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Relay Observation Scheduling of Global Distributed Telescope Array Based on Integer Programming

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Abstract

Certain transients require regular observations over several days at intervals of hours or shorter, which cannot be accomplished by telescopes at a single site. The deployment of globally distributed telescopes at geographic locations of different longitudes enables the periodic monitoring of transients through relay observation. However, the simultaneous relay observation of numerous targets requires a telescope array of multiple telescopes that can be efficiently coordinated, and an automated scheduler for the array. This paper proposes IPROS, an integer programming model relay observation scheduler for a telescope array, that accounts for the entire process of relay observation and is consistent with the practical scenarios. We introduce the integer programming mathematical model for the relay observation scheduling problem with the telescope array, upon which the scheduler is based. Additionally, we propose an algorithm to provide a comprehensive formulation of the optimization objective of minimizing cadence deviation in the model. Experimental results demonstrate that the relay observation scheduler based on the integer programming model can effectively address the telescope array relay observation problem. It shows superiority over a scheduler with non-specific consideration of relay observation in the modeling and a scheduler based on greedy thought.

Key words: telescopes – surveys – methods: data analysis – techniques: miscellaneous

1. Introduction

Time-domain astronomy is dedicated to systematically searching and studying various types of transients, such as supernovae, electromagnetic counterparts of gravitational waves, and gamma-ray burst afterglows (Morrell 2021; Hu et al. 2023). Astronomers hope to acquire requisite follow-up data of these transients on time in order to obtain light curves, for the study of their variations and exploration of their physical structures and interactions with other objects (Brown et al. 2013; Gal-Yam et al. 2014). This requires continuous monitoring of the transients through multiple observations with specific temporal spacing. The durations of monitoring vary from a few hours to a few months, and the temporal spacings of observations ("cadence") vary from a few minutes to a few days, related to the characteristics of the variations of the transients (Piran & Granot 2001; Förster et al. 2016; Hu et al. 2023). However, the rotation of the Earth imposes restrictions on telescopes located at a single location, making regular observations of transients with durations of days or months and cadences less than hours impossible. To address this issue, the coordinated observation of transients by globally distributed telescopes located at different longitude locations is essential. Specifically, transients would be observed sequentially using telescopes distributed at different longitudes as the Earth rotates. This ensures that transients with long durations and short cadences are always visible to some telescopes.

"Relay observation" can be defined as the observation of celestial targets that require long periods of continuous observation, using a group of telescopes at different longitudes on the Earth sequentially, due to the rotation of the Earth. The scientific objective of the relay observation is to obtain the long-duration, high-frequency data of celestial targets, including transients, asteroseismic targets, and others, in order to study their variations and explore the physical structures and interactions with other objects. As mentioned above, the relay observation is essential for transients with long durations and short cadences, and it serves as a mode of follow-up observation of transients. Additionally, it is utilized in the observation of asteroseismic targets with specific cadences over multiple days (Andersen et al. 2019).

The realization of relay observation requires scheduling a group of telescopes located at different longitude locations. While manual scheduling can achieve basic relay observation, the recent surge in transient detections poses a significant challenge to this method. Projects like the Zwicky Transient Facility (ZTF) survey and the Large Synoptic Survey Telescope (LSST, now called the Vera C. Rubin Observatory) can issue millions of transient alerts per night. After filtering false and low scientific value alerts, many candidates are still valuable for follow-up. It is impractical to ensure optimal and continuous monitoring with manual scheduling alone (Graham et al. 2019; Ivezić et al. 2019). The solution lies in the automated scheduling, requiring that telescopes distributed across different longitudes can be effectively coordinated, forming the telescope array. Some or all of the telescopes in the array would be used. Therefore, it is necessary to investigate the automated scheduling of such a telescope array for the relay observation.

The telescope array, composed of telescopes at different longitudes, along with the relay observation scheduling of such an array, together constitutes a large and complex astronomical observation project. In the field of astronomy, numerous projects of comparable scale currently exist, each characterized by its unique equipment and scientific goals. This diversity necessitates research into different types of automated astronomical observation scheduling. The primary challenge lies in effectively allocating observation tasks among telescope resources to achieve the diverse scientific goals of these projects. This necessitates the development and implementation of an appropriate scheduler that conforms to various constraints, including but not limited to astronomical observation conditions and the available number of telescope resources.

Noteworthy are the schedulers of the time-domain survey projects represented by LSST (now called Vera C. Rubin Observatory) and ZTF. Naghib et al. (2019) formulated the scheduling problem of the LSST as a Markov Decision Process (MDP) and proposed a feature-based scheduler which is an automated, decision-making algorithm. Bellm et al. (2019) presented a time-domain survey scheduling algorithm for implementing the survey of ZTF using integer linear programming (ILP). The ILP approach optimizes the observing plan for an entire night by assigning targets to temporal blocks. Similarly, Parazin et al. (2022) developed a mixed-integer linear programming scheduler for efficient follow-ups of gravitational-wave detections. Furthermore, research has extended to the scheduling of telescope arrays, consisting of telescopes at different locations, to achieve various scientific objectives. López-Casado et al. (2019) presented a probabilistic algorithm to determine the best telescopes in the telescope array for executing a requested observation. Zhang et al. (2023) proposed a multilayer scheduling model that can solve the generic problem of scheduling a telescope array. Jia et al. (2023) conducted the research on using telescopes to observe space debris.

The relay observation scheduling of a telescope array is a form of astronomical observation scheduling. The relay observation scheduling methods and some other types of astronomical observation scheduling both aim to optimize the allocation of observation tasks for telescopes under various constraints. Therefore, the initial analysis and modeling phases of some astronomical observation scheduling methods, particularly those involving telescope arrays, can provide insights for the relay observation scheduling.

The Las Cumbres Observatory Global Telescope (LCOGT)[4] is a globally distributed telescope network with fully robotic operations. Its scientific goal is to provide astronomical observation for targets through telescopes around the world (Brown et al. 2013; Pickles et al. 2014). The scheduler (Lampoudi et al. 2015) of LCOGT employs an ILP-based approach to solve the observation scheduling problem for celestial targets. This method maximizes the sum of priorities assigned to targets by the Time Allocation Committee (TAC). Similarly, the Burst Observer and Optical Transient Exploring System (BOOTES) network stands as a worldwide automatic telescope network (Hu et al. 2021; Hu et al. 2023), with the scientific goal of conducting the follow-up observation of transients and other celestial targets. The scheduling methodology employed by BOOTES also prioritizes observing higher priority celestial targets (Hu et al. 2023).

However, these existing scheduling methods for astronomical observation projects do not take into account the specific considerations related to relay observation, particularly the required cadence, in their initial analysis and modeling phases. In the relay observation, it is important to minimize the deviation between the actual cadence and the required cadence, due to the multiple observations over a long period. This helps to ensure the uniformity of relay observation. Failure to minimize the deviation may result in obtained light curves that do not meet the requirements, thereby compromising the study of transient variations, especially when telescope resources are limited. Moreover, neglecting cadence can lead to underutilization of telescope resources for relay observation. Therefore, developing a dedicated scheduler is essential for the automated relay observation scheduling using telescopes at different longitudes.

Moreover, it is worth noting that the concept and model of satellite periodic continuous observation share similarities with telescope array relay observation. Certain studies on satellite periodic continuous observation task provide valuable insights for the development of a dedicated relay observation scheduler of telescope array. For instance, Chen et al. (2017) presented a task scheduling algorithm based on a multi-objective evolutionary algorithm. The algorithm effectively manages the degree of timeout and energy consumption in the periodic and continuous observation of satellite targets.

In this paper, we achieve the automated relay observation scheduling of the telescope array. Our main contributions are summarized as follows:

1. We propose an integer programming model specifically designed for the telescope array relay observation scheduling problem.
2. We present a relay observation scheduler based on the integer programming model, which can systematically manage the relay observation process of telescope array, taking practical scenarios into account.
3. To address the crucial optimization objective of minimizing cadence deviation in the model, we propose an algorithm that provides a comprehensive formulation of the optimization objective.
4. We assess the practicality and effectiveness of the scheduler based on the degree of cadence deviation, and the observation

[4] https://lco.global/

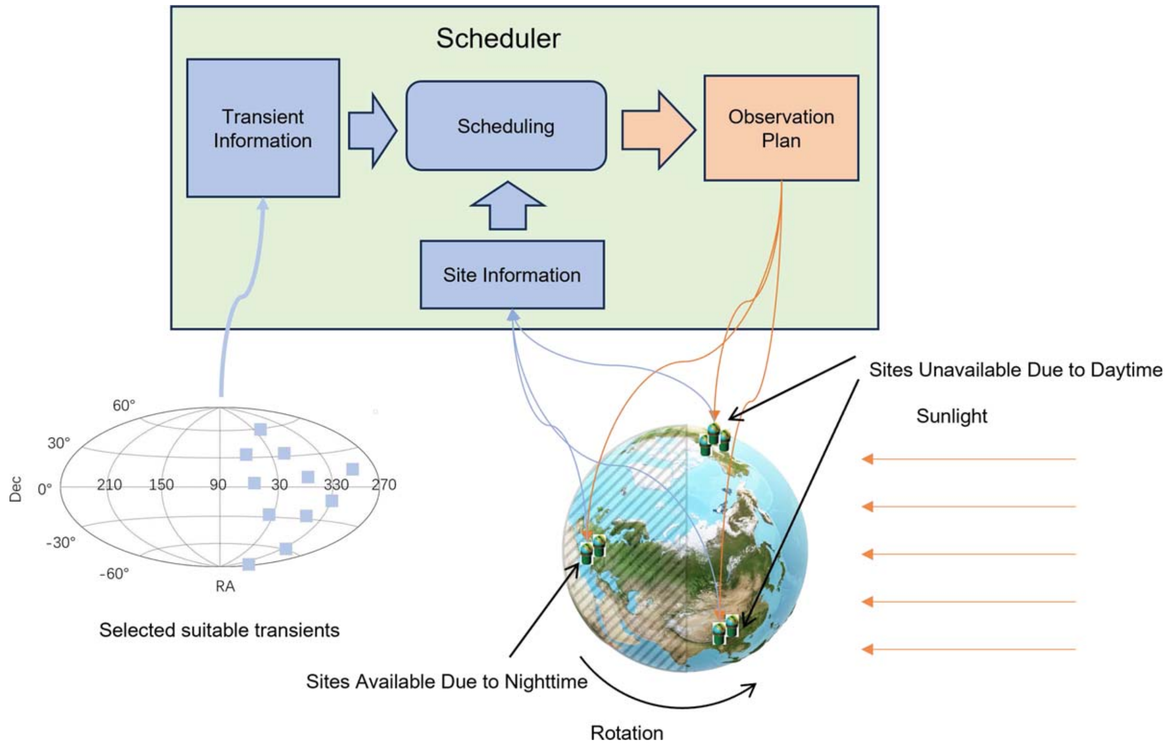

Figure 1. Relay observation scheduling of telescope array. The relay observation scheduling involves selecting transients, primarily sourced from other astronomical observation projects, to be received and coordinated by the scheduler. Light blue squares on the celestial sphere map represent selected transients. The illustration of the rotation of the Earth shows three sites at different longitudes. The shadowed areas indicate nighttime, during which sites are available for observation, while the sunlight areas indicate daytime, when sites are unavailable. Sites on the bottom of the illustration have recently been transformed to unavailable by the rotation of the Earth, and sites on the top will be transformed to available due to the rotation.

conditions represented by the average of airmass. The results demonstrate the appropriateness and advantages of the proposed scheduler as presented in this paper.

The paper is organized as follows. In Section 2 we describe the relay observation scheduling of the telescope array. We propose the mathematical model and the relay observation scheduler based on the model (Integer Programming model Relay Observation Scheduler, IPROS) in Section 3. We detail the experiments and the discussion of experimental results in Section 4. Finally, in Section 5, conclusions and future prospects are presented.

2. Description of Relay Observation Scheduling

We present the relay observation scheduling of the telescope array, drawing upon existing astronomical projects capable of implementing relay observation, as illustrated in Figure 1. The telescope array consists of multiple sites located at different geographic longitude locations, each equipped with multiple identical telescopes. A scheduler is incorporated to control the telescope array. This scheduler utilizes information regarding the transients and the current status of sites to determine the optimal observation times and sites for each exposure of transients, forming the observation plan. The observation plan serves as the foundation for subsequently coordinating the telescope array to conduct relay observation of transients. The entire process operates autonomously.

It is important to note that Sun altitude, moon phase, and moon separation are factors that must be considered in celestial observation. To ensure meaningful relay observation, we should evaluate whether the transients are affected by these factors before scheduling, and select the transients that are not affected and meet the requirements for the relay observation scheduler. This process of evaluating whether the transients are affected by these factors in advance is relatively independent, and there are existing software tools available for this task. Therefore, it is not in the discussion of this paper.

Furthermore, there is a distinction between relay observation and time-domain surveys with multiple sites distributed at geographic locations of different longitudes. The goal of a time-domain survey is to discover valuable celestial targets through the cadence of observations (Bellm et al. 2019). Conversely, relay observation serves as a long-duration observation with short cadences for discovered transients or celestial targets with specific cadences. Therefore, relay observation necessitates more stringent requirements for the cadence to gather the essential follow-up data for studying variations.

2.1. Impact Factors and Results of Relay Observation

To further clarify the relay observation scheduling of the telescope array, we analyze both the impact factors of scheduling, which include the information on transients and sites received by the scheduler, and the results of the relay observation scheduling.

The impact factors considered in the inputs of relay observation scheduling include the R.A., decl., start and end observation times, required cadence of observation, and exposure duration of each transient, as well as the latitude, longitude, elevation, and telescope numbers of each site. These factors significantly influence the observable time, required observation resources, and astronomical observation conditions, thereby impacting relay observation scheduling. Other information related to transients and sites falls beyond the purview of this paper. Therefore, we only focus on these factors as inputs for the scheduling process.

The result of relay observation scheduling is the observation plan, which serves as the basis for controlling the telescope array to perform observations. Notably, the relay observation scheduler discussed in this paper assigns sites for observation rather than specifying individual telescopes in sites. Consequently, the observation plan is defined as a combination of which site should be used to observe and at what time for each transient. A more detailed observation plan that can specify individual telescopes would require additional scheduling efforts, which are beyond the scope of this paper.

2.2. Handling the Received Relay Observation Scheduling

Due to the long duration of relay observation necessitated by transients, coupled with the potential occurrence of new transients or changes in site resources during this period, it is impractical for the scheduler to directly calculate the observation plan, for the entire duration of each transient based on the transient information and site information.

Therefore, we present an approach to handle the received transient information and site information to generate the observation plan, as illustrated in Figure 2. We define the "time period" as a segment of the transient monitoring duration, representing a specific interval within which the scheduler generates an observation plan based on the current transient information and site information. We segment the duration of transient monitoring into time periods and determine the observation plan for each time period through scheduling. When new transients or other changes occur, the scheduler immediately adjusts the time period division and reschedules the observation plan for the next time period. This approach ensures the robustness and adaptability of the scheduling mechanism in managing the relay observation over extended durations.

3. Relay Observation Scheduling Model and Scheduler

Drawing upon the description provided in Section 2, we conduct a comprehensive analysis of the relay observation scheduling problem. Subsequently, we propose a mathematical model for this issue and introduce a scheduler based on this model to address the relay observation scheduling problem.

3.1. Analysis of Relay Observation Scheduling Problem

The relay observation scheduling of a telescope array aims to appropriately allocate the observable time of each telescope to transients under limited resources.

As analyzed above, an important objective of the relay observation scheduling is to minimize the deviation between the actual cadence and the required cadence, aiming to achieve uniformity of observation as much as possible. This enables the acquisition of follow-up data that closely match the required cadence from transients, and ensures the study of their variations. Additionally, in cases where the actual cadence exceeds the requirement, a reduced cadence deviation aids in mitigating the duration of unmonitored intervals, ensuring the study of variations for the transients. Conversely, when the actual cadence falls short of the requirement, minimizing cadence deviation can reduce the unnecessary occupation of telescope resources. In summary, controlling the cadence of transients is essential for the relay observation.

However, the existing mathematical models and schedulers utilized for astronomical observation scheduling of a telescope array are not specifically designed to address the challenges of relay observation scheduling. They have focused on single observation exposures without considering the control of the cadence in the model. Therefore, it is necessary to research the relay observation scheduling starting from modeling.

Optimal astronomical observation conditions are another objective of the scheduling. The observation conditions could be quantified as the expected magnitude limits. Except for the specification of the hardware of the telescope systems, the airmass, sky brightness, atmospheric seeing, etc., which are independent of the hardware and vary with time, can affect the magnitude limits. Considering the difficulty of aggregating these time-varying features, we primarily use airmass to measure the observation conditions, as Rana et al. (2019) did for the scheduling of searching gravitational wave counterparts. Lower airmass means less atmospheric extinction and a deeper magnitude limit (fixed exposure time), thus representing better astronomical observation conditions. It is important to note that in real-world scenarios, relying solely on airmass as the measure of observation conditions could limit the ability to accurately capture all relevant conditions of the model. Therefore, the airmass is only used in studying the scheduler; we will replace it with "nominal extinction" eventually.

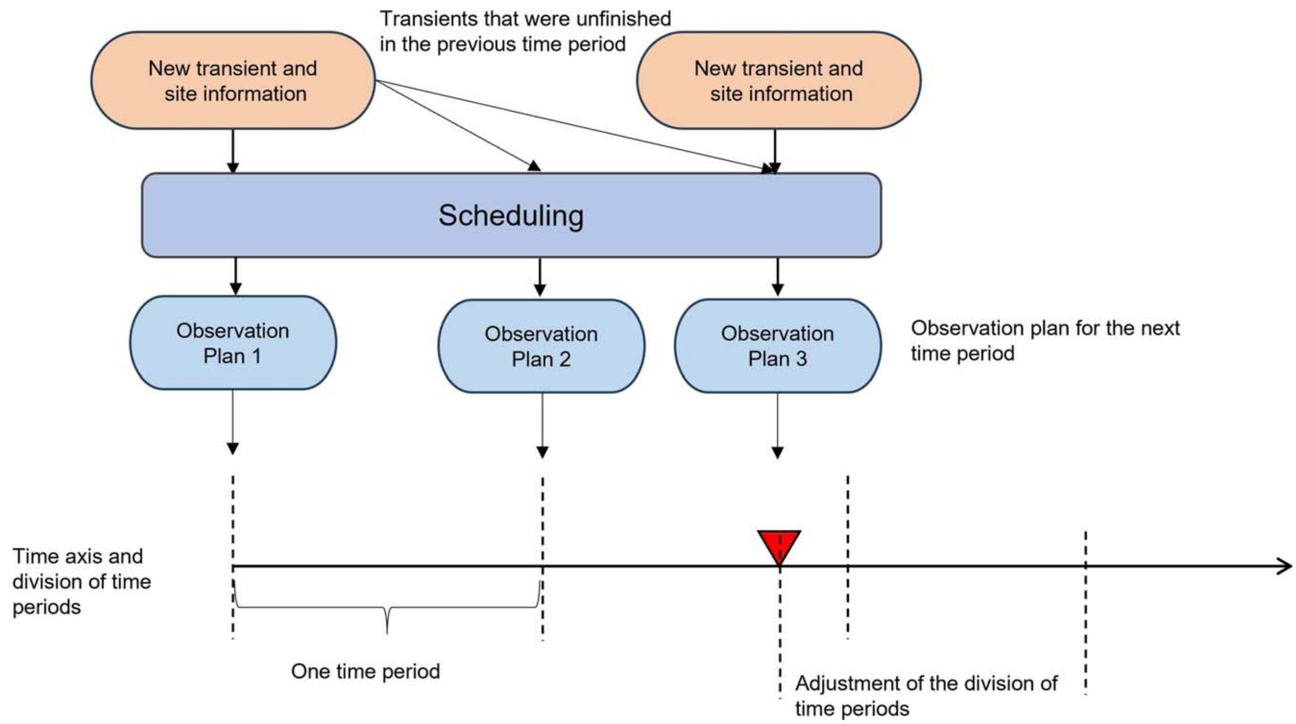

Figure 2. The process of the scheduler from receiving inputs to generating the observation plan. This figure follows the time axis at the bottom as it progresses from left to right. The entire scheduling plan consists of plans generated for each time period.

In addition, celestial target prioritization is usually an important part of observation scheduling. However, we mainly consider the problem of monitoring multiple transients without strict priority requirements. Therefore, celestial target prioritization is not explicitly treated as an objective in our scheduling.

In conclusion, the objectives of the relay observation scheduling are shown in Figure 3.

3.2. Mathematical Model of Relay Observation Scheduling Problem

From the preceding description and analysis of relay observation scheduling, we conclude that, similar to other astronomical observation scheduling problems, the telescope array relay observation scheduling problem can essentially be regarded as a job-shop problem (JSP), which is an NP-hard problem (Colome et al. 2012). Previous research has employed integer programming models and genetic algorithms to address the astronomical observation scheduling problem (Kubanek 2010; Parazin et al. 2022). Compared to methods utilizing genetic algorithms or similar algorithms, the integer programming method requires less initialization work, offers a more direct and comprehensible description of the problem, and is less likely to deviate from the optimal solution. The scheduling plan can be derived by formulating the appropriate integer programming model and solving it using solvers. Therefore, we utilize this approach to address the relay observation scheduling problem. In this section, we present a mathematical model of integer programming designed for the relay observation scheduling.

3.2.1. Formalization

To establish an effective mathematical model suitable for relay observation scheduling, it is imperative to delineate the relevant parameters. Table 1 presents a comprehensive list of parameter definitions. Notably, the time slot, as elucidated in the table, serves as the fundamental temporal unit for scheduling. Each observation exposure starts at a specific time slot and has a duration that spans one or more time slots. The length of cadence is also measured by the time slots. Additionally, it should be clarified that the observation plan, *ObsPlan* defined in the table, consists of when each transient in the set $O = \{O_1, \cdots, O_n\}$ will be observed within the time range $T = \{T_1, \cdots, T_l\}$ and by which site in the site range $S = \{S_1, \cdots, S_m\}$. The observation plan is derived from the values of the decision variables obtained by solving the model.

3.2.2. Decision Variables

The uncertainty associated with each observation of a transient makes it impossible to directly select the states of each observation as decision variables in the mathematical programming model. Consequently, we draw upon other scheduling problem models (Solar et al. 2016; Bellm et al. 2019; Parazin et al. 2022), and

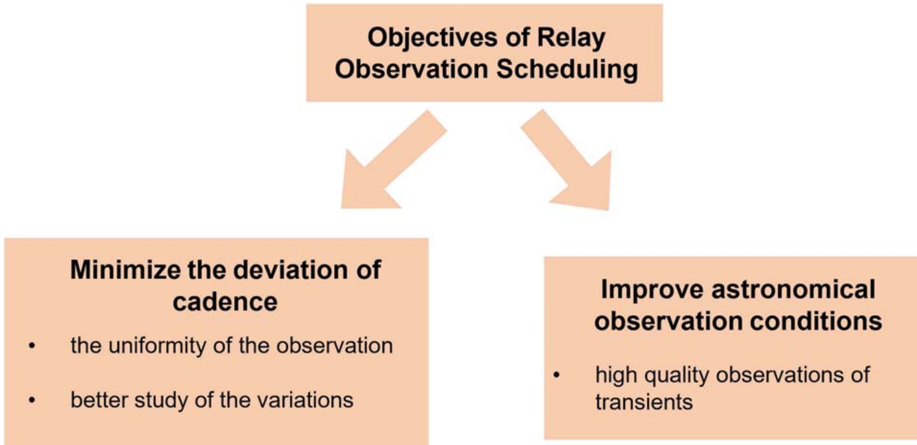

Figure 3. The objectives of the relay observation scheduling.

Table 1
Definitions of Parameters that Need to be Expressed

Parameters	Definitions
$O = \{O_1, \cdots, O_n\}$	A set of n transients to be observed
$C = \{C_1, \cdots, C_n\}$	Cadence for each of the n transients
$E = \{E_1, \cdots, E_n\}$	Exposure duration for each of the n transients
$S = \{S_1, \cdots, S_m\}$	A set of m globally distributed sites
$SN = \{SN_1, \cdots, SN_m\}$	Number of telescopes owned by each of the m sites
$T = \{T_1, \cdots, T_l\}$	Time that needs to be observed for transients is evenly divided into l time slots
$AM = \{AM_{111}, \cdots, AM_{nml}\}$	Airmass observed by m sites at l time slots for n transients
$SAlt = \{SAlt_{11}, \cdots, SAlt_{ml}\}$	Solar altitude angle values for m sites at l time slots
$ObsPlan = \{O_1: (T_{1a}, S_{1b}), \cdots, (T_{1c}, S_{1d}), \cdots, O_n: (T_{na}, S_{nb}), \cdots, (T_{nc}, S_{nd})\}$	Observation plan for n transients, consisting of time and site of each observation for each transient

employ the observation state of each transient at each site in each time slot as the decision variables.

$Y_{ijt} = 1$ if transient i is being exposed by site j starting at time slot t; 0 otherwise.

3.2.3. Objective Functions

Based on the analysis in Section 3.1, an essential optimization objective of the integer programming model is to minimize the deviation between the actual cadence and the requirement. However, the decision variables of the integer programming model determined in Section 3.2.2 make it impossible to calculate the temporal spacing of relay observation, thereby preventing us from directly quantifying the cadence deviation. Therefore, we choose to control the distribution of the observation time to achieve the optimization objective of minimizing the cadence deviation.

Specifically, we devise a metric of deviation that calculates the extent to which the number of times each transient starts observing in each time period of required cadence length deviates from 1. Minimizing this metric can indirectly minimize the cadence deviation

$$\min \sum_{i\in O}\left(\sum_{t\in T}\left(\left(\sum_{t}^{t+C_i}\sum_{j\in S} Y_{ijt} - 1\right)\cdot\left(\sum_{t}^{t+C_i}\sum_{j\in S} Y_{ijt} - 1\right)\right)\right). \quad (1)$$

Another optimization objective is to enhance the astronomical observation conditions of the transients. As described above, we minimize the airmass of the observations for better observation conditions

$$\min \sum_{i\in O}\sum_{j\in S}\sum_{t\in T}(Y_{ijt}\cdot AM_{ijt}). \quad (2)$$

3.2.4. Constraints

There are two main types of constraints on relay observation scheduling with a telescope array. First, each telescope can only serve for one transient with specific requirements at the same time. We assume that the observing requirements of transients are different, and those with the same requirements have already been combined. This means that the number of transients observed by a site within a time slot cannot exceed the number of telescopes available at that site. Second, the observation for transients must

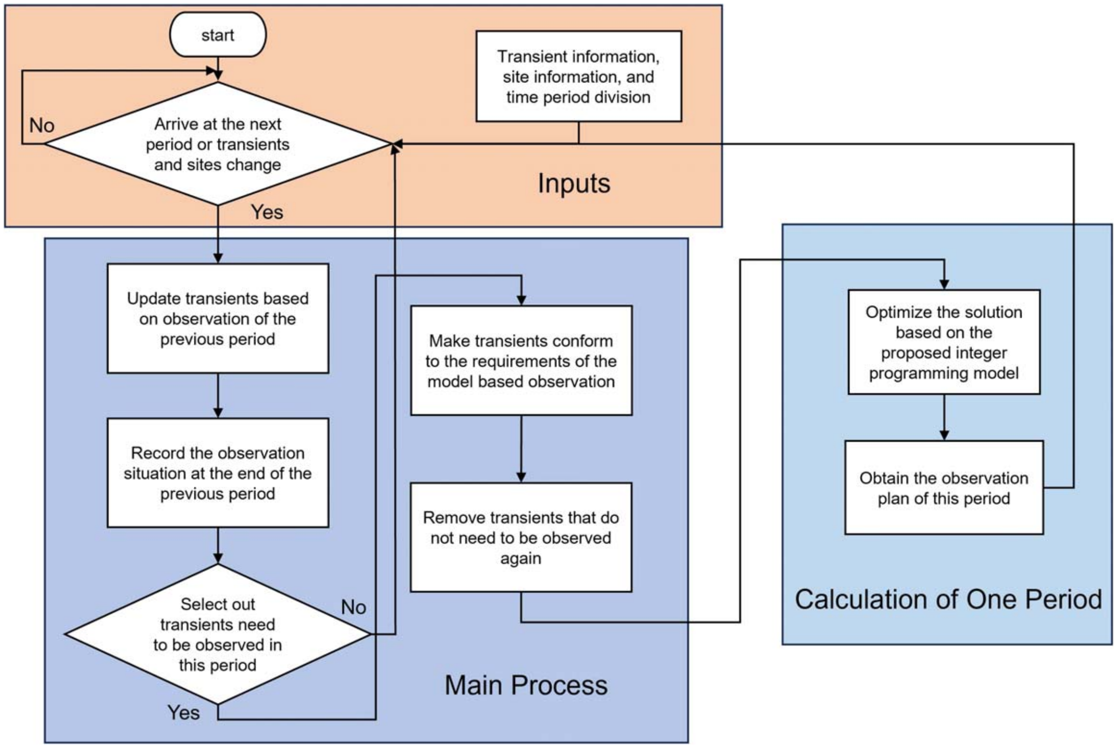

Figure 4. An illustration of the relay observation scheduler. We assume that the telescope array conducts observation strictly according to the formulated observation plan, without any variations. Consequently, upon deriving the observation plan, the scheduler returns to the determination in the initial phase.

adhere to certain rules. Specifically, transients are unobservable when they are below the horizon where the site is located. Additionally, observation is deemed non-compliant with the rules when the airmass exceeds 1.8, indicating an extreme observation angle, or when the solar altitude angle surpasses $-18°$, signifying substantial interference from sunlight. In summary, two constraints on relay observation scheduling are expressed as follows:

The number of transients dispatched for observation at one site in a time slot cannot exceed the number of telescopes at the site.

$$\sum_{i\in O}\sum_{t-E_i}^{t} Y_{ijt} \leqslant SN_j \quad \forall j \in S,\, t \in T. \tag{3}$$

Telescope sites cannot observe transients at irregular time slots.

$$\sum_{t-E_i}^{t} Y_{ijt} = 0 \quad \forall AM_{ijt} < 0,\, AM_{ijt} > 1.8,\, SAlt_{jt} < -18. \tag{4}$$

3.3. Relay Observation Scheduler and Algorithm

Optimizing and solving the integer programming model provided in Section 3.2 with transient and site information as inputs can yield the values of decision variables. These values subsequently determine the observation plan, indicating when a specific site should observe the corresponding transient. The relay observation scheduler is designed to receive transient information, site information, and time period division as inputs and calculate the observation plan in time periods. Therefore, the calculation of the observation plan for one time period, which is the core function of the scheduler, can be realized by solving this model. We name this scheduler IPROS.

The whole design of IPROS is illustrated in Figure 4. This scheduler determines whether scheduling is required based on the inputs received. If it is positive, the scheduling process proceeds, otherwise the determination continues. During the scheduling process, the scheduler calculates the observation plan for each time period by solving the model. It is important to note that observations conducted toward the end of the previous time period may take up telescope resources at the beginning of the subsequent time period. Therefore, it is necessary to record the last observations in the previous time period during the scheduling process. Additionally, the status of transients needs to be updated to determine which transients should be observed in each time period.

For the process of calculating the observation plan in the scheduler, we utilize the solver to solve the model optimization problem. However, the optimization objective of minimizing the cadence deviation in the model, as described in Equation (1), requires further consideration. Equation (1) serves as a general formulation of the optimization objective, but it is not complete. In practice, the objective is more intricate, particularly regarding the initiation of observation for transients. This is due to the difficulty of scheduling the first observation in the time period as accurately as possible. Specifically, when the transient needs to be observed at the start time slot of the time period, it is impossible to make the first observation close to the moment by the general description. When the transient does not need to be observed at the start time slot of the time period, the general description faces the problem of inconsistency between the length of the first temporal spacing of observations and the subsequent ones.

To address these challenges, we propose an algorithm to obtain a more refined formulation of this optimization objective, provided in Algorithm 1. We classify the transients into two categories based on whether they need to be observed at the starting time slot of the time period. These two categories are processed separately in the algorithm. We extend the front of the time period with additional slots of appropriate length and adjust the formulation of the optimization objective concerning the initial observation. The minimization of the result produced by this algorithm is the required optimization objective, which is more aligned with real conditions compared to the formulation in Equation (1). Note that the additional time slots appended to the front of a time period do not represent realistically available observation time. Therefore, sites cannot be scheduled to start observing the transients at these time slots, and the constraint that the decision variables can only be equal to 0 at these time slots should be added.

Algorithm 1. Formulation of the optimization objective of minimizing the deviation

Input: transients $O = \{O_1,\cdots,O_n\}$, cadence $C = \{C_1,\cdots,C_n\}$, exposure duration $E = \{E_1,\cdots,E_n\}$, start time of observation $St = \{St_{O_1},\cdots,St_{O_n}\}$, time period that has been divided into time slots $T = \{T_1,\cdots,T_l\}$, sites $S = \{S_1,\cdots,S_m\}$, and decision variables Y_{ijt}
Output: *Func*. The minimization of the *Func* is the required optimization objective

for $i \in O$ **do**
  if $St_i == T_1$ **then**
    Add some time slots of the length of the cadence to the front of the time period, make $T = \{T_{-C_i+1},\cdots,T_1,\cdots,T_l\}$
    for $t \leftarrow T_{-C_i+1}$ to T_l **do**
      Sum the decision variables Y_{ijt} for each site $j \in S$ at time t and assign the sum to Y_{it}
    end for
    $Y_i \leftarrow 0$
    for $t \leftarrow T_{-C_i+1}$ to T_{l-C_i} **do**
      Sum the decision variables $(Y_{it_0} - 1)^2$ for t_0 from t to $t + C_i$ and assign the sum to $oneExp_t$
      $Y_i \leftarrow Y_i + oneExp_t$
    end for
  else
    for $t \leftarrow T_1$ to T_l **do**
      Sum the decision variables Y_{ijt} for each site $j \in S$ at time t and assign the sum to Y_{it}
    end for
    $Y1_i \leftarrow 0$
    for $t \leftarrow T_1$ to T_{St_i} **do**

(Continued)

      Sum the decision variables $(Y_{it_0} - 1)^2$ for t_0 from t to $t + St_i$ and assign the sum to $oneExp_t$
      $Y1_i \leftarrow Y1_i + oneExp_t$
    end for
    $Y2_i \leftarrow 0$
    for $t \leftarrow T_{St_i+1}$ to T_{l-C_i} **do**
      Sum the decision variables $(Y_{it_0} - 1)^2$ for t_0 from t to $t + C_i$ and assign the sum to $oneExp_t$
      $Y2_i \leftarrow Y2_i + oneExp_t$
    end for
    $Y_i \leftarrow Y1_i + Y2_i$
  end if
  $Func \leftarrow Func + Y_i$
end for

4. Experiments

To evaluate the feasibility and the performance, we implemented the relay observation scheduler, IPROS, and performed a series of experiments. This section outlines the input information utilized in the experiments, introduces evaluation metrics for relay observation, and describes the experiments conducted to evaluate IPROS, along with comparisons against other relay observation schedulers of a telescope array.

The scheduler and experiments were executed on a Windows 11 system equipped with 32 GB of RAM and an Intel i7-12700H CPU. We developed the scheduler in Python and utilized Astropy, an open-source Python library related to astronomy (Price-Whelan et al. 2018). Additionally, we employed the mathematical high-performance solver Gurobi to obtain the optimal solution of the integer programming model presented in Section 3.2.

4.1. Sites and Transients of the Inputs

Considering the current limited availability of telescope arrays utilized for relay observation, there is a lack of substantial and actual data to evaluate schedulers. To address this gap, we construct and generate instances closely resembling real scheduling scenarios, providing input data for the scheduler.

To determine the site information of the scheduler, we referred to the BOOTES project, which has investigated site distribution. It was concluded that a uniform distribution of three sites at appropriate locations in each of the northern and southern hemispheres would enable continuous monitoring of celestial targets (Hiriart 2014). Given the current developmental state of astronomical sites, we selected three appropriate real astronomical sites in each hemisphere and used their information to simulate the telescope array for our experiments. Additionally, an extra site was designated as a backup to accommodate variations in the number of sites required for the research. The information of all the sites selected for simulation is presented in Table 2.

Regarding the transient information in the inputs of the scheduler, its complexity mainly arises from its unpredictable appearance at any given time. To address this challenge, we generate sets of targets specifically designed to require 24 hr continuous monitoring, each with different characteristics in R.A., decl., required observation cadence, and exposure duration, all of which affect the relay observation. This approach enables a comprehensive simulation of actual transients with diverse scenarios, facilitating complete experimentation and evaluation.

Further details on the sites and transients as inputs are provided in Section 4.3.

4.2. Evaluation Metrics

The analysis and modeling in Section 3 clarify that the optimization objectives of relay observation include minimizing the deviation between the actual and the required cadence, as well as enhancing astronomical observation conditions. We assume that the scheduling precisely follows the observation plan generated by the scheduler. Therefore, the scheduler can be measured by directly calculating the degree to which the observation plan achieves the two optimization objectives. We propose measuring the scheduler from the following two aspects:

1. *Degree of cadence deviation*. We calculate the average deviation of actual cadences and the required cadence for each transient in the observation plan. This deviation is divided by the length of the required cadence, and the resulting value represents the degree of deviation for one transient. The average of these values across all transients is then calculated to represent the degree of cadence deviation of the observation plan.

We define the required cadence of the transient α to be c_0, and the actual cadences of each two exposures to be $c_1, c_2, \cdots, c_{n_0}, \cdots, c_n$. The formula for calculating the degree of deviation for the transient α is

$$d\alpha = \frac{\sum_{n_0=1}^{n}|c_0 - c_{n_0}|}{n \cdot c_0}. \quad (5)$$

The details on the degree of cadence deviation for one transient are illustrated in Figure 5. The degree of cadence deviation for one transient is the average of $|c_0 - c_1|$, $|c_0 - c_2|$, and other similar differences, divided by c_0, as described in Equation (5).

2. *Average of airmass*. We calculate the average value of the airmass per observation for each transient. The average of airmass for the observation plan is defined as the average of these values.

Table 2
Sites Related to Telescope Array

Site	Longitude (deg)	Latitude (deg)	Altitude (m)
Lijiang	100.030	26.695	3200
Mazagon	−6.737	37.099	50
Baja California	−115.464	31.044	2860
Maselespoort	26.237	−29.039	1383
Anglo-Australian	149.066	−31.277	1164
Atacama	−68.180	−22.953	2440
Xinglong	117.575	40.393	950

We favor smaller values for both metrics. It is important to note that the airmass of observation conditions has relevant constraints, which have already ruled out extremely unacceptable situations. Therefore, the degree of cadence deviation, directly related to the acquisition of follow-up data of transients and the study of variations, is a more important evaluation metric. Nonetheless, the average of airmass should not be disregarded.

Furthermore, an additional explanation regarding the degree of cadence deviation is necessary. The purpose of relay observation is to enable astronomers to obtain the light curve and necessary follow-up data of the transients for research. A significant deviation between the experimental cadence and the required cadence can negatively affect the acquisition of data and subsequent studies on transients, even rendering the observation of them meaningless. Therefore, it is crucial to establish the acceptable limit of cadence deviation. The relay observation of one transient with varying degrees of cadence deviation is intuitively shown in Figure 6. In the figure, fewer blank portions and dark portions indicate a smaller degree of cadence deviation. Based on the scientific goals of relay observation, we propose that a 20% deviation serves as the acceptable threshold. Beyond this point, the observation plan may lack practical significance.

4.3. Experiments and Results of the Scheduler

In this section, we conduct experiments to investigate the scheduler, IPROS, with various inputs, and present a comprehensive analysis of the experiments and results of IPROS.

We generate experimental input data across various aspects based on the factors affecting relay observation, to explore the scheduler. These aspects include distributions of transients, numbers of transients for simultaneous observation, exposure durations, cadences, and situations of sites. By incorporating different cases of these aspects, the different real-world relay observation scenarios can be simulated.

We need a set of representative values from various aspects, which together form an experimental benchmark. Subsequently, we generate experimental data for different cases of

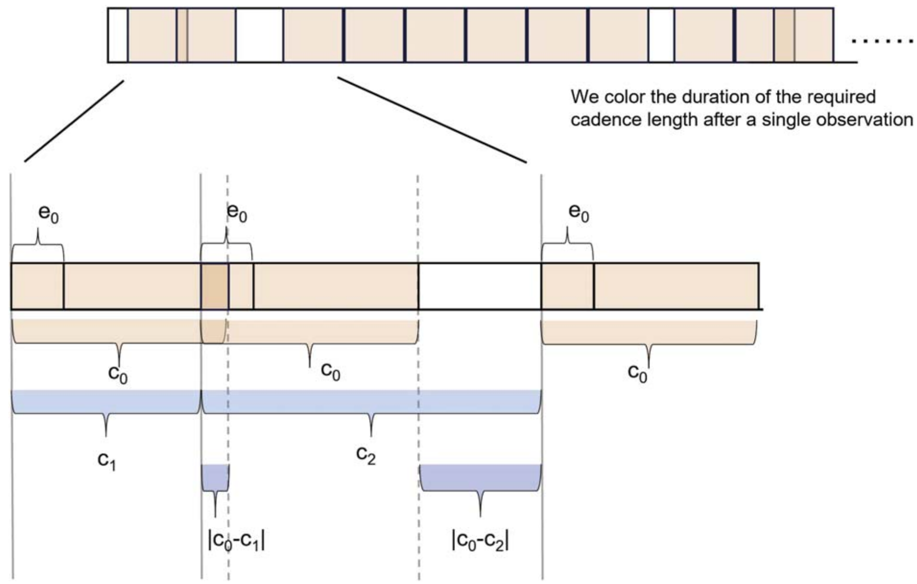

Figure 5. The detailed presentation of a part of the calculation of the degree of cadence deviation for one transient. The exposure duration of the transient is e_0. The solid line is the start moment of each exposure for the actual cadence, and the dashed line is the start moment of each exposure according to the required cadence.

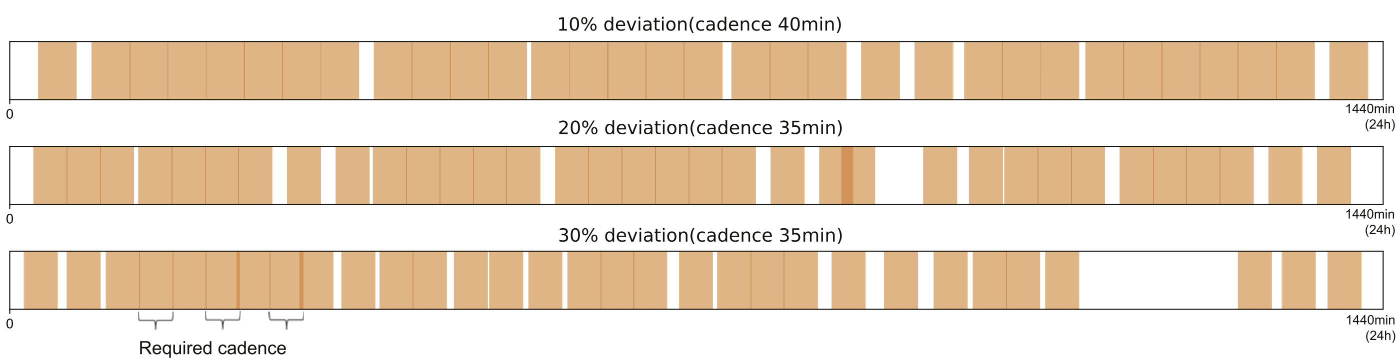

Figure 6. Reference examples of different degrees of deviation for a single transient. In the equal time intervals from the beginning of the observation of the transient to the end of the observation, we color the duration of the required cadence length after a single observation and mark each actual cadence. Empty portions indicate times that are not in the required cadence length range of a single observation, while dark portions indicate times that are in the cadence length range of multiple observations.

each aspect reference to the benchmark and study each aspect in turn with the control of variables of other aspects. This approach allows us to cover most real-world scenarios.

We select moderate telescope site data and transient data in all aspects for the benchmark. These ensure that the benchmark and experimental data are representative. First, the distribution of transients on the decl. can affect the feasibility and conditions of relay observation, whereas the distribution of transients on R.A. has negligible effects due to the long duration of the transients. Therefore, we generate the transients dispersed in the intermediate decl. region for the distribution of the benchmark. Considering the observation requirements of the early phase of a supernova, the afterglow of gamma-ray burst and others, the cadence of the benchmark should be selected randomly from a normal distribution with a mean value of 30 minutes (referred to as the relatively short cadence), and the exposure duration should be selected randomly from a normal distribution with a mean value of 12 minutes, 40% of 30 minutes (referred to as the relatively short exposure duration). Based on studies of the distribution of sites in the globally distributed telescope arrays, and their current developmental status (Brown et al. 2013; Hiriart 2014; Hu et al. 2023), the resources in the benchmark should be six sites with a uniform distribution, each having three telescopes. Considering the limitation of telescope resources, the number of transients for simultaneous observation in the benchmark is set to 12. In summary, the complete benchmark is presented in Table 3 and Figure 7.

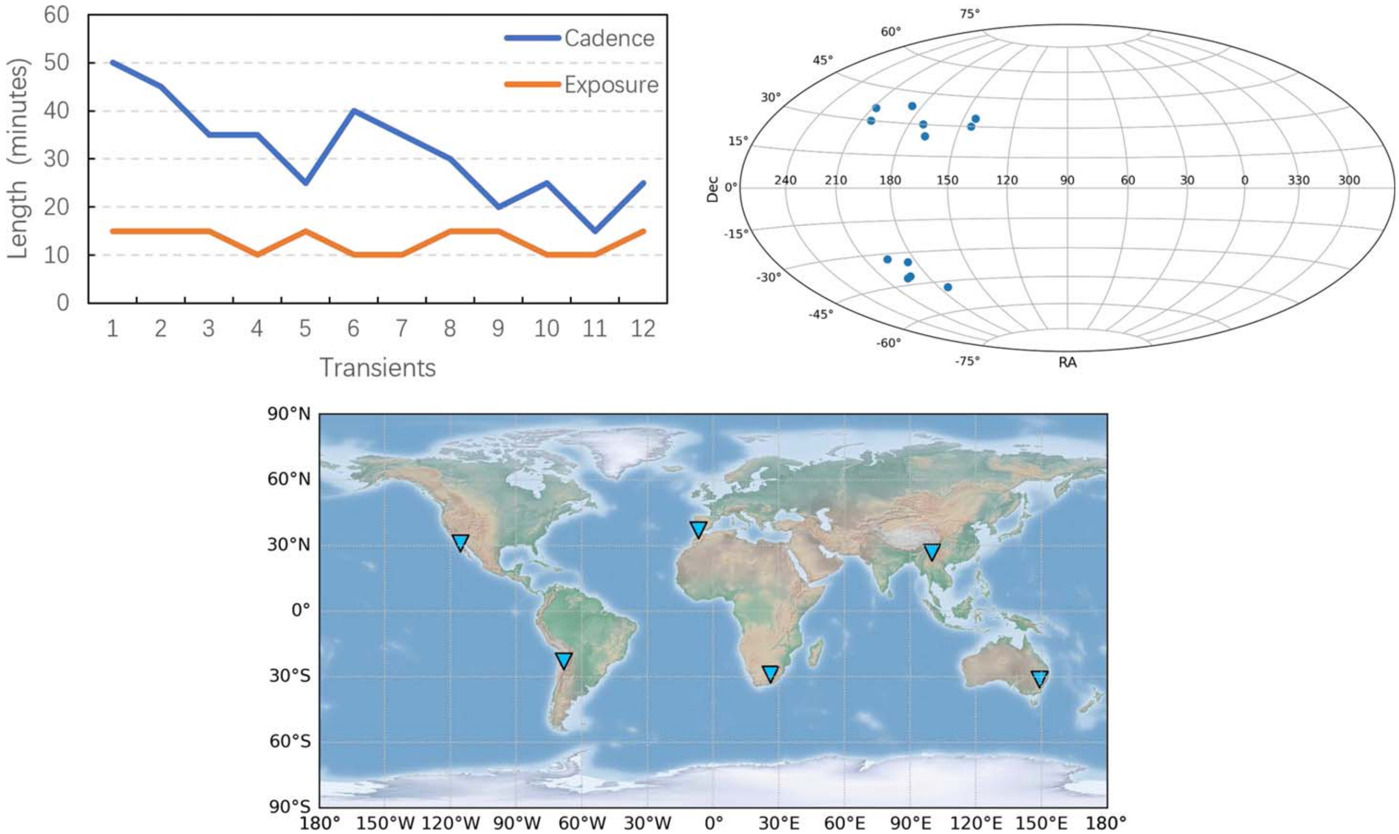

Figure 7. Specific presentation of the benchmark for the experiment. The length of cadence and exposure duration for the transients are illustrated in the left of the first row. The distribution of the transients is illustrated in the right of the first row. In the second row, we show the distribution of the sites.

Table 3
Characteristics of the Benchmark for the Experiment

Distribution of Transients	Number of Transients	Cadence	Exposure Duration	Situations of Sites
Dispersed in Intermediate decl.	12	Relatively Short	Relatively Short	18 telescopes at 6 sites

Meanwhile, for the experiments of the scheduling algorithm, it is essential to specify the length of each time period and the length of the time slot, which serve as the fundamental unit of time. These parameters can be adjusted flexibly by the user. In the upcoming experiments, we set the time period to 4 hr and the time slot to 5 minutes.

4.3.1. Different Distribution of Transients

The different decl. distributions of the transients can affect observation conditions and the available observation time. Therefore, we generate the experimental data sets focusing on transient positions concentrated in high decl., concentrated in low decl., and dispersed in intermediate decl. for the investigation, as shown in Figure 8. The characteristics of other items in experimental data sets remain consistent with the benchmark.

The results of two evaluation metrics for these different distributions are presented in Table 4. In cases where the transients are dispersed in intermediate decl. or concentrated in low decl., the degree of cadence deviation is minimal, and the average of airmass is reasonable. However, when the locations of the transients are concentrated in high decl., both the degree of cadence deviation and airmass increase significantly. These variations are attributed to the geographical latitude of existing sites and could be alleviated by establishing telescope sites at the poles.

4.3.2. Different Numbers of Transients

Different numbers of transients for simultaneous observation can significantly influence the realized results of relay observation. Considering the acceptable limit of the degree of cadence deviation, we generate experimental data sets with 10,

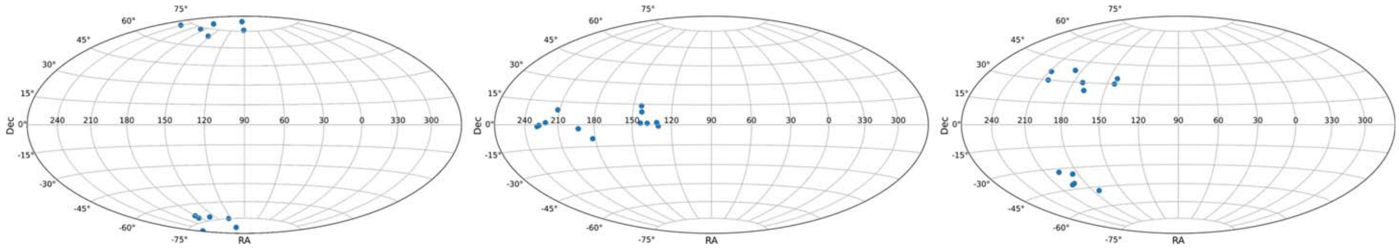

Figure 8. Left: Distribution of transients that are concentrated in high decl. Middle: Distribution of transients that are concentrated in low decl. Right: Distribution of transients that are dispersed in intermediate decl.

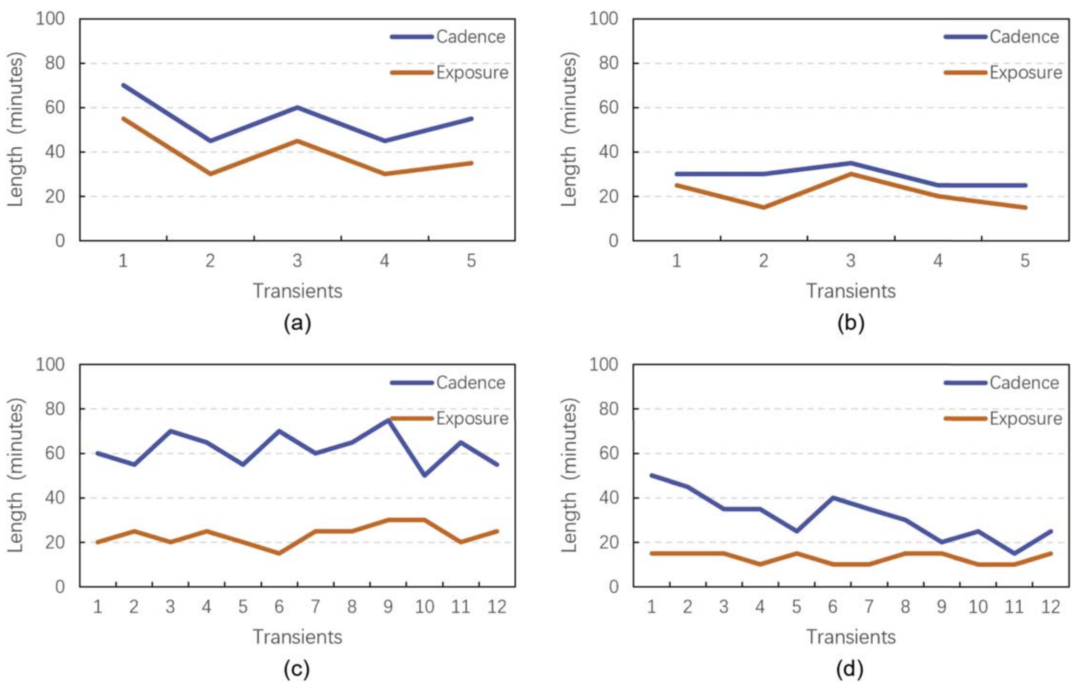

Figure 9. Length of cadence and exposure duration for the transients in different exposure situations: (a) longer exposure duration and cadence; (b) longer exposure duration; (c) longer cadence; (d) the benchmark.

12, and 15 transients for the experiments around the benchmark. The characteristics of other items also remain consistent with the benchmark.

The results of two evaluation metrics derived from the scheduler in these cases are presented in Table 5. When observing 10 or 12 transients, the cadence deviation is very minimal and the average of airmass is at a desirable level. However, when observing 15 transients, the degree of cadence deviation exceeds 30%, compromising the significance of relay observation. Therefore, it is unnecessary to investigate cases involving more transients, as additional telescope resources are required. Moreover, when fewer than 10 transients are involved, telescope resources are clearly abundant, and reasonable scheduling can be achieved without further research.

Table 4
Results for the Evaluation Metrics with Different Distributions

Evaluation Metrics	Distributions of Transients		
	High Decl.	Low Decl.	Dispersed in Intermediate Decl.
Degree of Cadence Deviation	64.34%	9.28%	11.36%
Average of Airmass	1.52	1.25	1.19

4.3.3. Different Exposure Situations of Transients

Transients with different exposure situations, including the exposure duration and the cadence length, have varying impacts on the relay observation. We generate the experimental data sets with different exposure durations and cadences for the

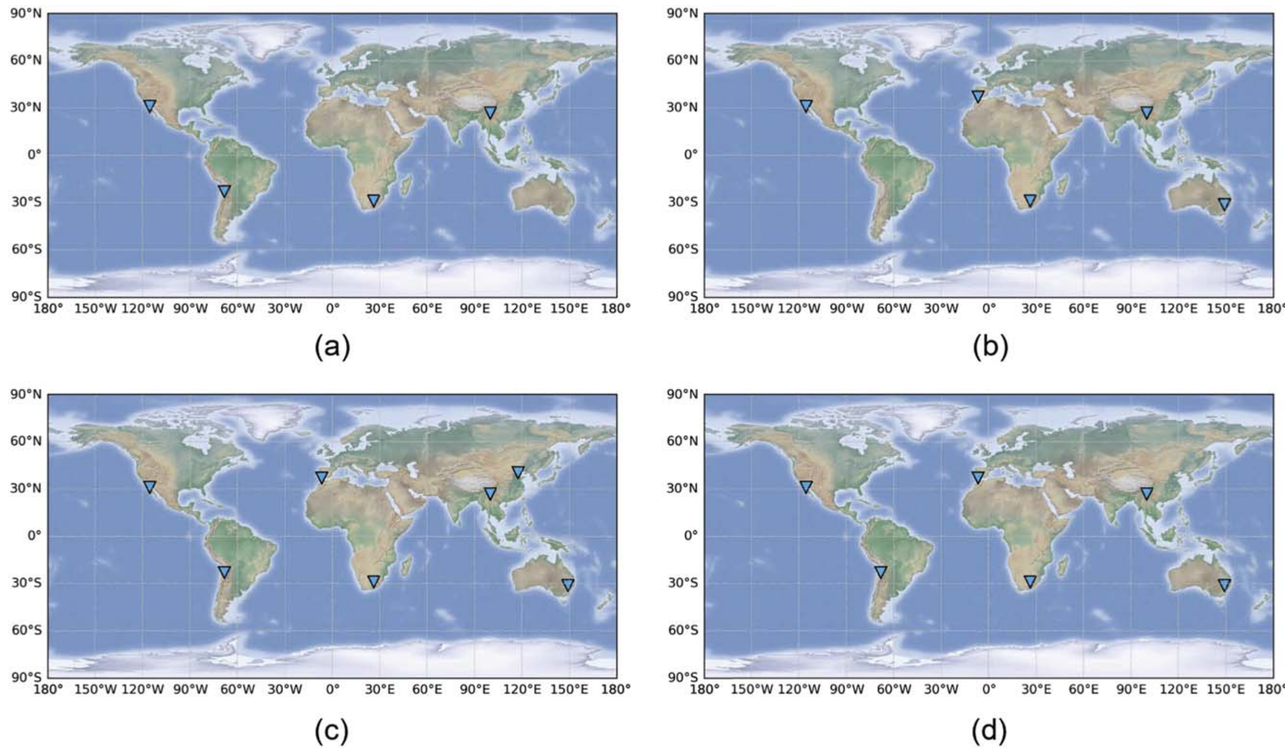

Figure 10. Distributions of different numbers of sites: (a) four sites; (b) five sites; (c) seven sites; (d) six sites.

Table 5
Results for the Evaluation Metrics with Different Numbers

Evaluation Metrics	Numbers of Transients			
	10 Transients	15 Transients	12 Transients	15 Transients (21 Telescopes)
Degree of Cadence Deviation	11.40%	32.01%	11.36%	21.93%
Average of Airmass	1.18	1.19	1.19	1.19

Table 6
Results for the Evaluation Metrics with Different Exposure Situations

Evaluation Metrics	Exposure Situations of Transients			
	Longer Exposure Duration and Cadence (5 Transients)	Longer Exposure Duration (5 Transients)	Longer Cadence	Relatively Short Exposure Duration and Cadence
Degree of Cadence Deviation	20.68%	13.22%	15.39%	11.36%
Average of Airmass	1.20	1.17	1.18	1.19

investigation, as illustrated in Figure 9. The longer cadence is randomly selected from a normal distribution with a mean of 60 minutes. The longer exposure duration is randomly selected from a normal distribution with a mean of 24 or 48 minutes, 80% of the mean of the cadence distribution. Other characteristics remain consistent with the benchmark.

Table 6 presents the evaluation metric results for varying exposure durations and cadences. It is noted that longer exposure durations necessitate more telescope resources, thereby reducing the number of transients that can be observed simultaneously. The reasonable degree of cadence deviation and average of airmass can be achieved when relay observation

Table 7
Results for the Evaluation Metrics with Different Situations of Telescope Resources

Evaluation Metrics	Situations of Telescope Resources					
	12 Telescopes at 6 Sites	12 Telescopes at 4 Sites	16 Telescopes at 5 Sites	21 Telescopes at 6 Sites	21 Telescopes at 7 Sites	18 Telescopes at 6 Sites
Degree of Cadence Deviation	31.78%	59.64%	28.50%	10.38%	7.96%	11.36%
Average of Airmass	1.20	1.21	1.18	1.18	1.17	1.19

of five transients with longer exposure durations is performed. For other cases involving changes in exposure durations or cadences, the degree of cadence deviation remains within acceptable limits, and the average of airmass remains favorable.

4.3.4. Different Situations of Telescope Resources

Experiments with different telescope resources can measure the capability of the scheduler and the significance of telescope distributions. Considering the current state and development of the global telescope network, we focus on a variety of cases with four to seven sites and 12 to 21 telescopes around the benchmark. Site distributions of these cases are shown in Figure 10. Other characteristics remain consistent with the benchmark.

Table 7 presents the results of the evaluation metrics for different telescope resource distributions and numbers. It is evident that a higher number of sites yields better evaluation metrics for relay observation with the same number of telescopes. However, this positive correlation is substantially weakened when the number of sites exceeds six. In addition, the number of telescopes and relay observation results are also positively correlated.

In summary, we generated experimental data across the four aspects reference to the benchmark and conducted experiments sequentially. The experimental data include transients with different decl. distributions (high, low, and intermediate), varying numbers of transients to be observed simultaneously (few, medium, and large), different lengths of exposure durations and cadences (long exposure and cadence, long exposure, long cadence, and short exposure and cadence), and different distributions of telescope resources (varying site distributions and telescope number distributions). These data comprehensively include a broad spectrum of possible cases across the four aspects, covering a wide range of real-world scenarios.

The results from these experiments across four aspects indicate that the observation conditions represented by airmass and the degree of cadence deviation are within reasonable ranges. This suggests that IPROS is feasible in a wide range of real-world scenarios, for implementing relay observation of multiple transients with varying distributions, quantities, exposure durations and cadences, and telescope resources. We confirm that a generalized approach, involving six telescope sites uniformly distributed in both the northern and southern hemispheres, is suitable for implementing relay observation. It is important to place telescope sites at six or more locations.

4.4. Other Feasible Schedulers and Comparative Experiments

Comparison with other schedulers capable of implementing relay observation scheduling, particularly those that do not specifically consider relay observation, and simpler, more direct relay observation schedulers, can demonstrate the value of IPROS and validate the effectiveness of our work. Based on the above analysis of the relay observation scheduling problem, we have identified two schedulers for comparison: one is an astronomical observation scheduler that does not specifically consider relay observation in the modeling; and the other is a greedy scheduler, which prioritizes the observation of transients with fewer available sites to form the observation plan. We name the first scheduler NSROS for the Non-Specific Relay Observation Scheduler, and the second scheduler GTROS for Greedy Thought Relay Observation Scheduler.

The inputs and outputs of these two schedulers are consistent with those of IPROS, and we provide a simple description of their specific processes. For NSROS, we construct a general mathematical model that does not specifically consider relay observation. This model assigns higher observation values to observations that can bring the cadence closer to what is required, and it is solved with observation values and observation conditions as the optimization objectives. For GTROS, we use a greedy strategy that prioritizes transients with fewer available sites in each time slot and prioritizes transients with better observation conditions if the available sites are the same, to obtain the observation plan.

In the experiments, we compare these three schedulers. The experimental design and the results of the evaluation metrics for the three schedulers are presented in the following figures and tables. The experimental inputs include different distributions of transients, different numbers of transients, different exposure situations, and different telescope resources, as in Section 4.3. These inputs comprehensively demonstrate the ability of the three schedulers to address the challenge of relay observation for multiple transients.

It is important to note that, as demonstrated in Section 4.3, when transients are concentrated in high decl. or the number of telescope sites is limited to four, the degree of cadence

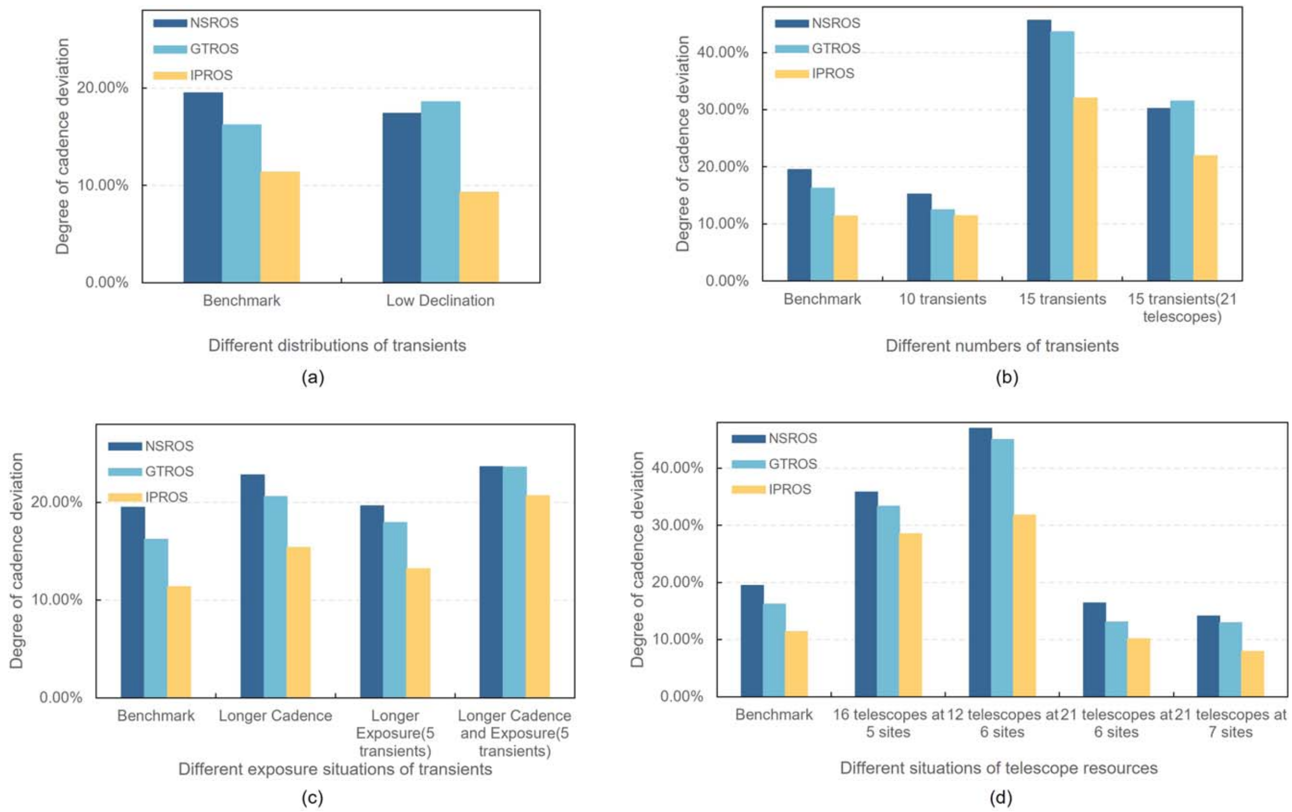

Figure 11. The degree of cadence deviation for IPROS, NSROS, and GTROS, with different transients and sites: (a) different distributions of transients, corresponding to Table 8; (b) different numbers of transients, corresponding to Table 9; (c) different exposure situations, corresponding to Table 10; (d) different situations of telescope resources, corresponding to Table 11.

Table 8
The Degree of Cadence Deviation for Three Schedulers with Different Distributions of Transients

Degree of Cadence Deviation	Distributions of Transients	
	Benchmark	Low Decl.
NSROS	19.49%	17.39%
GTROS	16.23%	18.60%
IPROS	11.36%	9.28%

Table 9
The Degree of Cadence Deviation for Three Schedulers with Different Numbers of Transients

Degree of Cadence Deviation	Numbers of Transients			
	Benchmark	10 Transients	15 Transients	15 Transients (21 telescopes)
NSROS	19.49%	15.17%	45.64%	30.17%
GTROS	16.23%	12.44%	43.61%	31.47%
IPROS	11.36%	11.40%	32.01%	21.93%

Table 10
The Degree of Cadence Deviation for Three Schedulers with Different Exposure Situations

Degree of Cadence Deviation	Exposure Situations of Transients			
	Benchmark	Longer Cadence	Longer Exposure (5 Transients)	Longer Cadence and Exposure (5 Transients)
NSROS	19.49%	22.81%	19.65%	23.65%
GTROS	16.23%	20.59%	17.93%	23.62%
IPROS	11.36%	15.39%	13.22%	20.68%

deviation becomes excessively large. Under such conditions, a comparison of the three schedulers is no longer necessary, as it lacks practical significance. Therefore, comparisons of these specific cases are omitted.

We present the results of the degree of cadence deviation in Tables 8, 9, 10, and 11 for different distributions of transients, different numbers of transients, different exposure situations, and different telescope resources, respectively. Compared to GTROS, the results of IPROS demonstrate improvements of at

Table 11
The Degree of Cadence Deviation for Three Schedulers with Different Telescope Resources

Degree of Cadence Deviation	Situations of Telescope Resources				
	Benchmark	16 Telescopes at 5 Sites	12 Telescopes at 6 Sites	21 Telescopes at 6 Sites	21 Telescopes at 7 Sites
NSROS	19.49%	35.84%	46.95%	16.39%	14.11%
GTROS	16.23%	33.31%	45.01%	13.09%	12.96%
IPROS	11.36%	28.50%	31.78%	10.14%	7.95%

Table 12
The Average of Airmass for Three Schedulers with Different Transients and Sites, Part 1

Average of Airmass	Benchmark	Distribution of Transients	Numbers of Transients		
		Low Decl.	10 Transients	15 Transients	15 Transients (21 Telescopes)
NSROS	1.18	1.25	1.17	1.19	1.19
GTROS	1.18	1.25	1.17	1.18	1.18
IPROS	1.19	1.25	1.17	1.18	1.19

Table 13
The Average of Airmass for Three Schedulers with Different Transients and Sites, Part 2

Average of Airmass	Benchmark	Exposure Situations of Transients			Situations of Telescope Resources			
		Longer Cadence	Longer Exposure	Longer Cadence and Exposure	16 Telescopes at 5 Sites	12 Telescopes at 6 Sites	21 Telescopes at 6 Sites	21 Telescopes at 7 Sites
NSROS	1.18	1.19	1.17	1.22	1.18	1.21	1.18	1.17
GTROS	1.18	1.20	1.17	1.21	1.18	1.18	1.18	1.17
IPROS	1.19	1.18	1.17	1.20	1.18	1.20	1.18	1.18

least 5% across different transient distributions and different telescope resources. For different numbers of transients and different exposures, the results show enhancements of at least 3%. Notably, in certain specific cases, the improvements in results exceed 10%. When compared to NSROS, IPROS exhibits significantly better performance across all four aspects, with improvements generally exceeding 5% and reaching around 10% in some cases. To make the comparison of the three schedulers more intuitive, these results are shown in Figure 11. It is apparent that IPROS consistently outperforms the other two schedulers by a margin of more than 5% in most cases. The results of IPROS are not worse than those of the other two schedulers in all four aspects. Considering that the degree of cadence deviation in our comparison experiments cannot be excessively large, the advantage of IPROS is significant.

Regarding the average of airmass for the three schedulers, IPROS, NSROS, and GTROS in all cases, as detailed in Tables 12 and 13, there are no significant differences between them.

In summary, the scheduler IPROS significantly surpasses other schedulers in cadence deviation, which is a more important metric, when applied for relay observation and monitoring of multi-transients. While the observation conditions represented by airmass are similar for the three schedulers, it can be concluded that IPROS achieves better relay observation.

5. Conclusions

In the future, there will be an increase in the number of transients with scientific value to monitor as the large observation projects represented by the ZTF and LSST become more widely used. The relay observation of these transients aids astronomers in studying their variations and advancing the development of time-domain astronomy. The numerous transients necessitate the automated relay observation scheduling, requiring that telescopes distributed across different longitudes can be effectively coordinated, forming the telescope array. Therefore, it is imperative to research the scheduler for the relay observation of telescope array.

This paper describes the relay observation process of telescope array and proposes IPROS, a relay observation scheduler for telescope array based on the integer programming model. The relay observation according to the observation plan generated by this scheduler can not only achieve a closer match to the required cadence but also ensure better observation conditions when the telescope array monitors multiple transients.

The model involved in the scheduler appropriately describes and addresses the telescope array relay observation scheduling problem. The optimization objective of minimizing the cadence deviation, articulated in the model, is described through a specific algorithm. This objective ensures the coordination of the cadence. Additionally, the scheduler can fulfill the recalculation and long-term monitoring requirements in relay observation scheduling, ensuring the successful implementation of relay observation.

The results from experiments conducted with various transients and sites as inputs demonstrate that the observation plan generated by IPROS is feasible in a wide range of real-world scenarios and effectively addresses the relay observation scheduling problem. Comparative experiments with the two designed direct schedulers, NSROS and GTROS, demonstrate that IPROS holds a 5% advantage in most cases. However, it should be noted that IPROS is more suitable for dealing with scheduling problems with numerous transients. The advantage of IPROS over direct schedulers, NSROS, and GTROS, will be relatively weaker when dealing with scheduling problems where the number of transients is significantly less than the telescope resources.

In future research, considering that the exposure duration and cadence of each transient may not remain constant, along with other functions of telescope arrays, we will further improve and refine the scheduler. This enhancement will enable it to adapt to the changing exposure duration and cadence and to integrate with other astronomical observation scheduling.

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