

Observation and research on small solar system bodies based on the Antarctic Tianmu Staring Observation Project

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Key Points:

- The Antarctic Tianmu Staring Observation Project (ATSOP) features a large field of view, short time scale, and long-term continuous observation.
- We have assessed the types of small solar system bodies detectable by the ATSOP telescopes, as well as the associated scientific research opportunities.
- The observational data collected by the Antarctic Tianmu prototype demonstrates the effectiveness of the ATSOP system in observing small solar system bodies.

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Abstract: The Antarctic Tianmu Staring Observation Project (ATSOP) entails the deployment of 30 small-aperture, wide-field optical telescopes in the Antarctic region. The system will perform long-term continuous observation campaigns over a period of 100 d (24 h per day) per year, as well as short-time-scale sampling at intervals of 5 min, across a sky area of approximately 1200 square degrees centered near the south celestial pole. We have assessed the types of small solar system bodies detectable by the ATSOP telescopes, as well as the associated scientific research opportunities. Our analysis indicates that the ATSOP is capable of detecting near-Earth objects (NEOs) with all orbital inclinations, as well as high-inclination small bodies located beyond the main asteroid belt. Potential research topics include the discovery and identification of small bodies, orbit determination, physical characterization, investigation into the activity characteristics and evolutionary patterns of active small bodies, and studies on their dynamical evolution. Observations of NEOs can also contribute to planetary defense efforts. On the basis of pilot observational data collected by the Antarctic Tianmu prototype (AT-Proto) between February 20 and October 26, 2023, a total of 478 asteroids and 9 comets were successfully identified, demonstrating the effectiveness of the ATSOP system in observing small solar system bodies. Looking ahead, with anticipated performance enhancements in the second-generation AT-Proto, the limiting magnitude will increase from 16 to 18, thereby enabling the detection of an even greater number of small solar system bodies.

Keywords: Antarctic Tianmu Staring Observation Project; small solar system bodies; observational techniques survey

1. Introduction

The Antarctic Taishan station (73°51'S, 76°58'E) experiences approximately 100 d of polar night annually, characterized by the absence of light pollution and high atmospheric transparency. These conditions enable 24-h continuous astronomical observations, offering an optimal environment for detecting transient celestial events such as gamma-ray bursts, gravitational wave counterparts, supernova explosions, and cometary outbursts.

The Antarctic Tianmu Staring Observation Project (ATSOP; Zhou D et al., 2025) is an innovative astronomical observation project led by China. It aims to leverage the unique geographical and climatic advantages of Antarctica to establish the world's first wide-field time-domain survey array featuring a minute-level high sampling rate and continuous 24-h observations. This initiative will address the current lack of observations on short-term transient celestial phenomena and advance frontier research in the field of time-domain astronomy. The ATSOP will deploy 30 small-aperture, wide-angle optical telescopes that will cover a sky area of 1200 square degrees (with the declination ranging from -75° to -65°), which includes the Large and Small Magellanic Clouds. The system will conduct dual-band coordinated observations: 15 tele-

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scopes operating in the B-band (450–650 nm) and another 15 in the R-band (650–850 nm), with a 20% overlap in the field of view (FoV) between each pair of telescopes. It will enable minute-level sampling, monitoring celestial objects brighter than magnitude 18.

Conventional telescopes face significant challenges in maintaining stable operation under the extreme environmental conditions of Antarctica, such as temperatures as low as -40°C , wind speeds exceeding 38 m/s, unattended operation, and limited power availability. The first phase of the project successfully developed the Antarctic Tianmu prototype (AT-Proto) telescope with a 180-mm aperture (Niu HB et al., 2025), incorporating drift-scanning charge-coupled device (CCD) technology, an intelligent temperature control system, and low-bandwidth remote control capabilities (Zhu J et al., 2024), effectively addressing the difficulties associated with polar astronomical observations. By synchronizing charge transfer with celestial motion, the system eliminates the need for mechanical tracking devices, thereby significantly improving operational reliability. The CCD camera installed supports adjustable scanning speeds ranging from 1 to 1000 ms per line, enabling adaptation to targets at various declinations. The telescope, CCD sensor, and control system are integrated within a thermally regulated dome maintained at 8°C . Furthermore, waste heat generated by the equipment is utilized for internal heating, effectively mitigating frost formation and preventing low-temperature malfunctions. On-site image preprocessing—including background and dark current correction—is conducted locally, with only the processed result data being transmitted, thus accommodating the limitations of the satellite-based network bandwidth. In October 2022, the AT-Proto telescope was deployed at Zhongshan Station as part of the 39th Chinese Antarctic Research Expedition. From 2023 to 2025, it operated continuously for more than 2 years without failure under extreme environmental conditions (temperatures as low as -37.3°C and wind speeds reaching 38.6 m/s). The exposure time for a single image of the AT-Proto is 30 s, the readout time is 12 s, and the time interval between two consecutive images is 42 s. If observations are conducted continuously for 24 h every day, the estimated number of observation images that can be obtained each day is 2057. During this period, it captured more than 320,000 images (approximately 6.15 TB of data), achieving an average full width at half maximum (FWHM) of 2 pixels, corresponding to an angular resolution of $11.25''$. These results validated the stability and efficiency of drift-scanning technology in polar environments. In 2025, the AT-Proto telescope was reoriented toward the south, serving as a foundation for future array deployment.

The ATSOP, which is based on an innovative technology integrating the polar environment with a drift-scanning telescope array and dual-band staring observation, has overcome the global challenge of regular astronomical observations at extreme conditions. The successful operation of its prototype signifies that China has achieved technological independence in the field of Antarctic astronomy. Upon completion in the future, the project is expected to drive groundbreaking discoveries in time-domain astronomy, particularly in areas such as short-duration transient celestial objects, extreme high-energy transient sources, microgravitational

lensing, and small bodies within the solar system, thereby offering new insights into understanding the dynamic universe.

2. The Observable Small Solar System Bodies Based on the ATSOP

Small bodies in the solar system, such as asteroids and comets, are remnants from the formation period of the solar system and retain original information from that era. Some of these bodies are rich in water ice and organic materials. Therefore, studying small bodies contributes to understanding the origin and evolution of the solar system and potentially the origin of life. Furthermore, the orbits of these bodies can be significantly altered by gravitational perturbations from major planets or nongravitational effects, posing a potential impact threat to Earth. Thus, research on small bodies is also crucial for planetary defense.

Considering the unique geographical location and sky coverage of the ATSOP, we have assessed the observability of small solar system bodies for the future telescope array. Figure 1 shows a schematic diagram of our approach for the assessment. The FoV of Tianmu points toward high declinations. Objects in the FoV will have different orbital inclinations, depending on their heliocentric distance. For objects with a heliocentric distance of approximately 1 au (astronomical unit), even with a low orbital inclination, they could still pass the FoV of Tianmu. For objects with a larger heliocentric distance, they will need to be at a higher orbital inclination to pass through Tianmu's FoV. Using this geometric model, we calculated the range of orbital inclinations for objects that are possible to pass through the FoV of Tianmu with respect to their semimajor axes (Figure 2). The actual case will be much more complicated in three dimensions, and a comprehensive, more accurate assessment will require numerical simulations with the orbit model and physical model of asteroid populations. But this simplified model suggests that the observability of small bodies by the ATSOP depends on their semimajor axes. Specifically, all near-Earth objects (NEOs), regardless of their orbital inclinations, main-belt asteroids with orbital inclinations exceeding 20° , Jupiter Trojan asteroids with orbital inclinations greater than 35° , and Kuiper Belt objects with orbital inclinations above 40° , could possibly be at a high declination as seen from the Earth and thereby observable by ATSOP (Figure 2). Because the limiting magnitude of the ATSOP telescope is 18th magnitude, we can obtain the absolute magnitudes corresponding to the apparent magnitudes at different heliocentric distances. Assuming that the phase angle is 0 when the asteroid is at opposition and that the asteroid's albedo is 0.1, we can further determine the diameters of asteroids observable at different heliocentric distances. For instance, at a heliocentric distance of 3 au, asteroids with diameters of 6.3 km or larger can be observed, and at 5 au, asteroids with diameters of 21.1 km or larger can be observed.

The detection capability of the AT-Proto telescope is such that when exposed to the G-band for 30 s, the corresponding limiting magnitude is 14.8 magnitude and the signal-to-noise ratio is 5 (Zhou D et al., 2025). By superimposing images, the detection capability of AT-Proto can be further enhanced. If 10 images are superimposed, the equivalent exposure time is 5 min, and the

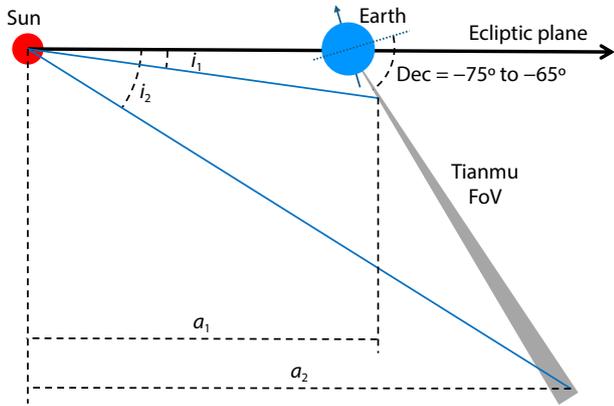


Figure 1. Schematic diagram showing the observability of small bodies with various heliocentric distances and orbital inclinations. The solar system is viewed from the side within the ecliptic plane and the ecliptic north points up. The arrow marks the direction of Earth’s north pole, and the dotted line mark the direction of Earth’s equatorial plane. The thin blue lines represent two example orbital planes with different semimajor axes, a_1 and a_2 , and orbital inclinations, i_1 and i_2 . The gray shaded sector shows an example FoV of Tianmu near summer solstice.

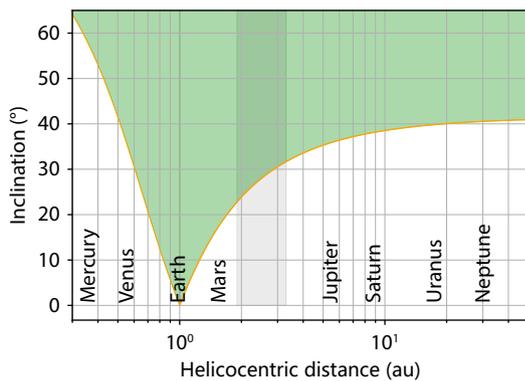


Figure 2. Relationship between the orbital inclination and heliocentric distance of observable small solar system bodies based on the ATSOP. The green shaded area marks the region that could be visible by Tianmu. The locations of eight planets are marked by their names, and the gray shaded region between 1.8 and 3.3 au is the location of the main asteroid belt.

limiting magnitude can be increased by approximately 1.25 magnitude. The peak FWHM corresponding to the 30-s exposure is 1.6 pixels (18 arc seconds). Among different types of small bodies, NEOs have the highest apparent motion speed, with a typical value of 20 km/s. A 30-s exposure corresponds to a movement distance of 600 km, and the geocentric distance corresponding to a peak FWHM of 18 arc seconds is 6.875 million km. That is to say, the influence of a 30-s exposure by Antarctic Tianmu on small bodies beyond 6.875 million km from the geocenter is equivalent.

3. Research Work to Be Carried Out Using the ATSOP

The current frontier scientific questions in the field of small solar system body research include the spatial distribution of these

bodies, the evaluation of potential impact risks, their activity characteristics, as well as their origin and evolutionary history. The ATSOP, which benefits from its unique geographical location and features, such as wide sky coverage, long-duration continuous observation capability, and high temporal resolution, is particularly well-suited for conducting observational studies on small solar system bodies.

3.1 Identification and Orbit Determination of Small Bodies (Large Sky Area)

The current number of asteroids discovered exceeds 1.45 million, with more than 4600 comets identified (<http://www.minorplanet-center.net/mpc/summary>). DeMeo and Carry (2014) and Weryk et al. (2016) illustrated the distribution of orbital inclinations of small celestial bodies located inside and outside Jupiter’s orbit, respectively. The results indicate that the majority of small bodies exhibit relatively low orbital inclinations, clustering closely around the ecliptic plane. Statistical analysis indicates that high-inclination small bodies—those with orbital inclinations greater than 30° and small bodies in retrograde orbits—account for less than 1% of all known small bodies. However, this proportion varies significantly across different groups of small bodies. Specifically, approximately 7% of NEOs, 25% of centaurs, 10% of trans-Neptunian objects, 75% of long-period comets, and 100% of interstellar objects exhibit high orbital inclinations. It should be noted that because of observational biases affecting the detection of high-inclination objects, the proportions presented here likely represent the lower limits. These biases arise from two primary factors: First, most observational instruments are designed to focus on regions near the ecliptic plane to enhance detection efficiency; second, the majority of ground-based observatories are situated in mid- to low-latitude regions, resulting in limited coverage of the polar sky areas. Consequently, numerous high-inclination small bodies may remain undetected. The ATSOP telescope is anticipated to contribute significantly to the discovery of new high-inclination small bodies, thereby enhancing our understanding and refining the spatial distribution models of such objects within the solar system.

Compared with NEOs with low orbital inclinations, those exhibiting high orbital inclinations have the potential to approach Earth at higher latitudes, a scenario that is often inadequately monitored by conventional detection systems. Although such high-inclination NEOs constitute a small proportion (7%) of the overall NEO population, they tend to impact Earth at higher relative velocities and offer shorter warning times. Consequently, it is imperative to improve observational capacities in high-latitude regions, such as the Arctic and Antarctic, and to advance rapid-response interception technologies.

3.2 Physical Characteristics of Small Solar System Bodies (Short Time Scale)

Although the number of small bodies identified has surpassed 1.4 million, research on their physical properties, spatial distribution, origins, and evolutionary patterns remains limited because of insufficient observational data. By analyzing the light curve of a small body, its physical characteristics—such as size, shape, and

rotation period—can be constrained. In addition, since ASTOP conducts simultaneous observations in the B-band and R-band, it can obtain color information on small bodies. This is helpful for classifying small bodies and further contributes to the study of their origins. The physical characterization of asteroids is crucial in multiple related areas, such as planetary science, space exploration, and planetary defense. It is key to understanding the origin, evolution, internal structure, physical properties, and dynamic behavior of asteroids.

The main methods for obtaining the shape of small bodies through ground-based observations include light curve inversion, radar imaging, stellar occultation, optical interferometry and adaptive optics, and thermal modeling. Compared with other methods, light curve inversion has the advantages of low cost, large samples, and long observable durations. The rotational period of an asteroid is indicative of its internal structure, orbital evolution, space weathering, and the formation and evolution of binary asteroid systems, among other properties.

Among all the asteroids discovered, accurately determined rotational periods are available for only 34,967 (Warner, 2021). Warner et al. (2009) illustrated the correlation between asteroid rotational periods and their sizes. They found that most asteroids exhibit rotational periods exceeding 2.2 h; however, many smaller asteroids have rotational periods shorter than 2.2 h and are classified as fast-rotating asteroids. For instance, (particularly) the rotational period of 2016 HO₃, the target of the Tianwen-2 mission, is merely 28 min (MinorPlanet, 2024). Determining the rotation periods of such fast-rotating asteroids requires high-cadence sampling of the light curve. For NEOs, acquiring these physical parameters is crucial for evaluating potential impact hazards to Earth.

3.3 The Activity of Small Bodies (Short Time Scale, Long Periods)

The activity of small bodies refers to phenomena involving mass loss, such as the release of gas and dust. The mechanisms underlying this activity are categorized into sublimation-driven and nonsublimation-driven processes. Small bodies exhibiting activity driven by the sublimation of water ice or other volatiles are classified as comets, whereas those displaying activity resulting from nonsublimation mechanisms—such as impacts, rotational instability, thermal fracturing, radiation pressure, and electrostatic forces—are referred to as active asteroids (Jewitt et al., 2015). Monitoring variations in their activity enables the characterization of their dynamic features and underlying mechanisms.

Under normal circumstances, the brightness of a comet gradually increases as its distance from the Sun decreases. However, certain comets may exhibit sudden and significant increases in brightness over a short period of time, an event commonly referred to as a comet outburst (Hughes, 1990). Investigating the complete outburst process necessitates short-term observational campaigns. Furthermore, the underlying mechanism driving comet outbursts is complex and the timing of such events is unpredictable (Xu RQ et al., 2022). Therefore, long-term, high-cadence monitoring is essential to accumulate sufficient observational data on comet outburst events. The activity mechanisms of

long-period comets and interstellar comets are also intricate and tend to vary as these comets travel from the outer solar system to the inner solar system (Meech et al., 2009). These variations can be observed in their long-term light curves (Ferrín, 2006, 2010), which display different slopes depending on the sublimation characteristics of various ice components. To better understand the transition between different activity mechanisms, continuous long-term monitoring is required.

3.4 The Dynamical Evolution of Small Bodies (Over Large Sky Areas and Long Periods)

There is ongoing debate regarding the origin of high-inclination small bodies (Nagasawa et al., 2001; Gladman et al., 2009; Batygin and Brown, 2016). These objects may originate from distant regions of the solar system, such as the Oort Cloud and the scattered disk, or they may have been gravitationally perturbed by planets into atypical orbits. Their orbital characteristics can provide insights into early dynamical events in the solar system, including giant planet migration and stellar flybys. By examining their distribution and orbital parameters, researchers can reconstruct the initial structure of the solar system and trace its evolutionary trajectory. High-inclination orbits are generally not easily produced through classical planetary gravitational interactions alone. Investigating their dynamical evolution—such as resonant effects, long-term perturbations, and chaotic behavior—can contribute to the refinement of models of celestial mechanics. Furthermore, assessing the long-term stability of high-inclination orbits helps validate theoretical predictions. Studies indicate that two primary mechanisms account for the formation of high-inclination small bodies: one driven by planetary migration and gravitational scattering by giant planets, and the other attributed to the Zeipel–Lidov–Kozai resonance (Zhao SJ et al., 2024).

Utilization of the ATSOP telescopes can improve the accuracy of orbit determination and expand the database for small bodies with high orbital inclination. This improvement facilitates in-depth studies on the origin and evolution of these small bodies, thereby contributing to the refinement of solar system evolution models.

4. Small Solar System Bodies in the Prototype Telescope Data

The FoV of the AT-Proto spans 9.5 square degrees. Each region of the sky can be observed for approximately 40 min per day. The limiting magnitude for a 30-s exposure in the G-band is 14.8 at a signal-to-noise ratio of ≈ 5 , and for a 110-s exposure, it reaches 15.3 at a signal-to-noise ratio of ≈ 5 (Zhou D et al., 2025). We analyzed the observational data collected by the AT-Proto from February 20, 2023, to October 26, 2023. During this period, the instrument was directed toward the north, with the center of its FoV located at a declination of -25° . Astrometric calibration was applied to the observed images. Using the REBOUND software (<https://rebound.readthedocs.io/en/latest/>), we calculated the positions of small bodies at the time of observation to identify solar system objects present in the AT-Proto data based on their observational parameters (FoV, limiting magnitude). The simulation took into account the influence of the eight major planets

and the Moon. In total, 478 asteroids (main belt: 455; NEOs: 11; other: 12) and 9 comets were detected. Figure 3 shows the asteroid 369 Aeria ($m_v = 12.3$) and the comet C/2020 V2 ($m_v = 12.0$) observed by the AT-Proto, and Figure 4 shows the distribution of orbital inclinations of asteroids observed by the AT-Proto. As the AT-Proto was pointing north in 2023 and its FoV was close to the ecliptic plane, a relatively large proportion of the small bodies observed had orbital inclinations of less than 20° . To facilitate future access and utilization of these data, we arranged the obtained database of small bodies identified by two sorting procedures: The first procedure was by the name of each small body to enable image access based on objects' names, and the other was by image identifier, listing asteroids and comets found within the corresponding FoV. At present, we have established a pipeline for processing AT-Proto telescope data and have completed Level-1 preprocessing of the 2023 observational data, which specifically includes two core product types: reduced FITS (Flexible Image Transport System) images and photometric catalogs (Niu HB et al., 2025). In the next step, our team will further optimize the data processing pipeline. These refined data products, along with the complete processing procedure specifications, will be published in an upcoming academic paper.

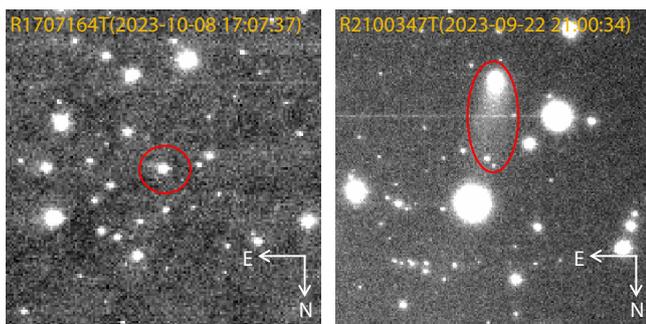


Figure 3. Examples of images obtained by AT-Proto. (Left panel) Asteroid 369 Aeria (cut FoV 26.25×26.25 arc minutes); (right panel) comet C/2020 V2 (cut FoV 37.5×37.5 arc minutes). In both images, the exposure time is 30 s; down is north and left is east.

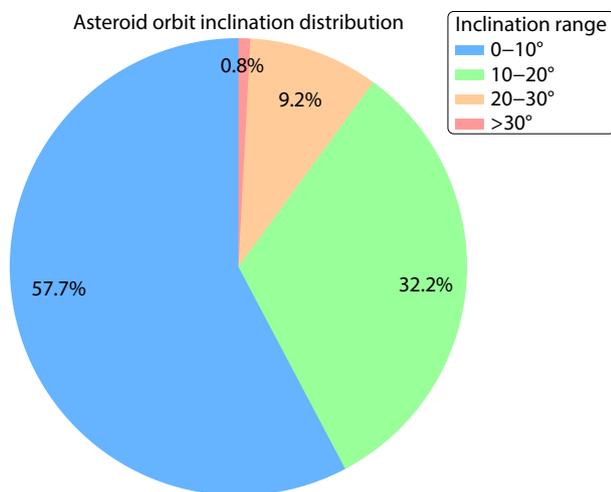


Figure 4. The distribution of orbital inclinations of asteroids observed by the AT-Proto from February 20, 2023, to October 26, 2023.

Considering that the limiting magnitude of the ATSOP is expected at 18th magnitude, this study examines the impact of varying limiting magnitudes on the theoretical number of observable small bodies. By analyzing image R1707164T captured by the AT-Proto on October 8, 2023, at 17:07:37, we found that when the limiting magnitude was 16th magnitude, the number of asteroids detected in the FoV was 3; when it was 17th magnitude, the number increased to 8; and at 18th magnitude, the count reached 34. These results indicate that the limiting magnitude significantly influences the number of detectable small bodies.

5. Summary and Prospects

The current surveys of small bodies are influenced by the observational bias toward the ecliptic plane and the geographical latitude of the telescope, leading to inadequate coverage of the polar regions. The ATSOP, with its unique geographical location and capabilities—including a large FoV, long-term observations, and short time interval sampling—is particularly well-suited for studying NEOs and small bodies with high orbital inclinations. These studies contribute to the discovery of new small bodies, orbit determination, analysis of physical properties, investigation of activity characteristics, and evolutionary patterns, and they provide valuable support for planetary defense initiatives.

The AT-Proto has operated continuously and reliably from February 20, 2023, to the present, demonstrating the stability and effectiveness of drift-scanning techniques utilized in Antarctica. Analysis of observational data obtained from February 20, 2023, to October 26, 2023, has led to the detection of 478 asteroids and 9 comets, proving the feasibility of using the ATSOP telescope for small solar system body observations.

Currently, the limiting magnitude of the AT-Proto is approximately 15th magnitude, which significantly limits the number of observable small bodies. Future improvements will focus on increasing the aperture of the telescope, with the goal of increasing the limiting magnitude to approximately 18th magnitude. This advance will significantly expand the capacity of the telescope to observe a larger number of small bodies and increase scientific results in the applicable studies.

Declaration of Competing Interests

The authors declare that they have no conflicts of interest.

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