GWOPS: A VO-technology Driven Tool to Search for the Electromagnetic Counterpart of Gravitational Wave Event

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Abstract

The search and follow-up observation of electromagnetic (EM) counterparts of gravitational waves (GW) is a current hot topic of GW cosmology. Due to the limitation of the accuracy of the GW observation facility at this stage, we can only get a rough sky-localization region for the GW event, and the typical area of the region is between 200 and 1500 square degrees. Since GW events occur in or near galaxies, limiting the observation target to galaxies can significantly speed up searching for EM counterparts. Therefore, how to efficiently select host galaxy candidates in such a large GW localization region, how to arrange the observation sequence, and how to efficiently identify the GW source from observational data are the problems that need to be solved. International Virtual Observatory Alliance has developed a series of technical standards for data retrieval, interoperability and visualization. Based on the application of VO technologies, we construct the GW follow-up Observation Planning System (GWOPS). It consists of three parts: a pipeline to select host candidates of GW and sort their priorities for follow-up observation, an identification module to find the transient from follow-up observation data, and a visualization module to display GW-related data. GWOPS can rapidly respond to GW events. With GWOPS, the operations such as follow-up observation planning, data storage, data visualization, and transient identification can be efficiently coordinated, which will promote the success searching rate for GWs EM counterparts.

Key words: Gravitational wave astronomy – Virtual observatories

Online material: color figures

1. Introduction

On 2017 August 17, the LIGO-Virgo Collaboration (LVC) gravitational wave (GW) detector network captured a GW signal from the spin of two compact star remnants (neutron stars). Only 1.7 s after the observation of this signal, a gamma-ray burst named GRB 170817A was detected by the Fermi gamma-ray burst monitoring telescope. The GW and gamma-ray alerts were sent to the astronomical community to launch a series of follow-up observations. Global astronomers eventually detected the decaying electromagnetic (EM) signals from the neighboring NGC 4993 galaxy. The multi-messenger observation with EM and GW facilities marks a new era in the multi-messenger and time-domain astronomy (Abbott et al. 2017).

GW sources can be roughly divided into three types: continuous GW sources, stochastic GWs, and burst GW. Continuous GW sources, such as fast-rotating neutron stars, emit quasi-sinusoidal GWs over durations much longer than the detectors’ lifetime. Stochastic GWs can take the form of a cosmological background, similar to the EM cosmic microwave background, or could arise from a cacophony of GW sources at closer distances. Burst GW are transient signals that have not been well modeled or unknown waveforms. Burst sources include the supernova, the merger and post-merger phases of merging compact binaries. Compact binary coalescence (CBC) is a binary system that rotates with each other, where either or both constituents are a black hole or neutron star. CBCs are the best characterized and one of the most promising sources for the advanced detectors, with a realistic expected rate of 20 such events per year observed at design sensitivity (Abbott et al. 2018).

As a significant tool for astrophysics and cosmology research, multi-messenger joint observations have important applications in GW cosmology study. GW sources (such as CBC) can be used as a standard siren to measure the geometry and expansion of the universe, and from this to test cosmological models, measure cosmological parameters, and study dark energy and dark matter (Del Pozzo 2012). As the EM wave band observation is the only way to determine the GW source’s location and redshift, it is necessary to complete the joint detection of the EM signals produced by the GW sources.
source for finding the astrophysical origin of GW or conducting further research on their physical properties. Therefore, from the perspective of GW astronomy, the significance of the observation of EM counterparts of GWs can be compared to the direct detection of GW signals.

However, the ground GW observation network has poor positioning ability to GW source, and it is only possible to obtain a rough sky localization of the event. For the most typical binary neutron star (BNS) system, a single detector is impossible to achieve positioning. When the number of detectors is increased to two, the positioning of the source of GWs can be limited to one ring zone. When three or more detectors are used, the localization region of the GW source can be reconstructed. In general, the elliptical localization region of the GW source is about 200 ~ 1500 square degrees. Even the aLIGO A+ detector network upgraded after 2020 has not improved much on positioning ability (Abbott et al. 2018). Due to the different sensitivity and maximum detection distance of GW detectors (aLIGO (Harry 2010) 190 Mpc, AdVirgo (Acernese et al. 2014) 125 Mpc, KAGRA (Aso et al. 2013) 140 Mpc), even if all planned detectors are built and used in the future, the localization region will still be large for GW events that exceed the detection range of AdVirgo and KAGRA. Besides, the per-year BNS search volume increases giving an expected up to 180 BNS detections annually. The high detection rate of GWs and the low accuracy of the positioning have brought great challenges to the follow-up observation of the EM counterpart. It requires new methods to search for them.

Gehrels et al. (2016) proposed a strategy to search for GW EM counterparts based on galaxy observations. The strategy assumes that sources of GWs reside within (or close to) the normal matter seen as galaxies. With the host galaxy’s information, the estimation of the localization region of the GW event can be improved. Based on the strategy, we can retrieve the galaxies which locate in the GW localization range and follow-up observe them to find if any transients there. This strategy has been widely adopted and further studied such as Arcavi et al. (2017), Chan et al. (2017), and Ducoin et al. (2020). After summarizing these works, we believe that building an efficient and automated software system for GW follow-up observation collaboration based on the galaxy observation strategy, is essential to improve the efficiency of GW EM counterpart’s search. In the system the issues need to be solved are how to rapidly select host candidates in such a vast GW localization region, and how to sort the observation priorities of them, as well as how to identify the GW source from observational data efficiently. In response to these issues, a series of technical difficulties need to be resolved. In order to rapidly respond to GW events, the galaxies contained in the GW localization region need to be found out from the database in real-time, which requires an appropriate data retrieval method. Besides, for the identification of transients, except the observation data itself, additional data are needed to be retrieved to assist in the identification, including the light curve data of known transients in the region, and observation data of the target area from other survey projects, etc. Moreover, a unified organization, management and visualization framework for observational data is also needed to enable observing scientists to understand the data of GW follow-up observations more intuitively. Virtual Observatory (VO) (Cui & Zhao 2007) specifies a series of technical standards for data retrieval, interoperability and visualization, which provide technical solutions for working out these issues. In this paper, we introduce a GW follow-up Observation Planning System, referred to as GWOPS for short, which is constructed base on VO technologies. GWOPS has a pipeline to automatically process GW alerts and filter the host candidates as follow-up targets, and it also consists of the components to realize the identification of the EM counterpart of GW and data visualization.

In Section 2, we briefly introduce the overview of this system, including the system architecture, data stream, and the database schema. Section 3 describes the components of GWOPS in detail, especially the VO-related technologies in host galaxy filtering, transient identification and data visualization. Section 4 presents the current status and the future work of the system. GWOPS has supported the follow-up observation of GW events for six optical telescopes in China during the third observing run (O3) of LVC. It also has good scalability to provide other telescopes around the world with the support of follow-up observation of GW events. We conclude in Section 5 with a discussion.

2. System Overview

2.1. System Architecture and Data Processing Stream

GWOPS consists of three parts, the GW host galaxy filter, the transient identification, and the data visualization component. As Figure 1 shows, the GW host galaxy filter monitors the GW event alert released by LVC via the NASA Gamma-Ray Coordinates Network (GCN) (Barthelmy 2016). After receiving the alert, it automatically downloads the GW localization data from the GW candidate event database (GraceDB). Based on the localization data, the galaxies database is queried to obtain all the host candidates in the localization region. The candidates are further filtered and sorted. Then the top 150 of the ranking are sent to telescopes for follow-up observation, with all the observation data storing in the database. The transient identification component is used to identify candidates of GW EM counterpart from the observation targets (OT), which are extracted from observation data by image recognition method. The processes of host

5 GWOPS can be accessed at: https://nadc.china-vo.org/gwops/.
6 GraceDB: https://gracedb.ligo.org/.
galaxy filtering and OT candidates extraction runs in the backend of GWOPS and are transparent to users. Registered users can check the original observation data by logging into the GWOPS web portal, and can manually identify the OT candidates there. Non-registered users can view the Hierarchical Progressive Survey (HiPS) (Fernique et al. 2017) generated based on the observation data, as well as the follow-up observation list on the GWOPS visualization component, which is web-based and provides intuitive data visualization effect. The original observation data and transient lists will be released to non-registered users before the start of the LVC O4 run.

2.2. Database Design

Based on the data obtained by follow-up observations, we have established a GW observation database. The core data tables in the database are the Event table, Galaxy table, Observation table, Template table, Diff table, and OT table. The schema of the database is shown in Figure 2.

1. Event table: It records the ID, issued time, estimated distance, and localization region of each GW event.
2. Galaxy table: It stores galaxy information in the range of 200 MPC, including each galaxy’s location, distance, redshift, as well as B-band luminosity, based on the Galaxy List for the Advanced Detector Era (GLADE) catalog (Dálya et al. 2018), which version is 2.3. GLADE is a fusion of galaxy data through multiple catalogs, specifically used for GW host galaxy search and the filtering of EM counterpart target for follow-up observation. The five galaxy catalogs used to obtain GLADE are GWGC (White et al. 2011), 2 MPZ (Bilicki et al. 2013), 2 MASS XSC (Jarrett et al. 2000), HyperLEDA (Makarov 2014) and SDSS DR12Q (Kozlowski 2017), and they complement each other in the wavelength and galaxy types. GLADE contains a total of 3.6 million galaxies and is complete up to \( \sim 37 \) Mpc, has a completeness of \( \sim 61 \) percent within the maximal value of single-detector BNS ranges for aLIGO during O2.
Figure 2. GWOPS database schema. The database is implemented with the open source database software PostgreSQL (https://www.postgresql.org/). Each table uses the self-increasing ID as the primary key, and the foreign key as the association between tables. Each table has a B-tree index on ID column to improve retrieval efficiency.
(~100 Mpc), ~54 percent within the minimal planned BNS range during O3, and ~48 percent within the planned BNS range of single aLIGO detectors with design sensitivity (~173 Mpc) (Dálya et al. 2018).

3. Observation table: This table records the observation images for each GW event.
4. Template table: It contains the information of previously observed images as the templates for extracting OTs.
5. Diff table: It stores secondary data derived from the image subtraction of the observation image and the template image.
6. OT table: The table records information of OTs.

3. GWOPS Components

To respond rapidly to GW events and find EM counterparts efficiently and conveniently, GWOPS is meant to be a real-time follow-up observation planning pipeline, an efficient transient identification tool, and a user-friendly observation data browser. In this section, we will describe the components of GWOPS and the VO technology applied in them.

3.1. GW Host Galaxy Filter

The GW host galaxy filter component selects the potential GW host galaxies to reduce the search range in the sky. We implement filtering in two steps. The first step is to retrieve the galaxies covered in the localization region of the GW event. However, the number of galaxies we get in this step is around 10,000 ~ 50,000. For the operability of follow-up observation, we calculate each galaxy’s probability as the GW host and sort the observation list by their probabilities. These processes are completed automatically at the backend of GWOPS, and users can check the detailed information of each alert and the list of follow-up observations at the frontend, i.e., the web portal. Figure 3 shows the data flow of the components.

3.1.1. Galaxies Retrieving by GW Localization Region

A VO-event alert will be sent out by LVC through the GCN when a candidate GW event is detected. The alert contains a localization map with distance constraints. In general, the GW localization region is an irregular strip, but the general spatial search is a cone query or a polygonal query. So it is necessary to find out how to use the localization region as a query condition to retrieve galaxies from the database. The GW localization map is a FITS file, which records the event occurrence probability at each HEALPix (the Hierarchical Equal Area isoLatitude Pixelization) (Gorski et al. 2005) grid. We convert the FITS file into a multi-order coverage (MOC Map) file (Fernique et al. 2014) to speed up the query. The MOC is an International Virtual Observatory Alliance (IVOA) standard that used to specify arbitrary sky regions, and its mechanism is based on the HEALPix sky tessellation algorithm.

Then we build the spatial index for the galaxy data table in the database. For each entry in the data table, a HEALPix ID at the order 10 can be calculated by the coordinates of the entry. Then a clustered index is built on the HEALPix ID column,
which can make the entries that are nearby in space are also nearby on disk. The MOC which can make the entries that are nearby in space are also requiring only a few disk reads. consecutive blocks or pages on disk, which leads to fast access, disk means that all of these galaxy entries can be found in consecutive between two values prescribed by the lower order. Therefore, we convert all the indices which order lower than 10 to the property that all grids at a higher order have indices recursive nature of the HEALPix indexing scheme leads to the fact that all of the top 10 galaxies can be found in the range of 200 Mpc, in the 8.5% simulation results, the probability that the top 10 galaxies in the ranking are GW event host galaxies is 50%. In 10% of the simulations, the host galaxy is indeed located in the top 10 galaxies.

3.1.2. Sorting Candidates for Follow-up Observation

It is impossible to fully observe so many galaxies in the localization region within a limited time, so it is necessary to filter the host candidates and prioritize their observations. In GWOPS, a Bayesian inference based method (Fan et al. 2014) is adopted to calculate the probability that a galaxy is the GW event host, then sorted the galaxies by the probability. The method uses the galaxy’s physical characteristics (B-band brightness, distance) and the probability of the GW event occurred at the galaxy’s location as the prior, the posterior probability of each galaxy to be the host of the GW event is calculated. Equation (1) is applied to calculate the posterior probability.

\[ p(\gamma | D, S, M) = \frac{p(\gamma | S, M) p(D | S, \gamma, M)}{p(D | S, M)} \]  

The meaning of the parameters:

1. \( \gamma \): the common parameters observed by the GW event and the host galaxy, specifically referring to the position parameters of the galaxy in the localization region, \( \alpha \) (R.A.), \( \beta \) (decl.), \( d \) (Distance).
2. \( D \): observation data of GW event.
3. \( S \): observation data of EM.
4. \( M \): host galaxy candidate information.
5. \( p(D | S, \gamma, M) \) is the likelihood probability of the data set \( D \) given \( S, \gamma \), i.e., the probability of the corresponding position of galaxies given in the GW localization map.
6. \( p(\gamma | S, M) \) is the prior probability formula.

The prior probability formula is as Equation (2):

\[ p(\gamma | S, M) \propto \left( \frac{D_{\text{gc}}}{D_{\text{GW}}} \right)^3 \sum_{j=1}^{N} \delta(\alpha - \alpha_j, \beta - \beta_j) \]

\[ d - d_j) L_B + \frac{3L_{\text{linear}}}{4\pi D_{\text{GW}}^2} H(d - D_{\text{gc}}) d^2 \]  

Where \( N \) denotes the total number of galaxies in the galaxy data table. \( D_{\text{gc}} \) denotes the range of the galaxy data table. \( D_{\text{GW}} \) denotes the detection range of the GW detector. \( L_B \) denotes the luminosity of the host galaxy in \( B \) band, and \( H \) denotes a step function.

Fan et al. (2014) have verified this method based on the simulation data of dense binary-star merger. The results show that in the range of 200 Mpc, in the 8.5% simulation results, the probability that the top 10 galaxies in the ranking are GW event host galaxies is 50%. In 10% of the simulations, the host galaxy is indeed located in the top 10 galaxies.

3.1.3. Transient Identification

The transient identification component extracts OTs based on the residuals between the observation data and the template data in the backend, and provides users with an operation interface for manually identifying OTs in the frontend. The data flow and modules of the component are shown in Figure 4.

The workflow in transient identification components is as follows:

1. Preprocessing: The observation data returned by the telescope are subjected to a series of processing, including reducing the flat field and background to make it a clean image.
2. Assign World Coordinate System (WCS) coordinates (Mink 1997): In this process, the WCS coordinate information is added into the observation data based on the coordinate of OTs. This is the basis for observation data retrieval and visualization. After completing this process, the observation data is stored in the observation data table.
3. Image subtraction: The OTs are obtained by subtracting the observation data from the template data. Template data mainly comes from two sources. One is the historical image taken by the observation telescope and stored in the template table. The second is to use the image cut out service (Mattu et al. 2005) in the IVOA’s Simple Image Access (SIA) protocol (Dowler et al. 2015) to obtain data taken by other surveys. The image cut out service we used extracts rectangular regions of some larger image, returning an image of the requested size to the client. Such images are usually drawn from a database or a collection of survey images that cover some large portion of the sky. GWOPS gets the template data from Pan-STARRS (Kaiser et al. 2002) in the absence of historical template data.
4. OT extraction: The SExtractor (Bertin & Arnouts 1996) is used to extract OTs from observation data, template data and residual data automatically. Then the position and brightness of the OTs obtained from the three are compared. OTs with significant brightness changes will be recorded and transferred to the next processing stage.
5. Score OTs for manual identification: Base on the investigation of the astronomical sources identification...
methods in PTF/iPTF/ZTF (Mahabal et al. 2019), Pan-STARRS1 (Wright et al. 2015) and Subaru/Hyper Suprime-Cam survey (Lin et al. 2018), we proposed a trained random forest model to evaluate the extracted OTs and give a score of the OT as a real transient. Only OTs with a score higher than 0.2 (maximum 1.0) will be listed for manual identification, and this score will also be used as a reference for manual identification.

After the automatic processing above, the high-scoring OTs will be listed on the web portal for manual verification. Besides, OTs related information will also be listed on the webpage for reference (as shown in Figure 5), including the observation data, template data, residual data of each OT, and its historical magnitude data, as well as the information on nearby galaxies of the OT. Besides, we also use the IVOA simple cone search protocol (Plante et al. 2008) to check whether other sky surveys find transient near the position of the OT. From the web portal, we can check if there is any sources in the OT’s position in SDSS, Transient Name Server (TNS), Simbad (Wenger et al. 2000), NED (NASA/IPAC Extragalactic Database) (Helou et al. 1991) and MPC (Minor Planet Center) (Marsden 1980). Finally, based on this information, we can determine whether the OT is a real transient and classify its type. The real transient will be sent to telescopes for further spectral verification.

### 3.2. Visualization

The visualization component allows users to view the observation data in the GW localization region intuitively. GWOPS uses Aladin Lite (Boch & Fernique 2014) as the facility for data visualization on the web. Aladin Lite is a WebGL-based Javascript library. It can display FITS images loaded WCS coordinates on the three-dimensional celestial sphere, and draw contours on the celestial sphere based on JSON files, which are resolved by GW localization data. The observation data is converted into IVOA HiPS for visualization. As shown in Figure 6, HiPS uses the HEALPix spherical segmentation method to mesh the observation data, convert the data from the original projection to the HEALPix projection, and recursively divides the data into image pyramids of different resolutions according to the hierarchical division of HEALPix.

The data in GWOPS can also be visualized in WorldWide Telescope (WWT) (Rosenfield et al. 2018). This requires the

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7. TNS: https://wis-tns.weizmann.ac.il/.
user to additionally install the China-VO version of Worldwide Telescope\(^8\) on the computer and start it in advance. WWT is a scientific data visualization platform launched in 2008 by Microsoft Research and then open-sourced in 2015. We have successfully implemented the HiPS schema in WWT (Xu et al. 2019), which make the observation data can be browsed freely on it. As for the visualization of GW localization data, the sky region file is converted into a series of key-value pairs files with HEALPix grid and positioning probability. These files are encapsulated as VOTable, and users can transmit the files to WWT via the IVOA SAMP protocol (Taylor et al. 2015) by clicking the “Send to WWT” button on the data browser page. The visualization of GW localization data in WWT is shown in Figure 7.

Figure 7. Transient identification support information displayed in the web portal. The upper left picture shows an OT original observation image, template image and residual image in turn. By clicking the buttons below the picture, users can view the data of the corresponding survey or database at the OT location. The line chart on the right is the historical magnitude data of the OT. The table below is the information of the galaxies near the OT, and the galaxy data comes from GLADE V2.3. (A color version of this figure is available in the online journal.)

\(^8\) China-VO WWT can be downloaded at http://wwt.china-vo.org.

We chose WWT as one of the visualization facilities not only because it has excellent visualization effect and supports a series of VO data access standards, but also because it has the unique feature of Guided Tour, which is a kind of recorded path with narration, text, and imagery. With this feature, users can create tours with the GW data to share their discovery with other researchers or the public, and further promote GW-related research.

4. Project Status and Future Work

Currently, six telescopes are using GWOPS to run their follow-up observation for the GWs EM counterpart searching. The telescopes are located in Nanshan Xinjiang, Xuyi Jiangsu, and Xinglong Hebei of China. Information about these telescopes is listed in Table 1.

The LVC has officially started the third observing run on 2019 April 1 (Ligo Observatory Status 2020). As of 2020 March, 53 GW events have been found (Farr 2020). GWOPS responded to each event promptly. We recorded the response efficiency of several events, which are shown in Table 2. Thanks to the construction of an efficient spatial index, GWOPS is able to complete the selection of host candidates in the GW localization region within 500 ms and can send follow-up observation lists to telescopes less than 30 s after receiving an alert.

Most of the GW events found during O3 are binary black hole merger events, and only eight events are considered to be BNS events, but too far away to capture clear EM signals, so
we have not been able to find any real EM counterparts of GW events.

The telescopes, which followed these GW events, are also surveying the northern sky. As of 2020 March, a total of 21,172 images have been taken, covering an area of 6133 square degrees, as shown in Figure 8. Based on the GWOPS transient identification component, these observations were processed in real-time, and the extracted transient candidates were manually identified.

In the next stage, we will work to turn GWOPS into an open collaboration platform. We notice that there is already a fantastic GW follow-up observation collaboration platform named Gravitational Wave Treasure Map (Wyatt et al. 2020). GWOPS has common features and differences with the Treasure Map. Both of them realize the visualization of information about each GW event. The difference is that GWOPS establishes a pipeline that implements the follow-up observation planning for observation facilities, and generates observation data based on these facilities to search for electromagnetic counterparts. Treasure Map has a great openness to form a collaborative platform, and GWOPS is currently

**Table 1**

| Telescope | Location          | Altitude | FOV      | CCD Size       | Aperture/m |
|-----------|-------------------|----------|----------|----------------|------------|
| HMT       | 88.5772E 45.5224N | 1795     | 60' x 40' | 4008 x 2672    | 0.5        |
| CNEOST    | 11.46E 32.73N     | 210.3    | 3' x 3'  | 10560 x 10560 | 1.2/1      |
| Schmidt   | 117.9640E 40.6508N| 950      | 1'5 x 1'58 | 4096 x 4096   | 0.6/0.9    |
| NOWT      | 87.1777E 43.4708N | 2080     | 1'3 x 1'3 | 4160 x 4136   | 1          |
| NEXT      | 87.1777E 43.4708N | 2080     | 20' x 20' | 2048 x 2064   | 0.6        |
| XL216     | 117.9640E 40.6508N| 950      | 10' x 10' | 2048 x 2048   | 2.16       |
mainly serving the observation facilities that joined in GWOPS and through the open data to collaborate with other researchers. We will make a series of improvements to GWOPS to make it more open and robust, which are listed as follows:

1. As an independent system from the observation facility, GWOPS can also support other telescopes to run GW follow-up observation. We have developed a subscription function which can send follow-up observation lists to subscribers via email, and we are planning to implement an interface to make other telescopes take advantage of the features provided by GWOPS, turning GWOPS into an open collaboration platform. The visualization system will also be upgraded to access multi-wavelength data from other observation facilities. Moreover, each candidate’s visibility will be calculated based on the

$\text{Table 2}$

The Response Efficiency of GWOPS to GW Events, where LDT Denotes the Time Consumption of Downloading the Localization Data from GraceDB

| GW Event   | LDT (s) | LRA (deg$^2$) | LCT(s) | RN | HCT (ms) | SCT(s) |
|------------|---------|---------------|--------|----|----------|--------|
| S190421ar  | 1.49    | 1444          | 17.76  | 36783 | 455.82   | 2.98   |
| S190426c   | 1.52    | 1131          | 17.44  | 15564 | 276.31   | 1.46   |
| S190512at  | 1.48    | 252           | 19.16  | 10967 | 166.22   | 0.91   |
| S190630ag  | 1.48    | 1486          | 17.53  | 84205 | 715.84   | 5.20   |
| S190701ah  | 1.51    | 49            | 19.05  | 2867  | 85.86    | 2.95   |
| S190816i   | 1.52    | 1467          | 17.49  | 74432 | 695.85   | 4.78   |
| S190910d   | 1.46    | 2482          | 16.86  | 67380 | 746.97   | 4.94   |
| S191105e   | 1.49    | 643           | 18.91  | 39365 | 342.44   | 2.46   |
| S191129h   | 1.50    | 852           | 17.13  | 41720 | 385.31   | 2.75   |
| S191204r   | 1.49    | 103           | 18.36  | 2938  | 87.26    | 2.69   |
| S191222n   | 1.51    | 1850          | 17.27  | 69673 | 690.73   | 4.89   |

Note. LRA represents the area of the localization region. LCT is the time consumption of converting the localization data to MOC. RN refers to the number of galaxies in the localization region. HCT denotes the time consumption of retrieving the host candidates from the galaxy data table. SCT denotes the time consumption of probability calculation and sorting of the host candidates.

Figure 7. The visualization of GW localization data (GW170817) in WWT. Different colors represent different confidence regions.
(A color version of this figure is available in the online journal.)
geographic location and the maximum pitch angle of each telescope, to exclude invisible sources from the observation list for a specific telescope.

2. Improve the OT automatic extraction and scoring algorithm for the transient identification component. At the current stage, the SExtractor is used to extract the OT from the image. A random forest model is used to determine whether the OT is a real transient, and a score is given. The accuracy of current algorithms is not high enough, resulting in more workload of manual verification. The pattern recognition algorithm based on deep learning is preferred to make many improvements.

3. The data retrieval method provided by VO allows us to obtain multi-wavelength data. These data can be used as an essential reference for transient identification. We will establish a multi-wavelength reference database for GWOPS transient identification. The database will cover observational data from ultraviolet to radio wavelength. While the OT identification and classification is performed manually, the known sources of other wavelengths at the target position can be obtained for auxiliary identification.

5. Summary

GWOPS is a system to improve the efficiency of follow-up observation and EM counterpart identification for the GW event. The system is composed of three components: GW host galaxy filter, transient identification, and the visualization component. Based on the galaxy observations strategy, the GW host filter selects galaxies from the GW localization area as the target of subsequent observation. As an automated pipeline, the GW host filter can respond to GW alerts in real-time. With the Bayesian inference algorithm, the probability of a candidate host galaxy can be calculated. Then the top 150 galaxies sorted by probability are sent as potential targets to telescopes by email for follow-up observations. The transient identification component will automatically process the observation data and use the image recognition software to extract the possible transients. A trained random forest model is used to score the transient candidates, and the candidates with higher scores can be manually identified in a user-friendly and efficient web portal. In the visualization component, we use Aladin Lite and WWT as the facilities for users to browse the observation data and GW event related data. Users can also make Guided Tour on WWT with these data to promote their latest research and perform GW related education and public outreach.

GWOPS is a VO technology-driven system. In each component of GWOPS, there are applications of VO related technologies. In the GW host galaxy filter, the MOC standard of IVOA is used to implement the database query based on the GW localization region. In the transient identification component, the IVOA SIA standard is used to retrieve images of Pan-STARRS as template data, and the IVOA SCS standard is applied to retrieve archived data of other surveys at the location of the transient candidate. In the visualization component, the HiPS schema of IVOA is implemented for the organization and visualization of observation data, and the SAMP standard of IVOA is adopted to transfer commands and data between components.

During the O3 of LVC, GWOPS has supported six optical telescopes in China to run the GWs follow-up observation. GWOPS can respond to GW event alerts in real-time, complete the filtering of GW host candidates and submit them to the telescope within 25 s. As of 2020 March, a total of 6133 square degrees of sky area was observed, and 21,172 targets were obtained. However, only 8 of the GW events during O3 are...
possible BNS events, and they are too far or not in the telescopes’ visible range. There are no real EM counterparts of GW events found yet by our system.

More features will be added to GWOPS to make it a robust and open collaboration platform for GW EM counterpart searching. We will provide an interface for other telescopes to utilize the features and data of GWOPS. We also try to apply deep learning methods to improve the accuracy of transient source identification. Meanwhile, a multi-wavelength reference database base on VO standards to assist in identifying the GWs EM counterpart will be integrated.

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