Postprint: Exposure Time Optimization for the W Survey of the Yunnan University Multi-channel Photometric Survey Telescope

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Abstract

The under-construction Yunnan University Multi-channel Photometric Survey Telescope (Mephisto) is scheduled to commence the W Survey (Mephisto-W Survey) in 2022. The Mephisto-W Survey will conduct a multi-channel, multi-epoch photometric survey of the northern hemisphere observable sky area (approximately 26,000 square degrees), offering a significant opportunity for detailed mapping of Milky Way structure, profound understanding of galaxy formation and evolution theory, precise constraints on cosmological models, and in-depth investigation into the nature of dark matter and dark energy. This paper, based on the full-year 2019 observational data from the Lijiang Site Astronomical Monitoring System (ASMS), employs machine learning methods to simulate a one-year site condition model for Lijiang Station. It provides rough estimates of the observable epochs and expected limiting magnitudes for the Mephisto-W survey fields throughout an entire year under various exposure times. Considering the scientific objectives of the Mephisto-W Survey, we recommend an exposure mode of 2 exposures per field per epoch, each with a duration of 20 seconds. Under this exposure mode, approximately 3.8 observations can be achieved for each filter combination (ugi and vrz) across the survey fields annually, with a single-epoch r-band limiting magnitude reaching 22.37 mag and a stacked magnitude reaching 23.11 mag.

Full Text

On the Exposure Time Optimization for the Mephisto-W Survey

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Abstract

The Multi-channel Photometric Survey Telescope (Mephisto) under construction at Yunnan University is expected to commence the Mephisto-W Survey in 2022. This multi-channel, multi-epoch photometric survey will cover the observable northern sky (approximately 26,000 square degrees), providing unprecedented opportunities to map the detailed structure of the Milky Way, deepen our understanding of galaxy formation and evolution, precisely constrain cosmological models, and investigate the nature of dark matter and dark energy. Based on 全年观测数据 from the Astronomical Site Monitoring System (ASMS) at the Lijiang Observatory in 2019, we have constructed a machine-learning-based model of the site conditions at Lijiang. We estimate the observable epochs per field and expected limiting magnitudes for the Mephisto-W survey under various exposure time configurations. Considering the scientific objectives of the survey, we recommend an exposure mode of two exposures per visit, each lasting 20 seconds. In this configuration, the survey can achieve approximately 3.8 observations per field for each filter combination (ugi and vrz) annually, with a single-visit r-band limiting magnitude of 22.37 mag and a co-added magnitude of 23.11 mag.

Keywords: Large-area survey; Site conditions; Limiting magnitude

1. Random Forest Model of Annual Site Conditions at Lijiang Observatory

Lijiang Observatory is one of China's premier optical astronomical sites, hosting several advanced telescopes including the 2.4-meter Lijiang Telescope (LJT) [1]. To support operations of both LJT and Mephisto, two Astronomical Site Monitoring Systems (ASMS) have been installed at separate high-altitude locations: ASMS-A near the LJT and ASMS-B at the Mephisto site [2][3][4]. ASMS-B has been operational since late 2018.

The ASMS comprises four subsystems: a weather station, an all-sky camera, a seeing monitor, and a video surveillance system. The collected data on seeing, cloud cover, temperature, wind speed, and sky brightness enable evaluation of observing conditions for the Mephisto survey. However, due to weather interruptions and instrument downtime, ASMS-B data contain significant gaps. Since ASMS-A and ASMS-B are separated by only about 100 meters, we supplement ASMS-B data with ASMS-A observations to construct a complete annual site condition model.

We employ the Random Forest Regressor algorithm to build a comprehensive model of site conditions for 2022. Random Forest is a key Bagging algorithm in machine learning that uses ensemble learning for classification and regression, applying averaging to improve prediction accuracy and control overfitting. During training, bootstrap sampling generates multiple distinct subsets from the input data to train individual decision trees; during prediction, the algorithm averages outputs from all trees to produce final results [5].

Using the Python package scikit-learn [6], we randomly selected 75% of the 2019 ASMS data for training and reserved 25% for testing. Atmospheric seeing, the blurring of stellar images caused by atmospheric turbulence, is a critical site selection parameter that depends on temperature, wind speed, and local topography [7]. Seeing exhibits two distinct temporal variations: seasonal changes throughout the year (modeled using day-of-year) and diurnal variations (modeled using local solar time). Since temperature and wind speed measurements are not synchronized with other ASMS subsystems, we first built separate Random Forest models for temperature and wind speed using time (day-of-year and local time) as features. We then constructed a seeing model using day-of-year, local time, wind speed, and temperature as input features. Comparison with test samples (Figure 2 left) yields a model score of 0.89 with a residual dispersion of 0.016.

Cloud cover, represented by integer values from 0 (clear) to 10 (fully overcast), is crucial for determining telescope operability. Like seeing, cloud cover varies both seasonally and diurnally, and correlates with temperature and wind speed. Using the same four features (day-of-year, local time, wind speed, and temperature), the cloud model achieves a score of 0.967 with residual dispersion of 0.645 (Figure 2 middle).

Sky brightness, which limits the observable limiting magnitude [8], varies with lunar phase (captured by day-of-year) and the altitude of the Sun and Moon throughout the night (captured by local time). Our sky brightness model uses day-of-year, local time, and cloud cover as features, achieving a score of 0.999 with residual dispersion of 0.103 (Figure 2 right).

[Figure 2: see original paper] Comparisons between the seeing, cloud and sky brightness values from the test samples and those from the Random Forest models. Red lines are the y=x curves.

These models provide complete annual predictions for seeing, cloud cover, and sky brightness at Lijiang Observatory. Figure 3 [Figure 3: see original paper] illustrates the observed and modeled variations for days 66.5–69.5. The ASMS observations (red crosses) contain substantial gaps, while our Random Forest predictions (blue dots) provide continuous coverage that closely matches available data. The high consistency between our models and observations demonstrates that the Random Forest approach successfully fills data gaps while maintaining physical realism.

[Figure 3: see original paper] Comparisons between variations of seeing (left panel), cloud (middle panel) and sky brightness (right panel) from the ASMS observations (red crosses) and those from the Random Forest models (blue dots) during days of the year between 66.5 and 69.5.

Based on these models, we estimate that Mephisto' s site will have 1,867 observable hours annually (defined as seeing < 2 arcseconds, cloud cover ≤ 3, and solar altitude $<$ -12°). During observable time, the median seeing is 1.06 arcseconds, with 39.47% of time having seeing better than 1 arcsecond; clear skies (cloud cover = 0) occur 66.45% of the time; and the median sky brightness is 21.30 mag (V-band), with 69.76% of observations having sky brightness > 20 mag.

2.1 Estimation of Observation Epochs and Limiting Magnitudes

To obtain precise astrometric data (proper motions, trigonometric parallaxes) and identify variable sources while capturing real-time color variations, we require multiple temporal observations of each field—more epochs are preferable. Conversely, detecting fainter objects and achieving deeper survey volumes requires longer exposures to reach fainter limiting magnitudes. These objectives conflict: more epochs favor shorter exposures, while deeper detection favors longer exposures. Additionally, telescope slewing between fields consumes time; excessively short exposures would result in disproportionate overhead.

We first estimate the average number of observations per field for the entire W survey area under different exposure times. Our site model indicates 1,867 observable hours annually. The W survey covers 13,742 fields, with each field observed twice per visit (with a small dither between exposures to fill CCD gaps). The observation time per field comprises four components: (1) total exposure time t_{exposure}; (2) dithering and stabilization time t_{dizzer}; (3) slewing time between fields $t_{\text{transform}}$; and (4) CCD readout time.

Assuming a slew speed of 2°/s and acceleration of $1°/\text{s}^2$, the telescope can move 6° in both right ascension and declination within 5 seconds, so we adopt $t_{\text{transform}} = 5$ s. The dither between exposures is typically $< 0.6°$, making its overhead negligible. Post-slew stabilization requires 10 s, so each field change incurs $t_{\text{transform}} + t_{\text{stable}} = 15$ s. With e2v 290 CCD chips, readout time is ≤ 10 s and can occur concurrently with telescope movement, adding no overhead.

We calculate the average observations per field N for total exposure times of 2×10 s, 2×15 s, 2×20 s, 2×25 s, 2×30 s, 2×35 s, 2×40 s, 2×45 s, 2×50 s, 2×55 s, and 2×60 s using:

$$N = \frac{t_{\text{total}}}{n_{\text{field}} \cdot (t_{\text{exposure}} + t_{\text{dizzer}} + t_{\text{transform}})}$$

where $t_{\text{total}} = 1,867$ hours and $n_{\text{field}} = 13,742$.

The exposure time fraction η, indicating survey time efficiency, is:

$$\eta = \frac{t_{\text{exposure}}}{t_{\text{exposure}} + t_{\text{dizzer}} + t_{\text{transform}}}$$

Higher η values (approaching 1) indicate more time spent observing versus slewing.

Telescope noise sources include target photon noise, sky background, CCD readout noise, and dark current. For a given exposure time, we estimate limiting magnitudes for each filter using the signal-to-noise ratio (SNR) calculation:

$$\text{SNR} = \frac{\text{flux}}{\text{noise}} = \frac{F}{\sqrt{F + B + R + D}}$$

where F is source flux, B is sky background, R is readout noise, and D is dark current.

The co-added SNR for N observations is:

$$\text{SNR}_{\text{coadded}} = \text{SNR} \cdot \sqrt{N}$$

We retain one decimal place for N and distribute fractional observations proportionally: for a survey with $N = 3.8$, 80% of fields receive 4 observations and 20% receive 3 observations. The final average co-added magnitude is weighted accordingly.

2.2 Results and Discussion

Table 1 presents results for all eleven exposure modes: average observable epochs, exposure time fraction η, single-visit limiting magnitudes (SNR = 5), and annual co-added magnitudes for all six filters.

The results of different exposure modes for Mephisto-W survey

Exposure Time t (s)	Average Epochs N	η	Single-Visit Limiting Magnitude (mag)	Annual Co-added Magnitude (mag)
2 × 10	5.4	0.40	20.94, 20.97, 22.01, 21.83, 21.50, 20.60	21.90, 21.93, 22.97, 22.78, 22.44, 21.55
2 × 15	4.5	0.55	21.34, 21.37, 22.37, 22.16, 21.80, 20.92	22.19, 22.21, 23.20, 22.99, 22.62, 21.76
2 × 20	3.8	0.62	21.63, 21.67, 22.60, 22.37, 21.99, 21.14	22.38, 22.40, 23.34, 23.11, 22.73, 21.88

Exposure Time t (s)	Average Epochs N	η	Single-Visit Limiting Magnitude (mag)	Annual Co-added Magnitude (mag)
2×25	3.3	0.68	21.84, 21.86, 22.78, 22.54, 22.14, 21.30	22.51, 22.52, 23.44, 23.19, 22.80, 21.95
2×30	2.9	0.73	22.01, 22.02, 22.92, 22.66, 22.26, 21.42	22.61, 22.62, 23.51, 23.25, 22.84, 22.01
2×35	2.6	0.76	22.15, 22.16, 23.03, 22.77, 22.36, 21.53	22.68, 22.69, 23.55, 23.28, 22.87, 22.05
2×40	2.3	0.80	22.27, 22.28, 23.13, 22.86, 22.44, 21.62	22.74, 22.75, 23.59, 23.32, 22.90, 22.08
2×45	2.1	0.82	22.37, 22.38, 23.21, 22.93, 22.52, 21.69	22.80, 22.80, 23.63, 23.35, 22.93, 22.11
2×50	1.9	0.85	22.47, 22.47, 23.28, 23.00, 22.58, 21.76	22.84, 22.85, 23.66, 23.37, 22.95, 22.13
2×55	1.8	0.87	22.55, 22.55, 23.35, 23.06, 22.64, 21.82	22.87, 22.87, 23.66, 23.38, 22.95, 22.14
2×60	1.7	0.89	22.62, 22.62, 23.41, 23.12, 22.69, 21.88	22.89, 22.89, 23.67, 23.38, 22.95, 22.14

The maximum average epochs (5.4) occurs for the shortest exposure (2×10 s), while the minimum (1.7) corresponds to the longest (2×60 s). When exposure time exceeds 2×25 s, the average drops below 3 epochs per field. For variable star identification and other science goals, 1–2 observations per year are insufficient. Among shorter exposures, the 2×10 s mode yields significantly shallower magnitudes than alternatives, failing to meet survey requirements. The 2×25 s mode reaches 4 epochs for only ~30% of fields, making it suboptimal.

Comparing the remaining options, the 2×15 s and 2×20 s modes provide 4.5 and 3.8 epochs respectively. The 2×20 s mode achieves slightly deeper limiting magnitudes and a higher time efficiency ($\eta = 0.62$) compared to 2×15 s ($\eta = 0.55$), where nearly half the time would be spent slewing and stabilizing. Therefore, the 2×20 s mode is superior.

In summary, the optimal exposure mode for Mephisto-W is 2×20 s. Under this configuration, Mephisto can observe each field an average of 3.8 times per year for both filter sets, with 80% of fields receiving 4 observations and 20% receiving 3. The single-visit r-band limiting magnitude reaches 22.37 mag, with co-added magnitudes of 23.15 mag for 4-observation fields and 22.99 mag for 3-observation fields.

3. Summary

To identify the optimal exposure mode that balances depth and cadence for the Mephisto-W survey, we constructed a Random Forest model of site conditions at Lijiang Observatory using 2019 ASMS data on seeing, cloud cover, and sky brightness. Based on model predictions, we estimated annual observation epochs, single-visit limiting magnitudes, and co-added magnitudes for various exposure modes (Table 1). The results indicate that the 2 × 20 s mode best satisfies the survey' s scientific requirements, enabling an average of 3.8 observations per field across 26,000 square degrees of the northern sky using both filter combinations (ugi and vrz). Specifically, 80% of fields will be observed 4 times and 20% 3 times annually, achieving co-added magnitudes of 22.38 (u), 22.40 (v), 23.34 (g), 23.11 (r), 22.73 (i), and 21.88 (z) mag.

A limitation of this work is the use of only one year of ASMS data. Long-term trends in site conditions, which may span decades, are not captured. Future work will incorporate historical meteorological data from the past decade to investigate these longer-term variations.

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