>
<td>-0.006</td>
<td>0.001</td>
</tr>
<tr>
<td>Coma x</td>
<td>0.007</td>
<td>-0.002</td>
</tr>
<tr>
<td>Coma y</td>
<td>0.025</td>
<td>-0.001</td>
</tr>
<tr>
<td>Trefoil x</td>
<td>-0.012</td>
<td>0.001</td>
</tr>
<tr>
<td>Tetrafoil y</td>
<td>0.006</td>
<td>0.000</td>
</tr>
<tr>
<td>Secondary Astigmatism y</td>
<td>-0.005</td>
<td>0.001</td>
</tr>
<tr>
<td>Primary Spherical</td>
<td>-0.023</td>
<td>0.001</td>
</tr>
<tr>
<td>Secondary Astigmatism x</td>
<td>0.005</td>
<td>0.000</td>
</tr>
<tr>
<td>Tetrafoil x</td>
<td>-0.056</td>
<td>0.005</td>
</tr>
</tbody>
</table>

Fig. 5: (a) Initial focal plane PSF image. (b) and (c) are the PSFs with different exposures achieved after the NCPE correction.

Fig. 6: The final spot image generated by the 2 fibers after the NCPE correction. Compared with the Fig. 2 (c) before this correction, the spots from both fibers are exactly overlapped.

Table 2 lists the associated Zernike coefficients of the wavefront error, before and after the NCPE correction. After the correction, all the Zernike coefficients are reduced, which indicates that the NCPE in the AO system is effectively corrected. The corrected wavefront map is shown in Fig. 7. The SR can be estimated by using the following rule

\[ SR = e^{-\sigma^2} \]  

where \( \sigma \) is the RMS wavefront error in radian. The 7-nm RMS error corresponds to 0.07 in radian at the 632.8-nm wavelength. This yields an SR of 0.995. As shown, the SR is improved from the initial 0.300 to the 0.995, which clearly demonstrates that our pupil-plane based NCPE measurement and correction approach can deliver an excellent performance.
5 THE COMPARISON EXPERIMENT

In this paper, we had introduced in detail a new pupil-plane approach for the NCPE measurement and correction. To fully evaluate the advantage of our pupil-plane approach, we will compare it with our previous focal-plane approach under the same experimental condition. The configuration of the focal-plane correction system is a typical AO system, except for that on the AO focal plane, the science camera is used for the evaluation by using the focal plane PSF, by using the SPDG optimization algorithm. Details of the focal plane correction approach are discussed by our previous publication (Ren et al. 2012). When an AO system has a large static wavefront error, it is difficult to be effectively corrected by the focal plane approach. For the above AO static wavefront error, an acceptable result is obtained by manually modifying the SPDG optimized parameters several times during the optimization process, with the correction result shown in Fig. 8. Now, the RMS error is 50-nm, which corresponds to an SR of 0.782. The focal-plane based correction takes about 150 min, which is much longer than that of the pupil-plane based approach.

The performance of both focal-plane and pupil-plane correction approaches are conducted and compared under the same experimental condition. In summary, when large initial static aberrations are presented in an AO system, the focal plane correction approach is more difficult to conduct to deliver good performance and it is easier to drop into a local optimization, which limits its performance. The experimental results show that the pupil-plane correction approach we presented in this publication can deliver much better performance, with much less required time for the optimization. Compared with the focal-plane method, the SR of pupil-plane method improves by 27% and the correction speed outperforms by a factor of 2.3. More important, it is easy to converge to a global optimization result, due to a perfect reference wavefront is used to guide the optimization direction. Sauvage et al. (2005) used a dedicated PD system for the AO NCPE correction. The experiment result shows that the corrected SR is 0.93 at the 632.8-nm wavelength (Sauvage et al. 2005). Recently, the PD technique can deliver a SR of 0.95 at the 632.8-nm wavelength for an AO system correction (Wang et al. 2017). Here, the pupil-plane approach we proposed delivers a better SR up to 0.995.
6 CONCLUSION

In this publication, a technique for fast and effective AO NCPE measurement and correction is demonstrated. This technique is based on the pupil-plane wavefront evaluation approach and is realized by using the SPGD iteration optimization algorithm that directly commands the DM, until all the SH-WFS spots generated by the AO science image path and that generated by a perfect reference wavefront are exactly overlapped. That is, the perfect reference wavefront is effectively copied by the AO system to remove any potential NCPE. Since the reference wavefront is used to guide the optimization direction, global optimization results can be achieved fast and reliably, which ensures that better correction is achievable than the traditional focal-plane based evaluation approach. Compared with other complex measurement techniques, such as the wavefront measurement by using dedicated interferometers, our pupil-based wavefront correction technique integrated both wavefront measurement and correction in a single step by directly commanding the AO DM via the SPGD optimization. With a perfect reference wavefront provided by a single-mode fiber, a Strehl ratio (SR) of 0.995 is achieved from an original value of 0.300, at the 632.8-nm test wavelength.

Since our pupil-based SPGD correction is based on the numerical iteration optimization, any local and temporal disturbance such as a short-period vibration or local air turbulence will only disturb a few iterations, which can be compensated by other following iterations and thus will not degrade the final optimization performance. It is a robust technique, which makes it more practice to be used in different environmental circumstances. This work provides a novel and robust technique for effective AO NCPE corrections.

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