Site testing campaign for the Large Optical/infrared Telescope of China: overview

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Abstract The Large Optical/infrared Telescope (LOT) is a ground-based 12 m diameter optical/infrared telescope which is proposed to be built in the western part of China in the next decade. Based on satellite remote sensing data, along with geographical, logistical and political considerations, three candidate sites were chosen for ground-based astronomical performance monitoring. These sites include: Ali in Tibet, Daocheng in Sichuan and Muztagh-ata in Xinjiang. Up until now, all three sites have continuously collected data for two years. In this paper, we will introduce this site testing campaign, and present its monitoring results obtained during the period between March 2017 and March 2019.

Key words: techniques: telescope — site testing

1 INTRODUCTION

Astronomy in China has been growing rapidly in recent years. After a community-wide survey in 2015, a new project, the Large Optical/infrared Telescope (LOT), was selected to be built in the following decade. The telescope is a general purpose ground-based telescope with a 12 m diameter primary mirror. It will provide multiple foci for mounting scientific instruments. Three first light instruments are planned to be installed at the telescope’s Nasmyth focus: a Broad band Medium Resolution Spectrograph (BMRS), a Wide-field Imaging SpEctrograph (WISE) and a High Resolution Spectrograph (HiReS). All three first light instruments are seeing limited. Wavelength coverages are the same for all three instruments, which are 340 nm to 1000 nm (Cui et al. 2018). Adaptive optics (AO) and diffraction-limited infrared instruments are planned as future upgrades to the telescope. In order to maximize the performance of the telescope and its instrument suite, it is important to find a suitable site that is excellent both in terms of its astronomical performance as well as operation and maintenance perspectives.

Early efforts have been made by the community and have been reported in papers such as Liu et al. (2012), Yao et al. (2013), Liu et al. (2015), Wang et al. (2016), Qian et al. (2015), Wu et al. (2016) and Liu et al. (2016). However, due to differences in data definitions, data acquisition methods, etc., results from these various site testing programs are not directly comparable and cannot help in reaching a consensus conclusion. Therefore, immediately after the go-ahead deci-
sion of the LOT project was announced in June, 2016, a decision to start a long-term site testing campaign was made, and related works soon commenced in late 2016.

Considering available site testing instruments at that moment, priority was given to astronomical performances of monitoring sites in the visible band in the early phase of the campaign. Parameters such as cloud cover, optical seeing, night sky brightness and meteorological parameters were required to be measured from the start. Relevant equipments were purchased, calibrated and installed within a short time frame, and by the beginning of 2017, all three candidate sites had already begun continuous routine site monitoring activities. Precipitable Water Vapor (PWV) was added into the monitoring parameter list in early 2018. Other infrared or AO (which still has no decent correcting performance for wavelengths shorter than the infrared) related site performances, such as vertical turbulence profile, wind vector profile, sodium layer characteristics, etc., are planned to be measured in the near future.

This paper is a general introduction to the results from this two year site monitoring campaign. Several other papers (Cao et al. 2020a,b; Liu et al. 2020; Song et al. 2020; Xu et al. 2020a,b,c; Wang et al. 2020) detailing different aspects of the site testing campaign will also be published in the same special issue. We would like to refer these papers to our readers for further details.

In Section 2, we will first briefly discuss how these three long-term monitoring sites were chosen. In Section 3, we will describe the technical aspects of these candidate sites, especially parameters that have been monitored, relevant site testing instruments and their setup at each site, as well as data processing methods. In Section 4, we will show site monitoring results from these two years (March 2017 – March 2019). We will discuss what has been learned during the first year’s operation in Section 5.

2 SELECTION OF THE THREE LONG-TERM MONITORING SITES

During the 1980s–1990s, survey results for astronomical sites already favored the western part of China. Several sites were selected and established in this period as a result, such as the Delingha site in Qinghai (operation started in 1983), the Nanshan site in Xinjiang (1991) and the Gaomeigu site in Yunnan (1995). Altitudes of these sites are in the range 2080–3200 m above sea level, much higher than previous sites in China which are usually located near sea level. The application of these sites results in a significant improvement to the performance of astronomical telescopes in China. In 2003, a dedicated site selection team was organized within National Astronomical Observatories, Chinese Academy of Sciences (NAOC), aimed particularly at investigating sites for next-generation telescopes in optical and other wavelengths. Large scale studies started from data collected at meteorological stations and cumulative cloud maps from satellite data. With these analyses and on-site inspections, the survey was focused on three sites for long-term monitoring which included Karasu in Pamir Plateau, and Oma and Gar sites in western Tibet. In 2010, a solar site survey for the next generation large solar telescope was discussed. Therefore, a site survey aiming for the project was initiated and this time, Ali in Tibet, Ganzi (Daocheng) in Sichuan and Deqing in Yunnan were inspected, particularly for their daytime performance.

A unified site testing campaign was initiated in 2016 by the LOT site testing working group. The first step conducted by the team was to utilize long term remote sensing data from satellites to analyze nationwide large scale cloud coverage. Two independent teams analyzed the cloud coverage, and each team utilized different data sources and adopted independent analysis methods (Cao et al. 2020b). The MODIS satellite data set provides two instantaneous images every night at local time of 22:30 and 01:30 from 2003 to 2015, with a pixel scale of 5 km × 5 km. The GMS+NOAA satellite data set supplies images every hour with a pixel scale of 36 km × 36 km. The GMS+NOAA data set has a record from 1996 to 2003, which is much dated compared to the MODIS data. Pixel scale for both data sets is not small enough to pinpoint optimum locations for monitoring sites. However, cloud estimation even on this large scale can indicate optimum regions where potential sites might be found. Besides, by examining the long term coverage of these satellite data sets, the development trend of clouds at interesting sites could also be observed which could be helpful for predicting cloud coverage in these regions in the near future. Considering GMS+NOAA data cover 1996–2003 with coarser spatial resolution while MODIS data cover a more recent span of 2003–2015 with finer resolution, these two data sets are complementary for our purpose. Cao et al. (2020b) discussed the analysis methods in more detail, cross-comparison results between these two data sources and data from ground based instruments, the evolution of clouds in China based on the data and the possible driving forces that contribute to this evolution. We kindly refer our readers to their paper for details. Here in this paper, we only excerpt part of their results as displayed in Figure 1.

Figure 1 depicts the annually averaged probability of cloudiness at night estimated from 2003–2015 MODIS data. Generally speaking, a pixel acquired at night is regarded as a cloudy night if that pixel is 100% covered with
clouds in both MODIS images at 22:30 and 01:30. From the upper plot of the figure which shows the nationwide cloud estimation, the western part of China has significantly less clouds. In the zoomed-in plot, which is color coded with a smaller range (from 0–50%), there are several bluer strips that indicate even less cloud probabilities along the western border of China. These regions are where Ali and the Pamir Plateau (Muztagh-ata, may also be referred to as Muztagh Ata) are located. In this plot, there is also a blue patch surrounded by a red region in the southeast where Daocheng is located.

In Table 1, we list the estimated fractions of annual percentage of clear nights compared to the total amount of nights for several sites from 1996 to 2015 with each data set. Existing sites like Xinglong and Delingha are also included for comparison. One interesting thing to note in this table is the significant increase of clear nights at Muztagh-ata as well as at Delingha and Nanshan during

| Region       | GMS+NOAA (%) 1996–2003 | MODIS (%) 2003–2015 |
|--------------|-------------------------|---------------------|
| Ali          | 74.5                    | 86.8                |
| Daocheng     | 71.7                    | 71.1                |
| Muztagh-ata  | 58.7                    | 77.8                |
| Xinglong     | 64.4                    | 67.9                |
| Delingha     | 65.6                    | 74.1                |
| Gaomeigu     | 64                      | 66.9                |
| Nanshan      | 60.3                    | 70.7                |
Table 2  Altitude and Location of the Monitoring Sites

| Site’s name   | Altitude (m) | Longitude | Latitude    | Established |
|---------------|--------------|-----------|-------------|-------------|
| Ali           | 5100         | 80.046E   | 32.306N     | 2012        |
| Daocheng     | 4750         | 100.109E  | 29.107N     | 2016        |
| Muztagh-ata  | 4526         | 74.897E   | 38.330N     | 2017        |

2003 ~ 2015 compared to 1996 ~ 2003. In their paper, Cao et al. explained that several climatic factors may lead to this behavior.

Estimation of cloud coverage from satellite data has an advantage in spatial coverage, and it is helpful for identifying optimum regions within China. However, the spatial resolutions of this method are not sufficient to identify the best location within its kilometers-wide single pixel. The different definitions of cloudiness between satellite and ground based observations would also lead to differences in the judgement of degree of cloudiness. The cadence of the satellite data is also on the scale of hours which is not enough to catch fast variations of parameters like wind, temperature, low level clouds, etc. Lacking other instruments on a satellite to measure regular astronomical climate performances, such as wind, relative humidity, temperature at ground, as well as seeing, transparency, etc., also limits the applicability of this single method to evaluate sites’ overall performance. Therefore, a long-term ground-based astronomical climate monitoring campaign is required. Combining with other considerations, such as geographical information, traffic/logistics, meteorological parameters and previous site testing results, three sites (listed in Table 2) were chosen at last for long term monitoring for the site testing campaign.

3 THE CANDIDATE SITES, TESTING INSTRUMENTS AND SETUP

Table 2 lists the three sites that were chosen and their coordinates. Figure 2 features their local topographical maps and photos. Both the Ali and Daocheng sites have already been constructed and have been monitored (Yao et al. 2014a; Yin et al. 2014; Liu et al. 2015; Wang et al. 2015; Yao et al. 2012; Liu et al. 2012; Yao et al. 2013; Wu et al. 2016; Liu et al. 2016) for a relatively long time. Preparation works for the Muztagh-ata site only began after initiation of the LOT project in late 2016. Due to the low temperature at Muztagh-ata during that winter, construction works, especially concrete works, were not finished until March 2017. Figure 2 displays some bird’s-eye views of these sites.

The Ali site is located in the southwest of Tibet autonomous region at the tip of a mountain range. It has an altitude of 5100 m. The closest town that could provide accommodation and be utilized as headquarters is Shiquanhe. The town is about 30 km north of the site with an average altitude of 4300 m, and it has a population of 20 000. The Ali Kunsha airport is on the south side of the site. A paved road linking both the airport and the town pass by the site. A branching path from this road to the site has been built. The current location of the site is called point A. Facilities, electricity and internet service have already been provided on the site. Several small telescopes with aperture diameters ranging from 0.3 m to 1.0 m are also there in operation. Another two locations (points B and C, with altitudes of 5160 m and 5380 m respectively) on the same mountain range in the downwind direction (southeast) are still under development at the time of this paper.

The Daocheng site is located between Ganze county and Daocheng county in Sichuan province. The altitude of the site is 4750 m. The closest town is Daocheng, ~27 km away from the site, with an altitude of 3750 m. Ganze county is ~65 km away, at a much lower altitude of 2750 m. The population of Daocheng is 7900. Although electricity and internet service have not reached the site yet, a generator and solar panels have already been built and could provide electricity to all equipments, but data transfer still requires personnel to download at the site and upload to a server after their return to the town. A concrete observation tower for monitoring the site’s performance has already been built and all equipments on its top deck are in operation.

The Muztagh-ata site is a newly selected site, with no facility or equipment set up previously. The site is located on Pamir Plateau and is 11 km away from the 7546 m-high Muztagh-ata Mountain, which is famous among mountain climbers. The site’s altitude is 4526 m, and it is about 220 km away from the city of Kashgar. The closest town is Bulunkouxiang at an altitude of ~3300 m, 50 km away towards the north.

It was decided at the beginning that during the site testing campaign, all sites should use the same or at least identical equipments so comparable measurements could be obtained and be processed with the same data processing method by an independent data analysis team. The top priority is to have comparable related parameters in the visible band as well as parameters involving the design and operation of the telescope for its early phase while additional equipments could be added into the list to measure infrared related parameters in the near future. The following part describes the parameters being monitored and instruments employed for these measurements.

1. Temperature, atmospheric pressure, relative humidity, wind direction and speed: These are climatic
parameters that represent characteristics of the local environment. They are important parameters for the design and construction of the facility. The reasons to monitor these parameters from an astronomical perspective are the following. Environmental temperature variation between night and day will have an impact on dome seeing when the dome is opened at night. Even when dome temperature is settled, because a large portion of the noise in infrared observation comes from thermal noise of the telescope structure which is at the temperature of the environment, it would be better if the environmental temperature of the site is low and stable. Temperature, atmospheric pressure and relative humidity combined could cause dew to condense on the surface of the mirror and interfere with observation. Wind near the ground will induce shake and vibration in the structure of the dome, and most importantly, on the surface of the mirror, so it is important to know the strength and direction of the wind. These parameters are measured continuously with a commer-
cial automated weather station (Huayun 2016). The weather station produces one value for each of these parameters every minute. Measurements are stored locally, copied out and transmitted manually to a central server by a local crew. One of these weather stations was installed at each of the sites.

2. **Cloudiness**: Clouds in the line of sight of the telescope will interfere with observations. They would reduce the flux arriving at the telescope to a certain degree depending on the amount of clouds during long exposures, or even make observations impossible to conduct. Therefore, it is important to know the typical statistics of cloud coverage within certain angles from zenith at night all year. As for the campaign, cloudiness is monitored by an All Sky Camera (ASCA) which is designed and fabricated by NAOC (Wang et al. 2020). The same type of ASCA was installed at all sites. The camera has two parts, a Sigma 4.5 mm fish eye lens and a Canon 700D camera providing a $180^\circ \times 180^\circ$ field of view. The ASCA has no filter. Its sampling frequency in daytime is one picture every 20 minutes with an exposure time of 1/3200 of a second. At nighttime, sampling frequency is increased to one picture every 5 minutes with exposure time adjusted to a value between 15 and 30 s depending on lunar phase. All raw images were stored and transmitted to a central server by the local crew everyday. The independent data analysis team utilized a similar manual cloud identification method as described in the Thirty Meter Telescope’s (TMT’s) site testing campaign paper (Skidmore et al. 2008). The same standard is applied to all ASCA images for all candidate sites to ensure comparability. More details on the data reduction method can be found in Cao et al. (2020a).

3. **Sky background in $V$ band**: Sky background is one of the main noise sources for observation in optical wavelengths. To evaluate sites’ $V$ band sky brightness, a commercial Sky Background Meter (SBM), Unihedron SQM-LE (Unihedron 2016), was utilized. The SBM is mainly a high sensitivity photodiode with a field of view of $\sim 20^\circ$ performing photometry in the zenith direction every minute at nighttime. A visible band filter is installed inside the instrument and the measurement is automatically converted into Johnson $V$ band. SBMs were set up at all sites, generally next to the ASCAs.

4. **Night seeing at 500 nm**: Local seeing reflects the total integral strength of atmospheric turbulence in the line of sight of the telescope. It will affect the image quality of the telescope if there is no correction from AO. To be able to compare between different sites, seeing is defined as the best angular resolution in the zenith direction with 0 s exposure time that a site can achieve. An instrument called a Differential Image Motion Monitor (DIMM) as described in Sarazin et al. (1990) is commonly used to measure this value. In the site testing campaign, three models of DIMMs were deployed at the candidate sites as shown in Table 3. All sites were equipped with at least two DIMMs, one for continuous measurement, the other one acting as a backup if the first one fails. An extra DIMM was first calibrated for two weeks with a DIMM that had been in operation for years at Xinglong Observatory. It was then installed side by side with all other DIMMs for cross calibration for at least two weeks at each site to ensure all measurements are comparable.

5. **Precipitable water vapor**: Water vapor in the atmosphere acts as an absorptive medium for the infrared band, thus it is necessary to monitor the content of water vapor above the sites. Column density of PWV is commonly considered for representing contents of atmospheric water vapor. To monitor it, we employed a commercial Low Humidity And Temperature Profiling Radiometer (LHATPRO) from RPG (Radiometer Physics 2014). The radiometer measures vertical profiles of atmospheric temperature and humidity, and based on these measurements, estimates vertical integrated water vapor every second. The advantage of LHATPRO is that it could be applied for night measurement because it operates in radio band compared to other PWV monitoring instruments which rely on the measurement of solar extinction. However, the cost of the LHATPRO is not affordable to equip this instrument at all three sites. Because seasonal PWV variation monitoring has a higher priority than daily variation, only one LHATPRO was deployed recently and was shifted around the three sites for short term periodic monitoring.

Figure 3 (upper left) illustrates the instrument setup at the Ali site. Initially, an 11 m tower was built for DIMM measurement. However, it was soon ascertained that the stability of the tower could not meet the requirements for DIMM measurement if the DIMM was installed on top of the tower (Cao et al. 2020a). The structure of the tower was reinforced soon after. However, a few months of data from the 11 m tower were missing because of this. Meanwhile, another Ali DIMM kept monitoring on the 3 m high roof of the observation building. ASCA and SBM were also installed on the roof. A 5 m tower was built in May 2017,
Fig. 3 Instrument setups at candidate sites. Ali site (upper left), Daocheng site (lower left) and Muztagh-ata (right).

Table 3 Information on DIMMs that were Operated at Candidate Sites

| Model name       | Ali DIMM | NIAOT DIMM | French DIMM |
|------------------|----------|------------|-------------|
| Availability     | custom   | custom     | ALCOR-SYSTEM (2016) |
| Telescope        | MEADE LX200 | GSO RC 8'' | 8 |
| Focal ratio      | 10       | 8          | 8 |
| Focal length (mm) | 2500     | 1600       | 2400 |
| Subapertures     | 2        | 4          | 2 |
| Subaperture diameter (mm) | 50      | 50         | 50 |
| Subaperture distance (mm) | 149    | 200        | 240 |
| Camera           | Basler aca2040 | Lumenera SKYnyx2-0M | DMK 33GX174 |
| Exposure method  | 10 ms    | 10 ms      | between 0.5 ms and 1000 ms, adjusted automatically |
| Wavelength (nm)  | 500      | 500        | 550 |
| Output frequency | one seeing value every minute | one seeing value every minute | one seeing value every 1000 images |
| Scaling and conversion | convert to zenith, no exposure | convert to zenith, no exposure time scaling | convert to zenith, no exposure time scaling |
| Sites equipped   | Ali      | Daocheng and Muztagh-ata | Ali, Daocheng and Muztagh-ata |

and the DIMM that was previously installed on the 3 m roof was moved onto this tower after it was built.

Figure 3 (lower left) demonstrates the Daocheng site’s setup. The 10 m automated weather station was attached to a previously built 22 m tower. All other instruments were installed on the 7.5 m concrete observation tower shown as the white building in the right panel of Figure 2(b).

Figure 3 (right) illustrates the layout of instruments at the Muztagh-ata site. Because the 11 m tower had the same design as the Ali 11 m tower, it also suffered from the same structural instability. Two DIMMS (an NIAOT DIMM and a French DIMM) were setup on the ground (upper figure in Fig. 3 (right)). The French DIMM was later moved to the platform of the 11 m tower while the NIAOT DIMM was transferred to the platform of a 6 m tower (details on these changes are described in detail in Sect. 4.1).

4 RESULTS FROM TWO YEARS

In this section, we will provide top level monitoring results from data gathered between 2017 March 10 and 2019 March 10. The selection of this period is to ensure that all equipment from all three sites was operating for two whole years. Unless monitoring equipment was found to be faulty with significant system error, all data gathered in this period were treated as effective data. The number of days with effective data for different types of instruments during this two-year period for all three sites are listed in Table 4. Data from all candidate sites were gathered and transmitted everyday by local teams to a remote central da-
ta server at NAOC, and were processed by an independent data analysis team using the same scripts across all sites to ensure minimal possibility of bias. However, even for data processed with such a method, there were cases, such as DIMM, at certain sites for which equipment was temporarily moved to an adjacent place for a brief period of time. In this article, we will note what and when such cases happen. Besides, statistics are done in a monthly manner to separate and alleviate their impacts on the final results.

Table 4 Data availability for instruments at the candidate sites between 2017 March 10 and 2018 March 10.

| Instruments   | Ali  | Daocheng | Muztagh-ata |
|---------------|------|-----------|-------------|
| DIMM          | 457  | 357       | 422         |
| ASCA          | 697  | 590       | 694         |
| Weather station | 675  | 559       | 705         |
| SBM           | 603  | 629       | 673         |

4.1 Seeing

Ali’s seeing was measured at three different heights: 3 m roof of the observation building, 5 m tower and 11 m tower as described in the previous section. Due to the construction work to reinforce the 11 m tower, before May 2017, seeing measurements came from the DIMM on the 3 m rooftop. After the 5 m tower was constructed and before the 11 m tower reinforcement work was done, seeing measurements mainly came from the DIMM on the 5 m tower, but if any malfunction appeared on that DIMM, we substituted the 3 m DIMM measurements to fill that day’s gap. After the 11 m tower was reinforced, data completely came from DIMM on the 11 m tower. Cross comparison results of 3 m and 5 m measurements indicated no noticeable difference. Actually, even seeing values measured at the 5 m tower and 11 m tower showed minor differences (refer to Cao et al. 2020a). Figure 4 displays the monthly statistics of these combined seeing measurements.

Daocheng’s seeing was measured from the 7.5 m tower at the site. During July 2018 and October 2018, DIMMs at the site were out of operation due to system failure which caused data to be missing from that period. Figure 5 depicts the monthly statistical seasonal variation of seeing at the site.

Measurements from Muztagh-ata are a bit complicated. NIAOT DIMM was installed on 2017 March 12 and kept running on the ground until 2017 November 15. It was then moved to the top of the 6-meter tower. A French DIMM was installed on 2017 April 15. It kept running on the ground until 2017 June 23, and later was moved to the top of the 11-meter tower. It was soon discovered that the structural strength of the tower was not sufficient for stable measurement of seeing. Therefore, the tower was reinforced with concrete, the same as at Ali by October,
Simultaneous measurements on the ground and on the 11 m tower in that duration showed that seeing measurements on the tower were approximately $0.3''$ better. After October 2017, all the measurements were done on the 11 m tower. Then, after the 11 m tower was rebuilt, for the purpose of ensuring two DIMMs can be accommodated on the top of it simultaneously, NIAOT DIMM was installed on the 11-meter tower on 2018 September 21. The two DIMMs were then operated at 11 m until 2018 November 20. Figure 6 depicts the monthly statistics of the site’s seeing.

Figure 7 features the histogram for all seeing measurements for all three sites. We would like to notify our readers that the lack of data in certain months (as can be seen from the other three monthly based boxplots) at certain sites could weigh the statistics into the direction of those months that have data, especially in regard to the median values expressed in the legend of this figure. Therefore, in the later Section 5, we chose to average the representative monthly median values for evaluating performance at the sites.

4.2 Cloudiness

Cloudiness was estimated from all the images taken by an All Sky Camera manually. Everyday, from dusk to dawn, every five minutes, a sky image pointing at the zenith direction was taken. The field of view of the image is $180^\circ \times 180^\circ$. Two circles are drawn within the image, with zenith angles of $44.7^\circ$ and $65^\circ$, as demonstrated in Figure 8. Depending on how many clouds are within different circles and the quality of the image itself, five degrees of cloudiness are defined:

- clear: no cloud within the inner circle and the outer circle;
- outer: no cloud within the inner circle, has cloud within the outer circle;
- inner: has cloud within both the inner and outer circles;
– covered: coverage of clouds within inner+outer circles is over 50%;
– none: cannot determine cloudiness from image.

The data analysis team adopted a similar method as TMT (Skidmore et al. 2008). Several people from the team watched a movie generated with every frame of the ASCA images, and judged and ranked the cloudiness for each image manually. Statistics were compiled on these generated rankings for each site.

We then defined an “observable night” if the night’s cloudiness was either clear or outer or inner for a continuous duration longer than 3 hours. A “good observable night” was defined if the cloudiness of the night was either clear or outer for a continuous duration longer than 3 hours.

With data from 2017 March 10 to 2019 March 10, the number of these different qualities of nights and the total number of nights that had determinable ASCA images are listed in Table 5. In Figures 9, 10 and 11, we depict the monthly variation of good nights at Ali, Daocheng and Muztagh-ata respectively. For Daocheng, during May 2018~July 2018, ASKA at the site was inoperable and data were missing in this period.
Fig. 11 Percentage of clear nights for Muztagh-ata for March 2017–March 2018 (top) and March 2018–March 2019 (bottom). The blue dotted lines represent the percentage of “observable nights” compared to total number of nights with effective data in each month. The red dotted lines signify the percentage of “good observable nights”.

Table 5 Data availability for instruments at the candidate sites between 2017 March 10 and 2019 March 10.

| Nights                  | Ali | Daocheng | Muztagh-ata |
|-------------------------|-----|----------|-------------|
| Observable night        | 568 | 401      | 507         |
| Good observable night   | 500 | 354      | 438         |
| Nights with effective data | 693 | 590      | 694         |

4.3 Temperature, Atmospheric Pressure and Relative Humidity

Temperature, relative humidity and atmospheric pressure were constantly measured by the automated weather stations. The model of the weather stations used at candidate sites was the same. However, the measurement frequencies of these weather stations were different. Temperatures of Ali and Muztagh-ata were measured once every minute, Daocheng’s temperature was measured once every 10 minutes. Another thing worth mentioning when interpreting the plot of the data is that between April 2018–June 2018, Daocheng’s weather station was inoperable. Therefore, in these three months Daocheng’s data were missing.

In Figure 12, we display the monthly variations of night temperatures at Ali, Daocheng and Muztagh-ata.

Monthly statistics of nighttime atmospheric pressure measurements for the three sites are depicted in Figure 13.

Figure 14 shows the relative humidity measurements for nighttime. The humidity sensor at Muztagh-ata was malfunctioning until 2017 August 3. Therefore, for
4.4 Wind Speed and Direction

Wind speed and direction were measured with anemometers mounted on top of 10 m masts of automated weather stations every minute. Figure 15 and Figure 16 highlight the monthly statistics of wind speed and wind direction at night for each of the three sites.

4.5 Sky Background

$V$ band sky background was continuously measured by the aforementioned SBM. Considering that lights from the Moon impact the brightness of the night sky, here in this paper we only report sky background statistics from moonless nights. Figure 17 features the $V$ band sky background of Ali, Daocheng and Muztagh-ata for those nights.

4.6 Precipitable Water Vapor

PWV values were measured with a LHATPRO. Until now, only one such instrument was acquired, and it was installed much later than all other equipments. Therefore, PWV values for each site were measured with a limited number of nights at the moment. Because local clouds can have a strong influence on PWV measurements, in this paper, we only showcase results obtained during clear nights.
Fig. 15 Monthly variation of wind direction (0° ∼ 360°) at the site. (Top to bottom) Ali, Daocheng and Muztagh-ata respectively. The upper tip, upper top of a box, mid-bar in a box, bottom of a box and lower tip represent 95%, 75%, 50%, 25% and 5% of the measured data for each month respectively. Red boxes signify data from March 2017 to February 2018, and blue boxes correspond to data from March 2018 to February 2019.

For Ali, PWV monitoring was conducted in a very short time (2018 March 19 to 2018 March 22). Data obtained were significantly less than at the other two sites. The PWV statistics for this site are provided here just for completeness, but we would like to remind our readers that this result may not be representative for the site. Because of this, we did not list any PWV value for Ali in Table 6. For Daocheng, all measurements were done between 2018 February 10 and 2018 March 5. Its statistics are displayed in Figure 18, middle panel. For Muztagh-ata, measurements were conducted between 2018 January 22 and 2018 February 4. The bottom panel of Figure 18 depicts its statistics.

Fig. 16 Monthly variation of wind speed at the site. (Top to bottom) Ali, Daocheng and Muztagh-ata respectively. The upper tip, upper top of a box, mid-bar in a box, bottom of a box and lower tip represent 95%, 75%, 50%, 25%, and 5% of the measured data for each month respectively. Red boxes signify data from March 2017 to February 2018, and blue boxes correspond to data from March 2018 to February 2019.
Table 6 Annual average with data from 2017 March 10 to 2018 March 10 for all three sites. The annual average is calculated by two steps: 1. Calculate the average value of each month with the two year monthly median values. If for some reason one year’s median value is missing, the average value is the other year’s median value. Thus, we could get a monthly average value for each month for these two years. 2. Calculate the average value of the monthly average values computed in the last step to represent the annual average value.

| Parameters                        | Ali  | Daocheng | Muztagh-ata |
|-----------------------------------|------|----------|-------------|
| good observable > 3hr (%)         | 71.76| 51.72    | 63.27       |
| observable > 3hr (%)              | 81.71| 58.89    | 73.00       |
| V band sky background (mag)       | 22.07| 21.91    | 21.76       |
| Seeing (")                       | 1.17 | 1.01     | 0.90        |
| Night temperature (°C)            | −5.18| −1.70    | −7.08       |
| Night Atm. pressure (hPa)         | 540.92| 564.54  | 586.08      |
| Night relative humidity (%)       | 41.25| 70.15    | 52.88       |
| Night wind speed (m s\(^{-1}\))  | 7.41 | 4.75     | 5.83        |
| Night wind direction              | SW   | SW       | SW          |
| PWV (mm)                          | —    | 2.01     | 0.52        |

Fig. 17 Sky background in V magnitude for moonless nights. (Top to bottom) Ali, Daocheng and Muztagh-ata respectively. The upper tip, upper top of a box, mid-bar in a box, bottom of a box and lower tip represent 95%, 75%, 50%, 25% and 5% of the measured data for each month respectively. Red boxes signify data from March 2017 to February 2018, and blue boxes correspond to data from March 2018 to February 2019.

Fig. 18 PWV in clear nights for Ali, Daocheng and Muztagh-ata from top to bottom respectively.

5 DISCUSSION

Table 6 is a summary of monitored performances for all three candidate sites with two years of data between 2017 March 10 and 2019 March 10. From these annual average results, one can see that Ali had the highest good observable night fraction and darkest night sky compared to the other two sites. All three sites manifested impacts of rainy seasons to different degrees. The most interesting part is Muztagh-ata, where although in the first year, cloud coverage was higher in summer, in the second year, the impact of the rainy season was lessened. We refer all our readers to Cao et al. (2020b) which might elucidate some insights into this behavior. Regarding seeing, the annual average values for all three sites had reached ~ 1 arcsec, while Muztagh-ata’s seeing was the best among the three, especially considering that the site’s best seeing season coincided with a cloudless time of the year (October to December). Daocheng had the highest night tempera-
ture of −1.7°C Celsius, and the other two sites were similar at around −6°C Celsius. For relative humidity, Daocheng was 70.15% and was much higher than the other two sites. Ali had the highest annual averaged wind speed of 7.4 m s⁻¹ compared to the other two sites which were around 5 m s⁻¹. With current relatively short PWV measurements, Muztagh-ata had the lowest PWV values of 0.52 mm among all three sites in roughly the same season.

It is still too early to jump to a conclusion that is scientifically sound and reasonable with only two years of data. It is also because of this reason that, in this paper, we are hesitant to directly combine all the two years of data together and generate the associated statistics, but rather consider weather variations from both years. Questions, such as why is there different behavior of clouds at Muztagh-ata in the second year compared to the first year, and what would the PWV be like for the whole season at all three sites, yearn for more data to gain a clearer understanding. Two years of data are not sufficient to answer whether one of the years or even both years were abnormal years. With current equipments, we could also not give a definitive answer to questions like how are the performances of these sites in infrared, or is it possible that a much better site exists near current ones? All these questions alike could only be answered by actual measurements from more monitoring instruments that will be installed soon and with more monitoring data covering a longer period.

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References

ALCOR-SYSTEM, ‘DIMM Seeing Monitor’ 2016, http://www.alcor-system.com/new/SeeingMon/DIMM_Complete.html
Cao, Z. H., Li, J., Zhao, Y. H., et al. 2020, RAA (Research in Astronomy and Astrophysics), 20, 81
Cao, Z. H., Liu, L. Y., Yao, Y. Q., et al. 2020, RAA (Research in Astronomy and Astrophysics), 20, 82
Cui, X. Q., Zha, Y. T., Liang, M., et al. 2018, in Proc. of SPIE, 10700, Ground-based and Airborne Telescope VII, 107001P
China Huayun, ‘Huayun CAWS 600 Automatic Weather Station’ 2016, http://www.cnhyd.com/showcpzs.asp?id=489
Liu, L. Y., Yao, Y. Q., Vernin, J., et al. 2012, in Proc. of SPIE, 8444, Ground-based and Airborne Telescope IV, 844446
Liu, L. Y., Yao, Y. Q., Vernin, J., et al. 2015, Journal of Physics: Conference Series, 595, 012019
Liu, Y., Song, T. F., Zhang, X. F., et al. 2016, in Proc. of IAU, 320, Solar and Stellar Flares and their Effects on Planets, 447
Liu, L. Y., Yao, Y. Q., Yin, J., et al. 2020, RAA (Research in Astronomy and Astrophysics), 20, 84
Qian, X., Yao, Y. Q., Wang, H. S., et al. 2015, PKAS, 30, 695
Radiometer Physics, ‘Humidity and Temperature Profilers’ 2014, http://alturl.com/3vwyw
Sarazin, M., Roddier, F. 1990, A&A, 227, 294
Skidmore, W., Schöck, M., Magnier, E., et al. 2008, in Proc. of SPIE, 7012, 701224
Song, T. F., Liu, Y., Wang, J. X., et al. 2020, RAA (Research in Astronomy and Astrophysics), 20, 85
Unihedron, ‘Sky Quality Meter - LE’ 2016, http://unihedron.com/projects/sqm-le/
Wang, H. S., Yao, Y. Q., Liu, L. Y., et al. 2015, Journal of Physics: Conference Series, 595, 012037
Wang, J. F., Tian, J. F., Zeng, X. Q., et al. 2020, RAA (Research in Astronomy and Astrophysics), 20, 83
Wu, N., Liu, Y., & Zhang, H. M. 2016, AcASn, 57, 729
Xu, J., Esamdin, A., Hao, J. X., et al. 2020a, RAA (Research in Astronomy and Astrophysics), 20, 86
Xu, J., Esamdin, A., Hao, J. X., et al. 2020b, RAA (Research in Astronomy and Astrophysics), 20, 87
Xu, J., Esamdin, A., Feng, G. J., et al. 2020c, RAA (Research in Astronomy and Astrophysics), 20, 88
Yao, Y. Q., Wang, H. S., Liu, L. Y., et al. 2012, in Proc. of SPIE, 8444, 84441
Yao, Y. Q., Wang, Y. P., Liu, L. Y., et al. 2013, in NARIT Conf. Ser., I, the 11th Asian-Pacific Regional IAU Meeting 2011, ed. Komonjinda, S. (IAU), 1, http://conference.narit.or.th/ncs/APRIM2011_proceedings/S7/S7P05.pdf
Yao, Y. Q., Zhou, Y. H., Liu, L. Y., et al. 2015, Journal of Physics: Conference Series, 595, 012038
Yin, J., Yao, Y. Q., Liu, L. Y., et al. 2015, Journal of Physics: Conference Series, 595, 012040