Optical turbulence at Ali, China – Results from the first year of lunar scintillometer observations.

Paul Hickson,1⋆ Lu Feng,2 Joschua A. Hellemeier,1,3 Zhixia Shen,2 Suijian Xue,2 Yongqiang Yao,2 Hualin Chen4 and Rui Yang5

1 University of British Columbia, Department of Physics and Astronomy, 6224 Agricultural Road, Vancouver, B.C., V6T 1Z1, Canada
2 National Astronomical Observatories, Chinese Academy of Sciences, 20 Datun Road, Beijing, China
3 European Southern Observatory, Karl-Schwarzschild-Str. 2, 85748 Garching bei München, Germany
4 National Astronomical Observatories/Nanjing Institute of Astronomical Optics & Technology, Chinese Academy of Sciences, Nanjing 210042, China
5 Department of Physics, Yunan University, Kunming, China

Accepted XXX. Received YYY; in original form ZZZ

ABSTRACT

The location an astronomical observatory is a key factor that affects its scientific productivity. The best astronomical sites are generally those found at high-altitudes. Several such sites in southern China and the Tibetan plateau are presently under development for astronomy. One of these is Ali, which at over 5000 m is one of the highest astronomical sites in the world. In order to further investigate the astronomical potential of Ali, we have installed a lunar scintillometer, for the primary purpose of profiling atmospheric turbulence. This paper describes the instrument and technique, and reports results from the first year of observations. We find that ground-layer turbulence at Ali is remarkably weak and thin. It contributes 0.31 arcsec to the median seeing above 11 m height and just 0.19 arcsec above 50 m. At the same time, initial data obtained using a crescent moon indicate that turbulence in the free atmosphere is comparatively large, contributing a median of 0.57 arcsec to the seeing. This may be due to high-altitude turbulence induced by air flow over the crest of the Himalayas. We suggest that a modified form of ground-layer adaptive optics, in which high-altitude turbulence is compensated rather than the ground layer, could be an effective strategy for high-resolution wide-field astronomy from this site.

Key words: site testing – instrumentation:adaptive optics – atmospheric effects

1 INTRODUCTION

China is engaged in the development of several high sites in mountainous regions of southern and western China and the autonomous region of Tibet. An extensive campaign of site testing, employing weather instruments, sky cameras, differential-image-motion monitors (DIMM), acoustic (SNODAR), and precipitable water vapour (PWV) monitors, has been conducted at three of these sites (Chen et al. 2018; Feng et al. 2019).

The highest of these sites is in the Ali region of Tibet, a desert plateau that has many peaks that rise more than 6000 m above sea level. It is known to have long periods of good weather, and little snow. The Ali sites are accessible by a paved road which connects to highway 219, the main route that links the nearby town of Shiquanhe to one of the highest airports in the world, and then follows the spine of the Himalayas to Lhasa. The airport has commercial jet service to Lhasa, with several flights each day.

The sites at Ali range in altitude from 5100 m (Site A1) to 5400 m (Site C). The relatively warm temperatures at these sites can result in density altitudes that exceed 6000 m. As the index of refraction fluctuation $\delta n$ is proportional to air density, and seeing is proportional to $\delta n^{6/5}$, one might expect a reduction in ground-layer seeing on the order of 20% compared to a typical ~ 4000-m site.

Fig. 1 provides a view of the Ali A1 site and surrounding area. The prevailing wind is from the south-south-west. In this direction, the ground falls away steeply, to the floor of a broad valley nearly 1 km below the site. On the far side of the valley is a range of mountains having peaks that rise as high as 6 km above sea level. These peaks can be seen in Fig. 2 and are approximately 20 km away.

In order to better assess the potential of the Ali sites for astronomy, we have begun a program to probe night-time

© 2018 The Authors

E-mail: hickson@physics.ubc.ca
Figure 1. View of the Ali ridge, as seen looking west from from site C. Site A1 is the peak, with buildings, that can be seen at the top of the paved road on the left side of the image.

atmospheric turbulence above them. To this end, a 6-element automated lunar scintillometer was installed at Ali Site A1 (80.02595° E, +32.32635° N). Although this is the lowest of the Ali sites, it has considerable infrastructure, including a paved road, power and internet, making it the most suitable location for our initial campaign.

This paper presents results from the first year of our campaign. We first describe the instrument and its characteristics, then discuss the observations. The results presented include statistics of ground-layer (GL) seeing, free-atmosphere (FA) seeing and clear sky fraction. We show that the ground-layer turbulence is remarkably weak. The free atmosphere appears to be dominated by a high-altitude turbulent layer that is generally the most important contribution to the seeing at this site. We conclude with a comparison of our results with other observations, and a discussion of the implications for optical astronomy from Ali.

2 INSTRUMENT DESCRIPTION AND PERFORMANCE

The scintillometer that we installed at Ali is the Arctic Turbulence Profiler (ATP). This instrument was originally designed for observations in the high arctic, and was operated at the Polar Environmental Arctic Research Laboratory on Ellesmere Island for a period of two years (Hickson et al. 2013). It was refurbished in 2017 and redeployed to Tibet in 2018. In this section we summarize the characteristics of this instrument and discuss its performance. Further details can be found in Hickson et al. (2010). Figure 2 shows the ATP installed at Ali in May, 2018.

2.1 Optics

The ATP employs 48 photodiode sensors, arranged in six rings. Each sensor has a field of view that is approximately 36°×24°. The 8 sensors in each ring are read sequentially as the Moon moves across the sky. In this manner, the Moon can be tracked without any physical motion of the instrument. A conductive film allows each window to be heated, if necessary, to remove frost or ice. To allow use of the ATP at the 30° latitude of Ali, a stand was made to hold the instrument so that its axis is aligned with the north celestial pole.

Because the ATP was designed for use in the arctic, its windows are angled northwards. The reason for this is that the Moon is only observed when sufficiently high above the horizon, which, in the Arctic, only happens when its declination is positive. As a result of this design, the Moon can only be observed at declinations δ > 16.0°, even at Ali. Nevertheless, this does allow the Moon to be observed for about one week each month. The design can be changed in a future instrument, to allow the Moon to be observed at all declinations.

The sensors are large-area photodiodes, Hamamatsu model S1336-8BK. They have a 5.8 x 5.8 mm active area and a typical peak quantum efficiency of 65 per cent. An optical filter that passes wavelengths greater than 665 nm, is installed in front of the sensor in order to block auroral and other night-sky emission lines.
2.2 Electronics

Each photodiode sensor is operated in photovoltaic mode, and amplified by a low-noise FET preamplifier having a gain of 200 mV/nA. A multiplexer passes this DC signal from the selected sensor in each ring to a 6-channel 16-bit analogue-to-digital converter (ADC), which digitizes them at a rate of 800 samples per second. At the same time, the fluctuating (AC) component of the signal is separated by a band-pass filter and further amplified. The AC passband is shaped by a 5-pole Bessel filter that has 3-db points at 0.5 mHz and 122 Hz. The AC signals can also be selected by the multiplexer and sent to the ADC. In normal operation, 10 seconds of DC data are recorded, followed by 110 seconds of AC data. This is repeated until the Moon is no longer accessible.

The instrument is controlled by a single-board computer (Technologic Systems TS-260), running TS-Linux, a compact version of Linux operating system. An application written in the python-3 programming language controls the operation of the multiplexers and records the digitized data.

2.3 Noise characteristics and sensitivity

At a good astronomical site, typical irradiance fluctuations for the full moon are at a level of $\sim 10^{-7}$. In order to obtain a good turbulence profile, it is generally necessary to measure covariances that can be smaller than $10^{-8}$. This requires a signal-to-noise ratio on the order of $10^5$, so careful attention to sources of noise is needed.

In photovoltaic operation, the dominant detector noise source is the Johnson noise associated with the photodiode shunt resistance. This resistance is typically 400 M$\Omega$ for the Si336-8BK diode. At a typical ambient night-time temperature of $\sim 5^\circ$ C at Ali (Feng et al. 2019), the resulting current noise is expected to be about 4 fA/Hz$^{1/2}$. The measured noise power spectral density for an ATP sensor is shown in Fig. 3. We see a white-noise floor of approximately 2.5 fA/Hz$^{1/2}$. The roll off at high frequencies is due to the band-pass filter in the AC amplifier. At frequencies below one Hz, we see a rise due to 1/f noise.

The corresponding noise equivalent power (NEP), for incident 850 nm radiation, is $\sim 60$ fW. The typical flux at the top of the atmosphere from the full moon at 850 nm is 1.87 $\mu$W m$^{-2}$ nm$^{-1}$ (Cramer et al. 2013). Assuming an average extinction of 0.10, The resulting detected power for an ATP sensor is $\sim 11$ nW. This corresponds to roughly $6 \times 10^7$ photons in 1.25 ms, so the photon noise component is $\sim 7.6 \times 10^3$ photons $\approx 1.4$ pW, which is about twenty times greater than the sensor noise. In fact, it is feasible, and desirable, to observe the crescent moon, at elongations as small as $\sim 45^\circ$. For this phase, the lunar flux is about 60 times smaller than for the full moon, but the photon noise still dominates. Averaging over two minutes (96,000 samples), gives a signal-to-noise ratio of approximately $2.4 \times 10^8$ for the full moon and $3.1 \times 10^5$ for the crescent phase.

3 DATA ANALYSIS

The theory of the lunar scintillometer has been discussed in several papers (Hickson & Lanzetta 2004; Hickson et al. 2009; Rajagopal et al. 2008; Tokovinin et al. 2010). Here we provide just a brief summary, as necessary to introduce our method of data analysis. The measured data are the covariances $C_i(r_i)$ of dimensionless irradiance fluctuations $\delta_i(t) = I(t)/\langle I \rangle - 1$ between sensors separated by a vector $r_i$ in the plane that is perpendicular to the line of sight to the Moon (the angular brackets represent an ensemble average).

These are related to the $C^2$ profile by the integral equation

$$C_i(r_i) = \frac{1}{2\pi} \int_0^\infty C^2_i(z \cos \zeta) W(r_i, z) dz,$$

where $W(r_i, z)$ are response functions giving the covariance on baseline $r_i$ produced by a thin turbulent layer at distance $z$ from the instrument. Here $\zeta$ denotes the zenith angle of the Moon.

The weight functions can be written as an integral over spatial frequency $\kappa$, weighted by filter functions $F_L, F_k, F_D$ and $F_D$. Respectively, these account for the modification of the frequency spectrum by the effects of diffraction, the outer scale of turbulence, and convolution with the finite angular size of the Moon and the finite size of the detectors. Thus,

$$W(r_i, z) = \left[\Gamma(8/3) \sin(\pi/3) \right]^2 \int d^2k \ k^{1/3} \exp(i\kappa \cdot r_i) \times F_L(k) F_k(k, z) F_D(k),$$

and the individual filter functions are

$$F_L(k) = \left[1 + (2\pi/k L_0)^2 \right]^{-11/6},$$

$$F_k(k, z) = \sin^2(\kappa z^2/2\kappa k),$$

$$F_D(k) = \left[\int d^2x I(x) \exp(-i\kappa \cdot x) \right]^2,$$

$$F_D(k) = \left[\int d^2x R(x) \exp(-i\kappa \cdot x) \right]^2.$$

Here $L_0$ is the outer scale, $k = 2\pi/\lambda$ is the optical wave number, $\lambda$ is the effective wavelength of the detector bandpass, $I(x)$ is the lunar intensity, normalized to have unit integral and $R(x)$ is the detector response function, also normalized to have unit integral.

The lunar photometric model that we employ is based on the Lommel-Seeliger scattering model (von Seeliger 1884), which is widely used in planetary science. In this model, the scattered intensity is given by

$$I(\mu, \mu_0, \alpha) = \frac{2I_0 f(\alpha) \mu_0}{\mu + \mu_0},$$

where $\mu_0$ is the cosine of the angle of incidence (with respect to the normal to the scattering surface), $\mu$ is the cosine of the angle of reflection, $I_0$ is the incident intensity and $\alpha$ is the angle between the incident and scattered rays and $f(\alpha)$ is the scattering phase function, normalized to unity at zero scattering angle. $f(0) = 1$.

For sunlight scattering off the lunar surface toward the Earth, one finds that the intensity depends only on the longitude $\phi$ of the point on the lunar surface, measured from the direction to the Earth, and on the solar phase angle $\alpha$ (the angle between the Sun and Earth as seen from the Moon),

$$I(\phi, \alpha) = \frac{2I_0 f(\alpha)}{1 + \cos \phi/\cos(\phi - \alpha)}. $$

The response functions for the ATP, for zero baseline
(i.e. the variance of $\delta I$) and different lunar phases, are shown in Fig. 4. The curves show the variance produced by a thin layer, having unit turbulence integral $J = 1$, located at a line-of-sight distance $z$ from the instrument. Typically, $J \sim 10^{-13}$ m$^{1/3}$ for the free atmosphere and ground layers (Tokovinin & Travouillon 2006), so the variance is on the order of $10^{-7}$. We see that for the full moon, useful response extends to roughly one km in range. However, for the thin crescent phase, the useful range is considerably larger, extending beyond 10 km. Although the flux from the crescent moon is lower, that is more than compensated by the larger intensity fluctuations that result from the smaller angular size.

The ability of the scintillometer to localize turbulence can best be seen by considering the ratios of the covariances, for the various baselines, to the variance. This is shown in Figs. 5 and 6. Here it can be seen that the ratios, which are independent of the turbulence strength, are functions of distance to the turbulence. We see that this sensitivity to distance extends to roughly 1 km for the full moon and to more than 10 km for thin crescent phases.

4 OBSERVATIONS & RESULTS

The ATP began operation at the Ali site on May 20, 2018. It has operated continuously since then, with occasional interruptions due to power outages at the site. A log of the observations obtained until June 2019 is shown in Table 1. Column (1) gives the date of the observations, column (2) lists the number of records that were obtained on that night. Each record corresponds to a 2-minute block of data, which is sufficient for a turbulence measurement. Column (3) is the number of records remaining after those obviously affected by cloud are removed. The clear/total ratio is reported in column (4). Column (5) gives the median lunar phase angle, for the clear records only, and column (6) reports the median fraction of the lunar disk that is illuminated by the Sun. Columns (7) – (10) give the wind speed and direction at the 500-hPa and 200-hPa pressure levels over the site at 18:00 UTC (close to midnight local time), according to the ERA5 climate dataset (ERA5 2017). Column (11) presents the GL seeing, computed from the turbulence integral between 11 m and 3000 m height above the site. For nights in which the Moon is in a crescent phase, Columns (12) and (13) give the derived FA and total seeing, respectively. For the purpose of this paper, FA seeing is defined to be the contribution of the atmosphere higher than 3000 m above the site.

The ATP instrument is programmed to record data...
Table 1. Log of observations

| Date (UTC) | Total records | Clear records | Clear fraction (%) | Phase angle (°) | Illum. fraction | 500-hPa wind speed (m/s) | 200-hPa wind speed (m/s) | GL seeing 2 (arcsec) | FA seeing 3 (arcsec) | Total seeing 4 (arcsec) |
|------------|---------------|---------------|-------------------|----------------|-----------------|--------------------------|--------------------------|-----------------------|----------------------|------------------------|
| 2018-05-20 | 56            | 51            | 91.1              | 109.72         | 0.33            | 5.7                      | 199                      | 32.9                  | 239                  | 0.424                  |
| 2018-09-29 | 187           | 186           | 99.5              | 57.21          | 0.77            | 3.8                      | 194                      | 278                  | 248                  | 0.302                  |
| 2018-09-30 | 165           | 105           | 63.6              | 70.61          | 0.67            | 4.2                      | 237                      | 40.2                  | 242                  | 0.489                  |
| 2018-10-01 | 137           | 76            | 55.5              | 82.58          | 0.56            | 2.3                      | 223                      | 32.2                  | 256                  | 0.360                  |
| 2018-10-02 | 110           | 56            | 50.9              | 96.32          | 0.44            | 1.5                      | 215                      | 25.8                  | 253                  | 0.231                  |
| 2018-10-03 | 80            | 33            | 41.3              | 110.06         | 0.33            | 1.9                      | 241                      | 32.5                  | 250                  | 0.277                  |
| 2018-10-04 | 48            | 40            | 83.3              | 123.53         | 0.22            | 2.5                      | 237                      | 34.3                  | 256                  | 0.507                  |
| 2018-10-26 | 87            | 87            | 100.0             | 28.04          | 0.94            | 2.5                      | 299                      | 18.4                  | 264                  | 0.251                  |
| 2018-10-27 | 234           | 224           | 95.7              | 39.65          | 0.88            | 4.8                      | 34                       | 5.3                   | 309                  | 0.264                  |
| 2018-10-28 | 210           | 197           | 93.8              | 52.87          | 0.80            | 4.4                      | 41                       | 14.9                  | 0                    | 0.251                  |
| 2018-10-29 | 182           | 115           | 63.2              | 66.65          | 0.70            | 3.0                      | 137                      | 13.1                  | 293                  | 0.302                  |
| 2018-11-23 | 310           | 290           | 95.5              | 7.08           | 1.00            | 4.7                      | 253                      | 46.0                  | 293                  | 0.277                  |
| 2018-11-24 | 282           | 213           | 75.5              | 21.11          | 0.97            | 5.7                      | 240                      | 32.8                  | 285                  | 0.442                  |
| 2018-11-25 | 257           | 257           | 100.0             | 34.42          | 0.91            | 6.8                      | 251                      | 44.5                  | 284                  | 0.317                  |
| 2018-11-26 | 228           | 130           | 56.8              | 47.18          | 0.84            | 5.4                      | 224                      | 33.4                  | 295                  | 0.371                  |
| 2018-11-28 | 38            | 38            | 100.0             | 74.15          | 0.64            | 11.4                     | 219                      | 41.3                  | 262                  | 0.462                  |
| 2018-12-23 | 302           | 189           | 62.6              | 15.71          | 0.98            | 15.1                     | 216                      | 81.2                  | 261                  | 0.465                  |
| 2018-12-24 | 271           | 262           | 96.7              | 28.92          | 0.94            | 10.3                     | 212                      | 63.6                  | 264                  | 0.266                  |
| 2018-12-25 | 238           | 229           | 96.2              | 43.01          | 0.87            | 6.8                      | 218                      | 66.6                  | 264                  | 0.398                  |
| 2019-01-17 | 232           | 114           | 51.4              | 47.09          | 0.84            | 5.4                      | 253                      | 31.1                  | 300                  | 0.297                  |
| 2019-01-18 | 257           | 60            | 23.3              | 34.95          | 0.91            | 5.7                      | 238                      | 35.0                  | 297                  | 0.401                  |
| 2019-01-19 | 289           | 35            | 12.1              | 19.20          | 0.97            | 4.5                      | 232                      | 54.3                  | 282                  | 0.285                  |
| 2019-04-09 | 30            | 26            | 86.7              | 129.93         | 0.18            | 3.5                      | 240                      | 17.5                  | 314                  | 0.445                  |
| 2019-05-08 | 14            | 9             | 64.3              | 134.45         | 0.15            | 4.0                      | 270                      | 41.4                  | 263                  | 0.372                  |
| 2019-06-07 | 22            | 22            | 100.0             | 124.63         | 0.22            | 4.0                      | 270                      | 45.1                  | 249                  | 0.381                  |
| 2019-06-08 | 9             | 2             | 22.2              | 111.37         | 0.32            | 4.3                      | 266                      | 32.1                  | 249                  | 0.121                  |

Average 5,6 60.0 5.3 218 34.0 249 0.341 0.649 0.825

1. Generated using Copernicus Climate Change Service Information [2019].
2. Median seeing for 11-m height above ground, from the atmosphere below 3000 m height above ground.
3. Median seeing contribution from the atmosphere above 3000 m height above ground.
4. Median seeing for 11-m height above ground, from the entire atmosphere.
5. Average clear fraction is the ratio of the total number of clear records to the total number of records.
6. Values for seeing are the median values of all records (crescent phase only for FA and total seeing).

Whenever the Moon’s declination exceeds +16°, its altitude above the horizon exceeds 20°, and the Sun is at least 15° below the horizon. The instrument has no way of knowing if clouds are present, so the data must be vetted for this during the analysis. Clouds generally result in large fluctuations in the lunar flux, that can readily be identified by plotting the flux as a function of time. Thin clouds can be identified from large values of the covariance, typically greater than 1 ppm, seen on the longest baselines. The fluxes and covariances for every record were examined and those that had obvious contamination by clouds were rejected.

As an illustration, Fig. 7 show data obtained on the night of December 24, 2018. This night was nearly completely photometric, and close to full moon. More than 9 hours of data were obtained. The figure shows the result of integrating the reconstructed \( C_n^2 \) profile upwards from the specified height above ground, to a height of 3 km, in order to predict the seeing contributed by this air column for a telescope located at the specified height. During the night, the GL seeing above 11 m slowly varied from less than 0.2 arcsec at the start of the night to about 0.35 arcsec at the end.

Fig. 8 shows the distribution function for total ground-layer seeing up to a height of 3 km above the site (8.1 km above sea level). The curve shows a log-normal distribution, having a mean value of 0.382 arcsec and a standard deviation of 0.293, that is the best least-squares fit to the histogram.

5 DISCUSSION

The results presented here indicate that Ali site A1 has remarkably-weak GL turbulence. In median atmospheric conditions, the seeing contributed by turbulence between 11 and 3000 m height is just 0.309 arcsec. For a telescope having a primary mirror vertex, or dome opening, located at a height of 30 m above ground, the GL seeing is less than 0.25 arcsec 50 per cent of the time, and less than 0.19 arcsec 10 per cent of the time. For a height of 50 m, the corresponding values are 0.16 and 0.12 arcsec, respectively. For comparison, Chun et al. (2009) report a median GL seeing of 0.51 arcsec for the summit of Mauna Kea, in the height range 0 – 650
Figure 7. GL seeing inferred from the data of the night of December 24, 2018. The curves show the seeing FWHM for a telescope located at several heights above ground. This is for zenith observations at a wavelength of 500 nm, and does not include turbulence higher than 3000 m above the site.

Figure 8. Statistics of GL and FA seeing from all data. The dark histogram shows the contribution of the atmosphere between a height of 11 and 3000 m above the site. The lighter histogram shows the contribution of turbulence above a height of 3000 m. The curves show the best-fitting log-normal distributions.

CONCLUSIONS

In summary, we have installed and are operating a lunar scintillometer at one of the world’s highest-altitude sites. The ATP instrument has proven to be well-suited for remote operations in harsh environments. The first year’s observations, reveal a weak surface layer having half of its turbulence below a height of approximately 30 m. A relatively-strong layer of high-altitude turbulence is seen, which dominates the total seeing at the site. For the median total seeing, measured during a lunar crescent phase, we find preliminary values of 0.79 arcsec for an 11-m height and 0.66 arcsec for a 30 m above the roof of the Coudé room of the University of Hawaii 2.2-m telescope.

The 500 hPa winds shown in Table 1 are representative of the winds at the Ali site. The wind speed varies from less than 2 to more than 15 m s\(^{-1}\). However, we find no significant correlation between the wind speed or direction and the GL seeing. It would seem that the air flow is largely laminar as it passes over the site. This was also our impression when standing in the wind. We found a steady flow, with little buffeting.

Crescent-phase observations indicate that high-level turbulence may be stronger than expected for a site at this latitude. The median value that we obtain for the seeing contributed by turbulence above 8100 m altitude is 0.58 arcsec. However that is based on only eight hours of data spread over eight nights. This can be compared with a median FA seeing of 0.42 arcsec for Mauna Kea (Chun et al. 2009).

A strong layer of high-altitude turbulence might explain the relatively-high values of seeing found by Feng et al. (2019) from DIMM measurements. Unfortunately, no simultaneous DIMM and ATP measurements exist, so a direct comparison is not possible.

The closest high peaks of the Himalayas are located approximately 100 km to the south-west of Ali. These might induce strong high-altitude turbulence that does not fully dissipate by the time that it reaches Ali. The upper level (200 hPa) winds, shown in Table 1, generally come from this direction. If the high-level turbulence is increased by these mountains, one might expect to see a correlation between the 200 hPa wind speed and direction and the FA seeing at Ali. At this time, there are insufficient data to draw any conclusions. We hope that with further ATP observations, we may be able to test this hypothesis.

If the FA turbulence is indeed stronger than that of the GL, that would reduce the performance of conventional ground-layer adaptive optics (GLAO), which aims to improve image quality over a wide field of view by compensating the GL turbulence alone using a single deformable mirror (DM) conjugated near ground level (Rigaut 2002). However, one could reverse this idea and instead conjugate the DM to the high-altitude turbulence and compensate that alone. One should then achieve an image quality, for wide-field observations, that is comparable to that of the GL seeing alone. For a telescope having a primary mirror 30 m above ground, it should be possible to achieve image quality on the order of 0.23 arcsec in median atmospheric conditions. An investigation of the potential of this idea is beyond the scope of the current paper, but we believe that it is worth further study.

Our observations also provide an independent confirmation of the sky quality at the Ali sites. The ATP records data whether the sky is clear or not, so the fraction of time that the sky is clear is easy to determine. As can be seen in Table 1, for 60 percent of the time the sky was photometric. During this time, short-term transparency fluctuations were typically less than 0.2 per cent. This is consistent with results from long-term sky-camera observations reported by Feng et al. (2019). It shows the high-quality of this site, particularly for photometric observations.
Table 2. Seeing percentiles

| Height (m) | 10% (arcsec) | 25% (arcsec) | 50% (arcsec) | 75% (arcsec) | 90% (arcsec) |
|-----------|--------------|--------------|--------------|--------------|--------------|
| GL seeing (all data) | 11.0 | 0.227 | 0.295 | 0.309 | 0.413 | 0.542 |
| | 20.0 | 0.200 | 0.227 | 0.265 | 0.351 | 0.463 |
| | 30.0 | 0.181 | 0.201 | 0.232 | 0.297 | 0.385 |
| | 50.0 | 0.153 | 0.171 | 0.193 | 0.236 | 0.290 |
| | 100.0 | 0.122 | 0.138 | 0.153 | 0.179 | 0.205 |
| | 200.0 | 0.133 | 0.129 | 0.142 | 0.164 | 0.187 |
| FA seeing (crescent phase only) | 3000 | 0.415 | 0.491 | 0.576 | 0.718 | 0.923 |
| Total seeing (crescent phase only) | 11.0 | 0.498 | 0.605 | 0.793 | 0.898 | 1.218 |
| | 20.0 | 0.480 | 0.576 | 0.710 | 0.857 | 1.187 |
| | 30.0 | 0.471 | 0.554 | 0.657 | 0.826 | 1.151 |
| | 50.0 | 0.451 | 0.532 | 0.627 | 0.775 | 1.085 |
| | 100.0 | 0.443 | 0.518 | 0.609 | 0.754 | 1.044 |
| | 200.0 | 0.440 | 0.513 | 0.601 | 0.746 | 1.023 |

30-m height. These values are lower than seeing found from earlier DIMM measurements.

The weak GL seeing that we find suggests that a modified form of GLAO, in which the high-level turbulence is compensated, instead of the GL, might be an effective way to achieve excellent image quality over a wide-field of view at Ali.

Our observing program is continuing, which should lead to improved statistics for Site A1. We anticipate that even lower GL seeing may be found for higher sites, such as Site C (5400 m), and plan to move the ATP instrument to that site when the necessary infrastructure is in place.

7 ACKNOWLEDGEMENTS

PH is pleased to acknowledge financial support from the Natural Sciences and Engineering Research Council of Canada, and from the Chinese Academy of Sciences (CAS), President’s International Fellowship Initiative, 2017VMA0013. He also thanks the National Astronomical Observatories of China (NAOC) for hospitality during a sabbatical visit. The research is partly supported by the Operation, Maintenance and Upgrading Fund for Astronomical Telescopes and Facility Instruments, budgeted from the Ministry of Finance of China (MOF) and administrated by CAS. We are grateful for on-site assistance provided by NAOC and members of the Ali site team.

REFERENCES

Chen H., Wang J., Pei C., Song Q., Dai S., 2018, in Proc SPIE.
Chun M., Wilson R., Avila R., Butterley T., Aviles J.-L., Wier D., Benigni S., 2009, MNRAS, 394, 1121
Cramer C. E., Lykke K. R., Woodward J. T., Smith A. W., 2013, J. Res. NIST, 118
ERA5 2017, Copernicus Climate Change Service Climate Data Store (CDS), https://cds.climate.copernicus.eu/cdsapp#!/home
Feng L., et al., 2019, Res Astron Ap, submitted
Hickson P., Lanzetta K., 2004, PASP, 116, 1143
Hickson P., Pfrommer T., Crotts A. P., 2009, in Masciadri E., Sarazin M., eds, Optical Turbulence: Astronomy Meets Meteorology. pp 26–35, doi:10.1142/9781848164864_0004
Hickson P., Carlborg R., Gagne R., Pfrommer T., Racine R., Schöck M., Steinbring E., Travouillon T., 2010, in Ground-based and Airborne Telescopes III. p. 77331R, doi:10.1117/12.857409
Hickson P., Gagné R., Pfrommer T., Steinbring E., 2013, MNRAS, 433, 307
Rajagopal J., Tokovinin A., Bustos E., Sebag J., 2008, in Optical and Infrared Interferometry. p. 70131P, doi:10.1117/12.789042, http://adsabs.harvard.edu/abs/2008SPIE.7013E..1PR
Rigaut F., 2002, Proc ESO, 58, 1116
Tokovinin A., Travouillon T., 2006, MNRAS, 365, 1235
Tokovinin A., Bustos E., Berdja A., 2010, MNRAS, 404, 1186
von Seeiger 1884, Astron. Nachr., 109, 305

This paper has been typeset from a TeX/LaTeX file prepared by the author.