Multi-instrument characterization of optical turbulence at the Ali observatory

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Abstract. In order to characterize the atmospheric optical turbulence at Ali observatory, we have deployed multi-instruments, which are able to continuously monitor the optical turbulence for site evaluation. These instruments include the DIMM, MASS, Single Star SCIDAR and Polaris seeing monitor, and we also plan to install SNODAR and Micro-thermal sensors for the turbulence on surface layer by the end of this year. This configuration allows us to collect a substantial database and make cross-comparison of the results. We have successfully obtained the profiles of optical turbulence and wind speed with Single Star SCIDAR, as well as the key parameters for adaptive optics application, such as seeing, coherence time, and isoplanatic angle. The DIMM seeing measurements are also carried out simultaneously. The median seeing measured by the DIMM and SSS in 2013 is 0.69 and 0.79 arcsec, respectively.

1. Introduction

The Ali observatory is located at 32°19′ (N), 80°01′ (E), with an altitude of 5100m, near the central town of Ali area, Tibet (Fig.1). The remote studies and local site testing have been performed, the first results show that Ali observatory is promising for very large optical-infrared telescopes [1]. The Ali observatory has begun construction since 2010, and up to date, there are nine domes already be installed for site testing. The site testing instruments including automatic weather station (AWS), cloud monitor, water vapor monitor, and multi-instruments for atmospheric optical turbulence characterization. Due to optical turbulence seriously limits the performance of high angular resolution instruments, the characteristics of optical turbulence is important to evaluate astronomical observatory. In this paper we introduce the instruments for turbulence measurement at Ali observatory, and present preliminary results of the site testing campaign in 2013.

2. Instruments

In this section, a brief description is given to the principles and observations of multi-instruments in Ali observatory. DIMM is a portable instrument for detection of optical turbulence, but it only senses the integrate atmosphere. The Single Star SCIDAR (SSS) is a portable version of the SCIDAR, which provides the profile of optical turbulence and velocity of the whole atmosphere from ground to 25 km. Microthermal sensors, equipped on a 40m mast, can detect the surface layer turbulence. Although Polaris seeing monitor is fully automated, the measurements easily...
be affected by gusty winds. MASS can subdivide the whole atmosphere into 6 thick layers, yet it tends to detect the turbulence in the free atmosphere. SNODAR is a profiler for the atmospheric boundary layer with a vertical resolution of 1 m. Fig.2 shows the layout of multi-instruments for turbulence measurements at the Ali observatory.

2.1. DIMM
The DIMM is a small transportable instrument [2], with the differential technique to accurately measure the seeing conditions. The seeing is measured via the differential positions of two sub-aperture images of a star, and therefore, DIMM seeing monitor is almost insensitive to tracking errors. This instrument yields the integrated seeing from telescope pupil to the top of the atmosphere.

The DIMM technique is widely employed in site testing. We have developed a DIMM for site testing [3] and installed it at the position C on Fig.2. The DIMM instrument is shown in Fig.3. The Fig.4 is the simultaneous measurements with 2 sets of DIMM for calibration. According to the principle mentioned above, our DIMM instrument has the following configurations:

(i) a Meade LX200GPS telescope, with the entrance pupil of 20 cm, and the focal length of 200 cm;
(ii) a mask with two sub-aperture, with diameter of 5 cm, and a separation of 15 cm;
(iii) an optical wedge installed on one sub-aperture, to adjust an appropriate separation between the two star images at focus;
(iv) a Lumenera SKYnyx 2.0M CCD camera, attached to the telescope focal plane for fast sampling star images ($\Delta t = 0.5 \text{ms}$), with a 640 $\times$ 480 format and the pixel size of 7.4 $\mu m$;
(v) two computers, one calculating seeing values and closed-loop guiding, and the other remotely monitoring the status via internet.

2.2. Single Star SCIDAR

SSS is a remote sensing technique to measure the vertical structure of the atmospheric turbulence by analyzing the scintillation patterns of single star. SCIDAR technique has been first proposed by Vernin in 1973 [4], which analyzing the double star scintillation in order to separate the effect of each optical turbulent layer. The SSS is a new member in SCIDAR family, and this instrument can deliver the distribution of $C_n^2(h)$ with height, by using a small telescope.

![Figure 5. The SSS instrument at Ali observatory (The position A in Fig.2).](image1)

![Figure 6. The MASS instrument at Ali observatory (The position D in Fig.2).](image2)

We have developed a SSS for remotely sensing atmospheric turbulence profiles [5]. Fig.5 shows the SSS location at the Ali observatory (The position A in Fig.2). The SSS consists of a 40 cm telescope and a CCD camera for fast sampling of stellar scintillation pattern. The single star images are analyzed, providing vertical profiles of optical turbulence intensity $C_n^2(h)$ and wind speed $V(h)$, and allowing the determination of seeing, isoplanatic angle and coherence time. Although the SSS is a low resolution optical turbulence profiler, it needs only 40 cm aperture telescope, showing a practical advantage of being transportable for field site testing. The main specifications of our SSS are the following.

(i) a 40 cm Meade M16 tube, on an Astro-Physics 1200 equatorial mount, with the focal length of 400 cm;
(ii) a collimating lens after the focus of the telescope, with 10 mm focal length, to make the beam parallel;
(iii) a CCD camera, after the collimating lens for fast sampling the star scintillation pattern. The fast readout Pixelfly CCD-200XS, 640 $\times$ 480 format with pixel size of 9.9$\times$9.9 $\mu m^2$, allows continuous acquisition with a high frequency rate without loss of any image. The exposure time is usually taken as 1 ms, every 5.6 ms, the pixel scale is 0.51 arcsec/pixel;
(iv) an auto-guiding system, made with a cube splitter;
two control computers, one capturing scintillation images from the CCD camera and computing the spatial auto-correlation and cross-correlation images, the other serving as real time tracking through a CCD guider.

2.3. Micro-thermal sensor

The refractive index variations arise from density variations in the air, so the refractive index fluctuation is related to its thermal fluctuations. The first micro-thermal measurements are made with resistance thermometers by Lynds [6]. The temperature structure coefficient $C^2_T$ is defined as: $C^2_T = <|T(x)-T(x+r)|^2> \times r^{1/2}$, where $r$ is a separation of two temperature sensors in meter. Assumed that fluctuations are passive under the constant pressure, the refractive index variations arise directly from temperature fluctuations and can be measured by using the temperature fluctuations as following:

$$C^2_N(h) = \left(7.9 \times 10^{-5} \times P \div T^2\right)^2 \times C^2_T(h)$$

where $C^2_N$ is the refractive index structure coefficient, $P$ is pressure in hPa, $T$ is temperature in K degree, and $h$ is height above ground in meter.

We have built a 40m tower for the micro-thermal measurements (The position B in Fig.2), and we plan to measure optical turbulence of the surface layer by cooperating with Japanese team at Ali observatory [7]. A total of 10 $C^2_T$ sensors on 5 levels of support stays will be installed on the 40m tower at the height of 36m, 19m, 10m, 6m and 4m above ground. A separation of a pair of $C^2_T$ sensors is set up to be 1 meter, and a temperature sensor is attached near the center of each stay.

2.4. Polaris Seeing Monitor

We have employed a Polaris seeing monitor (Made by SBIG) to determine the quality of seeing in the early site testing, because it is fully automated, and virtually no maintenance. The Polaris seeing monitor is fixed on the position F in Fig.2.

The seeing values can be calculated automatically according to the Polaris trail [8]. The monitor is developed using ST-402ME CCD with TDI readout mode, and the exposure time is set up to 5ms. The optical configuration is a set of F/5.3 lenses, providing a field of view of $2.7^\circ \times 1.6^\circ$. Due to the atmospheric turbulence, the line below Polaris image is deviated left and right as Polaris’s position is perturbed by seeing, and the SBIG software measures this perturbation and automatically calculates FWHM at the zenith. The comparison with SBIG seeing monitor and DIMM shows that SBIG seeing monitor is easily affected by gusty wind, resulting in larger seeing values [3]. Therefore, the SBIG seeing monitor just provide a trend of seeing variation.

2.5. MASS

MASS is an instrument to measure the vertical distribution of turbulence in terrestrial atmosphere by analyzing the scintillation of bright stars [9]. MASS can subdivide the whole atmosphere into 6 thick layers, e.g. 0.5, 1, 2, 4, 8, 16 km, and the turbulence intensity of each layer is measured. However, the MASS is not sensitive to the turbulence of the ground layer.

The turbulence of the ground layer in the first 0.5 km can be measured by combining MASS and DIMM. We have obtained a set DIMM-MASS from CTIO in 2009, and we installed it at Ali observatory in 2013 after some experiments. Fig.6 shows the SSS location at the Ali observatory (Position D in Fig.2). The DIMM-MASS will run the turbulence measurements next year.
2.6. SNODAR
We have ordered 2 sets of SNODAR from UNSW. SNODAR is a high resolution (5 kHz) acoustic radar designed specifically for profiling the atmospheric boundary layer, which can measure the atmospheric turbulence within the first 200m atmosphere with a vertical resolution of 1 m [10]. We plan to install the SNODAR in the position E in Fig.2, which is a platform without surrounding shelter.

3. Preliminary Results
We have performed site testing campaigns at Ali observatory to characterize the optical turbulence with the instruments of DIMM and SSS. One of the campaign are carried out the turbulence measurements from June 4 to 6 in 2013. One DIMM seeing value is calculated using a set of 100 images, and the final seeing corrected to the zenith angle. The SSS spatiotemporal cross-correlation functions are obtained every 11.2 sec corresponding to a set of 2000 images. Due to measurement errors caused by continuously changing sky background, especially during moon nights, the sky background is checked every hour during the SSS measurements.

Fig.7 presents the statistical distributions of the high angular resolution parameters with SSS. The seeing values (top left) span over the range [0.3 and 1.5 arcsec], with a half of the seeing better than 0.69 arcsec, and 75% of the seeing better than 0.9 arcsec. The isoplanatic angle (top right) follows a log-normal distribution, with an average of 2.81 arcsec, and a median of 2.96 arcsec, respectively. The coherence time (bottom left) also follows a log-normal distribution, and the average and median values are 5.70 and 5.28 ms, respectively. For the coherence étendue
Figure 8. The comparison distribution of seeing $\varepsilon_0$ with SSS (in blue) and DIMM (in red) at Ali observatory in 2013.

$G_0$ (bottom right) [11], the average and median values are 2.84, and 0.99 m$^2$.ms.arcsec$^2$.

Fig.8 shows the statistic comparison of the histogram and the cumulative distribution of the entire DIMM (in red) and SSS (in blue) data set. The DIMM mean seeing value is 0.85 arcsec, and the DIMM median value is 0.79 arcsec. There are 25% of the DIMM seeing values better than 0.65 arcsec, and 75% better than 0.95 arcsec.

4. Conclusions

Multi-instruments have been installed or planned at Ali observatory to investigate atmospheric optical turbulence properties. The set of instruments can obtain the turbulence profiles of surface layer, boundary layer, free atmosphere and the whole atmosphere. These instruments can provide optical parameters involved in high angular resolution astronomy, including seeing, isoplanatic angle, coherence time, coherence étendue, etc. The preliminary results in the site testing campaign in 2013 shows the median seeing with DIMM and SSS is 0.69 and 0.79 arcsec, indicating that Ali observatory is promising for large optical-infrared telescopes.

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