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The site conditions of the Guo Shou Jing Telescope *

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Abstract The weather at the Xinglong Observing Station, where the Guo Shou Jing Telescope (GSJT) is located, is strongly affected by the monsoon climate in north-east China. The LAMOST survey strategy is constrained by these weather patterns. We present statistics on observing hours from 2004 to 2007, and the sky brightness, seeing, and sky transparency from 1995 to 2011 at the site. We investigate effects of the site conditions on the survey plan. Operable hours each month show a strong correlation with season: on average there are eight operable hours per night available in December, but only one–two hours in July and August. The seeing and the sky transparency also vary with season. Although the seeing is worse in windy winters, and the atmospheric extinction is worse in the spring and summer, the site is adequate for the proposed scientific program of the LAMOST survey. With a Monte Carlo simulation using historical data on the site condition, we find that the available observation hours constrain the survey footprint from $22^{\rm h}$ to $16^{\rm h}$ in right ascension; the sky brightness allows LAMOST to obtain a limiting magnitude of $V = 19.5$ mag with S/N$= 10$.

Key words: telescopes — site testing — surveys

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1 INTRODUCTION

The Guo Shou Jing Telescope (also named Large sky Area Multi-Object fiber Spectroscopic Telescope, or LAMOST) is a quasi-meridian reflecting Schmidt telescope with a 4-meter aperture, a 5-degree field of view, and 4000 fibers installed on the focal plane (Cui et al. 2010; see also the overview by Zhao et al. 2012). It will be used as a spectroscopic survey telescope for Galactic (Deng et al. 2012) and cosmological science.

LAMOST is located at the Xinglong Observing Station (hereafter XOS) of National Astronomical Observatories, Chinese Academy of Sciences (NAOC). It is located ~ 114 km north-east of Beijing with longitude of $7^{\rm h}50^{\rm m}18^{\rm s}$ east and latitude of $40°23'36''$ north. The elevation of the site is ~ 900 m.

The weather at the site is extremely seasonal and is dominated by a continental monsoon in the summer. In this paper we show how the site's climate, weather, sky brightness, and seeing influence the design of the LAMOST survey. These constraints are extremely important not only to the field selection for the halo on dark nights (Yang et al. 2012), on bright nights (Zhang et al. 2012), and for the disk (Chen et al. 2012), but also for the science goals of the LAMOST survey (Deng et al. 2012).

There have been a few previous papers on the XOS conditions. The early work on monitoring the site's conditions with a Schimdt telescope was done by Zhou et al. (2000). Liu et al. (2003) used the the North pole monitoring data collected from 1995 to 2001 by the 60/90 cm Schmidt telescope on the same site to investigate the sky brightness, the seeing and the atmosphere extinction. They found that the mean sky brightness in the V band reaches 21.0 mag arcsec^{-2} and the mean seeing measured from the imaging FWHM varies with season; specifically, the seeing is better in summers but worse in winters. The camera used for seeing measurements on the Schmidt telescope under-samples the point spread function, so that the seeing measurements are not reliable when measured seeings are better than $\sim 2''$. The site seeing was also measured using a Differential Image Motion Monitor (DIMM) (Liu et al. 2010). Previous studies either used old data or included only a short time baseline. These measurements do not reflect the current weather and long term variation of the site conditions. Since LAMOST will last at least five years, understanding the long term variation of the site conditions is very important in designing and planning LAMOST surveys. In this paper we will revisit XOS quality as an astronomical observing site using the largest and latest site parameter data set available, covering almost 16 years since 1995.

In Section 2, we describe how the data are collected. In Section 3 the weather patterns, the sky brightness, the seeing, and the atmospheric extinction are analyzed. We then create a simplified but realistic simulation of the survey with the priors of the site conditions so that the probability of the sky coverage and the total number of spectra can be estimated, and present that in Section 4. Finally, in Section 5 we give general guidelines that will be used in the design of the survey.

2 DATA ACQUISITION

In this work we use two sets of data, both obtained from the BATC survey (Beijing-Arizona-Taipei-Connecticut multi-color photometry survey, Fan et al. 1996) using the Schmidt telescope at XOS.

The observation logs of BATC from 2004 to 2007 provide the duration of actual observing time from opening to closing the dome on each night of operation. It is noted that the BATC is a 60/90 cm Schmidt telescope on an equatorial mount, therefore it can point to whatever part of the sky is clear, so that it is more time efficient than LAMOST. LAMOST is limited to point only within 2 h on each side of the meridian, and is also restricted to $-10°$ to $60°$ in declination. (Higher declinations are possible, but at a significant cost to the field of view.) Therefore, the actual observation time available for LAMOST could be lower than BATC's statistics.

The other data set comes from monitoring images of an area around Polaris collected by BATC from 1995 to 2011. The BATC survey took an image of the celestial north pole before normal observations began each night. Although it does not use the zenith, which is a better direction for monitoring the sky brightness, it still represents a great legacy of quantifying XOS conditions. Liu et al. (2003) used the first six years of data in their work. In the current work, we extend it to 2011; Liu et al (2003) used the data from 1995 to 2001 in their work, 10 years more than what was previously available.

We follow the same procedure used by Liu et al. (2003) to measure the seeing, night sky brightness and extinction from the Polaris dataset.

The sky brightness ADU was measured from the background of the images, then instrument magnitude zero points derived from photometric nights were interpolated to each observing night to convert the sky brightness ADU into a magnitude in the V band. The photometric software package SExtractor (Bertin & Arnouts 1996) was used to measure the FWHM, magnitude and other parameters of stellar objects on the image. The average FWHM of those stellar objects was taken as the seeing of that observation. The sky transparency, which is quantified by the extinction coefficient, was derived by comparing measured magnitudes of the selected stars with the known magnitude of the same objects from the Guide Star Catalog (GSC, Lasker et al. 2008).

3 SITE PARAMETERS

3.1 Weather Patterns

Figure 1 shows hours per night used for actual observations by BATC from 2004 to 2007. Although the recorded observed hours from BATC should not necessarily be identical to those for GSJT, they still reflect the general weather pattern at XOS.

Figure 1 shows that the actual observation hours per night is about six hours less than the theoretical value at all times of the year. In this period of time, 43% of observing time was lost due to bad weather. The maximum observing time is in December and January, when about eight hours on average are available each night, while in July and August the average observing time is less than two hours. This pattern is similar to figure 1 in Zhang et al. (2009). Because it is restricted to observe within $\sim$ two hours of the meridian, LAMOST hardly has any observation time in summer. Such a site dependent weather pattern means that LAMOST will have a better chance to observe right ascensions that are observable in winter: the Galactic anticenter and the south Galactic cap. The north

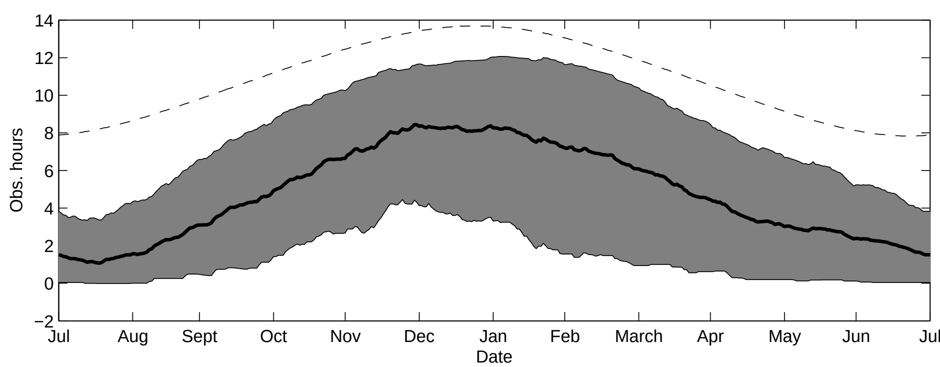

Fig. 1 The statistics of the number of hours of BATC observations per night from 2004–01–01 to 2007–09–30. The thick solid line shows the actual mean observing hours, smoothed with a 2-month window, for each night from July 1 to June 30 the next year. The shaded area shows the minimum and maximum hours of observation each night smoothed with the same time window. As a reference, the dashed line shows the theoretically available time between evening and morning twilights.

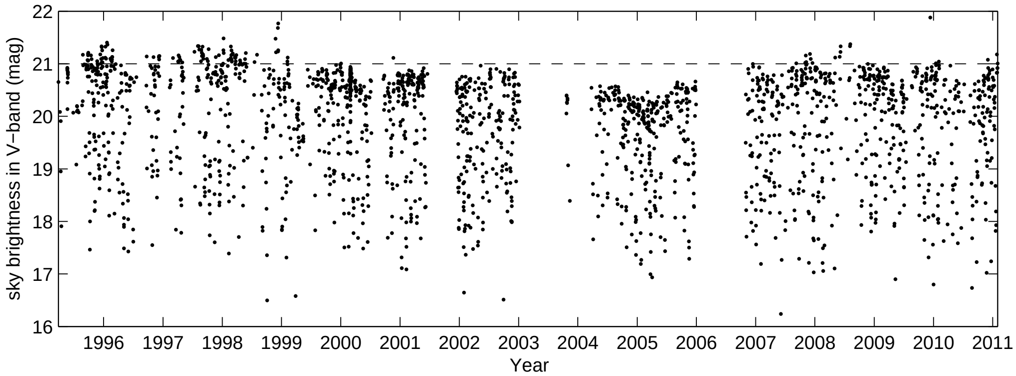

Fig. 2 The sky brightness in the V band obtained from BATC Polaris monitoring data, as a function of time from 1995 to 2011. The dashed line is 21 mag arcsec^{-2}.

Galactic pole and the inner Galactic disk, on the other hand, are difficult to completely sample with LAMOST.

3.2 Sky Brightness

Figure 2 shows the all sky brightness measurements from the BATC Polaris images as a function of time. There are some long term features in the data. First, there is a significant brightening between 2005 and 2006, which is due to the construction of the buildings for LAMOST. Lights from the construction site significantly affected the BATC telescope, which is only a few hundred meters away. After the construction was done in 2007, the monitoring data from BATC returned to the normal level for the site.

Secondly, there seems to be an annual (probably seasonal) variation in the sky brightness. The periodic pattern is much clearer from 2007 to 2011. It seems that around the end of a year, in the winter, the sky is darker, sometimes fainter than 21 mag arcsec^{-2}, while in the middle of a year, in the summer, it is brighter by as much as 0.5 mag. It is not well understood what causes the seasonal pattern in the sky brightness. Several factors could have contributed to the pattern, including dust storms in the spring, more construction in local areas in summer or local agricultural activities. All of these factors reduce the transparency of the atmosphere, which can result in more scattered light from nearby cities.

3.3 Seeing

Although a DIMM instrument has been used recently to monitor the natural seeing for GSJT (Liu et al. 2010), there are no historical seeing data from long term monitoring for the site quality at XOS. The only feasible data set that can be used for seeing assessment is BATC data archive. However, note that the Schmidt telescope has a classical dome, with attached office and living facility, so the measurements are likely dominated by dome seeing. Indeed, the site's natural seeing is likely around 1 arcsec (Liu et al. 2010), much better than the measurements from BATC. The long term record of seeing at XOS derived from BATC is shown in Figure 3. The seeing spans a huge range and is probably seasonal, as can be clearly seen in the figure. In the winters of 1999 and 2000, it was rather bad in general, and sometimes was worse than 4 arcsec. It became slightly better in 2006. After 2007, the BATC telescope installed a new 4k$\times$4k CCD, hence the new camera improved the

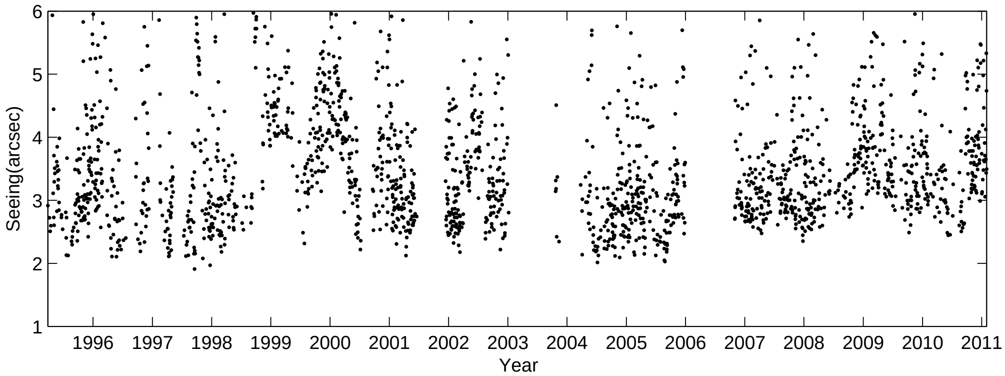

Fig. 3 The seeing measured from the FWHM of the images obtained in the region around Polaris by BATC from 1995 to 2011 is shown.

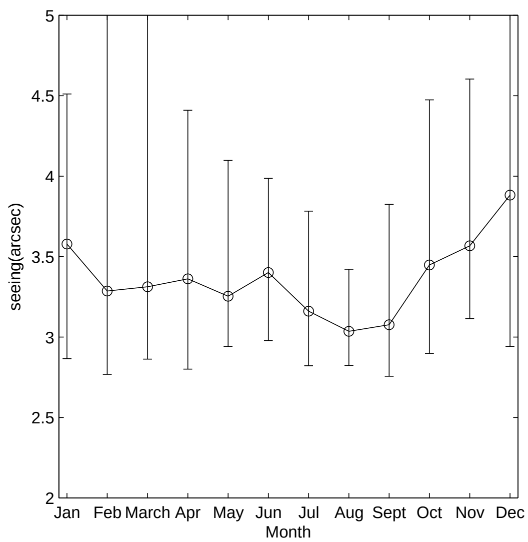

Fig. 4 The median seeing and its $1-\sigma$ range using the data after 2007 in Fig. 3 in each month are shown.

imaging resolution from 1.7 arcsec pixel^{-1} to 1.36 arcsec pixel^{-1}. In order to keep consistency of the data we only use those after 2007 for subsequent analysis.

Figure 4 shows the average seeing for each month using the data after 2007. The best seeing occurs in August and September, while the worst is in December and January. Meanwhile, the dispersion of the seeing (the error bar shown in the figure) also follows the same trend. This pattern is similar to figure 7 of Liu et al. (2003), and also figure 5 of Zhang et al. (2009). Experience from other telescopes at the same site shows that it is true that the seeing is worse in the winter and better in the summer. This is related to the climate. In winter the strong and frequent wind significantly enhances the turbulence in the atmosphere and hence the seeing is worse and more unstable. By contrast, in summer there is very weak or no wind and this makes the seeing smaller and more stable.

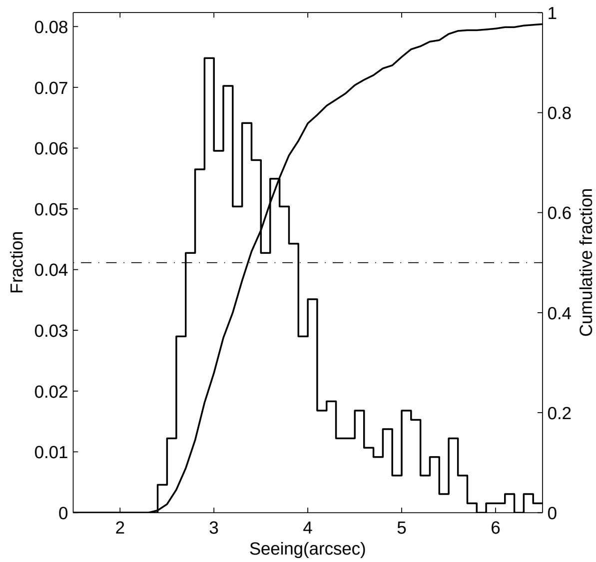

Fig. 5 The distribution and cumulative distribution of the seeing after 2007, using data from Fig. 3. The solid lines show the distribution for all data. The dash-dotted horizontal line shows the position of 50%. It indicates that 50% of the observations are in the seeing lower than 3.4 arcsec for the data.

Figure 5 gives the statistics of the seeing after 2007. The peak of the histogram of the seeing is around 3 arcsec. Based on the cumulative distribution of the seeing data, 50% of the seeing measurements are better than 3.4 arcsec. Due to under-sampling, BATC images are not perfect for accurate seeing measurements. Even with the slightly improved pixel scale of 1.36 arcsec, the images do not yield good measurements of the FWHM below 2 pixels ($\sim$2.7 arcsec). Additionally, it is dome seeing that is dominant and not the natural seeing at the site. For these reasons, we will use the results only as a reference for the long-term variations in seeing condition. Nevertheless, although the seeing is not perfect compared with other famous sites, it is adequate for the proposed science program of the LAMOST spectroscopic survey.

3.4 Extinction

The sky transparency at XOS shows significant seasonal variations, as shown in Figure 6. The best value occurs in October, and the worst value appears in May and June, when the local area suffers from sand storms and/or climate factors such as humidity and dust.

4 A SIMULATION FOR THE LAMOST SURVEY WITH SITE CONSTRAINTS

We run a Monte Carlo simulation to simulate the sky coverage of the LAMOST survey based on the site conditions. The simulation helps to clarify how the site conditions affect the survey and consequently what science goals are the most feasible for LAMOST.

In the simulation, we assume that LAMOST can only observe 864 predefined non-overlapping 5-degree-diameter fields of view (hereafter called plates) covering all space between $\delta = -10^\circ$ and $\delta = 60^\circ$ (Fig. 7). This is an oversimplified assumption since in practice LAMOST scans the sky with many overlapping plates. However, this assumption makes the simulation quite simple and sufficient for investigating impacts of the site conditions on survey planning. No fiber assignment is included

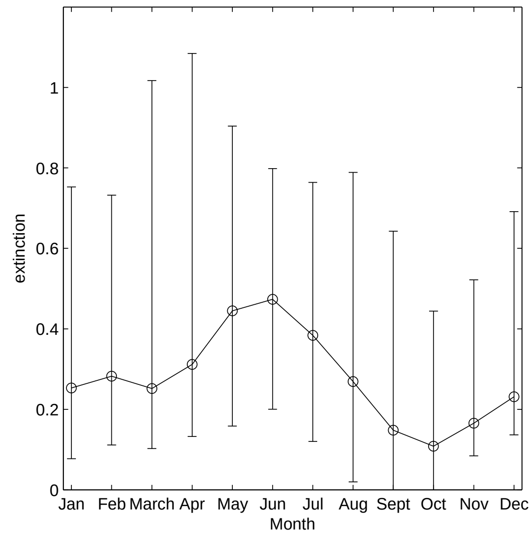

Fig. 6 The circles show the median atmospheric extinction coefficient for each month. The error bars show the range of 1-σ. Only the data after 2007 are used.

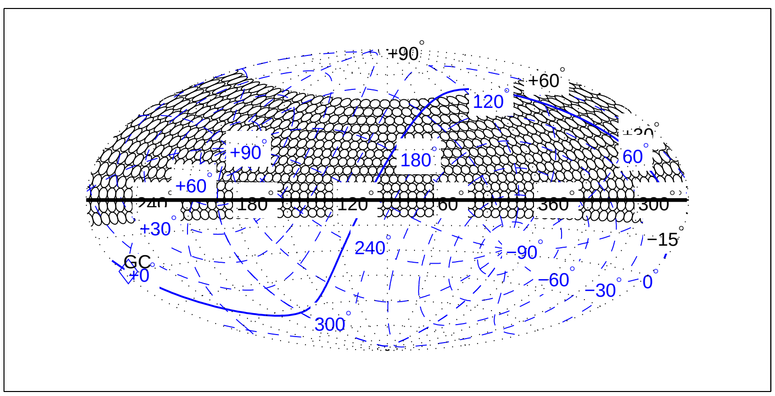

Fig. 7 The footprint map in an equatorial Aitoff projection of the Monte Carlo simulation. The circles show the possible plates that LAMOST can observe in the simulation. The blue grid shows the Galactic coordinates. Note that some plates are blocked by the coordinate labels, but they do actually exist behind the numbers.

in the simulation. We also do not give any presumption of a favorite sky region, e.g. the emphasis of the anticenter direction as we did in Deng et al. (2012), but just evenly cover all available sky regions for LAMOST.

We also assume that on dark/grey nights LAMOST observes the faint objects with 1.5 h exposures (3×30 min), while at bright nights it only observes the bright objects with 0.5 h exposures (3×10 min). The overhead for each plate is 0.5 h, including telescope movement, active optics op-

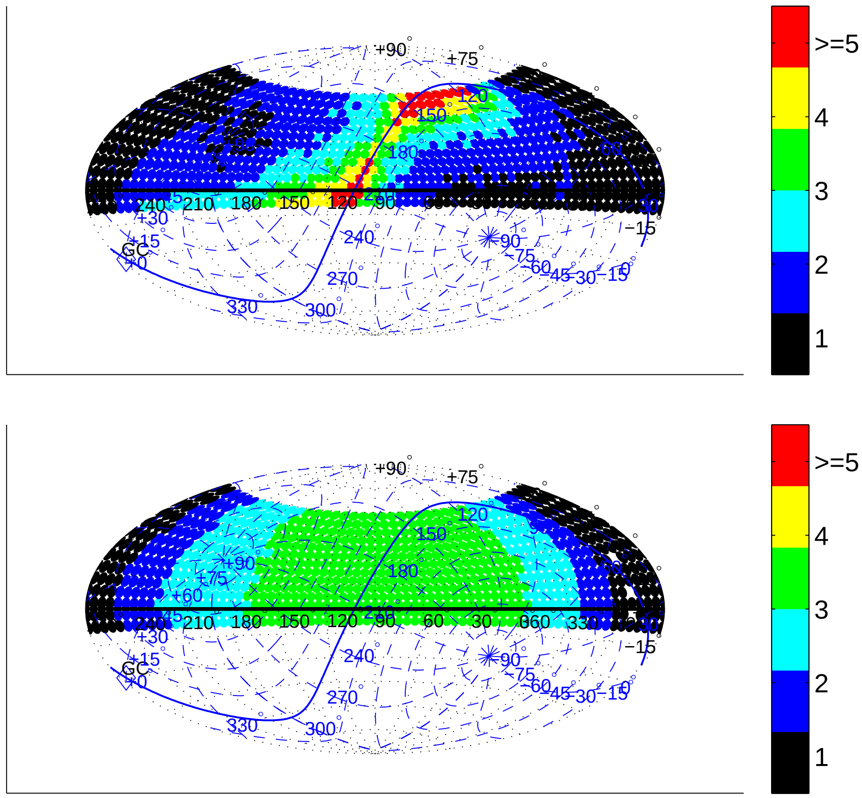

Fig. 8 *Top panel:* The number density equatorial map of the observed plates for bright nights in a five-year simulated survey. *Bottom panel:* The number density equatorial map of the observed plates for dark/grey nights.

eration, fiber positioning etc. In addition, we add 2 more hours to each night for the telescope's preparation and configuration, including focusing the mirrors on a bright star twice per night.

We adopt a very simple strategy for the simulation. On dark/grey nights, when LAMOST starts to observe, it arbitrarily selects the one with the minimum number of observations from all available plates within 2 h on each side of the meridian. On bright nights, the plates with zero observations will be the highest priority for observation. Additionally, the probability of plate selection follows the star counts in the area of sky covered by that plate; therefore plates near the Galactic mid-plane will be observed more than those at high latitudes.

We run the simulation for a five-year survey (2011–2015) and repeat it 50 times to smooth out the random fluctuations. The mean number of plates observed in five years, at each location, is shown in Figure 8. The bright night survey can reach more than five observations per plate along the Galactic mid-plane. Since the Galactic plane, in particular the anticenter direction, is right in the most weather favorable sky region for LAMOST, it seems that LAMOST is suitable for an anticenter Galactic plane survey. Since the dark/grey night survey does not use any prior knowledge of the star distribution, it simply follows the actual number of observing hours available, considering the weather, seasonal variation in the number of hours per night, and Moon phase. In five years, the dark/grey night survey can cover the sky between $\alpha = 22^{\rm h}$ and $16^{\rm h}$ at least three times. The rest of the region is the summer sky, which can be essentially covered only once. The actual observation hours in the summer restrict the sky coverage of LAMOST.

5 CONCLUSIONS

From a compilation of site condition data over the last 16 years, we find that the strongest constraint for the LAMOST survey is from the actual observation hours, which are significantly lower than the available hours due to weather constraints. This results in very few or even zero observation hours in summer. Considering the special quasi-meridian design, the observable sky is constrained to the autumn, winter and spring, so that LAMOST performs best in the regions of the Galactic anticenter and the South Galactic cap. Consequently, the survey plan has to be very carefully designed under this limitation.

The sky brightness reaches roughly $V = 21$ mag arcsec^{-2} on the best nights at Xinglong. Therefore the limiting V magnitude for spectroscopy should be around 19.5 mag with S/N$= 10$ for point sources. This is the upper limit of the capability of LAMOST. Because the seeing at the LAMOST site becomes worse during the months when the actual observation hours are long, LAMOST will suffer from flux lost due to the larger PSF, which will reduce the total throughput of the fibers to some extent.

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