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Introduction to the environmental monitoring instruments for LOT

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Abstract The Large Optical/infrared Telescope (LOT) is a ground-based 12m diameter optical/infrared telescope, which is proposed to be built in the western part of China in the next decade. To select the best site which satisfies the construction and future operation of LOT, data monitoring and comparing are required for all the candidate sites. The comparison of most of the instruments was done at Xinglong Observatory. These instruments include weather station, all sky camera, sky background meter and differential image motion monitor (DIMM). This paper introduces the instruments used in LOT site monitoring and the instruments comparisons. The results show that the instrument is stable and the data uniformity of the identical instruments is good. This paper provides a fundamental description of LOT site monitoring.

Key words: atmospheric effects — light pollution — 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 elected to be built in the following decade. 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 from its astronomical performance as well as operation and maintenance perspectives. In July 2016, the LOT Preparation Committee was found by the Center for Astronomical Mega-Science, Chinese Academy of Sciences to be fully responsible for organizing the effort to construct and operate the LOT. Site selection is one of the pre-research parts. The ground-based optical telescope is a crucial tool for exploring and researching the universe. The quality of an image obtained by an optical telescope can be affected by the atmosphere due to the atmospheric scattering and absorption of the radiation energy from celestial objects. Thus, LOT needs an excellent site.

Three potential sites in China were selected for the LOT project: Ali, Daocheng and Muztagh-ata. Ali and Daocheng have the completed multi-year evaluation, but the data are still not enough for scientific research. Muztagh-ata needs data accumulation and a long-term monitor. The historical data of these sites are archived from various instruments, which is inconvenient for sites comparison. Inconsistent and incomplete observational data produce uncertainty in LOT site selection.

Site working group was found to select the best location for LOT (Feng et al. 2020). The group oversees the site selection and coordinates the related institutes. The instruments for site monitoring were decided and deployed to each candidate site. Every instrument needed to be tested was compared at Xinglong Observatory, National Astronomical Observatories, Chinese Academy of Sciences (NAOC). The researchers learnt the installation, alignment, application and treatment of common faults of these instruments at Xinglong Observatory.

This paper introduces the instruments used in LOT site testing and instruments comparisons. In Section 2 we present the site testing instruments. The comparison of the instruments is described in Section 3. Section 4 provides the conclusion.

2 INSTRUMENTS INTRODUCTION

An excellent observational site is necessary for the ground-based LOT. More clear nights mean more effective data. Seeing is vital for high precision imaging and high-resolution photometry. Sky brightness is crucial for the limitation of LOT to observe the faint targets. The meteorological properties such as water content, air temperature, relative humidity, wind speed and direction influence the site observational environment. In addition, the altitude, topography, vegetation coverage, road construction, water and electricity supplement, logistics support, light pollution in surrounding cities and industrial areas are also important factors that affect the site observational environment.

2.1 Weather Station

Analysis of the meteorological conditions with time can be used to assess the quality of a site, which is very important for astronomical site monitoring. It provides an essential reference for large optical telescope design and the astronomical observations. The fundamental meteorological properties for site characterization are the air temperature, barometric pressure, relative humidity, wind speed and direction (Jabiri et al. 2000). In LOT site selection, long-term statistical data on these five fundamental meteorological properties were mainly taken into consideration.

The weather station used for site monitoring is CAWS600 from China Huayun Group, which is an intelligent monitoring system with functions of fully automatic data collection, storage, processing and transmission. It is a filed intelligent meteorology station for multi-application with no person on duty; in addition, it actualizes automatic monitoring, storage, processing and transmission of various weather elements under extreme environment. The collection system adopts an advanced collection core, which has strong expansibility and can actualize any observation combining multi-element observational items. The main technical indicators of weather station are shown in Table 1. This weather station had been professionally calibrated at the factory.

2.2 All Sky Camera (ASCA)

For a site dedicated to ground-based observations, one of the most important site parameters is the number of clear nights. It determines the time of effective observation every year. Clear nights can be analyzed by statistical analysis of the cloud coverage of the sky.

The methods for monitoring cloud coverage include satellite monitoring, ASCA, cloud meters, and visual observations. Satellite monitoring is mainly used for the early site searching. Cloud meters provide the cloud data but not the cloud distribution. The visual observation cannot be quantitatively evaluated due to the influence of subjective factors, and it is generally used as an auxiliary criterion. Therefore, ASCA becomes an important equipment for the astronomical site monitoring.

ASCA consists of wide-angle lens and DSLR camera or CCD detector. Due to the advantages of portability, accessibility, and high spatial resolution, it has been widely used in various observatories all over the world, such as Kitt Peak, Cherenkov Telescope Array (CTA) gamma-ray observatory, the Large Synoptic Survey Telescope (LSST) and the Thirty Meter Telescope (TMT) site monitoring (Skidmore et al. 2011; Mandat et al. 2013; Kamp 2015; Walker et al. 2006).

An ASCA system in visible band was designed by Xinglong Observatory to monitor the cloud coverage automatically. The system uses mature commercial products and develops a special control program to achieve low-cost ASCA.

The control program automatically calculates the exposure parameters based on the altitude of the Sun, the Moon phase, or the sky brightness to ensure the properly exposed during the day and night. Observational data are transferred to the computer via network or USB cable and saved to the folders by date. Figures 1 and 2 show the appearance of the ASCA and the images obtained, respectively. The main technical indicators of ASCA are shown in Table 2.

The ASCA system has been operating stably for many years at Xinglong Observatory and has collected a large amount of data. LOT site working group decides to use the ASCA images to determine the number of clear nights. Several tests were conducted at Xinglong Observatory to estimate the consistency of the camera system. The detailed test is described in Section 3.

2.3 Sky Background Meter (SBM)

Sky brightness refers to the background brightness in the night sky, which affects the limitation and photometric precision of a telescope. With the city developing and the population increasing in recent years, the light pollution becomes more and more serious, having a great impact on

Table 1 The Main Technical Indicators of Weather Station

Meteorological Elements	Resolution	Measuring Range	Precision
Air Temperature	0.01°C	−50 ∼ +60°C	± 0.1°C
Relative Humidity	0.1%	0 ∼ 100%	±2%
Pressure	0.1 hPa	500 ∼ 1100 hPa	±0.2
Rainfall	0.1 mm	0 ∼ 4 mm min^{-1}	±4%
Wind speed	0.1 m s^{-1}	0 ∼ 75 m s^{-1}	±0.3 m s^{-1}
Wind direction	3°	0 ∼ 360°	±5°

Fig. 1 Parts of the ASCA: sky quality (*left*), fish-eye camera (*middle*), and DSLR (*right*).

Fig. 2 A picture taken by the ASCA.

optical astronomical observation. The sky brightness becomes a major consideration in the astronomical site selection.

Measurements for sky brightness include photometric observation, spectral observation, satellite monitoring, and portable measurement equipment. The portable measurement equipment is the reasonable instrument for site monitoring. The sky brightness of the Xinglong Observatory has been monitored by a commercial device Sky Background Meter (SBM) from Unihedron company for many years. The SBM provides real time sky brightness of magnitudes per square arc second (mag arcsec^{-2}) automatically. The appearance of SBM-LE is shown in Figure 3. The main technical indicators of SBM are presented in Table 3.

Based on the successful experience of Xinglong Observatory, the same SBM is used in LOT site monitoring to collect sky brightness. The tests of different SBMs were conducted at Xinglong observatory to compare the consistency of each SBM. See Section 3 for details.

2.4 Differential Image Motion Monitor

Astronomical seeing refers to the blurring and twinkling of astronomical objects due to turbulent of atmosphere

Table 2 The Main Technical Indicators of ASCA

Parameters	Specific values
Exposure interval	Minimum 35 s (recommended: 20 min during the day, 5 min in the night)
Exposure time	Minimum 1/3200 s, maximum 30 s
Aperture value	2.8 ~ 22
ISO	100 ~ 3200
Picture formats	JPEG/RAW
Picture resolution	Maximum 3456 × 5184
Field of view	180 degrees

Table 3 The Main Technical Indicators of SBM

Parameters	Specific values
Interface	10/100 Mbit network port
Precision	± 0.10 mag arcsec^{-2}
Measurement band	Visible band
Measurement angle	20°
Minimum sampling time	1 s

Fig. 3 Sky Background Meter (SBM).

(Young 1974; Sarazin & Roddier 1990). The most common seeing measurement is the Differential Image Motion Monitor (DIMM). Sarazin and Roddier demonstrated the principle and designed the first DIMM in 1986. To ensure the unified seeing measurements for each site, LOT site working group decided to use the DIMM with the same configuration from ALCOR-SYSTEM. Since the DIMM is produced in France, we refer to it as DIMM-FR hereafter.

The DIMM-FR works in fully automatic operating mode with the GM-2000 German equatorial mount of track precision rms $15''$. The DIMM-FR is a RC telescope with a diameter of 300 mm, focal ratio f/8. The camera is DMK 33GX174 with resolution of 1920×1200 and pixel size of 5.86 μm. The diameter of the sub-pupil on the mask is 51 mm, separated 240 mm. The DIMM-FR is shown in Figure 4. The main technical indicators of DIMM-FR are listed in Table 4.

The DIMM's control program PRISM controls the mount, cameras and make all DIMM observations automatically. When solar elevation angle is below –5 degrees to –10 degrees, PRISM will automatically select the appropriate target, move the telescope to point and track the target, then start seeing measurements. If the altitude of the current target is too low to observe, PRISM selects the new target and avoids the Moon. PRISM can control the telescope to return to the park position before twilight and automatically begin observation the next night.

Fig. 4 DIMM-FR.

Before the start of the LOT site, Tibet Ali and Sichuan Daocheng used their DIMMs to monitor the seeing, respectively. Daocheng uses Nanjing Institute of Astronomical Optics & Technology (NIAOT) DIMM (DIMM-NIAOT), Ali uses self-research DIMM (DIMM-Ali). The main technical indicators of the DIMM-NIAOT are shown in Table 5, and the main technical indicators of DIMM-Ali are provided in Table 6.

Several tests were conducted at the Public Observatory of Xinglong Observatory to estimate the consistency of the DIMM-FR. At the same time, the contrast test of DIMM-FR and DIMM-NIAOT and DIMM-Ali was carried out in different locations. The detailed test is shown in Section 3.

3 COMPARISON TESTS

The LOT site working group used the same instruments and conducted comparative tests on ASCA, SBM and

Table 4 The Main Technical Indicators of DIMM-FR

Parameters	Specific values
Mirror Tube	Diameter: 300 mm; focal ratio: f/8; focal length: 2400 mm
Equator	10 Micron GM2000 HPS, German-style, precision $< 15''$
Hole	Number of holes: 2; hole diameter: 51 mm; hole center distance: 240 mm
CCD	5.86 μm
Calculate wavelength	550 nm
Exposure time	According to the selected star and other automatic calculation of exposure time

Table 5 The Main Technical Indicators of DIMM-NIAOT

Parameters	Specific values
Mirror Tube	GSO RC 8, focal ratio: F/8; focal length: 1600 mm
Finderscope	LM100JC
Equator	AP1600, German-style, precision $< 10''$
Hole	Number of holes: 2; hole diameter: 50 mm; hole center distance: 149 mm
Wedge Mirror Angle	50 arcsec
Finder Camera	Basler aca2040, 2k × 2k, pixel size: 5.5 μm × 5.5 μm
DIMM camera	Basler aca2040, 2k × 2k, pixel size: 5.5 μm × 5.5 μm
Exposure time	5 ms and 10 ms alternating exposure (0 exposure correction)
Calculate wavelength	500 nm
Sampling	One seeing value per minute, number of samples 1000 – 2000

Table 6 The Main Technical Indicators of Ali DIMM

Parameters	Specific values
Mirror Tube	MEADE LX200 GPS, aperture: 25 cm, focal length: 2500 mm
Equator	LX200
Exposure time	10 ms
Wedge Mirror Angle	60 arcsec
Calculate wavelength	550 nm
Hole	Hole diameter: 50 mm; hole center distance: 200 mm
DIMM camera	Lumenera SKYnyx2-0M; resolution: 640 × 480; pixel size: 7.4 μm × 7.4 μm

DIMM at Xinglong Observatory to make the measured data statistically comparable. This section describes the test process and the results of each instrument.

3.1 ASCA

From 2016 December 14 to December 22, six ASCAs were tested at the Public Observatory of Xinglong Observatory arranged in the same direction to compare the imaging quality. The cameras started shooting automatically when power was turned on.

The ASCA images were interpreted by astronomers that the images of the six cameras were basically the same and coincident with the real sky, as shown in Figure 5. The images from these ASCAs can be used to determine the number of clear nights of each LOT candidate. The comparison test was completed and the cameras were sent to each site.

3.2 SBM

To compare the consistency of the data measured by different SBMs and to facilitate the comparison between each site, tests were conducted on the roof of the auxiliary telescope building at Xinglong Observatory.

Three SBMs (identifier 1, 2 and 3, respectively) were installed side by side on the roof during the test. They observed the same direction simultaneously every one minute. Figure 6 is the picture of the three SBMs.

The tests were conducted from 2018 February 12 to 21 for a total of 10 days. The results show that the difference between the data measured by each SBM is small and the variation trend is consistent. Figure 7 shows the results of the SBMs on 2018 February 2. The black, blue and green lines represent SBM1, 2, 3, respectively. The SBM1 is the reference data, obtain the difference between the other two SBM and the first SBM. It can be seen from the figure that the differences between the three SBMs are very small. The differences between SBM1 and the other two SBMs are within ± 0.1.

The differences of all measured data were analyzed with a reference to SBM1. The frequency histogram of the difference between SBM2 and SBM1 is shown in Figure 8. The median is –0.02.

The frequency histogram of the difference between SBM3 and SBM1 is shown in Figure 9. The median is 0.

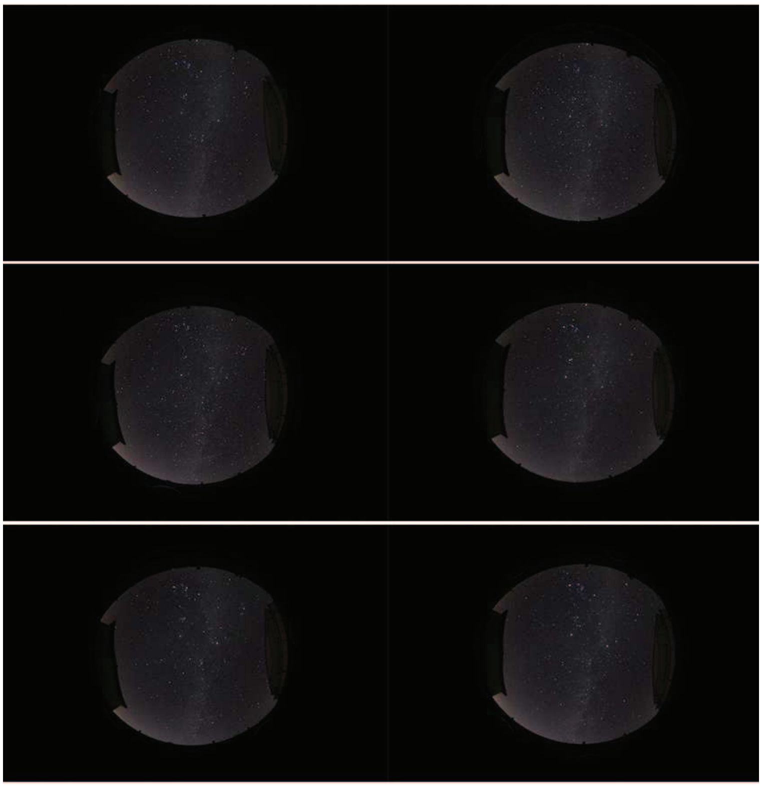

Fig. 5 Images from six ASCAs.

Fig. 6 Comparison of three SBMs.

There are still slight differences even the three SBMs are very close. For long-term statistics, the difference is less than 0.2. As a result, these three SBMs are similar and can be used in sky brightness comparison between different sites.

3.3 Comparisons of two DIMMs

The seeing data consistency test was conducted at Public Observatory of Xinglong Observatory, with two DIMMs in the same model. Two DIMMs mounted at two piers observed the same object simultaneously at the same location and in the same condition. Due to the limitation in the space of the Public Observatory, two DIMMs were arranged along east-west direction (Fig. 10).

The two DIMMs are named by their serial number, DIMM3 and DIMM4. At first, DIMM3 was in Position 1 near the dome and DIMM4 was in Position 2 away from the dome.

The dome was open at least 30 min before observation to ensure the uniform ambient condition. The remote control was used to avoid human influence. The comparison-

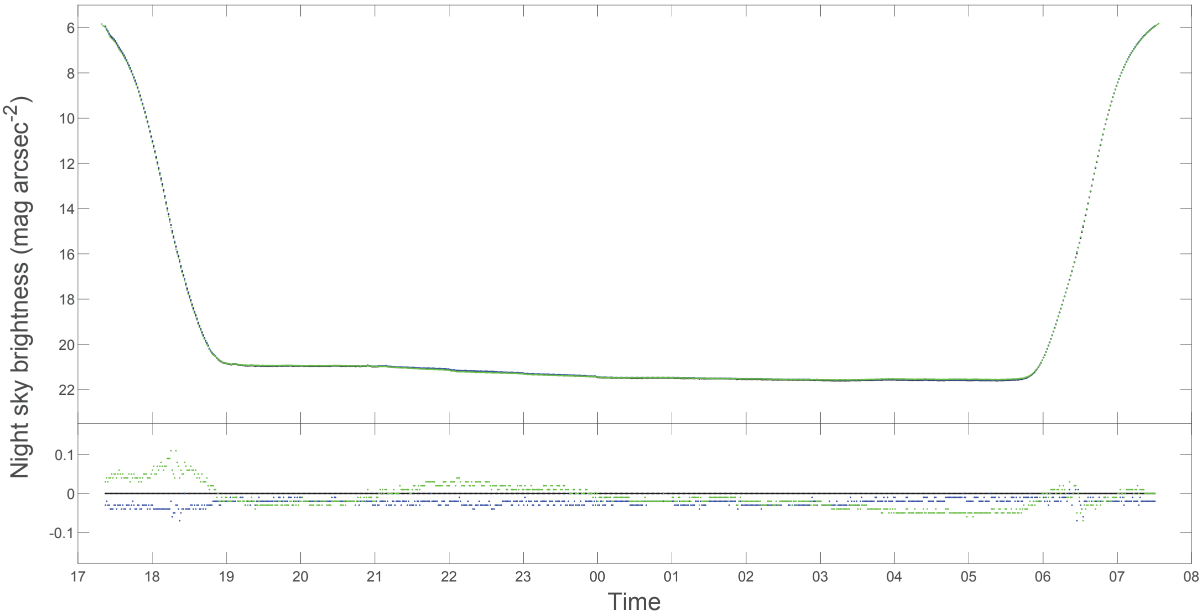

Fig. 7 SBM results on 2018 February 2.

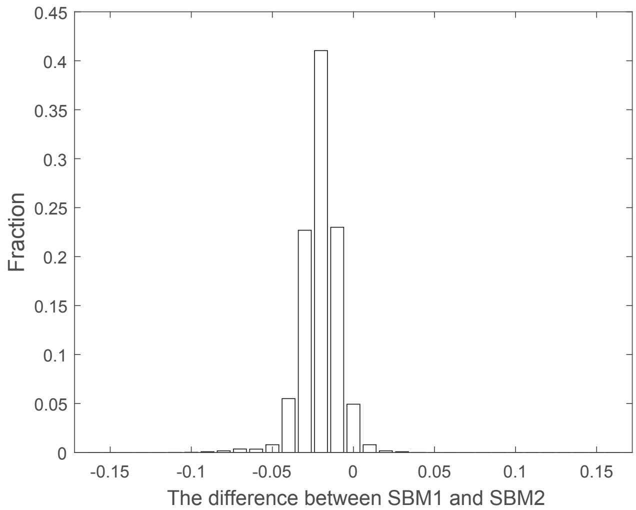

Fig. 8 Frequency histogram of the difference between SBM1 and SBM2.

s were made during 12 nights from 2017 March 3 to 14. Each DIMM obtained almost 20 000 valid data. The first 4 days were for commissioning, stability testing and preliminary analyzing. Then, the further tests were conducted from March 7 to 14.

Figure 11 shows the seeing results on 2017 March 3 from DIMM3 (blue dots) and DIMM4 (red dots). Tendencies of seeing with time of two DIMMs are almost the same.

The frequency histogram of seeing from March 3 to 6 is shown in Figure 12. The median seeing of DIMM3 is $0.1''$ larger than DIMM4. In this situation, another test should be conducted to check the repeatability. If it can be reproduced, we need to exchange the positions of DIMMs to test whether it is caused by the position differences of two DIMMs.

Figure 13 shows the frequency histogram of seeing from March 7 to 12. The median seeing of DIMM3 is $0.07''$ larger than DIMM4. There are several reasons for this: (1) optics systematic differences; (2) positions of DIMMs, where Position 1 is near the dome, causing local air turbulence; (3) algorithm difference, which may not be considered, because the same seeing calculation software has been used.

We exchanged the positions of the two DIMMs on March 13 to test whether the difference comes from the

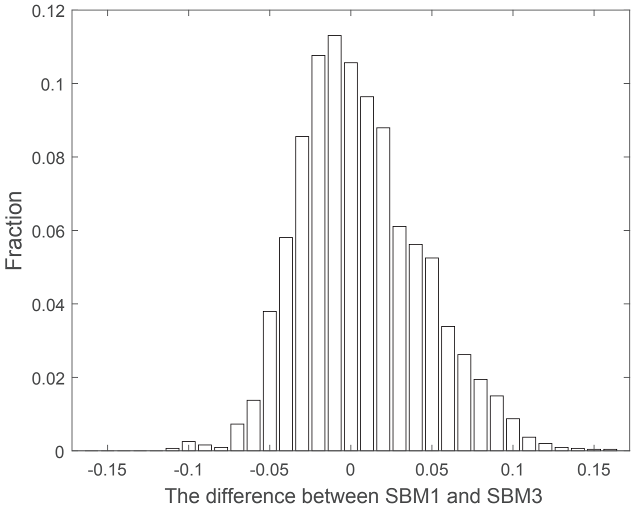

Fig. 9 Frequency histogram of the difference between SBM1 and SBM3.

Fig. 10 Layout of two DIMMs.

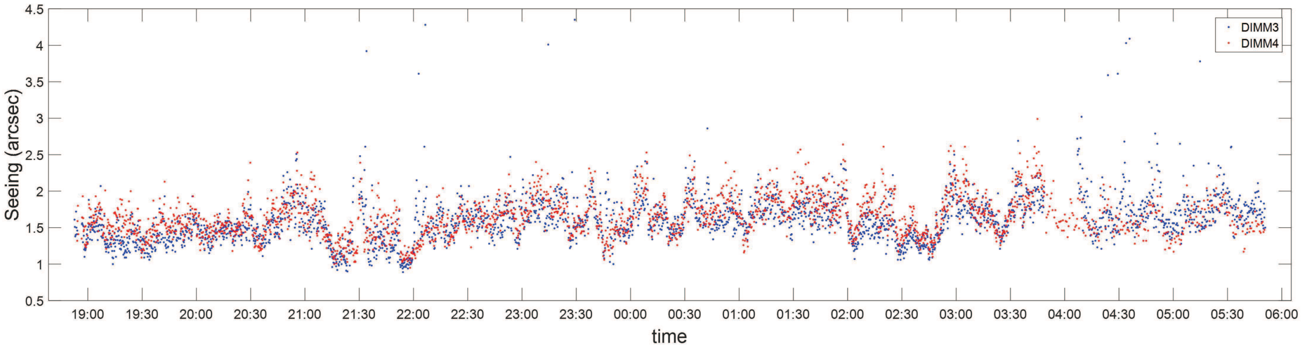

Fig. 11 Seeing results on 2017 March 3 from DIMM3 (*blue dots*) and DIMM4 (*red dots*).

Table 7 A Comparative Test of All the DIMMs Were Implemented at Different Locations at Different Times

Equipments	DIMM-FR vs DIMM-NIAOT	DIMM-FR vs DIMM-Ali
Sites	Muztagh-ata	Ali
Period	2017 April 02 – 2017 April 17	2017 April 26 – 2017 May 20
Result	DIMM-FR: 1.03″; DIMM-NIAOT: 0.96″	DIMM-FR: 0.67″; DIMM-NIAOT: 0.73″
Difference of medians	0.07″	0.06″

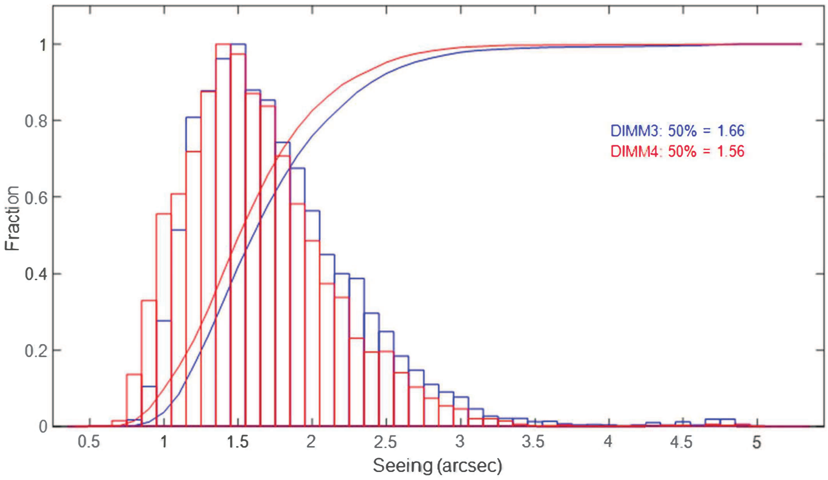

Fig. 12 Frequency histogram of seeing from March 3 to 6.

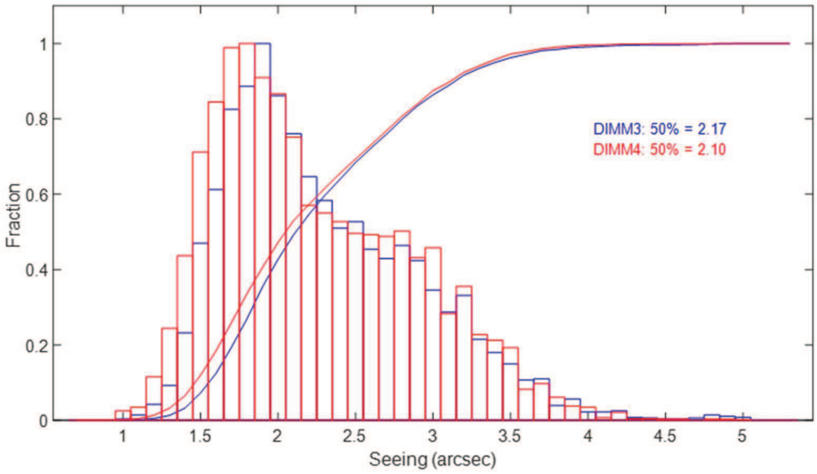

Fig. 13 Frequency histogram of seeing from March 7 to 12.

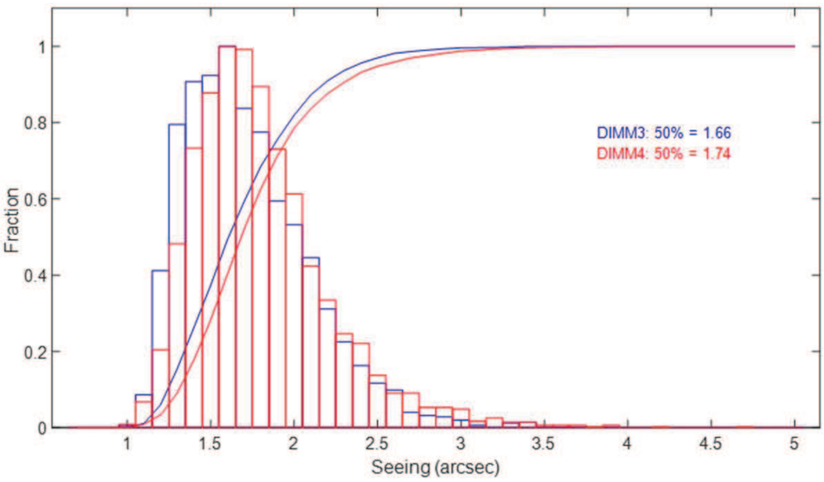

Fig. 14 Frequency histogram of seeing from March 13 to 14 after exchanging the two DIMMs.

tube systematic differences. A two-day observation was made by DIMM3 and DIMM4 mounted at position 2 and 1, respectively. As the frequency histogram shown in Figure 14, the median difference of seeing between DIMM3 and DIMM4 after exchanging the position is $0.08''$.

Conclusions could be made from the above tests:

(1) Tendencies of seeing with time of two DIMMs are consistency;

(2) The differences between DIMM3 and DIMM4 of median seeing before and after exchanging positions are $0.07''$ and $0.08''$, respectively. The seeing difference is related with the positions of the DIMMs (because of the dome), but not the DIMMs themselves.

The comparisons indicate that the difference between the two DIMMs (the same model) is small. As a result, these DIMMs can be used in seeing comparison between different sites. As shown in Table 7. From 2017 April 02 to 2017 April 17, a comparative test of DIMM-NIAOT and DIMM-FR was carried out in the Xinjiang Muztagh-ata. The test results are given as follows: the median values of DIMM-FR and DIMM-NIAOT are $1.03''$ and $0.96''$, respectively. From 2017 April 26 to 2017 May 20, we conducted a comparative test of DIMM-Ali with the DIMM-FR in Ali. Test results are provided as follows: the median value of DIMM-FR is $0.067''$, and the DIMM-Ali is $0.73''$. A more detailed introduction can be found in the article of Cao et al. (2020).

4 CONCLUSIONS

The identical models of data collection instruments (weather station, ASCA, SBM, DIMM, etc.) were deployed to each site candidate by general group of LOT site. Comparisons of several collection instruments were made to testify the instrumental stability and the data uniformity of the identical instruments. The results show that these instruments can be used in site monitoring and the standard data are valuable for site condition evaluation, which ensure the scientific and objective site selection.

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