# **One of Align Metrologies for Antarctic Telescopes**

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## ABSTRACT

The preliminary site testing performed since the beginning of 2008 shows that Antarctic Dome A is an excellent astronomical site. The Chinese Antarctic optical telescopes CSTAR and the first Antarctic Survey Telescope AST3-1 has been in operation on Dome A, and several Antarctic telescopes are being developed and proposed. However, the harsh environment and manpower shortage make the in-situ alignment task difficult. The study will introduce the completed alignment work of AST3 and discuss an improved align metrology based on the previous treatments of the field dependent optical aberrations, as well as its application on Antarctic Bright Star Survey Telescope BSST.

Keywords: Alignment, telescopes, field aberrations, Antarctica

# 1. INTRODUCTION

Lawrence et al. (2004) have shown that Dome C on the Antarctic plateau is an excellent site on Earth which has a free atmospheric seeing value of 0.27" at 30m above the ground<sup>[1]</sup>. Dome A ( $80^{\circ}25'2.8"$  S,  $79^{\circ}24'45.5"$  E) is the highest location of Antarctic plateau with an elevation of 4093m. Preliminary site testing, led by Chinese Center of Antarctic Astronomy CCAA, indicate that Dome A is one of the best observatories on Earth that could be as good as Dome C or even better<sup>[2]</sup>. In January 2005, Chinese Expedition Team firstly visited Dome A site, and in 2008, four stationary telescopes known as CSTAR with a 145-mm aperture and 20-deg<sup>2</sup> was mounted and operated for variable sources detection and site testing. The second-generation Chinese telescopes are three Antarctic Survey Telescopes AST3 with a 500-mm aperture and 4.14° field of view (FOV), mainly aimed for observations of supernovas and exoplanet searching. Moreover, several other telescopes are under construction or proposal such as a 4.8° FOV 300-mm BSST and a 1.5° FOV 2.5-m Kunlun Dark Universe Survey Telescope KDUST<sup>[3]</sup>.

All of the Antarctic telescopes require quality alignment for astronomical observations. However, the extreme environment multiplies the alignment difficulties. In order to accomplish efficient and accurate in-situ alignment, especially for the alignment of next-generation Antarctic telescopes, a more advanced align technology may be needed. By using a microscope alignment telescope (MAT) to measure the optical axis and locate the center of each optical element, we have successfully aligned the AST3-1 on Dome A in Jan. 2012 and AST3-2 during the test observations in. Dec. 2013.

The used traditional method of AST3 alignment, which is time-consuming, may not be suitable for precise alignment, and an advanced align metrology utilizing field aberrations measurement offers a possible method for solving the problem. Generally, measured aberrations are capable of scaling or even calculating misalignment. In 1980s, nodal aberration theory, firstly reported by R. Shack and K. Thompson, was used to describe the field aberrations introduced by misaligned optical elements<sup>[4]</sup>. According to the aberration theory, the misaligned telescopes performance is dominated by field uniform coma and field asymmetric field linear astigmatism<sup>[5]</sup>. Base on the insight, the misaligned error can be calculated by measuring the field dependent aberrations. In this study, a completed alignment work of AST3 is introduced and BSST alignment method based on the field aberration measurement is discussed.

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# 2. ALIGNMENT OF ANTARCTIC SURVEY TELESCOPES

The Antarctic Survey Telescopes AST3 are equatorially mounted and composed of three wide field catadioptric telescopes with 500mm entrance pupil and G (400-550nm), R (560-700nm), I (685-840nm) filter for each. The optical system consists of a transparent aspheric plate, an oblate primary mirror and a spherical lens corrector including a filter as Fig.1 illustrated. And the optical system delivered a image quality of 80 percent encircled energy less than 1 arcsec in R and I band. The telescopes can point and track autonomously and a precise auto-focusing mechanism is designed to make the telescope work at the right focus under large temperature difference<sup>[6]</sup>.

When aligning the AST3-1, a microscope alignment telescope (MAT) was used to mark the optical axis of AST3, and its optical axis is perpendicular with the declination axis. We used cross lines and reticles to mark the rotational center of each optical element and MAT axis, than located the centers on MAT axis as Fig.1 shows. Than we adjust the elements posture referring to the reflection of the MAT cross line.



Figure 1. Picture of in-situ AST3-1 alignment and schematic drawing

The alignment procedure can efficiently orientated the optical elements, and after qualified alignment of the optical system in 2011 at the Xuyi Station of China, the test observation of Double Cluster (NGC 884) demonstrated that a uniform image was obtained with FWHM (full width at half maximum) value of 2.4" and 2.3" as Fig.2 shows, respectively measured at the center and margin area of the image. Meanwhile the site seeing was about 2" simultaneously monitored by a Differential Image Motion Monitor device<sup>[6]</sup>.



Figure 2. Star profiles of AST3-1

Moreover the second Antarctic Survey Telescope AST3-2, which had finished test observation in Mohe Station of China in 2014 May, was also be aligned by a MAT instrument. The traditional alignment technology turns out to be successful, however the accuracy is highly depended on the instruments and the central mark accuracy of the elements. In order to accomplish a more accurate alignment we may need an more advance method.

# 3. ALIGNMENT OF ANTARCTIC BRIGHT STAR SURVEY TELESCOPE

Bright Star Survey Telescope (BSST) is another Antarctic telescope proposed for exoplanet searching. It is a Ritchey-Chretien type telescope with 300-mm aperture and 4.8° FOV as Fig .3 shows, and the optical system of BSST consists of a primary and a secondary mirror, which both are hyperboloid, and a spherical lens corrector. The telescope sealing window, which will be heated, is used to keep the in-tube mirror from frosting. The parameters are list in Table 1. Considering the temperature factor, low-expansion glass is selected for BSST optical elements except for lens 2 of the corrector, which is used for dispersion correcting. Besides, a 4K Andor® CCD camera is selected and used with a warm widow to keep the shutter functional in a extremely cold atmosphere. The telescope is now under construction.



Figure 3. The optical layout of the BSST

Table 1. The optical parameters of the BSST

Optical	Padii (mm)	Conic	Thickness	Diameter	Class	
element	Raun (mm)	coefficient	(mm)	(mm)	01055	
Telescope	Infinity	0	20	320	Fusad silian	
window	Infinity	0	30	320	ruseu sinca	
Primary mirror	-800	-1.519	235	300	Zerodur	
Secondary mirror	-606	-14.443	222	106	Zerodur	
Lens 1	-358.0	0	15	86	Fused silico	
	-160.0	0	10	86	ruseu sinea	
Lens 2	-160.0	0	8	80	TE2	
	-239.7	0	13	80	115	
Lens 3	-123.6	0	8	76	Fused silica	
	Infinity	0	40	76	Fused silica	

#### 3.1 Aberration of a misaligned R-C telescope

Based on the aberration theory, the performance of misaligned telescopes is dominated by low order coma and astigmatism. However, different misaligned degrees of freedom produce the same types of aberration. Typically, there is always a point on any 2-mirror telescope's axis for which the translation coma resulted from decenter  $\delta$  and the rotation coma resulted from tilt  $\theta$  will cancel out<sup>[7]</sup>, known as coma-free point (CFP) or neutral point for coma as Fig.4 shows. Therefore, rotate the secondary mirror around the CFP will bring about astigmatism without coma. Thus, the CFP is an important reference point for correcting the tilt error of secondary mirror, if the misaligned astigmatism can be detected. Moreover, misaligned coma aberration can be measured for decenter error correcting.



Figure 4. Coma free point of a R-C telescope

CFP of a R-C telescope normally locates behind the secondary, we can calculate the distance value  $Z_{cfp}$  by equation (1)<sup>[7]</sup>. In the equation, f ' represents telescope focal length,  $R_A$  is system obstructive ratio,  $m_2$  is magnitude of the secondary mirror,  $b_{s2}$  is conic coefficient of the secondary mirror. The CFP location of BSST is 62.8mm away from the vertex of the secondary mirror. Besides, resorting to ZEMAX® the  $Z_{cfp}$  value can be efficiently computed.

$$Z_{cfp} = \frac{2f'R_A(m_2^2 - 1)}{(m_2^2 + 1)[(m_2 - 1) - (m_2 + 1)b_{s2}]}$$
(1)

Model the system in ZEMAX® software, and the nominal residual aberrations are illustrated by Fig.5. The arrows represents the orientation and amplitude of third order coma (left figure) and astigmatism (right figure ) over  $0.6^{\circ} \times 0.6^{\circ}$  FOV. Then tilt the secondary mirror around the CFP, the misaligned aberrations are illustrated by Fig.6, which indicates that the coma map remains the same with the residual coma and the astigmatism map is obvious changed. The misaligned field dependent astigmatism, which is associated with the tilt error, can be measured and used for the solution of tilt error. For comparison, aberrations introduced by nominal misalignment are shown by Fig.7. Therefore, the misaligned aberrations of a typical R-C telescope are demonstrated as field dependent astigmatism and uniform coma, which can be used to respectively calculate tilt and decenter error of the secondary mirror.



F	igure	5.	Residual	3rd	coma	and	3rd	astigm	atism	of	BSS	Т
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Figure 6. Aberration maps of tilt secondary around CFP



Figure 7. Aberration maps of misaligned secondary mirror

#### 3.2 Alignment metrology of BSST

The misaligned aberrations of a R-C telescope can be described as field dependent astigmatism and field uniform coma, moreover, the Zernike polynomials provide a efficient way to interpret optical aberrations. Thus, third order coma and astigmatism can be characterized as follows,  $C_5 \sim C_8$  represent the Zernike coefficients of the sampling fields<sup>[8]</sup>.

$$W_{astigmatism} = C_5 Z_5 + C_6 Z_6$$

$$W_{coma} = C_7 Z_7 + C_8 Z_8$$
(2)

Base on the insight of nodal aberration theory, the field dependent misaligned aberrations can be described as Zernike coefficient functions of field coordinates  $(x_0,y_0)$  as equation (3) shows, and  $\alpha$ ,  $\beta$  are the parameters of the field Zernike functions.

$$C_{5} = 2\beta_{0}x_{0}y_{0} + \beta_{1}x_{0} + \beta_{2}y_{0} + \beta_{3}$$

$$C_{6} = \beta_{0}(x_{0}^{2} - y_{0}^{2}) - \beta_{1}y_{0} + \beta_{2}x_{0} + \beta_{4}$$

$$C_{7} = \alpha_{0}y_{0} + \alpha_{2}$$

$$C_{8} = \alpha_{0}x_{0} + \alpha_{1}$$
(3)

When aligning BSST, firstly, we perturb each degrees of freedom of the secondary mirror and record field aberrations which are characterized by Zernike coefficients. Than solve the function parameters based on equation (3), the solutions are listed in Table.2. For instance, tilt the secondary mirror of 0.1° along the x axis and solve the linear coma coefficient  $\alpha_0=0.147$  which is equal to the nominal system,  $\alpha_1 \alpha_2$  both are zero because the secondary is tilted around the coma-free point. And the quadratic astigmatic coefficient  $\beta_0=0.037$  which is the residual aberration, the linear astigmatic coefficient  $\beta_1=0.48$  which is the dominated aberration of misaligned BSST. Meanwhile the field constant astigmatic coefficient  $\beta_4=0.013$ , and  $\beta_4=0.052$  when there is a 0.2° tilt of the secondary. Therefore the field constant astigmatic coefficients  $\beta_3$   $\beta_4$ , which are not linear dependent with the misalignment, cannot be used in calculation misalignment.

Table 2. Coefficients of fiel	l Zernike functio	ons resulted from	unit perturbation
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	Nominal	Decx	Decy	Tiltx	Tilty
Perturbation value	0	0.1mm	0.1mm	0.1°	0.1°
$\alpha_0$	0.147	0.147	0.147	0.147	0.147
$\alpha_1$	0	-0.202	0	0	0
α <sub>2</sub>	0	0	-0.202	0	0
βο	0.037	0.037	0.037	0.037	0.037
$\beta_1$	0	0	0.05	0.48	0
β <sub>2</sub>	0	0.05	0	0	-0.48

β <sub>3</sub>	0	0	0	0	0
β <sub>4</sub>	0	0	0	0.013	-0.013

Model the misaligned BSST optical system with hypothetical misaligned error attached, then record the Zernike coefficients of different fields to solve the Zernike functions parameters which are listed in Table.3.

Table 3. Coefficients of field Zernike functions resulted from misalignment

$\alpha_0$	$\alpha_1$	α <sub>2</sub>	$\beta_0$	$\beta_1$	$\beta_2$	$\beta_3$	$\beta_4$
0.147	-3.20	-5.22	0.037	6.13	5.63	-4.14	0.27

The coefficients  $\alpha_0$  and  $\beta_0$ , which represent the residual aberrations, are excluded from calculation.  $\beta_3$  and  $\beta_4$ , which are not linear but quadratic dependent with the misalignment, are also excluded from calculation. Hence we use the four parameters  $\alpha_1$ ,  $\alpha_2$ ,  $\beta_1$ ,  $\beta_2$  to solve the misalignment and deliver a quality solution listed as Table 4. The four independent parameters can be used for precisely calculating four degrees of freedom misalignment, and when there are more degrees, the most sensitive misaligned degrees of freedom can also be solved by using singular value decomposition method.

Table 4. Hypothetical misalignment value and solution

	Decx	Decy	Tiltx	Tilty
Misalignment	1.6mm	2.6mm	1°	-1°
Solution	1.58mm	2.58mm	1.01°	-1.01°

#### 4. CONCLUSION

In the study we introduced a completed alignment work of AST3 and discussed an improved metrology for BSST alignment, which indicates that we can accurately solve the misalignment of the secondary mirror with the acquisition of field-dependent aberrations. Combining with the insight of CFP concept, the alignment metrology, which is based on measuring the third order astigmatism and coma, delivered a suitable solution of misaligned BSST. Several wave-front sensors will be assembled to automatically monitor the alignment statement and provide corresponding adjustment when needed. For now Dome A is still an unattended astronomical site, the align metrology will be very helpful to monitor the misalignment and do the close-loop adjustment to keep the next-generation telescopes in right condition. The authors are grateful for the support of the National Key Basic Research Program of China (973 Program)(2013CB834901).

### REFERENCE

- [1]. Lawrence, J.S., et al., Exceptional astronomical seeing conditions above Dome C in Antarctica. Nature, 2004. **431**: p. 278.
- [2]. Bonner, C., et al., Thickness of the atmospheric boundary layer above dome a, antarctica, during 2009. Publications of the Astronomical Society of the Pacific, 2010. **122**(895): p. 1122-1131.
- [3]. Li, Z., et al. Status of the first Antarctic survey telescopes for Dome A. in SPIE Astronomical Telescopes+ Instrumentation. 2012. International Society for Optics and Photonics.
- [4]. Shack, R.V. and K.P. Thompson, Influence of alignment errors of a telescope system on its aberration field. Proc. of SPIE, 1980. **251**: p. 146.
- [5]. Thompson, K.P., T. Schmid, and J.P. Rolland. Recent discoveries from nodal aberration theory. in International Optical Design Conference 2010. 2010. International Society for Optics and Photonics.
- [6]. Yuan, X. and D.-q. Su, Optical system of the Three Antarctic Survey Telescopes. Monthly Notices of the Royal Astronomical Society, 2012. 424(1): p. 23-30.
- [7]. Wilson, R.N., Reflecting Telescope Optics I. wide field telescope, ed. 3. 2007: Springer.
- [8]. Manuel, A.M., Field dependent aberrations for misaligned reflective optical systems, in College of Optical Sciences2009, The University of Arizona: Tucson, Arizona.