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ANTARES: A gateway to ZTF and LSST alerts

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ABSTRACT

With the avalanche of alerts to be delivered by Rubin Observatory's Legacy Survey of Space and Time and the limited resources for follow-up, we will need brokers to select intriguing alerts that warrant follow-up in a timely manner. At NSF's NOIRLab and University of Arizona, we are developing the Arizona-NOIRLab Temporal Analysis and Response to Events System (ANTARES, Saha et al. 2014, 2016, Narayan et al. 2018), to hunt for the rarest of the rare events in the time domain. In this work, we provide an overview of the ANTARES system, how we use real-time alerts from the ongoing Zwicky Transient Facility survey as a training set, and the way forwards to Rubin observatory.

Keywords: Time-domain astronomy, astronomy software, computational methods

1. INTRODUCTION

The arrival of wide-field digital camera in the last decade has enabled large-area and high-cadence optical surveys, e.g., Pan-STARRS,[1] Catalina Real-Time Transient Survey,[2] Palomar Transient Factory,[3] All-Sky Automated Survey for SuperNovae,[4] and Asteroid Terrestrial-impact Last Alert System,[5] that ushered in a new era of time-domain astronomy. The most notable example is Zwicky Transient Facility[6] (ZTF), the successor of Palomar Transient Factory that conducts a public survey to patrol the sky every three nights in the g- and r-band filters with its 47 deg^2 imager mounted on the Palomar 48-inch telescope from 2018 till now. With its high étendue, ZTF issues more than 10^5 alerts per night down to the detection limit of r = 20.5 mag.

The large number of alerts generated each night by these surveys have revolutionized time-domain astronomy in numerous aspects. On the transient front, ZTF has probed the previously uncharted territory of fast transients,[7,8] calcium-rich transients,[9] and tidal disruption events.[10] The high-cadence and long-baseline photometric data from ZTF also enable science with variable stars, from the eruptive cataclysmic variables,[11] to long-term variable like R Coronae Borealis stars,[12] and even ultra-short period eclipsing binaries with double white dwarfs[13] that can serve as potential gravitational wave sources for LISA. With its wide field-of-view and high-cadence survey capability, ZTF also benefits studies of Solar System objects, such as the discovery of the first Vatira[14]—a class of asteroids with orbits completely within the orbit of Venus. In addition, ZTF was able to trace the appearance of the first interstellar comet 2I/Borisov back to 2018, one year prior to its discovery in late 2019.[15] ZTF is also instrumental to multi-messenger astronomy, where the localization of gravitational wave events is poorly defined and the wide-field capability of ZTF provides great leverage to identify candidate optical counterparts of binary neutron star or neutron star-black hole merger events in a timely manner.[16] Besides gravitational wave events, ZTF also identified a tidal disruption event that coincided with high energy neutrinos.[17] In the near future, the Vera C. Rubin Observatory[18] is going to conduct its Legacy Survey of Space and Time

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with its wide-field (9.6 deg^2 field-of-view) camera mounted on the 8.4 meter Simonyi Survey Telescope on the El Peñón summit of Cerro Pachón. The Rubin Observatory will deliver up to 10 million alerts per night. Each exposure reaches a depth of ∼24 mag thus LSST will survey the transient sky beyond the reach of ZTF.

The aforementioned examples provide an indication of the science can be done with ongoing and future surveys. With the avalanche of alerts generated by these surveys, it is no longer possible for astronomers to manually inspect every alert. This requires a time-domain event broker that can automatically sift through and select the most interesting objects that worth follow-up. It is especially important as follow-up resources, especially spectroscopic instruments, are unmatched to the number of alerts. The time-domain broker will be essential to prioritize targets given the limited follow-up resources.

2. ANTARES TIME-DOMAIN BROKER

In order to tackle the flood of millions of alerts from ZTF (and Rubin Observatory in the future), it is imperative to have a software infrastructure that can sift through alerts. At the University of Arizona and NSF's National Optical-Infrared Astronomy Research Laboratory (NOIRLab), we are developing the Arizona-NOIRLab Temporal Analysis and Response to Events System[19–21] (ANTARES), outlined as follows.

2.1 Design

The sky surveys issue alerts from newly acquired images if there are objects varying significantly compared to reference images. However, the alerts may only contain a partial history of the detected objects. For example, ZTF provides historic photometry up to 30 days, while the Rubin Observatory is expected to provide alert history up to 1 year. To establish the full light curve of an object, one will need to associate alerts from the same object drawn from multiple sources. In addition, there could be multiple sources of alerts in disparate regimes, e.g., ZTF in the optical and LIGO in the gravitational wave regime, that we want to associate those alerts to obtain multi-messenger information. Even then, the alerts themselves may not provide much information beyond the timing and the fluxes of the detection. In this regard, cross-matching alerts with external catalogues that are rich in the types of objects (e.g., stars, variables, galaxies, quasars, AGNs) and across the electromagnetic spectrum (X-ray, UV, optical, near infrared, radio) will provide contextual information that helps unveil the nature of the underlying phenomenon. With the full alert history (or light curve) and contextual information in hand, we can then design filters that select the most intriguing alerts warranting follow up. The goal is—out of the 10 million alerts per night – to select 100 rarest of the rare objects that can be further investigated with the limited follow up resources.

2.2 Deployment

After years of planning and development, we launched the ANTARES beta version in December 2018 to process alerts from the ZTF public survey in real time. ANTARES aggregates alerts at the same point of the sky (within 1" radius) into a locus and forms light curves that have history back to the start of the ZTF survey. We cross-match the locus with external catalogues that provide different types of objects, e.g., stars and galaxies (SDSS,[22] NED,[23] RC3[24,25]), quasars and AGNs (Veron Catalog of Quasars & AGN,[26] NYU Value-Added Galaxy Catalog[27]), variable stars (Catalina Sky Survey,[28–32] ASAS-SN variable catalogue[4,33–35]), and in different wavelengths, e.g., UV (GALEX[36]), optical (Gaia[37]), infrared (2MASS[38] and WISE[39]) to obtain contextual information. With these pieces of information in hand, we can design filters to select interesting targets for further follow-up. We have pre-defined filters and incorporated several filters from external users. The alerts processed and tagged by these filters are then broadcast as alert streams via Kafka in real time.

After the beta version was launched, it appeared that the bottleneck of processing alerts was the response time to associate alerts in the SQL-based database. We thus switched to a non-relational database (Apache Cassandra[*]). To allow efficient search and query, we also built a search index over objects using Elasticsearch[†]. The alert processing and filtering are carried out concurrently in Docker containers orchestrated using Kubernetes[‡]. The current version of ANTARES[§] is now digesting ZTF alerts at full scale in real time, and can be scaled up

[*]https://cassandra.apache.org/

[†]https://www.elastic.co/

[‡]https://kubernetes.io/

[§]https://antares.noirlab.edu

to the data streams from Rubin observatory.

2.3 User Interfaces

Users can interact with ANTARES via three different avenues.

- *Web portal*
  The ANTARES web portal[¶] allows users to search and browse alerts and loci (see Fig. 1). Users can search for loci at a given position with a given search radius. Furthermore, users can specify the timing of the first and latest alerts within a locus to identify new transients. Users can select loci that have cross-matched catalogue objects, or tagged by filters. Users can upload their targets of interest as a watch list (with coordinates and search radius) and monitor alerts associated with the watch list objects. The web portal also allows users to submit their own filters (including sophisticated machine learning models), and ANTARES will process incoming alerts with customized filters in real-time when resources permit.

- *Slack*
  When submitting a filter, users can request ANTARES to send real-time notification of alerts that crash the filter. ANTARES can send the error report to the users via ANTARES Slack workspace[‖]. When a filter fails to process an incoming alert, ANTARES can send the error report to the users on slack. In such way users can reproduce the error and improve the filter design. Besides filters, ANTARES can also send real-time notification of alerts associated with watch list objects, to allow for prompt follow-up.

- *Client application programming interface (API)*
  Another route to connect to ANTARES is via our Python-based client API[**]. Users can use our client API to connect to the output Kafka streams from pre-defined or user-designed filters in real-time. In addition, the client API enables users to query the alert database with Elasticsearch in a programmatic manner. With access to alert database, users can also use the client API to develop customized filters with a subset of the alerts and loci.

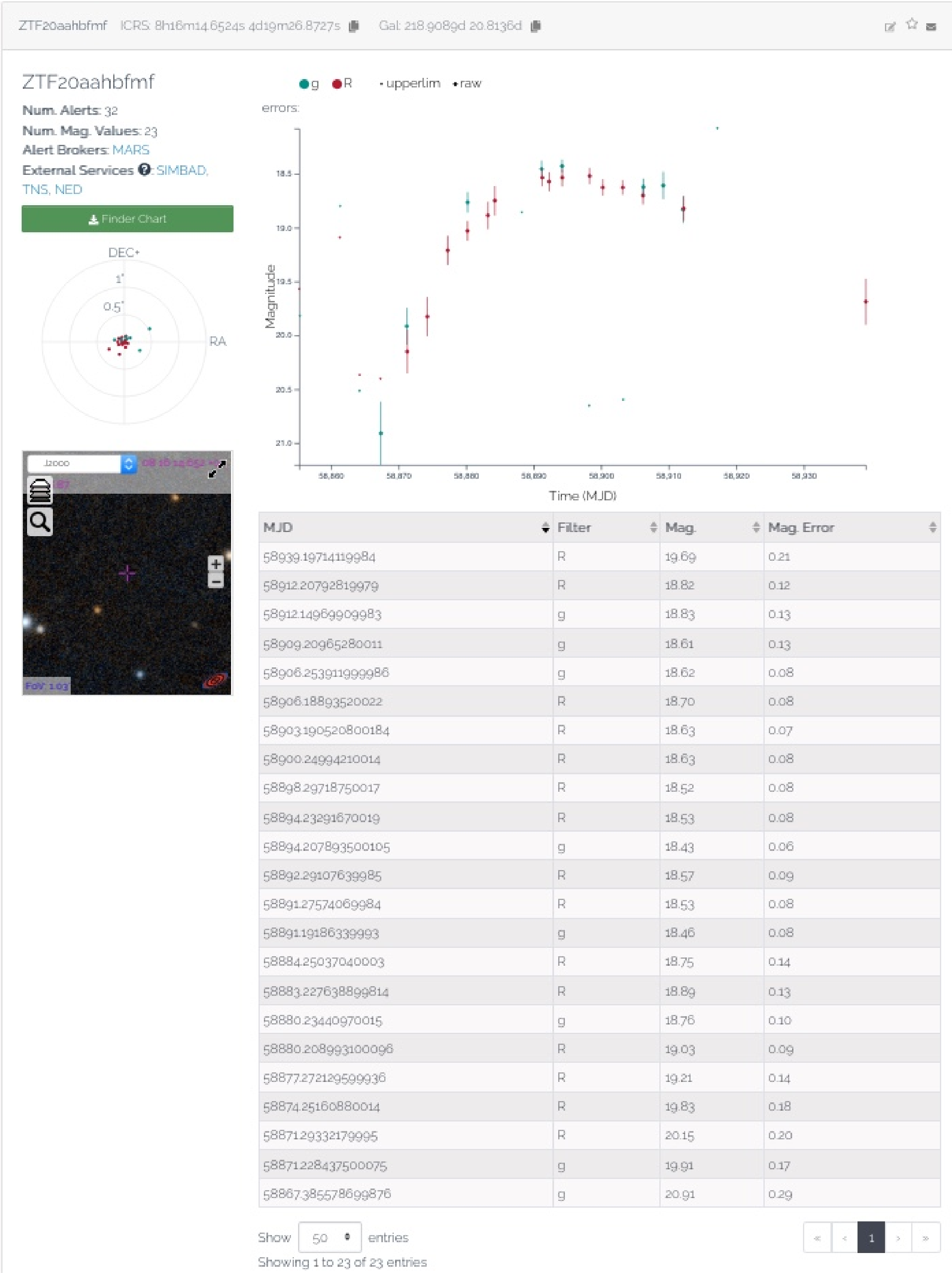
2.4 Connecting to downstream services

In the current and future time-domain ecosystem, brokers are not only digesting alerts from the sky surveys, but also providing intriguing targets to users and telescopes for follow-up. In this regard, ANTARES is connecting to a suite of services that are provided by the NOIRLab and the astronomical community. ANTARES is connected to the Astro Data Lab[††] that enables users to efficiently explore and analyze large datasets. Users can use the Astro Data Lab to search and analyze the entire ANTARES alert database, to design a customized filter, and to explore long term variables. On the follow-up front, ANTARES is connected to the Las Cumbres Observatory Target and Observation Manager (TOM) Toolkit[40] that enables users to share lists of targets, to trigger follow-up, and to track the acquired observations. Via TOM Toolkit, ANTARES is further connected to the Astronomical Event Observatory Network[41] (AEON)[‡‡], a network of facilities including (but not limited to) the Las Cumbres Observatory, the Southern Astrophysical Research (SOAR) Telescope, and the Gemini Observatory that can provide coordinated observations.

2.5 Science examples

ANTARES is currently digesting ZTF alerts in real time and broadcasting alerts tagged by pre-defined filters that are of potential interest for spectroscopic confirmation. Examples of our pre-defined filters include (but not limited to) 1) an extra-galactic filter tagging alerts associated with cataloged galaxies that can be extragalactic transients (e.g., supernovae); 2) an M31 filter that tags alerts within 2×2 square degrees centered on M31 that may contain M31 novae or luminous blue variables; and 3) a high signal-to-noise ratio (SNR) filter that flags alerts

¶ https://antares.noirlab.edu
‖ https://antares-noao.slack.com . This URL may change as NOIRLab implements Slack channels
** https://noao.gitlab.io/antares/client/
†† https://datalab.noao.edu
‡‡ http://ast.noao.edu/data/aeon



MJD	Filter	Mag.	Mag. Error
58939.19714119984	R	19.69	0.21
58912.20792819979	R	18.82	0.12
58912.14969909983	g	18.83	0.13
58909.20965280011	g	18.61	0.13
58906.253911999986	g	18.62	0.08
58906.18893520022	R	18.70	0.08
58903.190520800184	R	18.63	0.07
58900.24994210014	R	18.63	0.08
58898.29718750017	R	18.52	0.08
58894.23291670019	R	18.53	0.08
58894.207893500105	g	18.43	0.06
58892.29107639985	R	18.57	0.09
58891.27574069984	R	18.53	0.08
58891.19186339993	g	18.46	0.08
58884.25037040003	R	18.75	0.14
58883.227638899814	R	18.89	0.13
58880.23440970015	g	18.76	0.10
58880.208993100096	R	19.03	0.09
58877.272129599936	R	19.21	0.14
58874.25160880014	R	19.83	0.18
58871.29332179995	R	20.15	0.20
58871.228437500075	g	19.91	0.17
58867.385578699876	g	20.91	0.29

Figure 1. ANTARES locus page. We aggregate alerts from the same position (within 1" radius) of the sky and construct light curves. The ANTARES locus page displays images from static sky surveys, e.g., Pan-STARRS, and includes information about the alerts in this locus. All pieces of information (including light curves and finder chart) can be downloaded from the web portal. The example shown here is a type I superluminous supernova AT2020ank.

Table 1. Summary of Astronomer's Telegrams by ANTARES team and collaborations

ATel#	Name	Classification	Report date	Facilities
12935	ZTF19aazcxwk	SN Ia	07/12/2019	LCO 2m telescope
12943	ZTF19abfqlzi	M31 recurrent nova	07/15/2019	Gemini telescope
12946	ZTF19abdooly	dwarf nova	07/18/2019	LCO 2m telescope
12980	ZTF19abgsssu	dwarf nova	08/02/2019	Shane 3m Telescope, Lick Observatory
13053	ZTF19abpmetl	SN Ia	08/30/2019	Shane 3m Telescope, Lick Observatory
13055	ZTF19abraqpf	dwarf nova	08/30/2019	Shane 3m Telescope, Lick Observatory
	ZTF19abqstxq	dwarf nova	08/30/2019	Shane 3m Telescope, Lick Observatory
13115	ZTF19abtuflm	SN II	09/18/2019	Shane 3m Telescope, Lick Observatory
13119	ZTF19abpvysx	SN Ia	09/21/2019	Shane 3m Telescope, Lick Observatory
	ZTF19abrelog	SN Ia-91T	09/21/2019	Shane 3m Telescope, Lick Observatory
	ZTF19abulrfa	SN IIP	09/21/2019	Shane 3m Telescope, Lick Observatory
13141	M31N2019-09b	M31 nova	09/28/2019	Gemini telescope
13149	ZTF19abyukuy	Galactic nova	10/01/2019	Shane 3m Telescope, Lick Observatory
13153	ZTF19abxnerq	M31 nova	10/01/2019	Gemini telescope
13178	ZTF19abzpkss	dwarf nova	10/09/2019	Shane 3m Telescope, Lick Observatory
13183	ZTF19abydbvw	dwarf nova	10/11/2019	Shane 3m Telescope, Lick Observatory
13200	ZTF19acbwmqd	SN IIP	10/18/2019	Shane 3m Telescope, Lick Observatory
13210	ZTF19acbzgog	M31 nova	10/21/2019	Gemini telescope
13231	ZTF19acfsteg	M31 nova	10/28/2019	Gemini telescope
13261	AT2019tsc	M31 nova	11/04/2019	Gemini telescope
13286	ZTF19acmdpyr	SN Ia	11/12/2019	Shane 3m telescope, Lick Observatory
	ZTF19acklbjr	SN Ia	11/12/2019	Shane 3m telescope, Lick Observatory
13317	ZTF19acnfsij	M31 nova	11/28/2019	Shane 3m telescope, Lick Observatory
13358	ZTF19acxrihd	M31 nova	12/19/2019	Gemini telescope
13362	ZTF19acqprad	M31 nova	12/21/2019	Shane 3m telescope, Lick Observatory
13399	ZTF20aabbimu	dwarf nova	01/11/2020	Shane 3m telescope, Lick Observatory
13406	ZTF19acoqctv	SN IIP	01/15/2020	Shane 3m telescope, Lick Observatory
13430	ZTF20aakdppm	M31 nova	01/30/2020	Gemini telescope
13527	ZTF20aahpagw	SN IIn	02/27/2020	Shane 3m telescope, Lick Observatory
13570	ZTF19actabny	SN IIn	03/20/2020	Shane 3m telescope, Lick Observatory
13706	ZTF20aawbodq	Anomalous	05/03/2020	Anomaly filter by Soraisam et al. (2020)
13865	ZTF19aamdmcs	SN Ia	07/14/2020	Shane 3m telescope, Lick Observatory
13952	ZTF20abqhsxb	M31 nova	08/18/2020	Shane 3m telescope, Lick Observatory
14109	ZTF20acjpwas	dwarf nova	10/20/2020	Shane 3m telescope, Lick Observatory
14150	ZTF20acoqrpm	M31 nova	11/05/2020	Shane 3m telescope, Lick Observatory
14184	ZTF20acplkub	M31 nova	11/17/2020	Shane 3m telescope, Lick Observatory
14190	ZTF20acpeyoo	SN Ia-CSM	11/17/2020	Shane 3m telescope, Lick Observatory
	ZTF20acpgzif	SN Ia	11/17/2020	Shane 3m telescope, Lick Observatory
	ZTF20acpmtjf	dwarf nova	11/17/2020	Shane 3m telescope, Lick Observatory
	ZTF20acpvbbh	unknown/TDE?	11/17/2020	Shane 3m telescope, Lick Observatory

with high SNR detection. These alerts are bright transients (likely in the Milky Way, e.g., novae, dwarf novae) that can be classified spectroscopically even with small apertures telescopes; and 4) a solar system filter that tags all known solar system objects charted by JPL. As a demonstration of ANTARES and its integration with the time-domain ecosystem, the ANTARES team is actively acquiring spectra and classifying objects flagged by our filters. This includes observation resources with AEON and from our collaborators. We have issued more than 30 Astronomer's Telegrams since July, 2019, confirming objects ranging from supernovae, novae in the Milky way and M31, and dwarf novae. A list of the Astronomer's Telegrams by the ANTARES team and collaborators is shown in Table 1.

Once intriguing alerts are classified, the ANTARES team will conduct detail investigation with both photometric and spectroscopic information. For example, using the anomaly filter developed by Soraisam et al.[42] an anomalous transient, ZTF20aawbodq, was identified. Further observations revealed its nature as a WZ Sge-type dwarf nova superoutburst, preceded by a precursor large amplitude brightening and decay (> 3 mag). Such large decay suggests ZTF2020aawbodq may be composed of binary with extremely small mass ratio ($q<0.05$),[11] where dwarf nova theoretical models have not yet been tested. Besides real-time brokering, the ANTARES alert database hosts light curves of objects since the inception of ZTF in 2018. This provides a great leverage to explore variables with long term variation. For example, Lee et al.[12] used the ANTARES alert database to search for R Coronae Borealis stars – possible mergers of double white dwarfs – preselected from their mid infrared colors. This led to the discovery of the first R Coronae Borealis star, ZTF18abhjrcf, from the ZTF survey.

These examples demonstrate the efficacy and efficiency of ANTARES, both in digesting the full streams of alerts from ZTF in real-time, and in triggering follow-up observations in a prompt manner.

3. SUMMARY

Time-domain alert brokers play an important role in the current and future time-domain ecosystem, in particular to identify the rarest of the rare events that will benefit follow up. ANTARES is actively ingesting and disseminating alerts from ZTF in real-time, and can be scaled up to match the amount of alerts distributed by Rubin observatory. On the follow-up front, ANTARES is well-connected to a suite of services developed by NOIRLab and the community. ANTARES connects to the Las Cumbre Observatory TOM Toolkit that shares target information, observation scheduling, and data visualization to enable coordinated follow-ups. ANTARES provides a searchable database that can be queried from its web portal or programmaticaly via a client API, Astro Data Lab science platform, and TOM Toolkit. This allows users to subscribe to alerts tagged by pre-defined or user-specified filters. The ANTARES team is actively acquiring photometric and spectroscopic observations to classify intriguing alerts, in particular with the Las Cumbres Observatory and the Gemini Observatory as an integral part of AEON. ANTARES is well-connected to the upstream surveys and downstream services (TOM and AEON). ANTARES is thus an effective set of tools that enables the scientific community to assemble an end-to-end follow-up infrastructure to maximize the science outcome from millions of alerts delivered by ongoing and future sky surveys.

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