The Measurement and Correction of Atmospheric Dispersion in 4-Meter Telescope With Adaptive Optical System

Guoqing Gao , Hao Chen , Yuanyuan Tang, Wenru Li, Hua Bao, and Lingxiao Li

Abstract—**Atmospheric dispersion is a wavelength-dependent effect that affects astronomical observations performed using ground-based telescopes. The effect of atmospheric dispersion for a 4-meter telescope is analyzed and an atmospheric dispersion corrector (ADC) system was designed for its adaptive optical system. With the help of adaptive optical system and a line fit method, the science images can be conveniently used to measure the atmospheric dispersion and to control ADC to correct the dispersion, and thus the full-width at half-maximum of the final images can approach the diffraction limit of the telescope.**

Index Terms—**Adaptive optics, atmospheric dispersion corrector, resolution, telescope.**

I. INTRODUCTION

ATMOSPHERIC dispersion is an effect introduced by Earth's atmosphere that affects astronomical observations performed using ground-based telescopes. The conventional atmospheric dispersion correctors (ADC) are made of two pairs of glass prisms that provide an average correction over the full telescope field-of-view. The atmospheric corrector operates by rotating two prisms, which constitute the ADC system. The combination of these two prisms effectively controls both the amplitude and direction of dispersion [1], [2]. The orientations of the counter-rotating prisms are usually based on the models used to estimate the on-sky dispersion to be corrected. In this article, the effect of atmospheric dispersion of the telescope is analyzed and the ADC is designed and used in the adaptive optical (AO)

Guoqing Gao is with the Key Laboratory on Adaptive Optics, Chinese Academy of Sciences, Chengdu 610209, China, with the University of Electronic Science and Technology of China, Chengdu 611731, China, also with the Institute of Optics and Electronics Chinese Academy of Sciences, Chengdu 610209, China, and also with the University of Chinese Academy of Sciences, Beijing 101408, China.

Hao Chen, Yuanyuan Tang, Wenru Li, and Lingxiao Li are with the Key Laboratory on Adaptive Optics, Chinese Academy of Sciences, Chengdu 610209, China, and also with the Institute of Optics and Electronics Chinese Academy of Sciences, Chengdu 610209, China (e-mail: lingxiaoli_ioe@163.com).

Hua Bao is with the Key Laboratory on Adaptive Optics, Chinese Academy of Sciences, Chengdu 610209, China, also with the Institute of Optics and Electronics Chinese Academy of Sciences, Chengdu 610209, China, and also with the University of Chinese Academy of Sciences, Beijing 101408, China.

system. The AO closed-loop science images which are used to calculate the atmospheric dispersion and the prism rotated angle directly are based on a line fit method. The full-width at half-maximum of the images can approach the diffraction limit of the telescope.

II. METHOD

A. The Design of ADC

Several attempts were done to measure the refractivity of dry air, we can derive the atmospheric dispersion using the following [3]:

$$\Delta R\left(\lambda\right) \approx 206265 \left[n\left(\lambda\right) - n\left(\lambda_{\text{ref}}\right)\right] \times \tan Z \qquad (1)$$

where Z is the zenithal angle, and λ_{ref} is the reference wavelength, and the atmospheric parameters, such as temperature and pressure, are also taken into consideration.

In 1966, an improved version of the dispersion formula was provided by Edlén (1966) [4]. The main dispersion formula is given by (2), followed by the effects of temperature, pressure, and altitude, respectively.

$$n_\lambda = 1 + 0.379$$
$$\times \frac{7.5 \times 10^{-3} p \left[1 + 7.5\, p\left(0.817 - 0.0133\, T\right) \times 10^{-9}\right]}{T + 273.15}$$
$$\times \left(83.4212 + \frac{24060.3}{130 - \lambda^{-3}} + \frac{159.97}{38.9 - \lambda^{-2}}\right) \times 10^{-6}$$

$$(2)$$

where h = 4520 m, T = 270 K, p = 600 Pa, $\lambda 1 = 0.7\ \mu$m, $\lambda 2 = 0.9\ \mu$m.

The full-width at half-maximum (FWHM) can approach the diffraction limit of the telescope without atmospheric dispersion. Fig. 1 shows atmospheric dispersion as an elongation in FWHM. The amount of dispersion is very big compared in most states.

Rotating prisms are used in collimated light are the common solution for atmospheric dispersion, as represented in Fig. 2. It can function as a dynamic prism when the telescope is rotated to observe different stars at different altitudes and zenithal angel.

B. Measuring and Correcting Atmospheric Dispersion

Traditionally the atmospheric dispersion correction is done by using a look-up table. The orientations of the counter-rotating
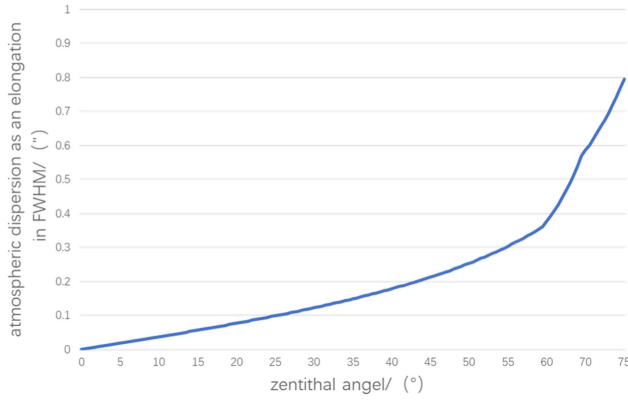
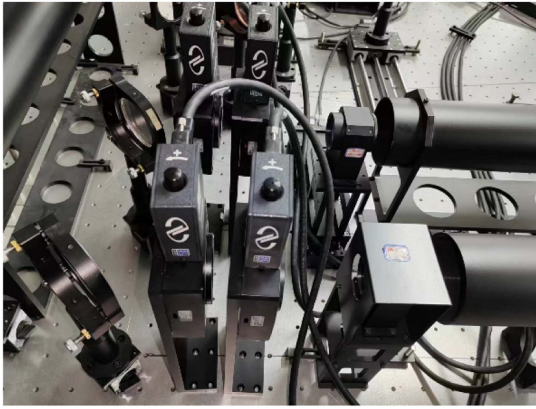Fig. 1. Atmospheric dispersion as an elongation in FWHM.

Fig. 2. Counter-rotating prisms are used in the telescope.

prisms are usually based on the models used to estimate the on-sky dispersion to be corrected. This consists of pre-calculated values of atmospheric dispersion based on the elevation of the telescope.

Traditional methods to determine angular offsets during the commissioning of ADCs rely either on indirect measurement of the several orientations (optical alignment of prism axis in barrel, etc.) or on an analysis of the dispersion effect at extreme wavelengths of the spectral range (using two narrow bandpass filters) [5]. Although the first method does not provide a direct measurement on the sky and has low accuracy, the later has a limited sensitivity, does not give direct information on how to correct the alignment.

Even if the design of the ADC is done to obtain an almost perfect correction, this design is always based on theoretical models that try to mimic the sky dispersion, leading to some additional uncertainty in the correction. In this article, we propose a simple method for ADC on-sky commissioning tests capable of optimizing the rotation alignment of the ADC in terms of its orientation angles along the dispersion. The method can avoid error caused by the fierce change of the atmospheric and control ADC to correct the atmospheric dispersion in time.

As mentioned, an ADC is a set of two counter-rotating prisms that are used to correct for the atmospheric dispersion. To do so,
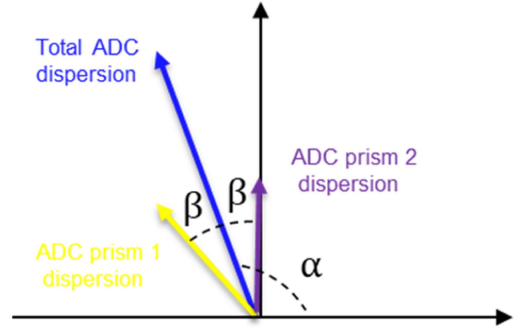

Fig. 3. Total ADC dispersion and the corresponding ADC prisms orientation angles.
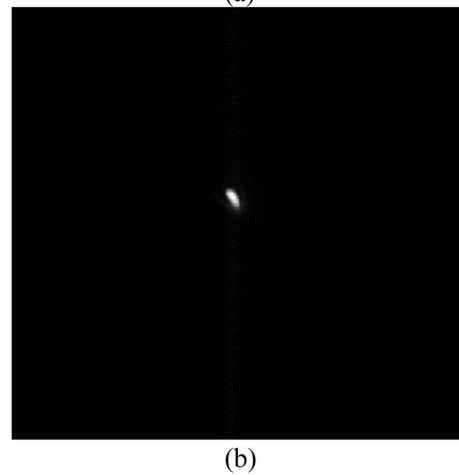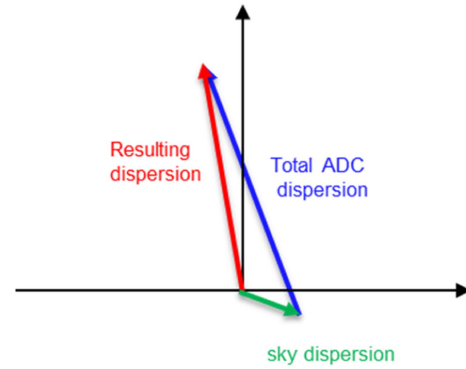

(a)

(b)

Fig. 4. Resulting dispersion (a) and the corresponding elongated image (b).

we have to think of the ADC as a dispersion vector [6], having a magnitude and a direction, as represented in Fig. 3.

The ability to counter-rotating the prisms allows for control of the amount of ADC dispersion (angle β in Fig. 3). The ability to rotate both prisms simultaneously allows for control of the dispersion direction (angle α in Fig. 3). The relation between ADC prism 1 and prism 2 angles and the angles α and β is given by the following equations:

$$P_1 = \alpha - \beta \tag{3}$$
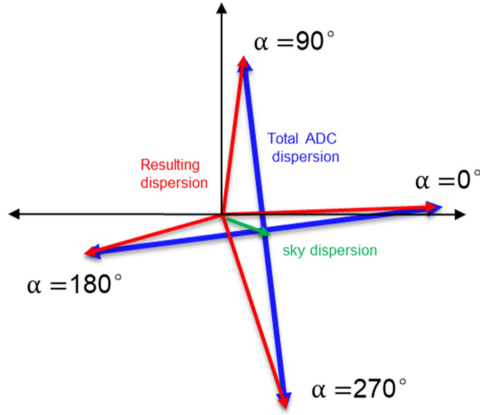
$$P_2 = \alpha + \beta \tag{4}$$

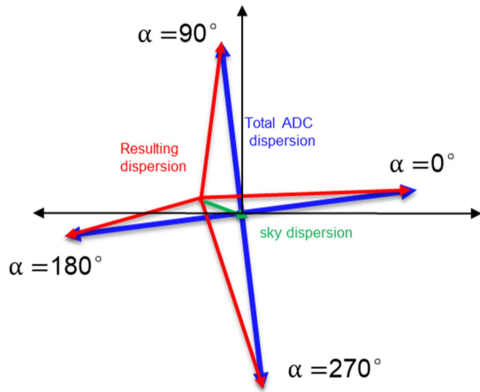Fig. 5. Example of an α rotation in which t the two ADC prisms rotate together from 0° to 270°.

Fig. 6. Example of the coordinate of the sky dispersion vector as original point.

The resulting dispersion which is also thought as a vector is determined by total ADC dispersion and sky dispersion. In the presence of atmospheric dispersion and total ADC dispersion, the shape of the target at the end of the instrument is not circular, as Fig. 4 shows.

The elongated image that is obtained in the EMCCD is dispersed along one direction [7]. Nevertheless, as we will show, considering it as a line is a simplification that is straightforward to implement and efficient in terms of elongation characterization [8], [9]. The amount of dispersion is very big compared with the image size when most states, so the elongated image can be used to measure the resulting dispersion. The atmospheric dispersion can also be calculated once we know the magnitude and direction of the total ADC dispersion.

1) Measuring Atmospheric Dispersion: The two ADC prisms rotate together to four different angles, in what we could get four different elongated images. The four angles are 0°, 90° 180° and 270° in our method to simplify the calculation process. β is set as 60°, so the magnitude of the total ADC dispersion equals the magnitude of ADC prism 1 and prism 2 dispersion, respectively.

We think of the elongated images as resulting dispersion vectors, as represented in Fig. 5 . The zero point $(0, 0)$ is defined

as the top left corner of the science image, so the coordinate of the four resulting vectors which can be obtained directly from the images is defined as (x_1, y_1), (x_2, y_2), (x_3, y_3) and (x_4, y_4).

The direction of the vector is given by:
For $y \geq 0$,

$$\theta = \cos^{-1}\left(\frac{x}{\sqrt[2]{x^2 + y^2}}\right) \quad (5)$$

$y < 0$,

$$\theta = -\cos^{-1}\left(\frac{x}{\sqrt[2]{x^2 + y^2}}\right) \quad (6)$$

For simplicity, we get

$$\theta = \frac{y}{|y|}\cos^{-1}\left(\frac{x}{\sqrt[2]{x^2 + y^2}}\right) \quad (7)$$

The magnitude of the total ADC dispersion in the four images is same, so the coordinate of the atmospheric dispersion vector is given by,

$$x_a = \frac{x_1 + x_2 + x_3 + x_4}{4} \quad (8)$$

$$y_a = \frac{y_1 + y_2 + y_3 + y_4}{4} \quad (9)$$

Now substituting (8) and (9) into (7), the direction of the atmospheric dispersion is given by,

$$\theta_a = \frac{y_1 + y_2 + y_3 + y_4}{|y_1 + y_2 + y_3 + y_4|}\cos^{-1}$$
$$\times \left(\frac{x_1 + x_2 + x_3 + x_4}{\sqrt[2]{(x_1 + x_2 + x_3 + x_4)^2 + (y_1 + y_2 + y_3 + y_4)^2}}\right) \quad (10)$$

The magnitude of the atmospheric dispersion can be calculated as

$$r_a = \frac{\sqrt[2]{(x_1 + x_2 + x_3 + x_4)^2 + (y_1 + y_2 + y_3 + y_4)^2}}{4} \quad (11)$$

2) Correcting Atmospheric Dispersion: In order to correct atmospheric dispersion, we should know the magnitude and the direction of the total ADC dispersion.

We set the coordinate of the sky dispersion vector as original point, and the coordinate of the total ADC dispersion vectors when α is 0 is given by,

$$x_{t1} = x_1 - x_a = \frac{3x_1 - x_2 - x_3 - x_4}{4} \quad (12)$$

$$y_{t1} = y_1 - y_a = \frac{3y_1 - y_2 - y_3 - y_4}{4} \quad (13)$$

Now substituting (12) and (13) into (7), the direction of is given by,

$$\theta_{t1} = \frac{3y_1 - y_2 - y_3 - y_4}{|3y_1 - y_2 - y_3 - y_4|}\cos^{-1}$$

$$\times \left(\frac{3x_1 - x_2 - x_3 - x_4}{\sqrt[2]{(3x_1 - x_2 - x_3 - x_4)^2 + (3y_1 - y_2 - y_3 - y_4)^2}} \right) \tag{14}$$

The magnitude of the atmospheric dispersion can be calculated as

$$r_{t1} = \frac{\sqrt[2]{(3x_1 - x_2 - x_3 - x_4)^2 + (3y_1 - y_2 - y_3 - y_4)^2}}{4} \tag{15}$$

The coordinate of the total ADC dispersion vectors when α is 90 is given by,

$$x_{t2} = x_2 - x_a = \frac{3x_2 - x_1 - x_3 - x_4}{4} \tag{16}$$

$$y_{t2} = y_2 - y_a = \frac{3y_2 - y_1 - y_3 - y_4}{4} \tag{17}$$

Now substituting (16) and (17) into (7), the direction of is given by,

$$\theta_{t2} = \frac{3y_2 - y_1 - y_3 - y_4}{|3y_2 - y_1 - y_3 - y_4|} \cos^{-1}$$

$$\times \left(\frac{3x_2 - x_1 - x_3 - x_4}{\sqrt[2]{(3x_2 - x_1 - x_3 - x_4)^2 + (3y_2 - y_1 - y_3 - y_4)^2}} \right) \tag{18}$$

To cancel the atmospheric dispersion, the equal amount and be oriented in an opposite direction to that of the sky. The direction of the correcting atmospheric dispersion vector is given by,

$$\theta_c = 180 + \theta_a \tag{19}$$

α_c allows for control of the dispersion direction is given by

$$\alpha_c = (180 + \theta_a - \theta_{t1}) \times \frac{\theta_{t2} - \theta_{t1}}{90} \tag{20}$$

In which, $\frac{\theta_{p2} - \theta_{p1}}{90}$ decides the direction of rotation.

The magnitude of correcting atmospheric dispersion vector r_c is given by

$$r_c * \cos 60 * 2 = r_{t1} * \cos \beta c * 2 \tag{21}$$

Thus, β_c allows for control of the amount of ADC dispersion is given by,

$$\beta_c = \cos^{-1} \frac{r_a}{2 r_{t1}} \tag{22}$$

Substituting (20) and (22) into (3) and (4), the ADC prism 1 and prism 2 angles can be calculated through the four different elongated images directly.

III. ON-SKY RESULTS

The control architecture behind the measurement and correction of dispersion is shown in Fig. 7.

The first step is set $\alpha = 0°$ and $\beta = 60°$, so the elongated image is obtained with AO close-loop. The coordinate of the resulting vectors (x_1, y_1) be obtained from the image directly. Then α is equal to 90°, 180° and 270° to obtain (x_2, y_2), (x_3, y_3) and
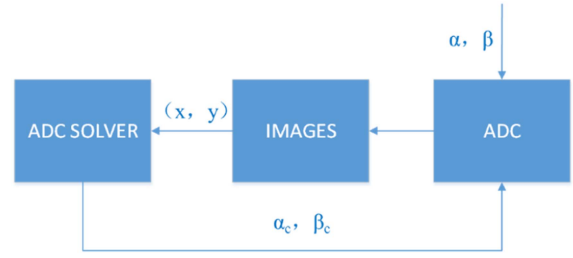

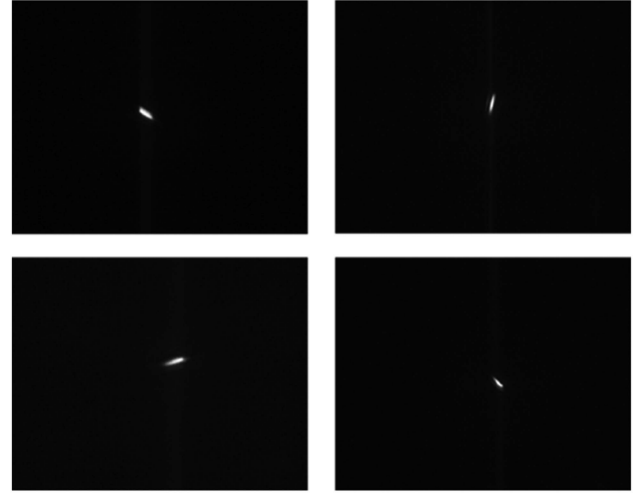Fig. 7. Schematic showing the measurement and correction of dispersion.

Fig. 8. Four different elongated images ($\alpha = 0°$, 90°, 180° and 270°).

(x_4, y_4). By using these parameters, the atmospheric dispersion vector and the different total ADC dispersion vectors can be calculated using the equations presented in Section II. By using the atmospheric dispersion vector and the total ADC dispersion vectors, the direction and magnitude of correcting atmospheric dispersion vector can be calculated. The value of α_c and β_c can obtained for the parameters, and the prism 1 and prism 2 angles can be put in ADC, which will give us a correction of dispersion.

For our tests, these data were collected from the thousand-unit double deformable mirrors adaptive optical system, the 4-meter telescope facility AO instrument. In AO closed loop, it offers Strehl ratios in the I-band between 20% and 50%. To capture the elongated images, the light from the I-band was captured by the EMCCD (1024 * 1024 pix). The target was HIP 72105 (268°, 49°), and the telescope zenith angle for on-sky observations is 41°. The theoretical atmospheric dispersion value is 0.145 arcsec, which can cause an elongation about 6 pixels. Four different elongated images can be obtained in the camera as expected, as shown in Fig. 8.

The on-sky results of the correction of atmospheric dispersion are presented in Fig. 9. Fig. 9(a) shows the elongated image with no correction. Fig. 9(b) shows the image after correcting for dispersion. The full-width at half-maximum (FWHM) is used to quantitatively analyze the imaging quality after correction and the results are presented in Table I, The values of FWHM$_x$ and FWHM$_y$ shown in the table represent FWHM in two directions,
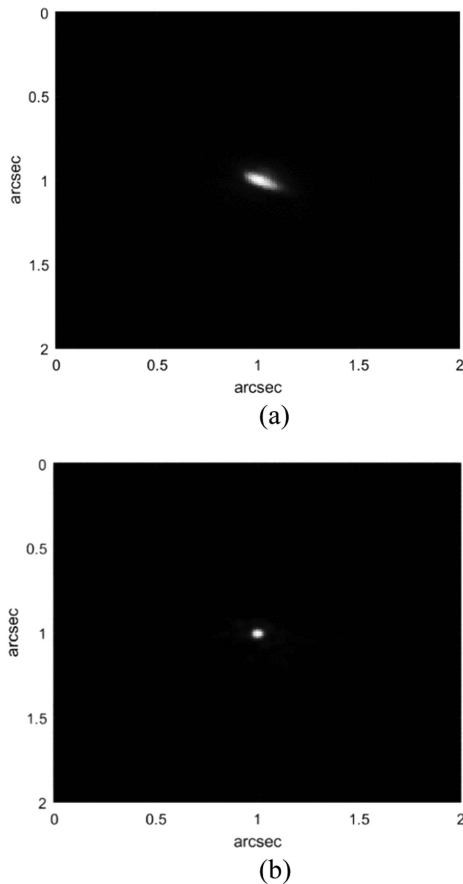
(a)

(b)

Fig. 9. On-sky result (a) Before correcting atmospheric dispersion. (b) After correcting atmospheric dispersion.

TABLE I
THE FULL-WIDTH AT HALF-MAXIMUM (FWHM)

	FWHM$_x$/pixels	FWHM$_y$/pixels
Without Correction	9.03	5.79
With Correction	4.15	3.76

in units of pixel values. The FWHM of the diffraction limit of the 4-m telescope at 700–900-nm band is 3 pixels.

The Fig. 10. shows the cross-sectional view of the maximum value of the correction image. The FWHM of the star image with AO was approximately 0.05 arcsec, which is 1.25 times the diffraction limit of the 4-m telescope at 700–900-nm band. In conclusion, the star observation results show that the 4-m telescope can work satisfactorily based on the ADC and the thousand-unit double deformable mirrors of the adaptive optics system.

The method has been used to correct the dispersion at different zenithal angles. The comparison between the counter-rotating angle calculated by the science images and estimated based on the model is presented in Fig. 11. The counter-rotating angles of the calculated result and theoretical model are different in all zenithal angel, and where is some additional uncertainty in the correction. The difference of the counter-rotating angels is large when the zenithal angel is from 35° to 60°, and it is maybe
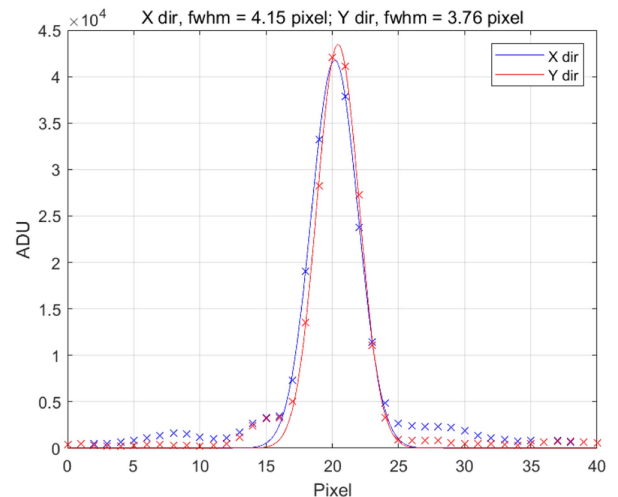

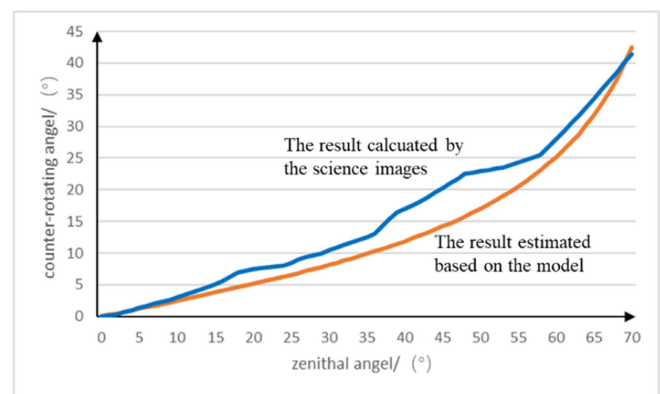Fig. 10. Two-dimensional section of the correction image.

Fig. 11. The coparison between the counter-rotating angle calculated by the science images and estimated based on the model.

caused by the fierce change of the atmospheric. The difference of the counter-rotating angels is small when the zenithal angel is from 60° to 75°, which shows the atmospheric is relatively stable in that time. The counter-rotating angels of the calculated and estimated result are similar when the zenithal angel is from 0° to 35°. The atmospheric dispersion effect is weak in small zenithal angel, so the changes in the environment also have a limited influence on the counter-rotating angel in this situation.

V. CONCLUSION

In this work, we demonstrated the on-sky measurement and correction of atmospheric dispersion using the science image. The procedure is based on a line fit method on the target image obtained in an EMCCD. The full-width at half-maximum of the final images can approach the diffraction limit of the telescope.

REFERENCES

[1] M. Bahrami and A. V. Goncharov, "The achromatic design of an atmospheric dispersion corrector for extremely large telescopes," *Opt. Exp.*, vol. 19, no. 18, pp. 17099–17113, 2011.

[2] R. J. Sarlot and D. W. McCarthy Jr., "Cryogenic 1-5 micron atmospheric dispersion corrector for astronomical adaptive optics," *Curr. Develop. Lens Des. Opt. Eng. II.*, vol. 4441, pp. 72–78, 2001.

[3] G. Bönsch and E. Potulski, "Measurement of the refractive index of air and comparison with modified Edlén's formulae," *Metrologia*, vol. 35, no. 2, 1998, Art. no. 133.

[4] B. Edlén, "The refractive index of air," *Metrologia*, vol. 2, no. 2, 1966, Art. no. 71.

[5] A. Cabral and B. Wehbe, "Simple concept for atmospheric dispersion corrector on-sky commissioning tests," *J. Astronomical Telescopes, Instrum., Syst.*, vol. 7, no. 3, pp. 035003–035003, 2021.

[6] J. Pember, C. Schwab, and D. Greggio, "Selecting optimal glass combinations for atmospheric dispersion correctors," *Proc. SPIE*, vol. 11451, 2020, Art. no. 1145153.

[7] R. T. Blackman et al., "Performance verification of the extreme precision spectrograph," *Astron. J.*, vol. 159, 2020, Art. no. 238.

[8] P. Pathak et al., "First on-sky closed loop measurement and correction of atmospheric dispersion," *Proc. SPIE*, vol. 9909, pp. 1523–1533, 2016.

[9] P. Pathak et al., "A high-precision technique to correct for residual atmospheric dispersion in high-contrast imaging systems," *Pub. Astronomical Soc. Pacific*, vol. 128, no. 970, 2016, Art. no. 124404.