The Automatic Observation Management System of the GWAC Network. I. System Architecture and Workflow

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Abstract

The Ground Wide Angle Camera Network (GWAC-N) is a network of robotic multi-aperture, multiple field-of-view (FoV) optical telescopes. The main contingent of GWAC-N instruments are provided by the Ground Wide Angle Cameras Array (GWAC-A), and additional, narrower FoV telescopes are utilized to provide fast multi-band follow-up capabilities. The primary scientific goal of the GWAC-N is to search for optical counterparts of gamma-ray bursts that will be detected by the Space Variable Object Monitor (SVOM) satellite. The GWAC-N performs many additional observing tasks including follow-up of Target of Opportunities (ToO) targets and the detection (and monitoring) of variable objects and optical transients. To handle these use cases (and to allow for extensibility), we have designed ten observation modes and 175 observation strategies, including a joint strategy with multiple GWAC-N telescopes for the follow-up of gravitational wave (GW) events. To perform these observations, we develop an Automatic Observation Management (AOM) system capable of performing object management, dynamic scheduling, automatic broadcasting across the network, and image handling. The AOM system combines the individual telescopes which comprise the GWAC-N into a network and smoothly organizes all associated operations, completely meeting the requirements dictated by GWAC-N. With its modular design, the AOM is scientifically and technically viable for other general-purpose telescope networks. As the GWAC-N extends and evolves, the AOM will greatly enhance its discovery potential. In this first paper of a series, we present the scientific goals of the GWAC-N and detail the hardware, software, and workflow developed to achieve these goals. The structure, technical design, implementation, and performance of the AOM system are also described in detail. We conclude with a summary of the current status of the GWAC-N and our near-future development plan.

Unified Astronomy Thesaurus concepts: Optical observation (1169); Automated telescopes (121)

1. Introduction

In the last decade, a new paradigm of networked telescope operations has emerged due to modern computing and communication technologies. Examples include the Las Cumbres Observatory Global Telescope (RCOGT, Brown et al. 2013), the Global Relay of Observatories Watching Transients Happen (GROWTH, Kasliwal et al. 2019), the All-Sky Automated Survey for Supernovae (ASAS-SN, Shappee et al. 2014), the Robotic Optical Transient Search Experiment (ROTSE, Akerlof et al. 2003), the Pan-STARRS Survey (Chambers et al. 2016), the Rapid Action Telescope for Transient Objects (TAROT, Boër et al. 1999), and the Master-Net (Lipunov et al. 2010). The incorporation of distinct observing facilities into larger (sometimes global) coordinated networks greatly enhances discovery and follow-up capacity, and will likely play a key role in multi-messenger astronomical studies in the coming decade. There are, however, challenges that remain in scaling and deploying such networks;
most notably, organizing and scheduling. These challenges stem largely from the fact that individual facilities are often designed only for a specific purpose, which in turn dictates different telescope sizes, photometry parameters, and control techniques. As a result, human intervention is still substantially involved in the scheduling process for most modern networks (Mora & Solar 2010, pp. 111–120).

Under the framework of the Chinese-French Space Variable Object Monitor (SVOM) mission, an array consisting of nine Ground-based Wide-Angle Cameras (GWAC-A) has been designed to simultaneously search for the optical prompt emission of gamma-ray bursts (GRBs) detected by the SVOM’s onboard gamma-ray instruments (ECLAIRs and GRM, Cordier et al. 2015; Wei et al. 2016). In addition, several robotic, multi-band, small Field of View (FoV) telescopes have been deployed to automatically validate and follow candidates detected by the GWAC-A. Combining the wide FoV telescopes which comprise the GWAC-A with these additional telescopes in a well-organized network yields better observational coverage and detection performance that enables multiple tasks, including large-sample surveys and the observation of periodic and quasi-periodic objects, transient targets, and moving objects. Successfully performing these observations depends not only on instrument properties but also on the network’s ability to provide efficient communications, observation scheduling, observation controlling, and data processing between all incorporated telescopes. These functions, combined with the nature of different scientific targets, require the network to implement different observation strategies optimized for specific use cases, all the while balancing limited telescope resources and competing targets. We, therefore, develop an automatic observation management system (AOM) to integrate the facilities and software into the GWAC network (GWAC-N), named as such because the majority of the network is comprised of the GWAC-A. The AOM system provides target management, fully automated dynamic observation scheduling, autonomous telescope dispatching, and data management. The system greatly enhances the efficiency of the GWAC-N by enabling automatic multi-target, multi-telescope, simultaneous joint observations. With a modular data interface, this system is readily adaptable to other applications in time-domain astronomy and can be extended to other collaborative telescopes.

In 2014, 12 mini-GWAC telescopes (the pathfinder telescopes of the GWAC-A) started operation in the GWAC dome at Xinglong observatory (Huang et al. 2015). Two 60 cm follow-up telescopes (GWAC-F60A/B) were installed in 2015 and achieved first light the same year. The first GWAC mount equipped with four Joint Field of View (JFoV) cameras and one Full Field of View (FFoV) camera was installed and tested in 2017. In 2018, two fully equipped GWAC mounts, two GWAC-F60A/B, and one GWAC-F30 were in operation.

Figure 1 shows the dome and telescopes of the GWAC-N. Although the telescopes were in place at this time, they were not yet connected as a network and were thus operated separately and controlled by two observation assistants. In this uncoordinated state, response speed and observation efficiency were low, making the facility’s capabilities for studying scientific targets suboptimal. Thus, the AOM system was developed in 2019 to integrate the hardware and software of the GWAC-N to fulfill the scientific requirements described in Section 4. In late 2019 and early 2020, the Tsinghua-NAOC (National Astronomical Observatories of China) Telescope (TNT) at Xinglong Observatory and the Chinese Ground Follow-up Telescope (CGFT) at Jilin Observatory entered a collaboration with the GWAC-N as external partners by taking advantage of the ToO alert processing and management capabilities of the AOM. As of 2020 December, the GWAC-N meets all scientific requirements of the network, thanks to the AOM. The complete GWAC-N will comprise nine mounts equipped with 36 JFoV and nine FFoV cameras, with several additional follow-up telescopes. Two sites and advanced CMOS detectors are expected to be utilized by the GWAC-N in the near future, with the exact development timeline depending on future funding levels and the maturity of new technologies. Since the GWAC-N is still under development and evolving, this paper describes the structure of the network based on its current configuration.

In this paper, we present the GWAC-N’s telescopes, the AOM system, and the opportunities and science outputs that the GWAC-N will pursue. The remainder of the paper is organized as follows. Section 2 describes the structure of the GWAC-N and its instruments, including internal telescopes and those from external partners. In Section 3, we present the AOM that we developed for performing multi-purpose, flexible, highly efficient observations. We describe the scientific opportunities planned for study via the GWAC-N in Section 4. We discuss the limitations of the AOM, along with solutions and open questions in Section 5. In Section 6, we summarize the current status of the GWAC-N and describe prospects for the near future.

2. System Structure of the GWAC-N

The entire apparatus of the GWAC-N (shown in Figure 2) comprises three main parts: the target input interface, the AOM system, and the telescopes. In this section, we describe the target input interface and the telescopes. The AOM system is described in Section 3.

2.1. Target Input Interfaces

The GWAC-N provides multiple external interfaces to connect with various alert streams, survey/catalog planners, the GWAC-A
self-detected transient validation system (Xu et al. 2020b), and scientists. All automatic or manual observation requests are inserted into the system via these interfaces.

During the O3 run of LIGO/Virgo, the SVOM team developed the Gravitation Wave Skymap Processor (GWSP) at Irène Joliot-Curie Laboratory (IJCLab at CNRS/IN2P3), France. The GWSP ingests LIGO-produced GW sky maps and produces an optimized tiling observation strategy based on the telescope parameters of the GWAC-A, the GWAC-F30, and the CGFT. Using the Mangrove galaxy catalog (Ducoin et al. 2020b), the GWSP can create optimized galaxy lists for small FoV telescopes like the GWAC-F60A/B. The format of the tiling coordinates and galaxy lists are standard, and therefore, can be readily broadcast to other telescopes; e.g., the GRANDMA (the Global Rapid Advanced Network Devoted to the Multi-messenger Addicts) network (Antier et al. 2020). The tiling and galaxy lists are sent to the Chinese Multi-Messenger (CMM) server using the VOEvent protocol via brokers. The CMM Service can also receive GRB and neutrino alert streams from GCN public access by using the pygcn\(^{11}\) code. The GWAC-N provides an interface to automatically receive GW alerts from the CMM in real time.

We utilize several observation planning codes to create target lists for each telescope while performing routine observations. Each planner can insert the target list into the AOM using a client provided by the GWAC-N. The GWAC-N also accepts observation requests from scientists via a tool which allows for customized parameters and complex observation programs either for fast ToO follow-up or for long-term monitoring. The GWAC-N has another type of target: the self-detected transient candidates of the GWAC-A validated by the Real-time Automatic transient Validation System of the GWAC-N (RAVS, Xu et al. 2020b). The target needs to be

\(^{11}\) https://github.com/lpsinger/pygcn/
quickly identified and followed up by the GWAC-F60A/B. Therefore, an interface has been developed for real-time communication between the RAVS and the AOM. These tools provide observation requests containing the following information: target data (name, type, coordinates, priority, and ranking number for the multi-messenger ToO), observation parameters (instrument, observation mode, filter, and exposure time), and long-term planning information (begin and end date, frequency of observation).

2.2. Telescopes

The GWAC-A telescopes are the main instruments of the GWAC-N. Two are being operated (and two more are currently being tested) at the Xinglong Observatory (latitude = 40°23′39″N, longitude = 117°34′30″E), funded by the National Astronomical Observatories (NAOC, Chinese Academy of Sciences). Each GWAC-A mount is equipped with two types of cameras:

1. the Joint Field of View (JFoV) camera consists of a refractive lens with an aperture of 180 mm, and is equipped with 4k × 4k CCD camera. The FoV of a JFoV camera is ≈12°8 × 12°8. The CCD camera consists of a 4K E2V chip and a customized liquid cooler system, which allows the CCD to operate at −50 °C relative to the local environment. Four cameras are installed on a connection frame with an angle adjustment mechanism. By carefully adjusting the pointing angles of the cameras, the four JFoV cameras cover a square sky field. The collective FoV for one mount (i.e., four JFoV cameras) reaches ≈ 25° × 25°. The limiting magnitude of the JFoV camera reaches $R$-band $\sim$16 mag for a single image (10 s exposure) on a dark night without clouds. By stacking images, a typical limiting magnitude of $R$-band $\sim$18 mag is obtained.

2. the Full Field of View (FFoV) camera, a SIGMA 50mm F1.4 lens with an aperture of 3.5 cm, is equipped with an Apogee U9000X 3k×3k CCD camera. The FoV of a FFoV camera is ≈30° × 30°, which covers roughly the same area on the sky as the collective FoV of the four JFoV cameras. The FFoV performs guiding and extends the optical flux coverage to $R$-band $\sim$6 mag at the bright end.

Both cameras work in the clear band (i.e., without a filter) and with variable image cadences depending on objectives (typically 15 or 25 s). An automatic focusing mechanism developed by Huang et al. (2015) is employed to obtain optimal image quality during observation. We define a pre-planned grid format, in which the sky is partitioned into 148 fixed grids whose sizes fit the GWAC-A mount’s FoV, see Figure 3. The grid format is adopted for the GWAC-A telescopes to carry out all types of observation modes.

Remote control via data link is available for these automated GWAC-A telescopes. This combined with the features described above make the GWAC-A well suited for the optical follow-up of multi-messenger events. The real time catalog cross-matching, stacking image analysis, and transient classification pipeline provide the GWAC-A with the capability to independently detect both fast and slow optical transients.
Two robotic GWAC-F60A/B telescopes and one robotic GWAC-F30 telescope are installed inside the GWAC dome. The GWAC-F60s are used for automatic validation of the GWAC OT candidates. They have a \( \sim 10 \text{ deg s}^{-1} \) slewing speed and an \( 18' \times 18' \) FoV with 2k \( \times \) 2k Andor iKon-L 936 CCDs. The GWAC-F30, with an FoV of \( 1.8' \times 1.8' \), can complete the gaps of flux coverage and FoV between the GWAC-A and the GWAC-F60A/B. All three telescopes are equipped with Johnson UBVRI filters. With remote control and real-time data processing, they can be readily integrated into the GWAC-N. The parameters of each type of telescope are summarized in Table 1.

By using a customized data link, the GWAC-N can incorporate external telescopes to extend the network. The external network currently includes two telescopes: the 80 cm Cassegrain reflecting TNT telescope located at the Xinglong Observatory of NAOC and the 1.2 m CGFT at the Jilin Observatory of NAOC. The parameters of the TNT can be found in Zheng et al. (2008), Huang et al. (2012) and those of the CGFT are being tested as the telescope is undergoing hardware upgrades.

3. AOM System

For a highly efficient telescope network, a robust observation management system is a key factor. In particular, the use of an AOM is the only reasonable way to scale up operations to tens of telescopes in a single, coherent network (e.g., the GWAC-N). We have therefore developed the AOM system for the GWAC-N to manage all input targets, distribute them to telescopes in the network, and organize observations with multiple strategies. The system consists of the following subsystems: ToO follow-up, target management, a scheduler, a dispatcher, and a CC. The architecture of the AOM is shown in Figure 4. We detail the function of each subsystem in the following subsections.

3.1. ToO Follow-up Subsystem

The ToO follow-up subsystem monitors the CMM database for new alerts. Currently, three types of events are selected for ToO follow up: LIGO/Virgo GW alerts, Swift GRB alerts, and Fermi GRB alerts. The subsystem generates a target (or sequence of targets) with observation parameters (e.g., instrument, observation mode, exposure time) when an alert meets the alert selection criteria. The observation parameters are set based on predetermined observation strategies for different cases, which, along with alert selection criteria, are defined based on the variable behavior of the target and the capabilities of the utilized telescope(s) to increase the chance of detecting the optical counterpart. The details of the selection criteria and observation strategies will be thoroughly described in a subsequent paper (X. H. Han et al. 2021, in preparation).

An external dispatcher automatically provides ToO follow-up observation information to the external telescopes in the GWAC-N. The external dispatcher classifies and filters the alerts before customizing\(^{12}\) the necessary information for each external telescope. Specifically, the dispatcher selects Swift GRB alerts (suitable for the TNT) and broadcasts the GRB coordinates with errors through a socket interface. The TNT receives the socket package by a client connected to the dispatcher in the local network. The CGFT does not have an automatic follow-up system. During the O3 LIGO/Virgo GW observation campaign, the dispatcher sent tiling lists with rankings to the operators of the CGFT via the WeChat Enterprise app\(^{13}\) and via email.

Currently, the GWAC-N does not offer a standard interface for non-GWAC telescopes. However, the GWAC-N can provide information from GRB alert including the alert type, coordinates, error, and signal-to-noise ratio to anyone who has joined the WeChat group or registered in the email list.

3.2. Target Management Subsystem

All targets are stored in a database, which is maintained by the target management subsystem in order to prevent conflicts or duplication during the ingestion of targets across all interfaces. The workflow of the target management subsystem is shown in Figure 5. The subsystem automatically checks the format of inputs and allows scientists and operators to make any necessary corrections. A target input operation can result in the addition of a new target, the update of an existing one, or the deletion of a target from the subsystem. During observation and testing, different interfaces and/or different users could conceivably attempt to input identical targets; these duplicated inputs will be rejected by the subsystem to avoid the waste of telescope resources. On the other hand, the subsystem allows

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\(^{12}\) The external dispatcher interface is bespoke for each external GWAC-N telescope.

\(^{13}\) https://work.weixin.qq.com
Another purpose of the target management subsystem is to build the daily target list during system initiation of the GWAC-N. The subsystem selects the targets from the target database and computes their observable time windows based on the targets’ positions and telescope pointing constraints. The targets and the time windows are then inserted into the daily target list.

### 3.3. Dynamic Scheduling Subsystem

Among its other scientific goals, the GWAC-N aims to provide ToO detection, follow-up, and confirmation. For this purpose, we have developed different observation modes that are comprehensively described in Table 2. The goal of the scheduler is to dynamically generate observation plans for all telescopes to perform their tasks. Therefore, efficiency is not a major factor to be considered by the scheduler. Instead, the priority of targets is the scheduling principle we adopt for the GWAC-N. The scheduler satisfies observation requests for targets with the highest priorities, subject to telescope resource limitations.

To define priority, we first define a set of observation modes for various types of observation requests. Based on the scientific goals of the GWAC-N, each observation mode is given a primary priority, \( p_1 \) (see Table 2). The primary priority for a given mode can be a range of scores to deal with different cases. For instance, in the automatic ToO follow-up mode, the event type, alert version, time delay and signal-to-noise ratio are used to determine the \( p_1 \) score. Targets with higher \( p_1 \) scores can interrupt the observation of targets with lower \( p_1 \) scores.
Aside from the primary priority score, multiple secondary levels of priority are defined to deal with complex relations among the target, observation mode, and telescope. The secondary priority determines the ordering for the targets with the same primary priority in the scheduling process. However, targets with higher secondary priorities do not interrupt observations of targets with the same primary priority. The standard for scoring can be changed from mode to mode and from telescope to telescope. Table 2 shows the parameters that determine the secondary priorities for each observation mode.

As examples, we describe the strategies to define the second and third level priorities ($p_2$ and $p_3$). For the Multi-messenger ToO follow-up observation mode, the rankings of probabilities need to be adopted in both the tiling and the galaxy targeting strategies. In our system, the rankings of tiles and galaxies are defined as $p_2$, while the altitude angle is $p_3$. For the validation mode, the trigger time (receiving time of target in the system) is $p_2$. We assign $p_3$ as the sequential order of each observation (see Xu et al. 2020b, for details of the observation strategy).

When any update is made in the database, the scheduler invokes a target list re-sorting process for each telescope based on the priorities and the observability of the targets. The updates are made not only from the insertion, update, or deletion of a target, but also from starting, finishing, or breaking an observation. Therefore, the scheduler constantly re-sorts during observations. We use two tables in Figure 6 to demonstrate the sorting sequence during a night of observing to show the result of sorting (left: unsorted, right: sorted). The targets are listed in order of primary and secondary priorities in the right table. Green cells show the targets that have observable time windows longer than 30 minutes. The yellow row shows a target that is currently unobservable but can be observable later in the night. This target will not be sorted until it becomes observable. Other targets shown in gray including the ones that are already completed or have no observation time windows (or very short time windows) that night, are removed from consideration.

Since some factors determining the secondary priorities, such as altitude, hour angle, angular distance to the current coordinates of telescopes, are continuously changing, the secondary priorities are re-calculated before each scheduling process. After re-sorting, the observation plans are refreshed with the new target list and updated exposure settings. Each time, the dispatcher picks the first target in the list for a given telescope. The priority, observability, status of observation and telescope are constantly updated, which makes the scheduling dynamic.

### 3.4. Dispatching Subsystem

The scheduler does not send any observation commands to the telescope controller; instead we use a dispatching system which consists of a dispatcher for GWAC-N internal telescopes and another for those from external partners.

The internal dispatcher submits observation commands to the GWAC-N telescope controller via a one-way link after receiving an observing plan from the scheduler and checking the availability of the assigned telescope. The observation status is obtained through a link between the monitor server and a client. The observation status is obtained through a link between the monitor server and a client. The dispatcher starts multiple threadings to different telescopes. The work flow is shown in Figure 7. The dispatcher starts multiple threads to different telescopes, and we treat multiple telescopes of the same type as one. If one telescope in the group is available, the dispatcher will check the observability of the target. If yes, an observation command will be sent to the telescope controller. If all telescopes are observing, the dispatcher compares target priorities; If a new target has higher priority than those being observed, it can interrupt an observation. The dispatcher constantly monitors the observation status from the observation status monitor, and the actions of the dispatcher are based on that real time status. Completion of an observation on any telescope will immediately trigger new scheduling and dispatching processes, which keeps all telescopes busy during...
| Observation Mode        | Grades of Primary Priority | Factors of Secondary Priorities                  | Telescope                  | Notes                                                                 |
|------------------------|----------------------------|-------------------------------------------------|----------------------------|----------------------------------------------------------------------|
| routine                | 10–19                      | altitude, observable duration, moon distance     | GWAC-A                     | including surveys with GWAC-A                                        |
| normal target          | 20–29                      | altitude, distance of slewing                    | GWAC-F60, GWAC-F30         | including automatic and manual monitoring of targets and supernova survey |
| normal queue           | 20–29                      | altitude, sequential order                       | GWAC-F60, GWAC-F30         | including queue observation for periodic objects                      |
| automatic validation   | 40–49                      | trigger time, sequential order<sup>a</sup>       | GWAC-F60, GWAC-F30         | including automatic validation observations of the self-detected targets of GWAC-A |
| manual validation      | 50–59                      | trigger time, sequential order<sup>a</sup>       | GWAC-F60, GWAC-F30         | including manual validation observations of the self-detected targets of GWAC-A |
| automatic ToO follow-up| 60–69                      | probability, altitude                            | GWAC-A, GWAC-F60, GWAC-F30 | including automatic follow-up observations for GW, GRB and neutrino    |
| manual ToO follow-up   | 70–79                      | probability, altitude                            | GWAC-A, GWAC-F60, GWAC-F30 | including manual follow-up observations for GW, GRB and neutrino      |
| revisit ToO follow-up  | 20–29, 30–39, 80–89        |                                                 | GWAC-F60                   | including revisit observation for interesting targets                 |
| calibration            | 90–99                      |                                                 | GWAC-A, GWAC-F60, GWAC-F30 | calibration observation for instruments                                |
| manual                 | 100+                       |                                                 | GWAC-A, GWAC-F60, GWAC-F30 | including manual controlled observations for all telescopes           |

Note.
<sup>a</sup> Xu et al. (2020b).
the night. In this sense, the load on the group of telescopes is evenly distributed.

The observation status monitor running on the telescope side sends status updates back to the server, including command receipts, observation status updates, and completeness alerts. If applicable, an error code is also sent back to the server, which can be used for system error analysis.

3.5. Communications Center

The AOM system is composed of many subsystems and a database. As a result, communications are very complex and frequent among external interfaces, subsystems, and telescopes. To avoid conflicts, a sequential control mechanism is crucial for the AOM system. In an earlier version, all subsystems were directly communicating to the database. When a large number of concurrent entries occur in the database, a protection mechanism is triggered. These chance faults are rare but fatal to our system. Another “stress point” is the scheduler. Unlike the multi-instance dispatcher, only one instance of the scheduler can be run at a time. The AOM system must ensure that the scheduling is well organized in such a complex situation. A sequential controller can solve these communication issues. Therefore, we have developed a communications center (CC) by joining the communicating and sequential controlling functions. The CC provides a communication client deployed on each subsystem. The CC runs a server and many instances (communication modules). An instance is launched when a
A connect request is created by a server or a client running on a subsystem. All messages between the server and the clients are marked with flags to indicate different types of messages. On the server side, the messages will be classified and distributed to the dedicated clients in the proper order. The procedures of observation scheduling and dispatching depend on the ordering of the messages. On the client side, each message will be treated as an independent message, and will thus be processed only by order of arrival. In this paper, we simulate four scenarios to show how the observational procedures are executed smoothly in the GWAC-N. The following scenarios are the most typical cases of communication time sequences during scheduling and dispatching (see Figure 8):

**Case 1.** In the normal case, the procedure starts when a target is added into the target list. The next steps are scheduling, dispatching, and observation. The final step is a re-scheduling process. Specifically, after a new target is put into the target list from an interface (TC1), the target management client will...
process it, format it, and send a message (TM1) with observation parameters to the CC. The message will be added to a message list organized by a sequencer in the CC. The target message is instantaneously sent to an instance of the scheduler (SC1) that will start to make an observation plan. The scheduler generates the observation plans not only for that new added target but also for all observable targets in the target list. After the scheduling is done, a message with a scheduling status (SM1) is returned back to the CC, then a command of dispatching will start an instance of the dispatcher client (DC1). The dispatcher client decides to choose a target with top priority from the target list for the next observation or to await completion of the current observation. There are multiple instances of dispatcher clients running simultaneously to control different telescopes. The client of the dispatcher sends messages (DM1) to inform the CC when the observation is started and finished. After the observation is done, the scheduler client receives a command from the CC to start rescheduling to update the observation plans. The instance of the dispatcher client is closed at this point, marking the end of the overall procedure.

Case 2: When a target is added to the target list, the scheduler will first compute the observational time window. The one without the observational time window from TC2 will not be scheduled. The instance of the scheduler (SC2) will still communicate to the CC for the scheduling status (SM2) to...
inform the dispatcher (DC2) of the update of the target list. The procedure ends at the dispatcher (DC2).

**Case 3.** In certain cases, multiple telescopes are needed to observe one target (e.g., when synchronized multi-band photometry is performed for a target). In Figure 8, we assume that two telescopes are used in such a circumstance. After receiving target information from an interface (TC3), the scheduler (SC3) generates two observation plans for two telescopes, respectively. Then the CC starts the first instance of a dispatcher client (DC3); the second instance (DC4) will not be started until the CC gets a feedback message (DM3, the starting status of observation) from the DC3. Then, the DC4 sends an observation command to the second telescope and observation status message (DM4, the starting status of observation) to the CC. When the DC3 receives the observation completion message, the SC3 will start the re-scheduling process. In the meantime, the DC4 obtains the status of the second observation, but the message transmission (from DM4 to an instance of SC4) is put on hold until the observation plans are refreshed by the SC3. Then the SC4 is started. The procedure is finished when the SM4 is received.

**Case 4.** In this case, dozens or even hundreds of targets are added into the system at nearly the same time. This situation happens frequently during Multi-Messenger follow-up observations. We simulate the scenario when two targets (TC5 and TC6) are inserted at the same time. A scheduler instance (SC5) is started immediately when the message of target (TM5) is transmitted. The SC5 and a dispatcher client (DC5) are executed successively. The message (TM6) for the second target (TC6) will be transferred after the status message (DM5, the starting status of observation for the TC5) is received. Then the second instance of the scheduler (SC6) and a dispatcher client (DC6) are executed for the TC5. The observations and re-scheduling are finished for the TC5 and the TC6, the procedures ends.

In the procedures described for each case above, both the actions of scheduling and dispatching are triggered by dedicated messages. The sequential controller organizes the messages properly, preventing sequential confusion during observations.

### 3.6. AOM System Workflow

On top of the specifics of its subsystems as described above, the overall workflow of the AOM system is as follows. Targets are manually or automatically inserted into the system via system-provided interfaces (all observation requests are treated as targets). All targets are processed and classified by the target management subsystem before insertion into the target database. Some targets are sent by the external dispatcher to trigger follow-up observations with external telescopes. The targets for the GWAC-N will be initially scheduled in order to compute the observation time windows and to make the initial observation plans. The targets having observation time windows are added to the daily target list and stored in the database. This daily target list contains all the targets to be observed in a given night. This list is kept updated during the night as new targets come in, observation parameters and status of targets are updated, and when targets are removed from the list. Triggered by the CC, the dynamic scheduler makes observation plans for the targets in the target list, and the dispatcher selects a target to observe based on the observation plan, status of observations, and the status of the telescopes. The observation status monitor keeps observation statuses updated in the target list, so that the scheduling and dispatching can be fully dynamic. The system completes a closed control loop (shown in Figure 9).

### 3.7. Performance of the AOM System

Via the AOM, the GWAC-N integrates five internal and two external telescopes. By using the standard link provided by the AOM, the telescopes can easily join the network. The AOM also provides a customized link for external telescopes, which is an efficient option for those telescopes willing to join ToO follow-up campaigns without developing their own dedicated systems. The AOM can perform complex observations with (currently) ten observation modes and 175 strategies. To add or modify observation modes or strategies, users only need to edit a configuration file. During operations, the AOM provides many automated features, including target monitoring, GWAC OT validation, and ToO follow-up observations. Operators oversee the overall operation status and manually import targets with special observation requirements into the system.

The communication mechanism and system structure of the AOM ensure the stability of the system, which is another key factor for a robotic telescope network. The AOM has been implemented in the GWAC-N since August 2019. During the observation season of 2019–2020 (from October to April, weathers are better and night time is longer comparing with the rest of the year), the AOM is working with a high duty cycle and stable behavior. The AOM produced 622 observation plans per clear night on average (in 2020 December), with failure-free. On December 7th, the AOM produced 1064 observation plans, which is the highest working load in the month.

The efficiency of the AOM can be assessed by the time delay between target insertion and the issuance of an observation command. Reducing this time delay is very important for a ToO-oriented observation network. The delay is usually caused by communications, scheduling, and the observation status monitoring process. In the AOM, the main contributor is the scheduling process, which depends mainly on the number of targets in the target list. This is because once an observation is finished, the AOM will start a re-scheduling process for all targets in the list and send an observation command to a telescope. In 2020 December, the list contained an average of
1500 targets per night. On 2020 December 7, the AOM handled 3955 targets, which is the largest number for a night in that month. We investigated the time delay of each rescheduling process during that night. The longest is 0.33 s, which is negligible in comparison with the delay on the telescope side between stopping the previous exposure and starting a new observation. Moreover, we simulate the scenario of observing 15,000 targets with 10 telescopes (i.e., ten times the average number for the GWAC-N). The time for rescheduling is about 1.2 s, which makes the AOM qualified for all types of the ToO follow-up tasks for the GWAC-N. The results of the simulation are shown in Figure 10.

4. Scientific Opportunities and Output to the GWAC-N

The primary goal of the GWAC-N is to observe the prompt emission of GRBs in optical bands. We emphasize the capabilities of the telescopes of the GWAC-A with regard to this mission: e.g., their large sky coverage, high time resolution, and real-time transient detection capability. These features allow the GWAC-A to independently search for optical transients with a high cadence. Furthermore, the GWAC-A can be also used for follow-up observations of multi-messenger events. The associated multi-band small FoV telescopes in the GWAC-N are originally designed for the real-time automatic validation for the optical transients detected by the GWAC-A. These telescopes can be also used for other purposes, such as photometry of variable objects, galaxy targeting observations for multi-messenger events, and supernova surveys.

4.1. Gamma-Ray Bursts

The prompt emission of GRBs in optical bands is difficult to observe, owing to their very rapid temporal decays. To observe such a prompt emission, the response speed of telescopes to a GRB alert must be high. The idea behind the design of the GWAC-A is to eliminate the response time to a GRB alert. The total sky coverage of the full GWAC-A is as large as 5000 square degrees, which can cover the same sky area being monitored by the ECLAIRs telescope, the main GRB detector of SVOM (Wei et al. 2016). This extremely large sky coverage guarantees that the GWAC-A simultaneously discovers the optical counterparts for about 30% SVOM-detected GRBs at trigger time (T0). It also makes the GWAC-A a suitable
instrument to follow up the GRBs detected by other gamma-ray instruments, which cannot provide accurate localizations (e.g., the Fermi Gamma-ray Space Telescope).

The two GWAC-F60A/B telescopes and the GWAC-F30 telescope in the GWAC-N robotically follow-up the GRBs detected not only by SVOM but also by the Swift satellite. Since 2016, these three telescopes manually followed up six Swift GRBs (Xin et al. 2016, 2017a, 2019c, 2019d, 2019e; Han et al. 2018b). Since 2020, the AOM automatically followed up six Swift GRBs by using GWAC-A, GWAC-F60 and TNT telescopes (Xin et al. 2020a, 2020b, 2020e, 2021a, 2021b, 2021c, 2021d). For GRB 201223A, the optical counterpart was detected in a GWAC-A image taken at 2 s after the burst. The GWAC-F60A started follow-up observations for the counterpart 23 s after receiving the alert of the burst and 44 s after the burst trigger. These observations can provide consecutive light curves from the prompt emission phase to the afterglow phase (Xin et al. 2020a, 2020b).

4.2. Multi-messenger Target-of-opportunity Astronomy

The poor localization of Multi-Messenger Target-of-Opportunities (ToO-MM) alerts is a great challenge for all optical follow-up facilities. To quickly search for optical counterparts in a large sky area, two observation strategies are widely used by most optical telescopes for ToO-MM follow-ups: (i) tiling the large localization regions or (ii) performing galaxy-targeted observations. By using all the telescopes controlled by the AOM, the GWAC-N can conduct efficient follow-up observations with both strategies. Taking advantage of the wide FoV telescopes, GWAC-A can cover a significant portion of the ToO-MM localization regions in a very short amount of time by using the tiling strategy. At the same time, the GWAC-F60A/B and GWAC-F30 carry out galaxy targeting observations. As a group, three telescopes can search ~500 galaxies in a clear night. During the O2 and O3 GW runs, the pathfinder telescopes mini-GWAC array and the GWAC-A performed follow-ups of large sky covering for 25 GW events (8 in O2 and 17 in O3, Leroy et al. 2017; Xin et al. 2017b, 2019a, 2019b, 2020d; Wei et al. 2017a, 2017b, 2017c, 2017d, 2017e, 2017f, 2019a, 2019b, 2019c, 2019d, 2020; Dornic et al. 2019; Gotz et al. 2019; Han et al. 2019; Lachaud et al. 2019; Turpin et al. 2019a, 2019b, 2019c, 2019d, 2020b; Wang et al. 2019, 2020a, 2020b; Wu et al. 2019; Ducoin et al. 2020a, 2020c; Mao et al. 2020).

4.3. Optical Transient Targets

Thanks to the large sky coverage of the GWAC-A, the fast follow-up capability of the GWAC-F60A/B and GWAC-F30,
and the dedicated online data processing pipeline of each telescope, the GWAC-N is not only able to independently detect optical transients in the sky, but also to identify the types of candidates in real time. Since 2018, the GWAC-N has detected several super stellar flares (Han et al. 2018a; Wang et al. 2020c; Xin et al. 2018, 2020c). The GWAC 181229A, a super flare with an amplitude of $\Delta R \sim 9.5$ mag was detected by the GWAC-A and was classified as an ultracool M9 type star by the photometric follow-up of GWAC-F60A and spectroscopic observations of the NAOC 2.16 m telescope (Xin et al. 2020c).

The routine survey mode of the current GWAC-A covers $\sim 20,000$ square degrees of observable sky (galactic plane not included) on a clear night. The center of the sky coverage of the survey shifts $\sim 1$ degree in longitude each day, while most of the survey area is consistent in successive observation nights, which means a supernova survey with 1 day cadence can be made using the GWAC-A data. We adopt the ASAS-SN supernova detection relation (Figure 6 in Holoien et al. 2017) to estimate the detection rate of the GWAC-A. With limiting magnitudes of $m_R \sim 16$ mag in a single image and $\sim 200$ clear nights per year at the GWAC site, we estimate that the GWAC-A is capable of detecting around 30 bright, nearby supernovae per year by using a dedicated pipeline.

4.4. Variable and Periodic Objects

Much of the sky coverage of the GWAC-A’s survey is consistent over successive observation nights, which means that a given sky area can be monitored for dozens of days. With a high cadence observation mode (15 s per image), the GWAC-A can monitor variable or periodic objects in the sky area and obtain their variation. The online data processing pipeline of the GWAC-A can measure the photometric features for all sources in the images. Using a neural network mechanism, researchers have analyzed the massive data set of the GWAC-A to detect and to classify variable and periodic sources (Qiu et al. 2018; Turpin et al. 2020a).

4.5. Moving Objects

With its large field of view and high cadence, the GWAC-A can monitor hundreds of asteroids on an observation night. The GWAC-A also has the capability to detect decameter asteroids and meteors (Shugarov 2019; Xu et al. 2020a). Our team works on the algorithms and database that are responsible for recognizing and morphologically classifying them from the GWAC data. Figure 11 shows moving objects automatically detected in the GWAC-A images by an algorithm for selecting moving objects. An accuracy of over 85% can be reached for meteor candidate selection by using this algorithm (Xu et al. 2020a).

5. Discussions

In the GWAC-N, the goals and working tasks of different types of telescopes are not the same. The main goal of the GWAC-A is to search for the optical counterparts of GRBs on timescales of minutes. We also expect that the GWAC-A can detect stellar flares with durations from a few minutes to several hours. As a result of these goals, the observation strategy of the GWAC-A can be configured between maximizing sky coverage per night or maximizing monitoring time per sky field. For the GWAC-F60s, the main goal is to perform ToO follow-up observations and to provide confirmations of the GWAC-A self-detected transients. The observation strategy seeks to maximize the sum of priorities ($p_1$) to ensure observation time for higher valued targets. For instance, a Swift GRB (with $p_1 = 65–69$) is always more important than GWAC-A detected transients (with $p_1 = 41–44$). Particular optimization functions, such as the simple knapsack solver (Martello & Toth 1990) or linear optimization solvers (Lampoudi et al. 2015), may not be feasible for the GWAC-N, and the definition of a global

![Figure 11](image-url). Some moving object images of the GWAC-A. The top parts of images are original, while the bottom parts are residuals. (a) is a meteor candidate, while (b-f) are other types of moving objects including giant planets, minor planets and artificial satellites.
efficiency metric for the GWAC-N is still an open question. The scheduler of the AOM can meet the requirement for each type of observation, although it may not offer an optimum solution for the global efficiency of the GWAC-N.

A target with higher priority can interrupt the observation of one with lower priority, which ensures that the system is responsive. However, only primary priorities ($p_i$) can make interruptions, and in reality, are not frequent. Moreover, since the typical exposure times of the GWAC-N telescopes are short (from 10 to 70 s), the interruption does not cause much waste of telescope time. Therefore, optimization for efficiency is not urgent for the GWAC-N.

Figure 10 shows a simulation of processing times for the AOM scheduler. For a list containing $\sim$10,000 targets, the consuming time of the scheduling process is less than one second. The scheduler spends less than eight seconds in re-processing 100,000 targets, which is at LSST levels of alerts. We separate the functions of target filtering and observability calculating from the scheduling process because the observability calculation is more time consuming than scheduling. We simulate the observability calculation for inserting 10,000 targets at one time, and find that $\sim$170 s are required. In reality, the number of targets in one insertion is from dozens to hundreds, and this process is only performed once after target insertion. Therefore, the consuming time does not affect the performance of the system. If necessary, the program can be updated using multi-threading algorithms which can significantly reduce the consuming time.

6. Summary

The GWAC-N is currently composed of two GWAC telescopes, two GWAC-F60 telescopes and one GWAC-F30 telescope. It is also collaborating with two external telescopes: the CGFT and the TNT. By implementing the AOM, these telescopes can work as a network smoothly. Aside from routine observations, the GWAC-N has performed follow-up observations of LIGO/Virgo GW, Fermi GRB, and Swift GRB events. During the LIGO/Virgo O3 campaign, using the AOM system described in this paper, the GWAC-N observed 17 GW events and published 23 GCN circulars.

In the next two years, the complete GWAC-N will be installed at two observatories. The number of telescopes in the GWAC-N will be extended to nine GWAC-A telescopes and five 60 cm class telescopes. More external telescopes are also foreseen to join the network. The AOM will fully support the operations of the GWAC-N and greatly enlarge the scientific return of the GWAC-N. Its technology and mechanism, or as a whole, the AOM can be adapted to other world-wide, general purposed, telescope networks. The code of the whole AOM system is available at the Gitee\(^{14}\) for public download. Since the dispatching highly relies on the observation status, in the release version (v1.1), the dispatcher is replaced by a tool that allows the user to simulate the observation process without connecting to the real telescope.

The AOM is not only used to manage the operations of telescopes but also to manage the data. In the past, the massive data taken from the GWAC-N telescopes would amount to a significant workload for scientists and operators, but now, ToO follow-up observations taken by the GWAC-F60 and the GWAC-F30 are automatically collected and uploaded to the data center by the AOM. The data center provides centralized data processing, and in the future, we plan to integrate the data processing pipeline to the AOM system altogether.

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14 https://gitee.com/GWAC/aom

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References

Akerlof, C. W., Kehoe, R. L., McKay, T. A., et al. 2003, PASP, 115, 132
Antier, S., Agayeva, S., Aivazyan, V., et al. 2020, MNRAS, 492, 3904
Boër, M., Bringer, M., Klotz, A., et al. 1999, A&A, 138, 579
Brown, T. M., Baliber, N., Bianco, F. B., et al. 2013, PASP, 125, 1031
Chambers, K. C., Magnier, E. A., Metcalfe, N., et al. 2016, arXiv:1612.05560
Cordier, B., Wei, J., Atteia, J.-L., et al. 2015, arXiv:1512.03323
Domic, D., Han, X. H., Gotz, D., et al. 2019, GCN Circ. 26571, https://gcn.gsfc.nasa.gov/gcn3/26571.gcn3
Ducoin, J.-G., Corre, D., Leroy, N., & Le Floch, E. 2020a, MNRAS, 492, 4768
Ducoin, J.-G., Wang, X. G., Leroy, N., et al. 2020b, GCN Circ. 27169, https://gcn.gsfc.nasa.gov/gcn3/27169.gcn3
Dornic, D., Han, X. H., Gotz, D., et al. 2019, GCN Circ. 24974, https://gcn.gsfc.nasa.gov/gcn3/24974.gcn3
Gotz, D., Han, X. H., Domic, D., et al. 2019, GCN Circ. 24974, https://gcn.gsfc.nasa.gov/gcn3/24974.gcn3
Han, X. H., Wei, J. Y., Wu, C., et al. 2019, GCN Circ. 24136, https://gcn.gsfc.nasa.gov/gcn3/24136.gcn3
Han, X. H., Wei, J. Y., Xin, L. P., Wang, J., & Zheng, W. K. 2018a, TNSTR-2018-1916
Han, X. H., Zhang, R. S., & Xin, L. P. 2018b, GCN Circ. 23532, https://gcn.gsfc.nasa.gov/gcn3/23532.gcn3
Hofsten, T. W.-S., Stanek, K. Z., Kochanek, C. S., et al. 2017, MNRAS, 467, 1098
