

Postprint Study on Near-Earth Object Survey Planning Model Based on the Multi-Application Survey Telescope Array

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Abstract

There is a consensus that Near-Earth Asteroids (NEAs) pose a threat to global security, making their detection of great significance. The Multi-Application Survey Telescope Array (MASTA), characterized by its wide field of view, multiple telescopes, and relatively large aperture, is well-suited for asteroid detection, and its deployment can significantly enhance China's near-Earth asteroid detection capabilities. To leverage MASTA's advantages in near-Earth asteroid detection, we propose a near-Earth object survey strategy and develop a survey planning model based on integer linear programming methods. To evaluate the performance of this model and MASTA's near-Earth asteroid detection effectiveness under this framework, we establish an observation target set through sample expansion and conduct a one-year near-Earth object survey simulation. Simulation results demonstrate that the survey planning model adequately meets the requirements of MASTA's near-Earth object survey; it can optimize observation resource allocation for near-Earth object survey programs while accommodating MASTA's other scientific objectives; and the number of near-Earth asteroids detected by MASTA within one year can reach 1.29% of its estimated sample.

Full Text

Preamble

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A Near-Earth Object Survey Planning Model for Multi-Application Survey Telescope Array

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Abstract

Near-Earth asteroids (NEAs) are widely recognized as a threat to global security, making their detection of great significance. The Multi-Application Survey Telescope Array (MASTA), characterized by its large field of view, multiple telescopes, and relatively large aperture, is well-suited for asteroid detection and can significantly enhance China's NEA detection capabilities. To leverage MASTA's advantages in NEA detection, this paper proposes a near-Earth object survey strategy and develops a survey planning model based on integer linear programming. To evaluate the model's performance and MASTA's NEA detection efficiency under this model, we constructed an observation target set by expanding the sample size and conducted a one-year near-Earth object survey simulation. The simulation results demonstrate that the survey planning model effectively meets MASTA's near-Earth object survey requirements, optimizes observation resource allocation for NEA surveys, and accommodates MASTA's other scientific objectives. MASTA can detect NEAs reaching 1.29% of its estimated sample size within one year.

Key words: telescopes, near-Earth asteroids, surveys, optimization algorithms, methods: analytical

Near-Earth objects refer to solar system small bodies with perihelion distance $q \leq 1.3$ au, with asteroids being the primary component. NEAs whose orbits may intersect Earth's pose potential threats to global security, making their detection critically important. Wide-field telescope surveys are the main method for detecting NEAs. Among global survey programs, LINEAR (Lincoln Near Earth Asteroid Research) [?], CSS (Catalina Sky Survey) [?], and Pan-STARRS (Panoramic Survey Telescope And Rapid Response System) [?] have contributed most to NEA detection, having discovered 2,671, 15,474, and 10,547 NEAs respectively. China's NEA search efforts are also developing, with the China Near-Earth Object Survey Telescope (CNEOST), Wide Field Survey Telescope (WFST), and BATC (Beijing-Arizona-Taiwan-Connecticut) telescope having discovered 42, 7, and 5 NEAs respectively. These numbers indicate that China's NEA detection capability remains insufficient. MASTA (Multi-Application Survey Telescope Array), with its large field of view, multiple telescopes, and strong faint-object detection capability, is well-matched to asteroid detection needs and is expected to significantly improve China's NEA detection capacity.

To fully realize MASTA's potential for NEA detection, appropriate near-Earth

object survey strategies and planning methods are required. A survey strategy is designed to improve survey efficiency, specifically determining the sky coverage, revisit frequency, and exposure depth. For targeted searches like asteroid detection, two key factors must be considered: first, selecting sky regions that offer observational advantages for asteroids; second, choosing appropriate exposure times since survey depth and area vary inversely with exposure time [?]. Major international asteroid survey programs employ different strategies: LINEAR searches the entire visible sky once per month, with some regions observed multiple times monthly, taking five exposures per field per night spaced 30 minutes apart, with exposure times of 5–30 seconds and a limiting magnitude of 19.2 [?]; CSS uses two telescopes to search 1,000 deg² and 4,000 deg² of visible sky nightly, taking four 30-second exposures per field, reaching limiting magnitudes of 21.5 and 19.5 respectively [?]; Pan-STARRS' s 3π survey covers the entire visible sky, visiting each of the g, r, i, z, y bands four times annually, with two exposures per field per night of 30–60 seconds, reaching a limiting magnitude of 22 [?].

Survey planning implements survey strategies by assigning observation tasks to different telescopes at appropriate times and conditions to improve efficiency. Survey planning typically uses dynamic scheduling or advance planning methods. Dynamic scheduling responds to changing conditions in real-time to determine the next observation task, primarily including greedy algorithms and machine learning algorithms. The Liverpool Telescope' s scheduling system uses a greedy algorithm [?], while HST (Hubble Space Telescope) [?] and LSST (Large Synoptic Survey Telescope) [?] employ artificial neural networks and reinforcement learning respectively. Advance planning uses optimization algorithms to generate optimal observation lists for a period in advance, such as integer linear programming methods. LCOGT (Las Cumbres Observatory Global Telescope Network) [?] and ZTF (The Zwicky Transient Facility) [?] both use integer linear programming methods, with ZTF' s planning model being a new approach inspired by LCOGT' s model. ZTF' s model can incorporate prior information about observing conditions to seek optimal observation lists, achieving goals such as optimizing exposure sequences and improving observation quality. This model provides insights for MASTA' s survey planning model design but cannot fully meet MASTA' s needs because MASTA is a multi-telescope, multi-scientific-objective facility capable of more observation modes than ZTF. Specifically: (1) MASTA can execute multiple tasks or strategies simultaneously; (2) the number of telescopes assigned to different scientific objectives can be flexibly combined. Therefore, to fully leverage these characteristics while assuming limited observation time and resources for NEA surveys, MASTA' s NEA survey planning model must follow additional principles: (1) allocate more telescopes during periods with better observing conditions based on temporal variations; (2) optimize the total number of telescopes and total observation time used for NEA surveys to conserve resources.

Based on these principles, this paper proposes an NEA survey strategy and planning model for MASTA, evaluates the model' s performance through simu-

lation, and quantifies MASTA' s NEA detection efficiency under this model by expanding the NEA sample to create an observation target set.

2 MASTA Overview

MASTA consists of 20 telescopes at each of two sites: Lenghu in Qinghai (38.58° N, 93.88° E, 3800 m altitude) and Dayao in Yunnan (25.68° N, 101.05° E, 2500 m altitude). Each telescope is a prime-focus instrument with main parameters listed in Table 1 . This paper simulates based on MASTA' s Lenghu site, whose parameters are shown in Table 2 .

3 Survey Strategy and Planning Model

3.1 Advantageous Sky Regions for Asteroid Observation

Advantageous sky regions for asteroid observation are areas where asteroids are most easily discovered. To identify these regions, we must understand asteroid spatial distribution, motion patterns, and apparent brightness. Key findings from Stokes et al. [?] and Zhao Haibin [?] include:

First, observing near opposition is the most effective method for asteroid detection. As the heliocentric longitude difference from opposition ($\Delta\lambda = \lambda - \lambda_0$, where λ is the asteroid' s heliocentric longitude and λ_0 is the opposition' s heliocentric longitude) increases, the apparent motion speed difference between NEAs and main-belt asteroids decreases, making them harder to distinguish, while Earth' s velocity superposition advantage also diminishes.

Second, asteroids reach maximum brightness near opposition and the ecliptic plane, making the ecliptic region near opposition the best opportunity for detection.

Third, when the detection system is sufficiently powerful, the apparent number density of NEAs is highest at opposition distances of approximately $\pm 120^\circ$ ($\Delta \beta \pm 120^\circ$), yielding the highest discovery probability.

These findings lead to the following basic principles for asteroid observation:

1. Sky regions within 30° of opposition ($|\Delta\lambda| < 15^\circ$) and 20° of the ecliptic ($|\beta| < 10^\circ$) are optimal for NEA observation and require priority coverage, designated as Region A.
2. Two regions east ($\Delta\lambda - 120^\circ$) and west ($\Delta\lambda + 120^\circ$) of the Sun near the ecliptic are NEA-dense areas requiring priority observation, designated as Regions B and C respectively.
3. The local sky region with altitude $> 20^\circ$ based on site location and observation time should be searched when observation resources are sufficient.

Figure 1 [Figure 1: see original paper] illustrates these sky region definitions. The minimum sky division unit uses rectangular fields of 3.5° in right ascension

and 3.5° in declination, matching MASTA' s telescope field of view.

Considering MASTA' s multi-scientific-objective nature, we aim to complete observations of Regions A, B, and C within one hour while also conducting local sky surveys. This yields the following basic MASTA NEA survey strategy:

1. At astronomical twilight end, visit Region B three times within 60 minutes with 10-20 minute intervals between visits, and visit the local sky region once.
2. Around midnight, visit Region A three times within 60 minutes with 10-20 minute intervals between visits, and visit the local sky region once.
3. At astronomical dawn beginning, visit Region C three times within 60 minutes with 10-20 minute intervals between visits, and visit the local sky region once.

This strategy can accommodate other scientific objectives, such as supernova searches, enabling integration with NEA surveys.

3.2 Survey Rate and Exposure Time

Survey depth and area vary inversely with exposure time, requiring optimal exposure time selection to maximize survey efficiency. This paper introduces the Figure of Merit (FOM) metric to optimize exposure time, which combines survey depth and area:

$$\text{FOM} = \frac{R_{S/N}^2 \Omega_{\text{fov}}}{t_{\text{exp}} + t_{\text{OH}}} \cdot 10^{0.8(m_{\text{lim}} - m)} \cdot \frac{t_{\text{exp}}}{t_{\text{exp}} + t_{\text{OH}}} \cdot 10^{0.8m_{\text{lim}}}$$

where $R_{S/N}$ is the signal-to-noise ratio, Ω_{fov} is the telescope field of view, t_{exp} is exposure time, t_{OH} is observation overhead time, m is apparent magnitude, and m_{lim} is limiting magnitude. Equation (1) combines Ω_{fov} (related to survey area) and limiting magnitude m_{lim} (characterizing exposure depth), creating an exposure-time-dependent survey rate metric. Since limiting magnitude depends on filter, sky region, airmass, and sky background brightness, FOM also incorporates many image quality factors and can characterize observation quality for specific sky regions.

Using the telescope and site parameters from Tables 1 and 2, we calculated MASTA' s theoretical limiting magnitude and survey rate FOM, shown in Figure 2 [Figure 2: see original paper]. The two subplots show theoretical limiting magnitude versus exposure time t_{exp} and FOM' s dependence on overhead time t_{OH} and exposure time t_{exp} . Longer overhead time t_{OH} yields smaller FOM, while FOM increases monotonically with exposure time t_{exp} . Testing shows MASTA' s minimum telescope slew time is approximately 5 seconds. With 5-second overhead, the 40-60 second range shows slowing FOM growth, making 40-60 seconds appropriate for MASTA. Previous NEA surveys with 20th-magnitude detection

capability have achieved good results [?]. As shown in Figure 2, under Lenghu's excellent conditions, 40-second exposures reach a theoretical limiting magnitude of 21.3, making 40 seconds a suitable choice, with adjustments possible for weather and other time-varying factors.

3.3 Survey Planning Model

We divide the three observation periods of 20 telescopes into time blocks of length t_{block} , with all time blocks forming set T . The set of all observation tasks is I , with tasks for Regions A, B, and C forming subset I_1 , and local sky region tasks forming subset I_2 . The set of all telescopes is J . Both t_{block} and the total number of telescopes $\text{card}(J)$ are variable parameters, optimizing them achieves optimization of total observation time and telescope count. To prioritize advantageous sky regions, the model pre-assigns priorities to different region types. For any observation task $i \in I$, we can determine its priority P_i , required exposures k_i , and available time block set S_i .

The integer linear programming decision variable is defined as: $x_{ijt} = 1$ if task $i \in I$ is executed on telescope $j \in J$ during time block $t \in T$, otherwise $x_{ijt} = 0$.

To incorporate image quality preferences, we use the FOM metric to calculate weight V_{it} for any observation task $i \in I$ executed during time block $t \in T$ using equation (1). The objective function maximizes the weighted sum of task priorities and survey rates across all telescopes and observation periods:

$$\max \sum_{i \in I} \sum_{j \in J} \sum_{t \in S_i} (P_i + V_{it}) x_{ijt}$$

The model includes the following constraints:

1. Any advantageous region observation task can be executed at most once per available time block:

$$x_{ijt} \leq 1 \quad \forall i \in I_1, \forall t \in S_i$$

2. Any advantageous region observation task must be executed k_i times across all available time blocks:

$$\sum_{j \in J} \sum_{t \in S_i} x_{ijt} = k_i \quad \forall i \in I_1$$

3. Any local sky region observation task can be executed at most once across all time blocks:

$$\sum_{j \in J} \sum_{t \in S_i} x_{ijt} \leq 1 \quad \forall i \in I_2$$

4. The total task time assigned to each telescope per time block cannot exceed t_{block} :

$$\sum_{i \in I} (t_{\text{exp},i} + t_{\text{OH},i}) x_{ijt} \leq t_{\text{block}} \quad \forall t \in T, \forall j \in J$$

where $t_{\text{exp},i}$ and $t_{\text{OH},i}$ are exposure and overhead times for task $i \in I$.

The current model only assigns exposures to time blocks for each telescope without sequencing exposures within blocks, so all overhead times use the baseline value of 5 seconds. Sequencing exposures within a time block is essentially a Traveling Salesman Problem (TSP) [?], whose optimal solution yields the exposure sequence with minimum total slew distance.

TSP can also be solved using integer linear programming. To reduce computational complexity, we adopt the Miller-Tucker-Zemlin (MTZ) formulation [?]:

$$\min \sum_{m \in V} \sum_{n \in V} d_{mn} y_{mn}$$

subject to:

$$y_{mn} \in \{0, 1\} \quad \forall m \in V, n \in V$$

$$\sum_{n \in V} y_{mn} = 1 \quad \forall m \in V$$

$$\sum_{m \in V} y_{mn} = 1 \quad \forall n \in V$$

$$y_{mm} = 0 \quad \forall m \in V$$

$$u_m - u_n + (N - 1)y_{mn} \leq N - 2 \quad \forall 2 \leq m \neq n \leq N$$

where V is the set of nodes representing all exposures in a time block, N is the total number of exposures, d_{mn} is the slew distance from exposure m to n , u_m is a free variable describing node m 's position in the path, and $y_{mn} = 1$ if the order (m, n) appears in the final sequence.

4 Simulation Design

4.1 Simulation Target Set Generation

Since known NEAs with diameters below 1 km are incomplete, we must expand the simulation observation targets [?]. We use the Minor Planet Center's (MPC) 31,345 known NEAs as the original sample, expanding it tenfold.

Some samples have missing observation or orbital data, which we remove, leaving 31,322 valid samples. To preserve orbital distribution characteristics, we apply tenfold linear interpolation to expand the orbital data.

Stokes et al. [?] revealed the relationship between NEA number M and diameter D , proposing the NEA size distribution model:

$$M(> D) = 942D^{-2.354}$$

where diameter D is in km. This is a power-law distribution. Additionally, absolute magnitude H relates to diameter D and albedo P_v as [?]:

$$H = 15.618 - 5 \log D - 2.5 \log P_v$$

Using albedo $P_v = 0.14$ [?], we generate absolute magnitude data following the size distribution using the Inverse Cumulative Distribution Function (ICDF) method across diameters from 0.01 km to 50 km, yielding 313,220 absolute magnitude values [?].

Figure 3 [Figure 3: see original paper] compares original and simulated samples in orbital elements and absolute magnitude (blue: original, orange: simulated). Subplots (a), (b), and (c) compare semi-major axis, eccentricity, and inclination distributions, while subplot (d) shows the expanded absolute magnitude data following the power-law distribution relative to the original.

4.2 Observation Process Simulation

Quantitatively assessing MASTA' s NEA detection efficiency is a key objective. An intuitive method is simulating the number of NEAs detected per observation date. The simulation flow includes survey planning and target detection:

1. Generate daily observation tasks and simulation target sets from input data including observation date and telescope parameters.
2. Obtain the day's executable observation schedule from the telescope survey planner.
3. Combine the daily simulation target set with the executable schedule to screen observable targets based on the day' s survey coverage, producing the night' s NEA detection list.

The simulation flowchart is shown in Figure 4 [Figure 4: see original paper].

4.3 Result Evaluation Method

After removing duplicate detections, we can count the total number of targets meeting detection criteria at least once over a period—the cumulative detection count. From this we calculate the cumulative detection fraction, defined as the ratio of cumulative detections to total targets in the simulation set, which serves as our evaluation metric.

5 Simulation Results

5.1 Simulation Environment and Parameters

We simulate MASTA's 20 telescopes at the Lenghu site. The simulation program is written in Python using Gurobi 10.0.23 optimizer configured for 8 threads (all available cores). Considering central obstruction, MASTA's effective aperture is 60 cm. Based on Table 2, Lenghu's sky brightness is 21-22 magnitude, using 21 magnitude in the simulation. Other parameters are listed in Table 3 .

5.2 Survey Planning Model Performance

The survey planning model is solved using Gurobi, with results meeting both the basic objective of optimizing exposure sequences and the principles outlined in Section 1. We verified these requirements through simulation.

Figure 5 [Figure 5: see original paper] shows the distribution of time intervals between exposures for a sample night. The peak interval is 5 seconds, with approximately 90% of intervals at the baseline 5-second value after planning, demonstrating effective optimization of exposure sequences and reduced non-exposure time.

Since observing conditions vary temporally and FOM serves as each sky region's weight, the same region receives higher weight during better conditions, allowing the model to adjust telescope allocation across time blocks, deploying more telescopes during optimal periods. Figure 6 [Figure 6: see original paper] shows the number of telescopes used in different time blocks for a simulated night. The model also assigns different telescopes to different sky regions within the same time block to maximize search area, as shown in Figure 7 [Figure 7: see original paper].

The model prioritizes advantageous NEA sky regions, ensuring these tasks are completed first. Figure 8 [Figure 8: see original paper] shows task completion rates versus exposure time for telescope counts of 5, 10, 15, and 20. In all subplots, advantageous region tasks maintain 100% completion as exposure time increases, while local sky region completion remains at 100% initially then declines. Some subplots show stepped declines due to constraint (3) restricting the integer linear programming feasible region.

Figure 8 also reveals telescope redundancy when all NEA survey tasks are completed and exposure times are not excessive. Since MASTA serves multiple scientific objectives, wasting telescope resources should be avoided. The survey planning model optimizes the total telescope count for NEA surveys. Table 4 shows the minimum telescope requirements for NEA surveys at different exposure times when each observation period is 60 minutes. With 40-second exposures, only 10 telescopes are needed, leaving 10 for other scientific objectives.

Another optimization direction is reducing total observation time for NEA surveys when using all 20 telescopes. Table 5 shows the minimum observation time

per period at different exposure times with 20 telescopes. At 40-second exposures, MASTA requires only 30 minutes per observation period to complete all NEA survey tasks.

5.3 MASTA NEA Detection Efficiency Assessment

Beyond demonstrating the planning model's performance, we must assess MASTA's NEA detection efficiency. Using the simulated target set and the procedure from Section 4, we simulated 292 observable nights from January 1 to December 31, 2024, then calculated the cumulative detection fraction. The results show MASTA detected 4,026 NEAs, achieving a cumulative detection fraction of 1.29%. Figure 9 [Figure 9: see original paper] shows the cumulative detection fraction across the year.

Figure 9 also shows results for 60-second exposures. The cumulative detection fraction increases from 1.29% to 1.46% (4,026 to 4,559 NEAs) when exposure time increases from 40 to 60 seconds. However, as Table 4 shows, this requires increasing telescopes from 10 to 14 to complete all tasks each night.

6 Summary and Discussion

To fully leverage MASTA's NEA detection advantages, this paper proposes an NEA survey strategy based on asteroid spatial distribution, motion patterns, apparent magnitude distribution, and FOM, and develops a survey planning model using integer linear programming. Using an expanded simulated target set, we implemented and evaluated the model through simulation, quantifying MASTA's NEA detection efficiency. Main results are:

1. Surveying the visible sky three times per night with 40-second exposures is a suitable strategy for MASTA.
2. The planning model optimizes exposure sequences, compressing approximately 90% of non-exposure time to the 5-second baseline at 40-second exposures, while meeting MASTA's specific NEA survey needs including priority observation of advantageous regions and adaptive telescope allocation based on conditions.
3. The model optimizes observation resources: with 40-second exposures and 60-minute observation periods, the minimum telescope requirement is 10; with all 20 telescopes, the minimum observation time per period is 30 minutes, freeing resources for other science.
4. Annual simulation for 2024 shows MASTA can detect 1.29% of the simulated NEA sample with 40-second exposures under this planning model.

This survey planning model can be applied to MASTA's time-domain surveys and other scientific objectives, effectively utilizing MASTA's multi-telescope advantages compared to ZTF's model. As a multi-telescope array, MASTA can increase exposure depth through simultaneous or consecutive exposures of the

same field with multiple telescopes, which should be considered in future model improvements to maximize MASTA' s unique advantages.

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