

The Mini-SiTian Array: Optical Design Post-print

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Abstract

Time-domain astronomy is one of the most important areas. Large sky area, deep-field, and short timescale are the priority of time-domain observations. SiTian is an ambitious ground-based project processing all sky optical monitoring, aiming for a sky-survey timescale of less than 1 day. It is developed by the Chinese Academy of Sciences, an integrated network of dozens of 1 m class telescopes deployed worldwide. The Mini-SiTian Telescope Array is being carried out for demonstrations on optical design, group scheduling, and software pipeline developments, to overcome the high technical and financial difficulties of the SiTian project. One array contains three 300 mm F/3 telescopes, with an FOV of 5° over the 400–1000 nm wavelength range. The Mini-SiTian Telescope Array is now under commissioning in Xinglong Observatory, and a perfect platform for technical research and educational purposes.

Full Text

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The Mini-SiTian Array: Optical Design

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Abstract

Time-domain astronomy is one of the most important frontier areas, prioritizing large sky coverage, deep field, and short timescales for observations. SiTian is an ambitious ground-based project for all-sky optical monitoring, aiming for a survey timescale of less than one day. Developed by the Chinese Academy of Sciences, it consists of an integrated network of dozens of 1-meter-class telescopes deployed worldwide. The Mini-SiTian Telescope Array serves as a demonstration platform for the SiTian project, addressing its high technical and financial difficulties while enabling breakthroughs in optical design, group scheduling, and software pipeline development. Each array contains three 300 mm F/3 telescopes with a 5° field of view (FOV) over the 400–1000 nm wavelength range. Currently under commissioning at Xinglong Observatory, the Mini-SiTian Telescope Array provides an ideal platform for technical research and educational purposes.

Key words: telescopes – techniques: photometric – methods: observational

1. Introduction

Time-domain astronomy is one of the most important frontier areas, aiming to reveal changes in various astronomical objects throughout the universe and to discover new objects and phenomena through time-domain observations. Key scientific targets include gravitational wave electromagnetic counterparts, exoplanet detection, and other popular research directions in recent years. Influential large-scale time-domain survey projects such as the Panoramic Survey Telescope & Rapid Response System (Pan-STARRS, Kaiser et al. 2002), the Zwicky Transient Facility (ZTF, Bellm et al. 2019), and the Legacy Survey of Space and Time (LSST, Ivžić et al. 2019) are currently being carried out or planned for implementation. Other ground-based sky-survey telescopes in China, such as the 2.5 m Wide-Field Survey Telescope (WFST, Lou et al. 2016) and the Multi-Channel Photometric Survey Telescope (Mephisto, Yuan et al. 2020), have also been under commissioning in the past two years. However, these facilities all face limitations in effectively observing astronomical objects and phenomena with changing timescales within a one-day cadence. The cadence of LSST, ZTF, and WFST is about 2–4 days, while Mephisto’s cadence is about 2 weeks. A single telescope cannot simultaneously satisfy all requirements of large sky area, deep field, and high cadence for time-domain sky survey observations.

High-precision measurements enable precise extraction of useful information from photometric variability, especially in scenarios where the amplitude of variability is relatively weak (Li et al. 2022). Consequently, high-precision photometric survey telescopes are of great significance for research in time-domain astronomy, including studies of supernovae, active galactic nuclei (AGNs), gamma-ray bursts (GRBs), and tidal disruption events (TDEs) (Feng et al. 2021; Sun et al. 2024). The SiTian project is a next-generation, large-scale time-domain survey designed to build an array of 60 optical telescopes, primarily located at observatory sites in China. This array will enable single-exposure observations of the entire northern sky with a cadence of only 30 minutes, capturing true-color (gri) time-series data down to about 21 mag. The project is proposed and led by the National Astronomical Observatories, Chinese Academy of Sciences (NAOC; Liu et al. 2021).

The main science goals are the detection, identification, and monitoring of optical transients (such as gravitational wave event counterparts, fast radio bursts, and supernovae) on largely unknown timescales of less than one day. One SiTian node contains three prototype telescopes as an array (Chen et al. 2022), which present high technical difficulty and financial requirements during early development, making it relatively challenging to achieve key software technology breakthroughs such as telescope control and group scheduling in a short time.

As the pathfinder for the SiTian project, the Mini-SiTian project (Huang et al. 2025) utilizes an array of three 300 mm telescopes to simulate a single node of the full SiTian array. The Mini-SiTian has been conducting surveys since 2022 November. One Mini-SiTian Array is composed of three 300 mm F/3 telescopes with a field of view (FOV) of 5° , capable of observing in g, r, and i bands. The tracking accuracy is root mean square (RMS) ≤ 0.5 in 10-minute observations of stars and RMS ≤ 2.0 in observations of space targets. This article introduces the Mini-SiTian Telescope, with instrument design described in Section 2, instrument performances from laboratory tests and commissioning showcased in Section 3, and the project summarized in Section 4.

2. Instrument

A Mini-SiTian Telescope is specifically designed for sky-survey observations, featuring a large FOV and a fast focal ratio. The telescope uses a Cassegrain focus, which facilitates easier detector mounting. The telescope delivers good image quality across the full FOV, making it capable of astrophotography, astronomical sky surveys, and space debris observations.

2.1. Optical Design

The optical system of a Mini-SiTian Telescope builds upon heritage from the Chinese Small Telescope ARray (CSTAR, Liu & Yuan 2009). Evolved from the catadioptric optical system, it is a large-FOV optical design that corrects

the spherical aberration of the primary mirror at the entrance pupil to obtain a uniform star point spread function (PSF) distribution across the FOV. The telescope tube is compact with loose optomechanical tolerances. The main disadvantage is that it is difficult to install a stray light shield, leading to poor stray light control and thus requiring the addition of a front stray light shield. Key parameters of the telescope are listed in Table 1 .

The optical layout is illustrated in Figure 1 [Figure 1: see original paper]. The corrector lens belonging to group 1 serves as the incoming window block of the telescope, with reflective coatings applied on its last surface to shorten the telescope tube. The corrector belonging to group 2 enhances image quality at the marginal FOV. Three optical filters can be switched using a filter wheel. The focal plane size is Φ 80 mm, matching the 5° diameter FOV.

The optical spot diagram and diffraction encircled energy diagram are shown in Figures 2 [Figure 2: see original paper] and 3 [Figure 3: see original paper], respectively. The RMS radius is 8.728 μ m at the maximum FOV of 5° over the 400–1000 nm wavelength range. The diameter of 80% encircled energy (EE80) is less than 5.04 μ m (10.94 μ m), and the full width at half maximum (FWHM) is less than 2.89 μ m (6.29 μ m).

The telescope employs focusing mechanisms to compensate for defocus caused by transportation, temperature shifts, and optical path differences when switching waveband filters. Different waveband filters (g, r, and i) can be inserted into the optical path for multi-band observations.

Error budget analysis is essential in optical design to evaluate tolerances in manufacturing and mounting. Monte Carlo analysis is performed on different FOVs to analyze EE80 under various tolerances using ZEMAX software, with results shown in Figure 4 [Figure 4: see original paper]. The analysis indicates that at the central field with 90% probability, the EE80 diameter is approximately 7.16 μ m (3.31 μ m). Furthermore, the EE80 diameter of the Mini-SiTian under 90% probability is smaller than 8.21 μ m (3.79 μ m) for the maximum FOV, and under 99% probability is approximately 9.08 μ m (4.19 μ m) for the maximum FOV. These two values are extremely close, confirming that both the manufacturing process and alignment are feasible.

The primary and secondary mirrors feature enhanced aluminum coating with an average reflectance of 89.6% over 400–1000 nm. Anti-reflectance coatings are applied to the corrector lens with an average transmittance of 97.4% over 400–1000 nm. By calculating all working surfaces of the telescope optics, the overall efficiency of the telescope is about 68.5% across 400–1000 nm, with minimum and maximum values of 64% and 74%, respectively.

2.2. Stray Light Analysis

Stray light refers to light rays in an optical system that reach the detector or imaging surface through paths other than the intended imaging path, including

target light that reaches the detector via abnormal optical paths. Stray light degrades image contrast and modulation transfer function (MTF), resulting in reduced image quality, deteriorated clarity, and disordered energy distribution. Furthermore, stray light can generate bright spots on the image plane or even completely overwhelm the target signal with stray radiation noise. Therefore, suppressing stray light in the Mini-SiTian Telescope is essential.

The suppression level of stray light in optical-mechanical systems is generally evaluated using Point Source Transmittance (PST), defined as the ratio of irradiance reaching the detector surface after radiation from an off-axis point source at angle θ and wavelength λ passes through the system ($E_{\text{image}}(\theta, \lambda)$), to the irradiance of that source at the system's entrance aperture ($E_{\text{entrance}}(\theta, \lambda)$). Due to the telescope's compact structure and large FOV, it is difficult to place a large baffle inside to suppress stray light. Particularly when the incident angle of stray light is small, the telescope image is severely affected, leading to obvious ghost images. To more effectively suppress stray light, a long baffle must be installed in front of the telescope. Figure 5 (a) and (b) show the optical-mechanical models for stray light analysis without and with the front baffle, respectively.

Figure 6 (a) and (b) present the illuminance of stray light on the image plane at a 15° incident angle without and with the front baffle, respectively, where the stray light source irradiance is 1 W m^{-2} . Without a front baffle, stray light brightness on the image plane is high, with a bright ghost image appearing on the left side. Using the front baffle effectively suppresses both stray light brightness and ghost images on the image plane.

Figure 7 [Figure 7: see original paper] shows PST curves for both cases. Without the baffle, the stray light incident angle must exceed 30° for the system's PST to decrease to the order of 10^{-4} ; with the front baffle, this requirement is reduced to 15° .

2.3. Equatorial Mount

The equatorial mount is specially designed for sky-survey observations, as shown in Figure 8 [Figure 8: see original paper]. It uses Computerized Numerical Control (CNC) integrated processing and forming in manufacturing. To guarantee pointing and tracking accuracy, the mount employs an axial magnetic field torque motor and a high-precision industrial-grade 32-bit absolute encoder. The pointing accuracy is better than $10''$ after modeling, and star-tracking accuracy is better than $0.5''$ over 10 minutes. The equatorial mount can also be used for space target observations, with tracking accuracy better than $2''$.

The mount can be operated on either Windows or Linux platforms and features a SkyView graphical user interface (GUI). It supports ASCOM and RTS2 protocols, as well as third-party software such as SkyX. SDK and low-level commands are provided for further development purposes.

As shown in Figure 8 [Figure 8: see original paper], the equatorial mount can be quickly switched between alt-azimuth and equatorial configurations without any lifting equipment. The telescope mount has a maximum loading capacity of 200 kg and maximum power of 800 W with a 200–240 VAC power supply.

3.1. Testing Observations

Image quality, pointing accuracy, and tracking ability were tested in Nanjing, China, in 2021 July. With manufacturing errors incorporated into the optical design, the EE80 diameter of the optical system is about 5.1 and the FWHM is less than 3.4. The tested spot diagram and diffraction encircled energy diagram are shown in Figures 9 [Figure 9: see original paper] and 10 [Figure 10: see original paper], respectively.

To evaluate imaging performance, the telescope uses a ZWO ASI6200MM Pro CMOS camera mounted on its back. The camera sensor size is 36 mm \times 24 mm, corresponding to a FOV of $2.3^\circ \times 1.53^\circ$. The tested minimum FWHM is 2.35, as confirmed in Figure 11 [Figure 11: see original paper].

3.2. Pointing and Tracking Abilities

Pointing modeling was completed before testing observations. The maximum pointing error is 2.6 with an RMS value of 1.2, as shown in Figure 12 [Figure 12: see original paper]. This pointing error is much lower than the requirement (<10).

To test tracking ability, a star was observed without any guide stars. Figure 13 [Figure 13: see original paper] shows the tracking performance when observing a star over 10 minutes, with RA RMS of 0.175 and DEC RMS of 0.03. The tracking accuracy of both axes is lower than the design requirement (0.5). A satellite was also observed to test tracking accuracy. As shown in Figure 14 [Figure 14: see original paper], RA RMS is 1.297 and DEC RMS is 0.660, demonstrating the excellent tracking ability of the Mini-SiTian Telescope Array.

3.3. Commissioning

The Mini-SiTian Telescope Array was transported to the Xinglong Observatory of NAOC in 2021 August. Xinglong Observatory is located at coordinates 117°34'30", 40°23'39" with approximately 900 m average altitude. The mean and median seeing values at Xinglong Observatory are 1.9 and 1.7, respectively. Most of the time, the sky brightness is about 21.1 mag arcsec⁻² in V band at the zenith. The mounted Mini-SiTian Telescope Array at Xinglong Observatory is depicted in Figure 15 [Figure 15: see original paper].

4. Conclusions

The Mini-SiTian Telescope Array serves as a demonstration platform for the SiTian project, combining three telescopes in one node to enable multi-color observations. The 300 mm F/3 telescope has a 5° FOV, specially designed for sky survey imaging. Commissioning at Xinglong Observatory and development of the software pipeline and control strategy have been successfully demonstrated and verified. The Mini-SiTian Telescope Array has proven to be an excellent platform for technical research and educational purposes.

Acknowledgments

The SiTian project is a next-generation, large-scale time-domain survey designed to build an array of over 60 optical telescopes, primarily located at observatory sites in China. This array will enable single-exposure observations of the entire northern hemisphere night sky with a cadence of only 30 minutes, capturing true-color (gri) time-series data down to about 21 mag. The project is proposed and led by the National Astronomical Observatories, Chinese Academy of Sciences (NAOC). As the pathfinder for the SiTian project, the Mini-SiTian project utilizes an array of three 30 cm telescopes to simulate a single node of the full SiTian array. The Mini-SiTian began its survey in 2022 November. Both SiTian and Mini-SiTian have received support from the Strategic Pioneer Program of the Astronomy Large-Scale Scientific Facility, Chinese Academy of Sciences, and the Science and Education Integration Funding of the University of Chinese Academy of Sciences. This work is supported by the National Key Basic R&D Program of China via 2023YFA1608304.

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