Static Aberration Correction Technology for Adaptive Optical Systems Based on Wavefront Replication Method*

Li Haibo

2026-08-18

ChinaRxiv

Abstract

Non-Common Path Aberration (NCPA), caused by differences between the wavefront sensing path where the wavefront sensor is located and the imaging path where the scientific camera is located, is one of the key factors limiting an Adaptive Optics (AO) system from achieving diffraction-limited imaging performance. At the same time, optical components in the common optical path of an AO system also introduce static aberrations. To suppress static aberrations in an adaptive optics system, a technique based on wavefront phase template reproduction is used. This technique uses the perfect wavefront image generated by a laser source on a Shack-Hartmann Wavefront sensor in the scientific imaging optical path as the reference wavefront information, and takes this reference wavefront information as the optimization target. Through an iterative optimization algorithm, deformable mirror control commands are generated to optimize the wavefront of the scientific imaging optical path to be consistent with the reference wavefront. Experimental results show that even when the AO system has large initial static aberrations, this technique can still stably obtain globally optimized correction results, improving the system Strehl Ratio (SR) from 0.309 before correction to 0.995.

Full Text

doi: 10.15940/j.cnki.0001-5245.2026.04.010

Static Aberration Correction Technology for Adaptive Optical Systems Based on Wavefront Replication Method*

Li Haibo[1,2]
Tian Peilin[2]
Zhang Tianyu[2]
Shu Chenggang[1†]

(1 School of Mathematics, Shanghai Normal University, Shanghai 200234)
(2 Nanjing Astronomical Instruments Co., Ltd., Chinese Academy of Sciences, Nanjing 210042)

Abstract Non-common path aberration (NCPA), caused by the difference between the wavefront-sensing path where the wavefront sensor is located and the imaging path where the science camera is located, is one of the key factors limiting adaptive optics (AO) systems from achieving diffraction-limited imaging performance. At the same time, optical components in the common optical path of an AO system also introduce static aberrations. To suppress the static aberrations in an adaptive optics system, a technique based on wavefront phase template replication is used. This technique uses a laser source to generate, on the Shack-Hartmann wavefront sensor in the scientific imaging optical path, a perfect wavefront image as the reference wavefront information, and takes this reference wavefront information as the optimization target. Through an iterative optimization algorithm, deformable-mirror control commands are generated, optimizing the wavefront of the scientific imaging optical path until it is consistent with the reference wavefront. Experimental results show that, even when the AO system has relatively large initial static aberrations, this technique can still stably obtain globally optimized correction results, increasing the system Strehl Ratio (SR) from 0.309 before correction to 0.995.

Keywords Instruments: adaptive optics; instruments: detectors; instruments: high angular resolution; techniques: high angular resolution

CLC number: P111; **Document code:** A

1 Introduction

Medium- and large-scale ground-based telescopes around the world have widely introduced or upgraded high-performance adaptive optics (Adaptive Optics, AO) systems to compensate for real-time aberrations caused by atmospheric turbulence[1-3]. However, after the telescope beam is introduced into the optical path of the AO system, the static aberrations present in the AO system' s imaging optical path, such as non-common path aberration (Non-Common Path Aberration, NCPA), can seriously affect the final imaging quality[4-7]. In particular, when directly imaging high-value targets such as exoplanets, because the contrast between the exoplanet and its host star is on the order of 10^{-6} to 10^{-10}, contrast aberrations are extremely critical[8-10]. Therefore, the AO system must optimize the final Strehl Ratio (SR) to above 0.9 to improve imaging contrast, while static aberrations in the AO system will greatly reduce the overall correction capability of the system[11-13].

An adaptive optics system generally consists of a common-path aberration correction execution module, a non-common-path imaging module, and a wavefront sensing module. The so-called NCPA is caused by differences in the optical path between the imaging module and the wavefront sensing module. During operation of an adaptive optics system, the wavefront sensing module usually cannot perceive the static aberrations present inside the imaging module. Therefore, even if the system is in a closed-loop correction state, this portion of the static aberration cannot be identified and compensated by the system. At the same time, the initial surface shape of the deformable mirror in the aberration correction execution module also introduces static aberrations into the common path. In order for the AO system to obtain imaging performance close to the diffraction limit[14], various static aberrations within the system must be eliminated in advance before closed-loop correction is applied[15-16].

Ren et al.[17] proposed in 2012 a method based on random parallel gradient

Received original manuscript: 2025-12-08; received revised manuscript: 2026-02-09
* Supported by the Jiangsu Provincial Basic Research Program (Natural Science Foundation Project) (BK20251068)
† cgshu@shao.ac.cn

descent algorithm (Stochastic Parallel Gradient Descent algorithm, SPGD) for static aberration correction in AO systems. This method uses the focal-plane energy distribution as the evaluation function and generates the control voltage of the deformable mirror through the SPGD algorithm, with the optimization objective of concentrating the focal-plane energy of the AO-system scientific imaging optical path, thereby improving the imaging SR of the system. However, in practical operation, when the static aberration of the system itself is large, this SPGD-based energy-optimization method is very prone to falling into a local optimum and is difficult to achieve a truly globally optimal correction effect.

To overcome the drawback that energy-optimization methods are prone to becoming trapped in local optima, Zhang Tianyu et al.[18] proposed an AO-system static aberration correction technique based on focal-plane replication. The implementation of this technique begins by using an ideal point light source to generate a point spread function (Point Spread Function, PSF) image matched to the imaging system, and taking it as the standard reference image. Based on this reference image, the SPGD algorithm is applied to actively shape the wavefront in the system' s imaging optical path, driving the deformable mirror to perform continuous correction so that the PSF output by the system continuously approaches the reference image, until the static aberration is effectively corrected. However, during the correction process, this method is relatively sensitive to the light intensity of the reference PSF, and the size of the reference PSF image has a relatively large influence on the number of optimization iterations.

In view of the defects of the above methods, this paper develops a correction technique based on wavefront replication. The key to this technique is how to define a "perfect" reference wavefront: this paper directly uses the result imaged by a point light source on a Shack-Hartmann wavefront sensor (Shack-Hartmann Wavefront sensor, S-H WFS) as this ideal reference. Then, taking this reference wavefront as the target, an optimization algorithm is used to guide the wavefront state of the imaging optical path to converge toward it, thereby achieving effective elimination of static aberration. Compared with energy-optimization methods, the wavefront-replication method takes reference wavefront information as the optimization objective, which can reduce the number of optimization iterations and more stably obtain the global optimum.

Fig. 1 Block diagram of static aberration correction system

Figure 1: Fig. 1 Block diagram of static aberration correction system

2 Correction Principle

2.1 Static Aberration Correction System

Figure 1 is the schematic diagram of the static aberration correction system proposed in this paper. In this experiment, No. 1 laser (Light Source1) is used as the main light source. After its light is collimated by lens L1, it is guided to a fast steering mirror (Tip-Tilt Mirror, TTM) and a deformable mirror (Deformable Mirror, DM) for reflective modulation, and then is split by a beam splitter (Beam Splitter, BS) into the science imaging path (Science Image) and the wavefront-sensing (WFS) path. The optical components of the wavefront-sensing path include lenses L4 and L5, a microlens array (Microlens Array, MLA), and a wavefront-sensing camera (WFS Camera). In the system, three plane mirrors FM1, FM2, and FM3 are used to change the light-path direction. In order to correct the static aberration in the system, the scientific camera used for astronomical imaging in the science imaging path is temporarily replaced during static-aberration correction by lens L3 and an S-H WFS. L3 is used to form the wavefront image on the S-H WFS, i.e., the wavefront spot-array image. During static-aberration correction, this image is used as real-time wavefront sampling information for the AO-system wavefront imaging optical path. To provide the optimal optimization direction for the iterative optimization algorithm, No. 2 laser (Light Source2) is led out through a single-mode fiber and placed at the focal point of L3 as an ideal reference point light source, to generate a perfect reference wavefront and record the wavefront image with the S-H WFS. In this system, the reference light source is assumed by default to be a perfect point light source, and the aberration introduced by L3 is ignored. No. 2 laser serves as the reference light source only before correction begins; after the perfect reference wavefront is generated and saved as the reference wavefront image, it is removed from the wavefront imaging optical path so as not to interfere with the main light source in static-aberration correction. After the static aberration has been completely removed by the correction system, lens L3 and the S-H WFS in the science imaging path can be removed, and the scientific camera can be placed back at the focal point of L2. This position is calibrated and recorded with a graduated rail when the adaptive-optics system is built; it is unrelated to the positions of lens L3 and the S-H WFS during the correction process. Moreover, the entire correction procedure needs to be performed only once. In subsequent use, the entire AO system can be used normally for scientific observation by taking the DM control voltage obtained after correction as the initial voltage; the additional devices used during correction do not need to remain in the AO system for repeated operation.

图 1　静态像差校正系统原理图

Fig. 2 wavefront images

Figure 2: Fig. 2 wavefront images

Fig. 1 Block diagram of static aberration correction system

The correction steps are as follows:

(1) Turn off the primary light source, and place at the focal point of lens L3 a reference light source led out by a single-mode fiber, so that it serves as a perfect point light source. After passing through L3, it forms a perfect reference point-array wavefront image on the S-H WFS, as shown in Fig. 2(a). This image needs to be recorded only once; it can be directly invoked in subsequent correction.

(a) (b) (c)

Fig. 2 Wavefront images at different stages in the correction process. (a) Reference point-array image of the perfect wavefront; (b) point-array image of the perfect reference wavefront used as the background and displayed simultaneously with the real-time sampled wavefront point-array image; (c) image after correction, in which the real-time wavefront and the reference wavefront point array completely overlap.

Fig. 2 Wavefront images of different stages in correction process. (a) Reference wavefront grid image; (b) wavefront grid image displayed alongside real-time sampled image, using the perfect reference wavefront grid as background; (c) image after correction, where the real-time wavefront perfectly overlaps the reference wavefront grid.

(2) Move the reference light source out of the optical path, turn on the primary light source, sample the real-time wavefront image formed on the S-H WFS in the scientific imaging optical path, and use the perfect reference wavefront point-array image recorded in step (1) as the background to display it simultaneously with the real-time sampled point-array image, as shown in Fig. 2(b). Owing to the presence of static aberrations in the AO system, there are positional deviations between the spots in the corresponding subapertures of the two wavefront images.

(3) Invoke an iterative optimization algorithm, taking the perfect reference wavefront image as the iterative optimization target. When the point array on the real-time wavefront image overlaps the perfect image, the static aberration can be regarded as having been corrected, as shown in Fig. 2(c). After the correction is completed, remove the equipment that does not exist in the original AO-system scientific imaging optical path, and after reinstalling the scientific imaging camera, the adaptive optics system can be used normally.

2.2 Correction algorithm

This paper uses the SPGD algorithm, taking the reference wavefront as the iterative optimization target, to correct static aberrations present in the AO system. Because the SPGD algorithm has advantages such as fast convergence and easy deployment, it is often applied in wavefront-sensorless adaptive optics systems to accomplish tasks such as laser communication and astronomical target imaging

19–21

. The SPGD algorithm improves upon the gradient descent algorithm derived from traditional control theory; this method aims to estimate the gradient direction by applying parallel random perturbations. Specifically, in each iteration, a set of weak random perturbation signals is applied to all control signals, and the performance gradient is evaluated through the change in the metric function. The control signal is then adjusted accordingly until the metric function reaches the expected convergence effect. To generate multiple gradient directions for algorithm evaluation, the random perturbation signal is updated in each optimization iteration to ensure that the metric function can converge. The formula for generating the control signal in each iteration of the SPGD algorithm is:

$$u^{k+1} = u^k - \gamma \delta J^k \delta u^k, \qquad (1)$$

where k is the number of optimization iterations; u denotes the optimized control signal (the control voltage of the DM actuator); γ is the gain coefficient. When the metric function needs to be optimized toward a minimum, γ is taken as positive; otherwise it is taken as negative. δu is the applied random perturbation signal and follows a Bernoulli distribution. δJ is the change in the metric function, defined as:

$$\delta J = J(u + \delta u) - J(u), \qquad (2)$$

To improve the estimation accuracy of the change in the metric function, the method in this paper uses two-sided perturbation:

$$\delta J = J_+ - J_- = J\left(u + \delta \frac{u}{2}\right) - J\left(u - \delta \frac{u}{2}\right), \qquad (3)$$

To realize replication of the perfect wavefront into the wavefront imaging optical path, this paper proposes a metric function dedicated to wavefront-information replication. This function first evaluates the degree of overlap between the centroid coordinates of the spots in each subaperture of the perfect reference S-H WFS image and those in the real-time wavefront image formed on the S-H WFS. Through iterative optimization, the two are adjusted to overlap, thereby realizing wavefront replication and ultimately eliminating the static aberration within

Fig. 3 The experiment AO system for static aberration correction

Figure 3: Fig. 3 The experiment AO system for static aberration correction

the system. Suppose the S-H WFS image has n subapertures; i denotes the index of a subaperture; (x_i, y_i) denotes the centroid coordinates of the spots in each subaperture of the real-time wavefront image formed on the S-H WFS by the primary light source (laser No. 1) in the AO-system scientific imaging optical path; and (x_i', y_i') denotes the centroid coordinates of the spots in each subaperture of the perfect wavefront image prerecord by the reference light source (laser No. 2). β is an adjustment factor, with its value range set to $(0.001, 1)$. The main function of this coefficient is to calibrate the metric function, ensure that it has an appropriate dynamic range, and allow the optimization process to converge stably. The metric function proposed in this paper is as follows:

$$J = \sum_{i=1}^{n} \beta \left(\frac{x_i}{x_i'} + \frac{y_i}{y_i'} \right), \qquad (4)$$

From Eq. (4), it can be seen that, under ideal conditions, when the value of the metric function is equal to the ideal value $2\beta n$, the spots within each subaperture in the real-time wavefront image all overlap the spots in the corresponding subapertures of the reference wavefront image, and the wavefront state of the imaging optical path can be regarded as basically consistent with the ideal reference wavefront. However, in practical operation, due to photon noise and obser-

environment, the system metric function cannot be optimized to $2\beta n$. Usually, when it is optimized to within 0.3–0.5, the calibration can be regarded as complete. At this point, the central control unit records the optimized DM voltage and wavefront information, which can be used for subsequent normal closed-loop compensation in the AO system.

3 Experimental Test

The experimental test system built in this paper is shown in Fig. 3. Both the main light source and the reference light source use helium–neon lasers with a wavelength of 632.8 nm. In the scientific imaging optical path, the S-H WFS used for static aberration correction consists of an MLA and a CCD camera. The deformable mirror used in the experiment is model ALPAO DM97-15. From the comparison in Fig. 4, it can be seen that the focal-plane PSF image before correction exhibits obvious distortion, corresponding to a relatively large static aberration. After correction, the PSF image recovers to a clear Airy pattern, which means that the static aberration in the AO system has been effectively compensated.

图 3 AO 静态像差校正实验系统

Fig. 4 PSF images before and after correction

Figure 4: Fig. 4 PSF images before and after correction

Fig. 5 Metric function optimization iteration curve

Figure 5: Fig. 5 Metric function optimization iteration curve

Fig. 3 The experiment AO system for static aberration correction

(a) (b)

图 4 校正前后的 PSF 图像。(a) 校正前的 PSF 图像。(b) 校正后的 PSF 图像。

Fig. 4 PSF images before and after correction. (a) PSF image before correction. (b) PSF image after correction.

Fig. 5 shows the numerical variation curve of the metric function during the iterative optimization process of the algorithm. After about 10,000 iterations, the metric function decreases significantly from the initial value of 2.09 and converges to 0.44; in the subsequent iterations, its value remains stable. This convergence characteristic indicates that the static aberration in the system has been successfully compensated, thereby verifying the effectiveness of the proposed wavefront-copying SPGD calibration technique.

图 5 评价函数优化迭代曲线

Fig. 5 Metric function optimization iteration curve

Using a Thorlabs WFS31-7AR wavefront sensor, it was measured that, after correction, the wavefront RMS error of the scientific imaging optical path decreased from 109 nm to 7 nm. In this paper, the SR value of the system is estimated using the following formula:

$$\mathrm{SR} = e^{-\sigma^2}, \qquad (5)$$

where σ denotes the wavefront error RMS in radians. At a wavelength of 632.8 nm, 7 nm RMS is converted to 0.07 in radians, and the corresponding SR value can be calculated as 0.995. Table 1 gives the wavefront reconstruction coefficients based on the first 15 Zernike polynomials (excluding piston, tip/tilt, and defocus terms). After correction, all coefficient values are significantly reduced; this result also proves the effectiveness of the proposed method for correcting static aberrations. Fig. 6 shows the wavefront image of the AO system after correction, in which the color bar represents the magnitude of the Zernike polynomial coefficients (Zernike Coefficient), and the horizontal and vertical axes of the plane represent the pixel size.

4 Comparative Experiment and Analysis

To demonstrate the advantages of the wavefront-copying-based calibration method proposed in this paper, this section uses the energy optimization method previously proposed by our research group to perform static aberration correction under the same experimental conditions, and compares the correction effects of the two methods. The metric function used in the focal-plane energy method is as follows:

$$J_1 = \frac{I_o}{I_I}, \qquad (6)$$

where I_o denotes the sum of the energy outside the Airy disk and I_r denotes the sum of the energy inside the Airy disk. Optimization is carried out by evaluating the focal-plane energy distribution. The focal-plane PSF image and wavefront image after correction by the energy optimization method are shown in Fig. 7 and Fig. 8.

Table 1 Comparison of various Zernike coefficients before and after correction

Zernike coefficient	Before correction	After correction
Astigmatism y	−0.028	0.001
Astigmatism x	0.128	−0.002
Trefoil y	0.013	0.000
Coma x	−0.039	−0.003
Coma y	−0.034	0.001
Trefoil x	0.028	−0.004
Tetrafoil y	0.009	−0.000
Secondary Astigmatism y	−0.040	−0.000
Primary Spherical	−0.060	0.002
Secondary Astigmatism x	0.036	0.000
Tetrafoil x	0.111	−0.003

Fig. 6 The AO wavefront map after correction

Comparative experiments show that, under identical conditions, the energy optimization method corrected the SR from 0.309 to 0.789, reduced the wavefront RMS from 109 nm to 49 nm, and required approximately 23,000 iterative steps. Table 2 provides the detailed Zernike coefficients after correction by the two methods. In comparison, the wavefront copy method proposed in this paper further improved the SR by 26.1%, and increased the correction speed by a factor of 2.3, demonstrating significant advantages in both correction accuracy and efficiency.

Fig. 7 Focal plane PSF corrected by focal plane energy method

Fig. 8 The AO wavefront map after correction by focal plane energy method

Table 2 Zernike coefficients corrected through 2 methods

Zernike coefficient	Focal plane energy method	Wavefront copy method
Astigmatism y	0.036	0.001
Astigmatism x	0.002	−0.002
Trefoil y	0.001	0.000
Coma x	0.006	−0.003
Coma y	−0.007	0.001

Table 2 Continued

Zernike coefficient	Focal-plane energy method	Wavefront copy method
Trefoil x	0.005	−0.004
Tetrafoil y	0.005	−0.000
Secondary Astigmatism y	−0.004	−0.000
Primary Spherical	−0.004	0.002
Secondary Astigmatism x	−0.022	0.000
Tetrafoil x	−0.012	−0.003

5 Conclusion

Aiming at the difficult problem of calibrating static aberrations in AO systems, this paper introduces a wavefront-information copy strategy for aberration calibration. Through iterative optimization, this method matches the wavefront of the scientific imaging optical path with the ideal wavefront generated by a reference light source. Experimental verification shows that the method successfully optimizes the system SR from 0.309 to 0.995. By setting the energy optimization method as the control experiment, the dual superiority of this technique in calibration effect and efficiency is further confirmed, and its performance meets the practical requirements of astronomical imaging. In the future, this study will focus on optimizing the algorithm speed, with the expectation of extending this technology to more optical imaging fields.

Acknowledgments The authors thank the reviewers for their valuable suggestions on the manuscript, which significantly improved the quality of the article. We thank Nanjing Astronomical Instruments Co., Ltd., Chinese Academy of Sciences, for providing the experimental conditions.

References

[1] Jiang Wenhan. Opto-Electronic Engineering, 2018, 45: 170489

[2] Rao Changhui, Zhu Lei, Zhang Lanqiang, et al. Opto-Electronic Engineering, 2018, 45: 170733

[3] Zhu Y T, Dou J P, Zhang X, et al. RAA, 2021, 21: 082

[4] Paxman R G, Schulz T J, Fienup J R. JOSAA, 1992, 9: 1073

[5] Van D M A, Le M D, Macintosh B A. ApOpt, 2004, 43: 5458

[6] Hartung M, Blanc A, Fusco T, et al. A&A, 2003, 399: 385

[7] Wang Bin, Wang Zongyang, Wu Yuanhao, et al. Optics and Precision Engineering, 2013, 21: 1683

[8] Angel J R P. Nature, 1994, 368: 203

[9] Fusco T, Sauvage J F, Pettt C, et al. SPIE, 2014, 9148: 91481

[10] Poyneer L A, Palmer D W, Macintosh B, et al. ApOpt, 2016, 55: 323

[11] Ma Xinxue, Wang Bin, Li Zhengwei. Optics and Precision Engineering, 2014, 22: 3175

[12] Wang Liang, Chen Tao, Liu Xinyue, et al. Acta Photonica Sinica, 2015, 44: 0511001

[13] Sauvage J F, Fusco T, Rousset G, et al. JOSAA, 2007, 24: 2334

[14] Hippler S. JAI, 2019, 8: 1950001

[15] Chen Meicong, Jiang Wei, Mao Hongmin, et al. Acta Optica Sinica, 2023, 43: 0511001

[16] Baudoz P, Mas M, Galicher R, et al. SPIE, 2010, 7736: 77365S

[17] Ren D Q, Dong B, Zhu Y T, et al. PASP, 2012, 124: 247

[18] Zhang Tianyu, Wang Gang, Zhang Xi, et al. Chinese Optics, 2022, 15: 545

[19] Vorontsov M A, Yu M. JOSAA, 2004, 21: 1659

[20] Zhao H, An J, Yu M J, et al. ApOpt, 2021, 60: 7177

[21] Huang G, Lü G Y, Fan Y Y, et al. OptLT, 2022, 146: 107528

Static Aberration Correction Technique in Adaptive Optical Systems Based on Wavefront Replication Method

LI Hai-bo[1,2] TIAN Pei-lin[2] ZHANG Tian-yu[2] SHU Cheng-gang[1]

(1 Mathematics & Science College, Shanghai Normal University, Shanghai 200234)
(2 Nanjing Astronomical Instruments Co., Ltd, Chinese Academy of Sciences, Nanjing 210042)

Abstract Non-Common Path Aberration (NCPA), arising from the optical path difference between the wavefront sensing branch containing the wavefront sensor and the scientific imaging branch containing the science camera, is a fundamental limitation preventing Adaptive Optics (AO) systems from achieving diffraction-limited performance. Furthermore, static aberrations are introduced by optical elements within the common path of the AO system. To suppress the static aberration in the adaptive optics system, this paper introduces a technique based on wavefront phase template reproduction. The method employs a laser light source to generate an ideal wavefront pattern on the Shack-Hartmann wavefront sensor within the scientific imaging path, which serves as a reference wavefront. This reference wavefront is then used as the optimization target. Through an iterative optimization algorithm, control commands for the deformable mirror are generated to drive the scientific imaging path' s wavefront to converge with the reference. Experimental results indicate that this technique robustly achieves global optimization, even in the presence of substantial initial static aberrations, enhancing the system' s Strehl Ratio (SR) from 0.309 to 0.995 post-correction.

Key words instrumentation: adaptive optics, instrumentation: detectors, instrumentation: high angular resolution, techniques: high angular resolution