Simulation of low-order AO performance on LAMOST

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ABSTRACT

Large Sky Area Multi-Object Fibre Spectroscopic Telescope (LAMOST) is a large aperture and wide field telescope whose image quality requirement at Xinglong station is 80% light energy within 2 arcsecond. In fact, the designed image quality of the central field of view is diffraction limited under optical wavelength. Due to the 60m long light path and poor natural seeing, dome seeing and other errors, the image quality is averaged about 0.5arcsecond to 1 arcsecond. We consider deploying a low-order adaptive optics system on LAMOST to improve seeing conditions and the corresponding image quality. Based on the sounding balloon results on Xinglong Station, we make the numerical simulation of the AO performance and get Fried parameter, the final point spread function (PSF) characteristics of LAMOST including Strehl ratio, full width at half- maximum (FWHM), and the residual variance.

Keywords: low-order AO simulation, LAMOST, Xinglong Station, Strehl ratio, FWHM

1. INTRODUCTION

LAMOST is a large aperture and wide field telescope, the optical system of which includes a reflecting Schmidt corrector Ma, composed of 24 hexagonal planar sub-mirrors; a spherical mirror Mb, composed of 37 hexagonal spherical sub-mirror, and a 1.75m diameter focal plane equipped with 4000 optical fibers. The thin mirror active optics and the segemented mirror active optics are adopted to eliminate aberrations including the third-order spherical aberration of Mb, gravitational and thermal deformation, and low spatial frequency surface error produced in optical processing, and furthermore, to maintain the co-focus of all segments.

The designed image quality of LAMOST is diffraction limited under optical wavelength, and requires 80% light energy within 2 arcsecond. However, the 60m long light path, poor natural seeing, dome seeing and other errors worsen the image quality about 0.5-1.0 acsecond. Yuan & Cui designed a low-order adaptive optics system to lower the influence of the light path seeing. The related experiment is in progress. In this paper, we consider the adaptive optics performance of LAMOST on condition that the telescope has been corrected to approach to diffraction limited. Based on the sounding balloon results on Xinglong Station, we make the numerical simulation of the Ground Layer Conjugate Adaptive Optics (GLAO) performance and get Fried parameter, the final point spread function (PSF) characteristics of LAMOST including Strehl ratio, full width at half- maximum (FWHM), and the residual variance.

GLAO is a new AO mode which correct the aberrations induced by atmospheric turbulence over a field a few arc minutes by conjugating a deformable mirror to the ground layer altitude. The reasons that we investigate the performance of GLAO for LAMOST but not other AO modes, such as Multi-Conjugated Adaptive Optics (MCAO) and Single Conjugated Adaptive optics (SCAO), are as following: firstly, a large corrected field is of advantage to observation of LAMOST since the telescope is designed a wide field. Secondly, according to the atmospheric datum on Xinglong Station, the strongest turbulence layer is from the ground to 3 kilometers upwards, which is suitable for GLAO.

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Adaptive Optics Systems II, edited by Brent L. Ellerbroek, Michael Hart, Norbert Hubin, Peter L. Wizinowich,
Proc. of SPIE Vol. 7736, 773647 · © 2010 SPIE · CCC code: 0277-786X/10/$18 · doi: 10.1117/12.856824

We can estimate simply the isoplanatic gain and the corresponding number of sub-apertures in MCAO and GLAO mode. The isoplanatic gain is given by

$$G_\theta = 4[\sum_{i=1}^{N} \frac{(\bar{h} / h_i)^{5/3}}{N}]^{3/5} \qquad (1)$$

Where N is the number of atmospheric layers, h_i is the thickness of i-th layer atmosphere, $\bar{h}$ denotes the average atmospheric thickness. $\bar{h} = (\frac{\int_0^\infty z^{5/6} C_n^2(z)dz}{\int_0^\infty C_n^2(z)dz})^{6/5}$, and $C_n^2(z)$ is atmospheric refractive-index structure constant. h_i can be derived from $h_i = [(\sum_{i=1}^{N} h_i^{-5/3}) \frac{\int_{ki} C_n^2(z)dz}{\int_0^\infty C_n^2(z)dz}]^{-3/5}$, so the thickness of each layer and isoplanatic gain can be calculated while N and specific $C_n^2(z)$ is given. If the prospective performance is shown by Strehl ratio S, we can estimate the prospective numbers of subapertures through

$$N_{subaperture} = \frac{[0.051k^2 \int_0^\infty C_n^2(z)dz]^{6/5} D^2}{[\ln(1/S)]^{6/5}} \qquad (2)$$

where D is the aperture diameter of telescope.

We set $C_n^2(z)$ is the turbulent structure at Xinglong site, wavelength is 0.8 micrometer, D=4m which is similar with the aperture diameter of LAMOST, and S=0.15. The estimating results are shown in Table.1

Table.1 the thickness of layers, the prospective numbers of subapertures and the isoplanatic gain at N=2, 3, 4

N	H_1(km)	H_2(km)	H_3(km)	H_4(km)	$N_{subaperture}$	G_θ
2	4.57	15.43	_	_	341	1.04
3	2.23	7.62	12.38	_	318	1.74
4	1.51	4.04	6.56	13.46	295	2.31

From the results in Table.1, for the seeing of Xinglong site, the isoplanatic gains do not increase much and the numbers of subapertures reduce a few in MCAO mode. Taking account of the complexity and cost of MCAO system, we prefer to test GLAO on LAMOST at Xinglong site.

2. ATMOSPHERIC TURBULENCE ON XINGLONG STATION

The turbulence profiles that include atmospheric refractive-index structure constant profiles C_N^2 and horizontal wind speed profiles are essential in analyzing the performance of AO systems. The seeing measurements on Xinglong observatory were carried out by several study groups for the last 15 years. The observational results, published in Ref.2, may be summarized that the annual seeing ~1″-2″, among the total data, 25% seeing angles are less than 0.8″, and 75% seeing angles are less than 1.5″. Average wind speed is 2.4m/s~3.1m/s. The instant wind speed is larger than 8m/s about 90 days of a year.

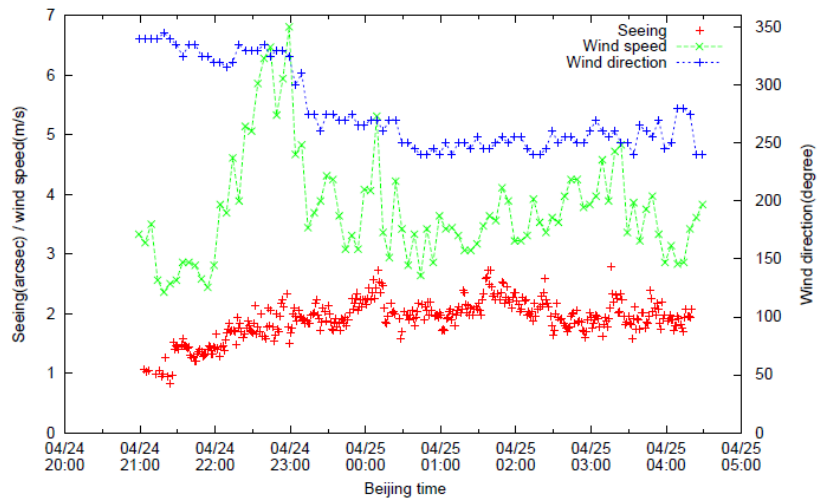

Fig.1 the Polaris Seeing value and wind profile at the night of April 24, 2007 in Ref.1

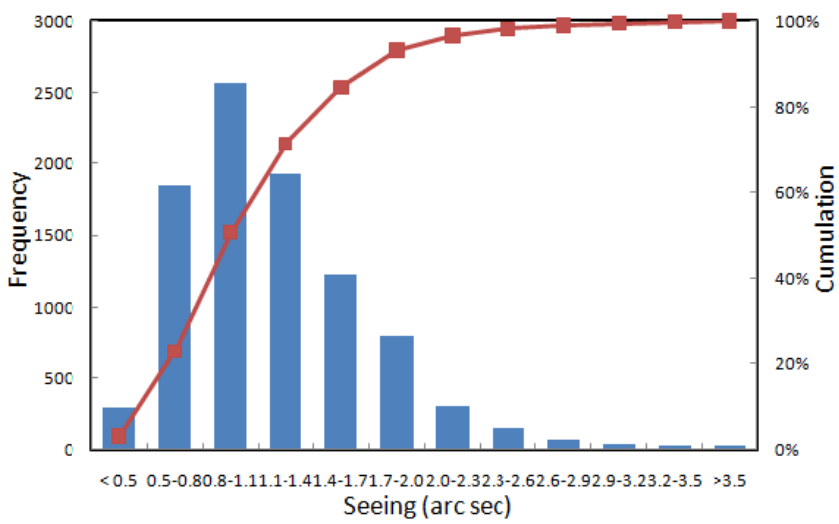

Fig.2 the statistical distribution of the seeing measurements from March to April, 2007 in Ref.1

A C_N^2 profile was obtained by the method of temperature fluctuation sonde in Ref.3. The profile shows characteristics: there is a strong turbulent layer below about 3km; as the height increases, C_N^2 descends sharply, and the second turbulent layer exists in about 10km. By analyzing and fitting data, C_N^2 is expressed as function of height z in Eq.3, which is approach to Hufnagel-Valley turbulence mode.

$$C_n^2(h) = 9.68\times10^{-23} h^{10} e^{-1.01h} + 8.1\times10^{-18} e^{-h/2.8} + 3\times10^{-15} e^{-h/0.812} \qquad (3)$$

3. SIMULATIONS AND RESULTS

We use PAOLA (Performance of Adaptive Optics for large Apertures), an analytic modeling tool in our simulation processing. In PAOLA code, the first step is building telescope pupil architecture, whereafter, calculate the point spread

function (PSF) and (optics transfer function) OTF. The effective pupil plane is not the Ma, but the projection of Ma on the plane parallel to focal plane, so the segmented pupil transmission may be written as follow:

$$P(u, v\cos\theta) = H(u, v\cos\theta) \otimes \sum_{i=1}^{N} \delta(u - u_i, (v - v_i)\cos\theta) \qquad (4)$$

Where $H(u, v\cos\theta)$ denotes the projection of the elementary segment transmission on the effective pupil plane, $(u_i, v_i \cos\theta)$ is the projection of each segment centre, and θ is the angle between the Ma plane and the effective pupil plane.

The telescope amplitude PSF is derived from the Fourier Transform (FT) of the pupil transmission:

$$APSF(x, y) = FT\{P(u, v)\} \qquad (5)$$

where (x,y) is the angular coordinates in the focal plane. PAOLA tool gives the two-dimensional FT of a hexagon in an analytical expression. From the scale property of the FT, the amplitude PSF of LAMOST is expressed as:

$$APSF(x, y) = \frac{1}{\cos^2\theta} G(f_x, \frac{f_y}{\cos\theta}) \frac{1}{S_p} \sum_{i=1}^{N} \exp[-j2\pi(f_x u_x + f_y v_y)] \qquad (6)$$

where the angular coordinates (x, y) in the focal plane and the pupil plane spatial frequencies (f_x, f_y) have a transform relation: $(x, y) = \lambda(f_x, f_y)$, G is the hexagon segments transmission FT, and S_p is the overall pupil surface. The seeing-limited and diffraction-limited PSF for LAMOST in the wavelength of 1.75 microns is illustrated in Fig.3, where $r_0 = 1.2', \theta = \pi / 6$. Turbulence greatly affects the designed diffraction limited performance for LAMOST, and the seeing-limited PSF is down to 1.6%, and FWHM is 816 mas.

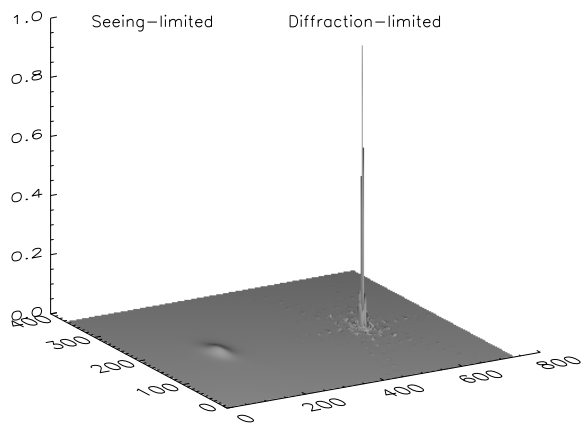

Fig.3 The seeing-limited and diffraction-limited PSF for LAMOST

The PAOLA tool is based on an analytical description of the residual phase spatial power spectrum, which is presented detailedly in Ref.8. Five main sources of residual phase error considered in the code include the fitting error, the wavefront sensor aliasing and noise, the servo-lag error and the anisoplanatism. In GLAO mode, we explore the total residual variance and the final Strehl ratio as a function of wavelength from J to K wavebands, for 0.5', 1', 2', and 3' corrected field. We adopt the altitude of conjugation is the weighted altitude

$< H >= (\int_0^\infty z^{5/3} C_n^2(z)dz / \int_0^\infty C_n^2(z)dz)^{3/5} = 3.32km$, and assume that 4 natural guide stars of 10 magnitudes, in which 3 guide star array on a circle of corrected field radius and one guide star is situated in the corrected field centre to attain more turbulent information. Certainly, it is not realistic situation, so we can regard the simulation results as an uplimit of realistic performance of AO. The results are displayed in Fig.4, 5, and other parameters used in calculation are listed in Table.2.

AO loop time-lag 5ms Pixel read noise of WFS CCD 5e/pixel transmission from the star to the WFS CCD 0.5	Outer scale 50m WFS integration optimized

Table.2 input parameters

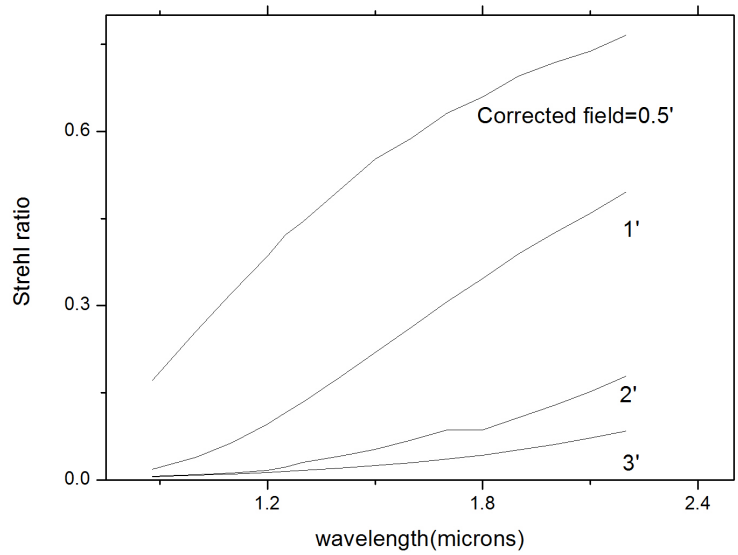

Fig.4 Strehl ratio versus wavelength for different corrected fields.

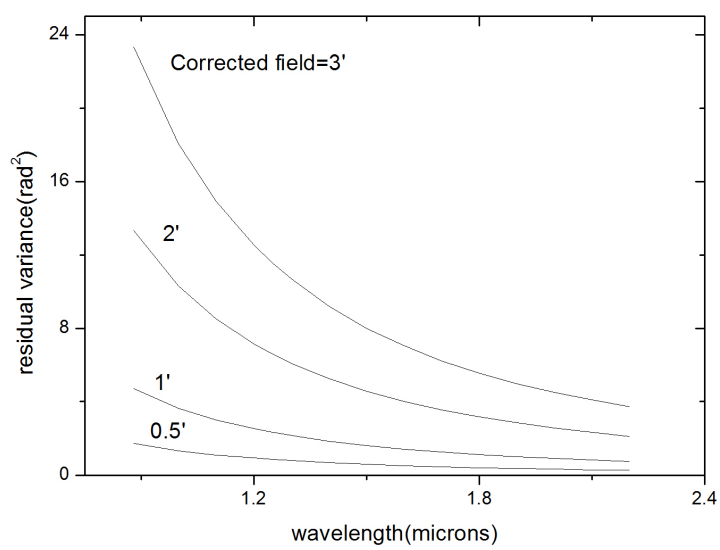

Fig.5 the residual variance as the function of wavelength for different corrected fields

It is obviously that the poor atmospheric seeing results in relatively bad performance of AO at Xinglong site. To attain better results, we correct adjust atmosphere turbulence in K or H wavebands, or carry out corrections in a relatively smaller field of view on LAMOST.

ACKNOWLEDGEMENTS

This paper was supported by the Knowledge Innovation Program of the Chinese Academy of Sciences, Grant No. KJCX2-YW-T17. The authors would like to thank Dr. Laurent Jolissaint for sharing the PAOLA code.

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