Ground layer adaptive optics system simulation for the 2.5m telescope in Dome A

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ABSTRACT

The Antarctic is an ideal place for optical and infrared astronomy observations. Chinese scientists are planning to build a 2.5m telescope in Dome A. The telescope will be built in a tower about 15 meters high to avoid the ground layer atmospheric turbulence. The Ground layer Adaptive Optics system (GLAO) will also be suggested to be installed to further reduce the seeing. The GLAO system with one laser guide star, one deformable mirror and one wide field Shack-Hartmann wavefront sensor is designed and simulated. The Strehl ratio has increased 2 to 3 times in visible and infrared band in 20 arc min field of view.

Keywords: Antarctic telescope, ground layer adaptive optics, rotation mirror, single laser guide star

1. INTRODUCTION

The adaptive optics (AO) system[1] is widely used in modern ground–based telescopes to improve the observation conditions. It compensates the wavefront errors induced by the atmospheric turbulence. The compensation results[2] depend on the scientific aims of the systems and the distribution of the atmospheric turbulence. The Antarctic 2.5m telescope is designed to make high resolution and wide field sky survey (image survey and precision photometry). The atmospheric turbulence distribution is unique in the Antarctic: it has highly turbulent stable ground layer atmospheric turbulence and the free atmospheric turbulence has small weight on the whole distribution. According to the natural conditions, several special designs have been made to achieve the scientific aims. The telescope will be built in a tower about 15m high to reduce most seeing induced by the ground layer atmospheric turbulence and the ground layer adaptive optics (GLAO) system can also be applied to further reduce the seeing.

2. THE ANTARCTIC 2.5M TELESCOPE

The Antarctic is considered to be one of the most excellent sites for ground–based telescopes in visible–infrared bands.[3] It is clean, cold, dry and the nighttime sky brightness is low. The atmospheric turbulence distribution is also very unique: the ground layer turbulence has big weight over the whole distribution which has also brought big isoplanatic angle and long coherent time comparing with the ordinary sites.

There are three promising Antarctic sites – Dome A, Dome C and Dome F. Dome A (80° 22' S, 77° 21' E, 4093 meters above sea level) is the summit of the massive East Antarctic Ice Sheet. It is considered to be the coldest and driest location on the earth. The weather conditions show great potential in astronomical observations. The Chinese National Antarctic Research Expeditions reached Dome A in 2005 and the Antarctic Kunlun station was set up in 2009. Several telescopes[4] are considered to be set up in Dome A. The CSTAR[5] and AST3[6] have already been set up. The Antarctic 2.5m telescope will be the next telescope to be set up in visible–infrared band. It is a telescope with a major mirror of 2.5m and a 0.625m secondary mirror. The telescope is set in a

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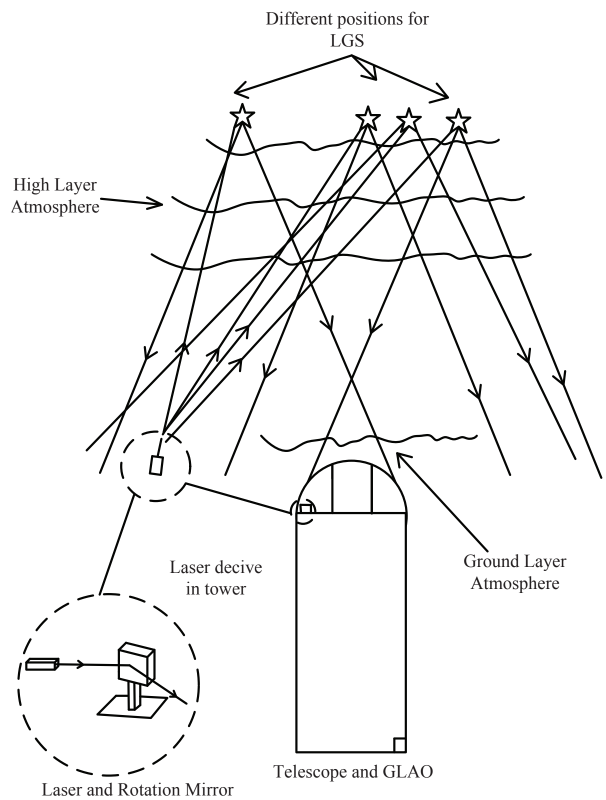

Figure 1. Schematic diagram of the GLAO for the Antarctic 2.5m telescope

tower to reduce the ground layer seeing. The scientific aim of this telescope is the wide field sky survey.[7] The observation modes of the telescope will be imaging and precision photometry.

3. THE GLAO SYSTEM FOR THE 2.5M TELESCOPE

The 2.5m telescope will be set up in a tower of 15m high to reduce the seeing. The GLAO will also be suggested to be applied to further reduce the seeing. The conventional GLAO will send a few guide stars to different areas in the sky and receive the wavefronts with a few wavefront sensors (WFS) from them. The wavefronts signal will be processed and sent to the a deformable mirror (DM) to compensate wavefront errors induced by the turbulence. Generally speaking the signal sent to the DM is the average of different wavefronts. The averaged wavefront is considered to be mainly induced by the ground layer atmospheric turbulence as shown in figure 1. If the ground layer turbulence has big weight in its whole distribution, the GLAO will significantly reduce the seeing in a wide field of view. The essence of the GLAO system is to sample the ground layer atmospheric turbulence and partly to correct it. Some new designs have been raised up to achieve this goal. Tokovinin[8] designed the GLAO system with a Rayleigh beacon and Morris and Myers[9] designed a single rotating laser guide star that can correct a wide field of view. These designs show the potential of the rotating Rayleigh laser guide star used to sample the ground layer atmospheric turbulence.

The rotating Rayleigh laser guide star will be used in the GLAO system for the Antarctic 2.5m telescope. The rotating Rayleigh laser guide star can cover a wide field of view and the deteriorated results brought by the lack of the high layer free atmospheric turbulence detection are negligible within a certain range because of the big weight of the ground layer turbulence. A Shack–Hartmann wavefront sensor with wide field of view will be used to sample the wavefronts from Rayleigh laser guide star in different positions. This GLAO system consists of a tip-tilt mirror, a quadrant detector, a deformable mirror, a laser device, a rotation mirror, a Shack–Hartmann wavefront sensor with wide field of view and a science camera. This system costs less than the ordinary GLAO system and the performance is acceptable according to our simulation.

4. SIMULATION OF THE GLAO SYSTEM

The GLAO system for the Antarctic 2.5m telescope is simulated under the Durham extremely large telescope adaptive optics simulation platform.[10] This system is different from the ordinary GLAO system. In the simulation of the ordinary GLAO system, the LGSs are considered to be static (they are fixed in different positions on the sky). While the GLAO system for the Antarctic 2.5m telescope, the LGS is a rotating star and it will change the position in time sequence. The frequency of the rotating of the LGS, of the correction of the GLAO system and of the sample rate of the wavefront sensor should be considered to match each other. Because there are many parameters (static and dynamic) to be defined, the system simulation has been divided into two stages. The first stage is to determine the static parameters of the system; In this stage, the laser guide stars will be assumed to be motionless (just like multiple laser guide stars distribute in different positions in the sky), and the working frequency of the overall system is 300hz. The second stage is to determine the dynamical parameters of the system. It is analyzed the frequency matching problem between the frequency of the correction of the system (not including the rotation mirror) and that of rotation mirror, and the optimal working frequency of the overall system (with the rotation mirror).

4.1 The system simulation with static parameters

There are two kinds of static parameters: the constant such as the atmospheric turbulence distribution, the structure of the telescope, the position and magnitude of the natural guide star (NGS), the field of view and the correction aims of the GLAO system and the variable parameters. The constant parameters are those that defined when the telescope and the scientific aims are defined. The variable parameters are those parameters that we alter to satisfy our needs, such as the number of the sub–apertures of the WFS, the number of the actuators of the DM, the number and type of the LGSs, the frequency of the correction of the system.

The constant parameters in the simulation are defined below. The field of view for the GLAO systems is 20 arcmins. It is bigger than the ordinary GLAO system because of the unique atmospherical turbulence distribution in the Antarctic. The system is designed to increase the Strehl ratio 2 to 3 times. Because the uniformity of the correction results is also important, the difference between the maximum and minimum Strehl ratio should be less than 0.05. The telescope is an ideal telescope with 2.5m major mirror and 0.625m secondary mirror (the aberations of the telescope are neglected in the simulation). The NGS, magnitude 10, is 10 arcsec to the middle of the filed of view. The GLAO is layer–oriented adaptive optics system. The atmospheric turbulence distribution is very important to the overall system performance evaluation. The detailed atmospheric turbulence distribution needs to be measured with scientific instruments (such as microthermal sensors) layer by layer (layer is defined as the areas with different heights). Right now, there is not detailed measure results of the distribution available in Dome A. But according to the early measure results, the condition in Dome A is pretty good. We use the four layer atmospheric turbulence model[11] derived from the data in the Dome C in the simulation. According to Lascaux,[12] the difference of the atmospheric turbulence between these two sites is not very notable. The average and the worst situations of the atmospheric turbulence distribution are shown in table 1 and table 2 respectively. The average set is used to test the system performance in ordinary situations and the worst situation is used to test the system's performance under severe conditions. The simulation without the GLAO shows that the Strehl ratio is 0.1146 under the average state and 0.06982 under the worst state (in 700nm band with r_0 is 30cm).

The GLAO for the Antarctic 2.5m telescope consists of a tip-tilt mirror, a quadrant detector, a deformable mirror, a laser device, a rotation mirror, a Shack–Hartmann wavefront sensor with wide field of view and a science camera. The laser device will work in 430nm, the wavelength for the natural guide star will be 500nm and the science camera will work in 700nm. A pair of dichroic filters will be used to divide the light from different objects. The initial parameters of the system is listed in table 3. The parameters will be altered one by one to

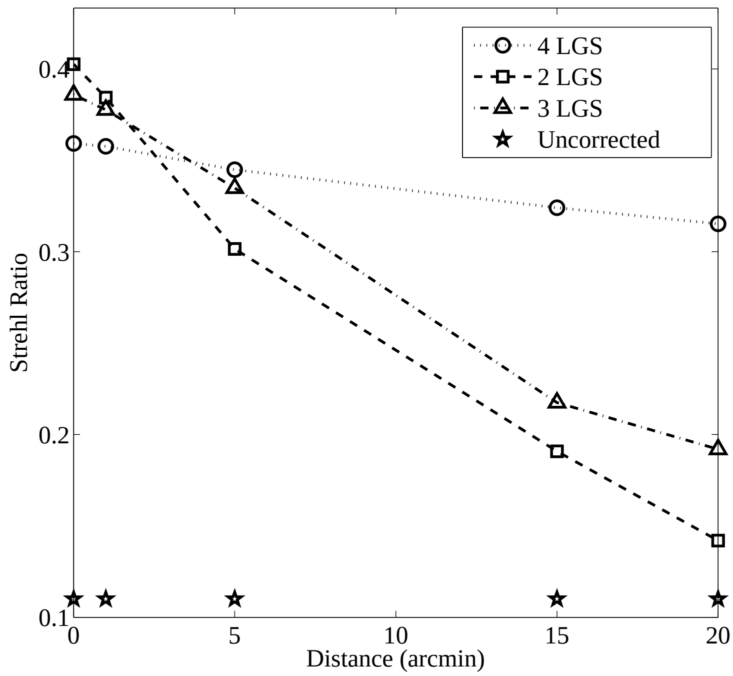

Figure 2. Relationship between the number of the positions of LGS and the Strehl ratios

Table 1. The parameters of the average state of the atmospheric turbulence

layers	height (m)	weight	wind velocity (m/s)	wind direction (degree)
1	19	0.8904	4	139
2	170	0.06849	7	185
3	4469	0.03425	15	239
4	10038	0.006849	20	300

Table 2. The parameters of the worst state of the atmospheric turbulence

layers	height (m)	weight	wind velocity (m/s)	wind direction (degree)
1	22	0.5319	7	139
2	220	0.4184	10	185
3	4900	0.04255	20	239
4	10038	0.007091	20	300

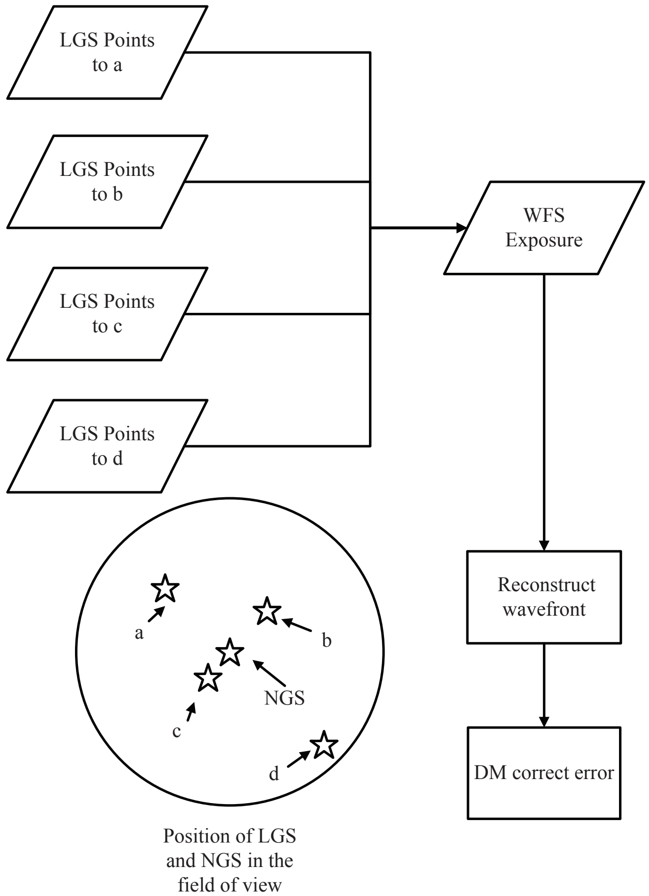

Figure 3. The flow chart of a cycle, the pointing positions of the LGS

Table 3. The initial parameters of the system

Device	Parameters
Laser Guide Star	3 guide star
Quadrant detector	Ideal detector
Tip–tilt mirror	remove the tip–tilt measured by the quadrant detector directly
Deformable mirror	11×11 actuators Gaussian profile response
Wavefront Sensors	11×11 subapertures Shack–Hartmann type
Correct method	Modal method (correct 9 Zernike parameters)
Control method	PID method

satisfy our needs (the frequency of the overall system is 300hz during this process).

The number and positions of the LGS are first considered. The LGS in the GLAO system for the Antarctic 2.5m telescope is different from that of the ordinary GLAO system. Because the wavefront sensor has to sample all the wavefronts from the LGS in different positions, the number of the guide stars will decrease the overall system frequency. For example, if the frequency of the rotation mirror is 1000hz and there are 5 positions for

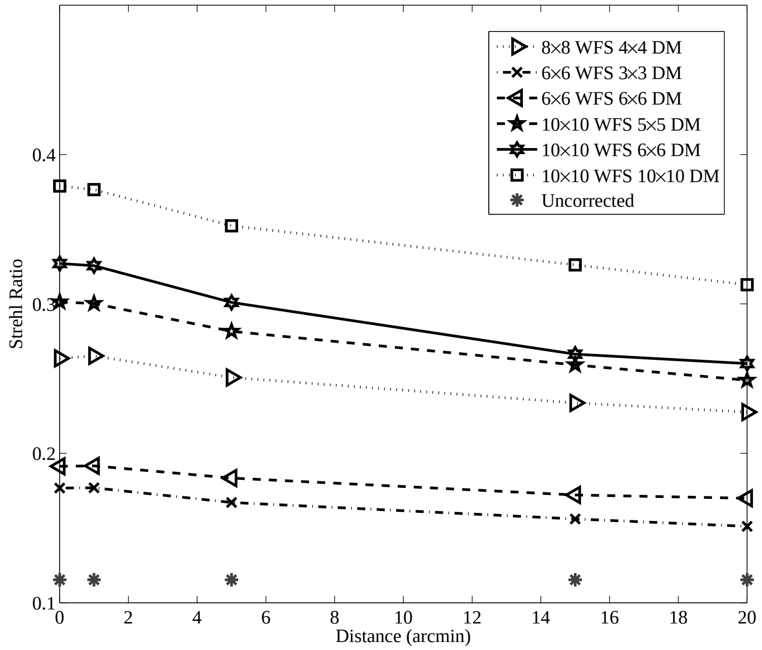

Figure 4. Relations between the number of the sub-apertures of the WFS and the number of the actuators of the DM

the LGS, the rotation mirror has to rotate to five positions before the all the information of the wavefronts is captured. So the frequency of the whole system is less than 200hz. Considering the cost of the rotation mirror and the frequency of the system, the number of the guide stars has to be no more than four. According to figure 2, LGS with four positions satisfies our requirements. The positions of the LGS are shown in figure 3 and table 4.

The GLAO correction method used in this simulation is the modal approach (the first 9 Zernike parameters are corrected without piston). Because no high order Zernike parameters are used, the density of the actuators of the DM can be sparse. When the system is operating, only part of the WFS may be used to sample the wavefront and the DM be used to correct the aberrations. The matching problems for the number of the actuators of the DM and of sub-apertures of the WFS in GLAO are also considered. Some of these situations results are in figure 4. When more than 10×10 sub-apertures of the WFS are illuminated and more than 6×6 actuators are used, the system performance is acceptable. According to the results of the simulation, the system will use WFS with 10×10 sub-apertures and DM with 10×10 actuators.

4.2 The system simulation with dynamical parameters

The LGS system in the GLAO system for the Antarctic 2.5m telescope is different from the ordinary GLAO system. The ordinary GLAO systems will use three to five laser devices to point to different areas in the field of view to generate laser guide stars. The cost for the laser devices are high and the power supplies for the devices in the south pole are also a problem in the Antarctic. Thanks to the unique atmospheric turbulence distribution in Dome A, a laser device with a rotation mirror can satisfy our needs. Because the atmospheric turbulence at Dome A distributes low, the isoplanatic angle and the coherent time are larger than those in other sites in the earth. The overall system operating frequency can be lower than GLAO systems in other sites. A laser device and a rotation mirror are used to generate the laser guide stars (the disadvantage of the system is the limitation of the frequency of the whole system caused by the rotation mirror, however, for the system at Dome A, the deteriorated results caused by the delay of the rotation mirror are negligible within a certain range). The working

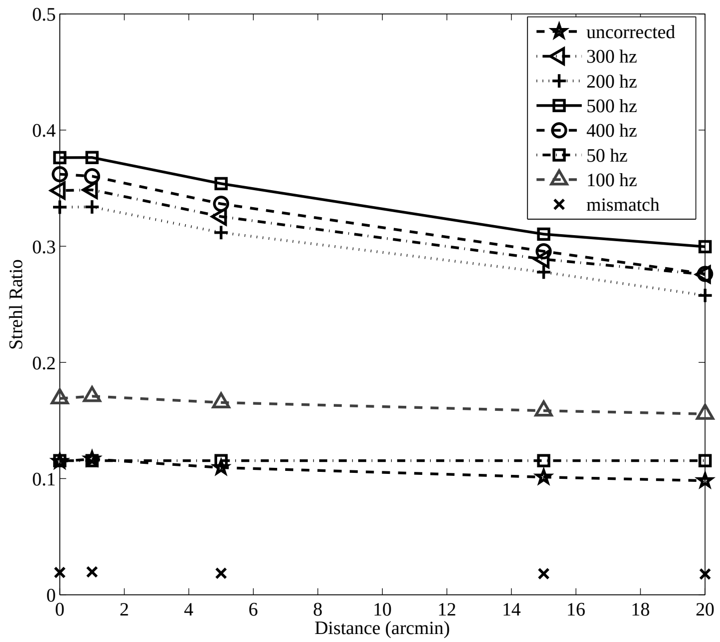

Figure 5. The system performance under different overall system frequencies. The mismatch stands for the situation when the exposure time and the shifting time of rotation mirror are not in integer times.

Table 4. The positions of the LGS

LGS flag	LGS position to the center (arcmin)
a	5
b	2.5
c	1.25
d	10

flow chart of the system are shown in figure 3. When the system is operating, the laser will point to a few pre–defined different positions sequentially in the field of view. Then the wide field Shack-Hartmann wavefront sensor will sample the wavefronts from different LGSs. When all wavefronts from the four positions are recorded by the WFS, the DM will correct the wavefront according to the signal from the WFS. This process is defined as a cycle.

The GLAO system and the LGS system should be synchronized. The external trigger will be used to keep them synchronous. When their frequencies are mismatched, the overall system performance will be deteriorated. The GLAO system with different frequencies is simulated. The results are shown in figure 6. According to the results, when the overall system frequency is larger than 200hz, the system satisfies our needs. Because there are four positions for the LGS to point, the rotation mirror has to be at least 4 times to the overall system frequency. The rotation mirror with 1000hz is chosen. Optical components on the shelf satisfy our needs.

5. CONCLUSION

The simulation of the GLAO system for the Antarctic 2.5m telescope shows great potential of application of the GLAO with a Rayleigh laser guide star and a rotation mirror. This system saves cost with only one laser device and deteriorated results caused by the delay of the rotation mirror and lack of the information of the high layer atmospheric turbulence are negligible within a certain range because of the unique distribution of the atmospheric turbulence in the Antarctic. The synchronous problem of the rotation mirror and the wavefront sensor is also analyzed. The experimental GLAO system is now being set up in the laboratory using the parameters defined by this simulation. Some of the new wavefront reconstruct methods and control methods will be tested and the results will be improved further with the new methods.

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REFERENCES

[1] Tyson, R. K., [*Principles of adaptive optics*], Boston, MA: Academic Press, 1998 (1998).

[2] Hubin, N., Arsenault, R., Conzelmann, R., Delabre, B., Le Louarn, M., Stroebele, S., and Stuik, R., "Ground Layer Adaptive Optics," *CR PHYS* **6**, 1099–1109 (Dec. 2005).

[3] Lawrence, J. S., Ashley, M. C. B., Burton, M. G., Cui, X., Everett, J. R., Indermuehle, B. T., Kenyon, S. L., Luong-Van, D., Moore, A. M., Storey, J. W. V., Tokovinin, A., Travouillon, T., Pennypacker, C., Wang, L., and York, D., "Site testing Dome A, Antarctica," in [*Proc. SPIE*], *Proc. SPIE* **6267** (July 2006).

[4] Stone, R., "In Ground-Based Astronomy's Final Frontier, China Aims for New Heights," *Sci* **329**, 1136–1136 (Sept. 2010).

[5] Yuan, X., Cui, X., Liu, G., Zhai, F., Gong, X., Zhang, R., Xia, L., Hu, J., Lawrence, J. S., Yan, J., Storey, J. W. V., Wang, L., Feng, L., Ashley, M. C. B., Zhou, X., Jiang, Z., and Zhu, Z., "Chinese Small Telescope ARray (CSTAR) for Antarctic Dome A," in [*Proc. SPIE*], *Proc. SPIE* **7012** (Aug. 2008).

[6] Cui, X., Yuan, X., and Gong, X., "Antarctic Schmidt Telescopes (AST3) for Dome A," in [*Proc. SPIE*], *Proc. SPIE* **7012** (Aug. 2008).

[7] Zhao, G.-B., Zhan, H., Wang, L., Fan, Z., and Zhang, X., "Probing Dark Energy with the Kunlun Dark Universe Survey Telescope," *PASP* **123**, 725–734 (June 2011).

[8] Tokovinin, A., "Seeing Improvement with Ground-Layer Adaptive Optics," *PASP* **116**, 941–951 (Oct. 2004).

[9] Morris, T. J. and Myers, R. M., "Wide-field Adaptive Optics correction using a single rotating laser guide star," *MNRAS* **370**, 1783–1789 (Aug. 2006).

[10] Basden, A. G., Butterley, T., Myers, R. M., and Wilson, R. W., "Durham extremely large telescope adaptive optics simulation platform," *APPL OPTICS* **46**, 1089–1098 (Mar. 2007).

[11] Trinquet, H., Agabi, A., Vernin, J., Azouit, M., Aristidi, E., and Fossat, E., "Nighttime Optical Turbulence Vertical Structure above Dome C in Antarctica," *PASP* **120**, 203–211 (Feb. 2008).

[12] Lascaux, F., Masciadri, E., and Hagelin, S., "Mesoscale optical turbulence simulations above Dome C, Dome A and South Pole," *MNRAS* **411**, 693–704 (Feb. 2011).