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Using the VO to Study the Time Domain

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Abstract. Just as the astronomical "Time Domain" is a catch-phrase for a diverse group of different science objectives involving time-varying phenomena in all astrophysical régimes from the solar system to cosmological scales, so the "Virtual Observatory" is a complex set of community-wide activities from archives to astroinformatics. This workshop touched on some aspects of adapting and developing those semantic and network technologies in order to address transient and time-domain research challenges. It discussed the VOEvent format for representing alerts and reports on celestial transient events, the SkyAlert and ATELstream facilities for distributing these alerts, and the IVOA time-series protocol and time-series tools provided by the VAO. Those tools and infrastructure are available today to address the real-world needs of astronomers.

1. Introduction

Virtual Observatory activities relating to time-domain astronomy have focused on the VOEvent celestial transient alert protocol since 2005.† VOEvent is a message format for conveying reports of time-varying astronomical observations (Seaman *et al.* 2011). The notion of VOEvent is to permit the several different pre-existing astronomical telegram standards and transient alert protocols to be expressed in a common form that will permit interoperability, while enabling modern virtual technologies to be used to construct autonomous workflows. The goal is to close the observational loop from the discovery of transient phenomena, for instance by large synoptic surveys, to their follow-up by robotic or human-mediated instrumentation and telescopes.

VOEvent is necessary but not sufficient. A common message format requires an interoperable transport infrastructure layer. Three of these—SkyAlert, ATELstream and the VAO Transient Facility—are discussed below. Others such as the VOEvent-enabled Gamma-ray Bursts Coordinates Network (GCN) and the IAU CBAT service (Central Bureau of Astronomical Telegrams) have also been adapted to VOEvent compliance. VOEvent, like any living standard, must also evolve to meet the needs of the community, so the recent VOEvent v2.0 Recommendation (standard) of the International Virtual Observatory Alliance (IVOA, an activity of Commission 5 of the IAU) is also discussed below.

A key aspect of time-domain astronomy is the collection and interpretation of time-series data sets. This is related to VOEvent, but is also a key area for IVOA-compliant data archives. Recent work on time-series tools, performed by the U.S. Virtual Astronomical Observatory (VAO), was demonstrated during the workshop.

† IVOA VOEvent Working Group Wiki: http://voevent.org

2. Skyalert

Skyalert‡ is a clearing-house and repository of information about astronomical transients, each described by a collection of VOEvent packets that may have multiple authors. The components of Skyalert are:

- A Web-based event broker, allowing subscription so that information about transients can be delivered to users and their telescopes immediately upon receipt.
- A Web-based authoring system, so that authenticated users can inject events directly from automated discovery pipelines, or fill in Web forms, that may be delivered rapidly to others.
- An event repository, storing all events that come through the broker, and allowing bulk queries and drill-down.
- A *click or code* paradigm that allows people Web-based access and machines Web-service access.
- A way to see recent and past transients: as tables, multi-layered Web pages, or with popular astronomical software.
- A development platform for building real-time decision rules about transients, and for mining the repository.
- Open-source software to allow local implementations as well as the Web-based application.

The crucial standard that enables interoperable exchange of events is called VOEvent, now a Recommendation of the International Virtual Observatory Alliance. Reading that standard, as described above, is a good basis for understanding more of this document. Skyalert installation shows on the front page all the recent events (last 200) ingested into the system, as clickable dots in a semi-log timescale, with the present moment at the right, and older events further top the left. Clicking on any of the dots brings up the portfolio for that event. Also available from the front page is a collection of Atom feeds of recent events (both system feeds and your custom feeds).

2.1. *Event Portfolios*

Each transient will have a collection of data that we call a data portfolio: a collection of numbers, links, images, opinions, search results, etc. A portfolio is defined through a citation mechanism inherent in the VOEvent packet, where one event can cite another. Thus, an event with no citation becomes its own portfolio, but an event with a citation to another joins the portfolio to which the other belongs.

As noted above, the portfolio detail page can be accessed by clicking on the dot for a recent event. One can also select a specific event stream via *Browse Event Streams*, choose the required table of portfolios, and then narrow the search to a specific event. A third route to get to a specific event is by selecting a feed (one's own or a system feed), and then choosing a portfolio at that point. There are three representations that are available for each event of a portfolio:

- Overview: created by running the event data through the overview template.
- Params: a table of parameters and their values, plus representation of any Tables in the event.
- XML: showing the actual XML that was loaded into Skyalert

‡ `http://skyalert.org`

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2.2. *Alerts*

An alert is a means of determining whether a portfolio is "interesting" in some way, and what to do if it is. From each "rule" (see below) is automatically generated a feed of interesting portfolios. It may be that the action which results from an interesting portfolio can cause another event to be loaded to the same portfolio, and that might in turn cause another rule to be satisfied, and another action to be taken.

Each alert has a collection of streams; for the rule to operate on a portfolio, it must have an event drawn from each of its needed streams. The simplest rules, however, need only events from one stream; for example, an event from a stream called *apple* might be interesting if it is bright; if there is a Param named *magnitude* then the trigger expression might be:

```
apple[magnitude] < 18
```

The trigger expression is interpreted by Python, within a sandbox environment that allows only math. functions. Thus, a trigger expression like `os.system(rm *)` will fail because the `os` module cannot be imported into the sandbox environment.

A rule runs on a collection of events (i.e. a portfolio). The simplest rule considers only one stream. Rules can be created only by a user who is registered and logged in. To build a rule, the user first clicks on *my feed and alerts*, then on *for a new alert*, and then selects an event stream (but should not click the advanced option). A name for the alert is entered, to start to make the trigger expression. The simplest expression is *True*, meaning that all of the events are interesting. The user must explicitly save the rule before the latter can do anything; the expression is checked for syntax before being saved, so that only syntactically correct trigger expressions get into the database. The alert-editor screen also has a button to show all the past events that would have satisfied the trigger. More complex rules can use multiple event streams to make a joint decision on the portfolio; suppose (for example) that an event from the *apple* survey has a follow-up from the `fruitObserver` catalogue, and that bright apple events are required which are also bright in the `fruitObserver` stream:

```
apple[magnitude] < 18 and fruitObserver[gMag] < 18
```

This a joint criterion on two different event streams, authored by different people. In one stream the author chose to use the Param called *magnitude*, and in the other stream the author chose to use the name *gMag*. Because of the underlying VOEvent model, Skyalert is able to integrate information from multiple authors.

2.3. *Layering facilities on VO-compliant protocols: VOEvent2*

The IVOA VOEvent standard was first defined, and a prototype created, in 2005, and reached official Recommendation status in 2006. It has been adopted successfully by many astronomical time-domain projects since then. It was recognized from the start that more advanced features would be needed in order to grapple with the challenging time-domain projects looming in the near future. The recently-adopted VOEvent2 standard embraces such features.

2.4. *VO compliant protocols: Distributed Transient Facility*

The time-domain community wants robust and reliable tools to enable the production of, and subscription to, community-endorsed event notification packets (VOEvents). The proposed Distributed Transient Facility (DTF) is being designed to be the premier brokering service for the community, not only collecting and disseminating observations about time-critical astronomical transients but also supporting annotations and the application of intelligent machine learning to those observations. Two types of activity associated with the facility can therefore be distinguished: core infrastructure, and user services. The prior art in both areas were reviewed by the workshop, and planned capabilities of the DTF were described. In particular, it focused on scalability and quality-of-service issues required by the next generation of sky surveys, such as LSST and SKA.

3. ATELstream

Bob Rutledge of the Astronomer's Telegram described to the workshop the new ATELstream† facility that provides a UNIX socket-based XML-driven messaging service for celestial transient event notices. Much interest was exhibited in ensuring that ATELstream and VOEvent remain interoperable and that the community meld together the two technologies for the benefit of all.

4. VOEvent2

This workshop was only the latest in a long line of workshops, meetings and sessions over the past half-dozen years concerned with using Virtual Observatory standards and protocols for studying the time domain. All have been tied to VOEvent, but also come more generally under the banner of *Hot-wiring the Transient Universe*‡. Copies of the same-named book (Williams, Emery Bunn & Seaman 2010) were made available for distribution.

The system architecture of the IVOA consists of numerous protocols, data models and services. The VOEvent Recommendation is one of the many diverse international standards of the IVOA. VOEvent refers to, and relies on, several of those, and other standards may in turn depend on VOEvent. VOEvent is also engaged in numerous external projects; several are currently distributing messages in VOEvent format, others are connected to major future surveys, and still others represent existing projects with a stake in enhancing their interoperability.

Planning is underway for a third-generation transport infrastructure. The diverse prototype technologies of the original VOEventNet were followed by the deployment of the operational SkyAlert system discussed above. Future celestial transient event transport infrastructure within the Virtual Observatory is anticipated to develop from the VAO transient facility project described below. In the mean time, numerous efforts will continue at working with other transient alert technologies and projects to ensure interoperability both across the community and for all types of time-varying celestial phenomena. Building such an infrastructure is an exercise in creative bootstrapping.

The IVOA VOEvent standard became a Recommendation of the IVOA in 2006. Evolution of the format was planned, and a major milestone was reached in 2011 with the acceptance of the VOEvent v2.0 update to the standard. Its major features include:

- The definition of VOEvent *Streams* in support of ongoing work to enhance the registration of VOEvent resources in the Virtual Observatory.
- VOEvent has always been transport-neutral. In recognition of the rapidly changing landscape of transport technologies, the explicit description of transport options has been removed from the standard.
- The VOEvent ⟨*Param*⟩ element has been generalized.

† `http://blogs.astronomerstelegram.org/atelstream/`
‡ `http://hotwireduniverse.org/`

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- A facility was added to embed general-purpose tabular data structures within VOEvent packets.
- Time series will be supported as tables with *utypes* referencing an IVOA time-series data model.
- The VOEvent ⟨*Reference*⟩ element has been generalized.

In addition to changes to the VOEvent format, the v2.0 efforts focused on creating a more robust XML schema and on enhanced libraries and Web access compatible with the format and schema. The fundamental nature of the VOEvent format has remained the same between versions. VOEvent exists to support the engineering of empirical workflows (Seaman 2008) and with key elements:

- ⟨*Who*⟩ – author's provenance
- ⟨*What*⟩ – empirical measurements
- ⟨*WhereWhen*⟩ – targeting in spacetime
- ⟨*How*⟩ – instrumental signature
- ⟨*Why*⟩ – scientific characterization
- ⟨*Citations*⟩ – building threads of transient-response follow-up

5. VAO Time-Series Tools

Systems to disseminate event notifications are a major component of the VO's infrastructure for supporting time-domain science. Equally as important, however, are the tools and services that enable and facilitate the discovery and analysis of collections of time-series data. In view of the increasing number of new time-domain surveys now in progress or being planned, providing a framework to interconnect the data in distributed archives and appropriate services can only aid both the discovery of previously unknown phenomena and improve our understanding of already known ones. Through a number of activities, the VAO aims to create such interoperability, allowing astronomers to locate the data they want and then effortlessly connect the data providers to different types of available tools, such as a periodogram service or a time-series modeller, as part of a workflow or scripted analysis session.

As an illustration of such a system, one might consider an astronomer who is using variable stars, say RR Lyræ types, to study Galactic structures such as spiral arms, stellar streams or the like. A major contaminant in that kind of analysis can be eclipsing binaries, and the usual light curves of both classes can be difficult to distinguish. However, the binaries can easily be filtered out using phased light curves. The astronomer could therefore create a pure data set for the analysis by identifying suitable data through the VAO Time Series Archive Interconnectivity Portal and sending them to the periodogram service at the NASA Exoplanet Archive. The VAO infrastructure will handle the data transfer for the astronomer and the result that is returned is a phased light curve (see Fig. 1).

A pathfinder for this kind of collaboration is being developed by the VAO, initially connecting the Harvard Time Series Center, the NASA Exoplanet Archive and the Catalina Real-Time Transient Survey. As more data sets and tools become available, they will be integrated seamlessly. Provision for bulk activities, such as the large-scale characterization of time series, is also being considered.

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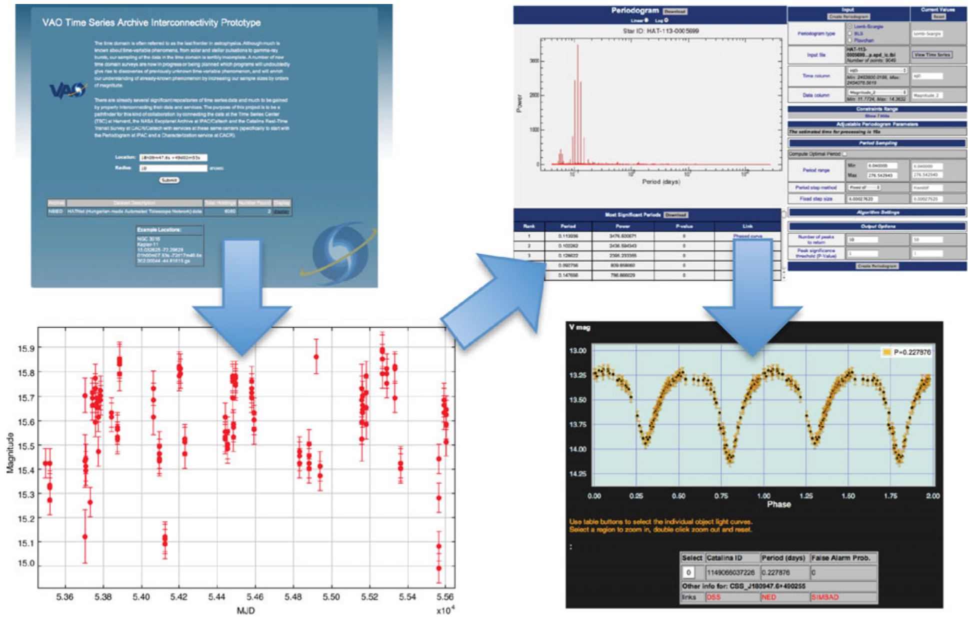

Figure 1. Time-series data workflow facilitated by the VAO.

6. Looking Ahead

During the workshop a wide-ranging discussion followed (and often interrupted) the presentations. There appeared to be a strong consensus that not only would the time domain increase in importance for astronomy in the future, but that to take advantage of its full potential virtual and semantic technologies would be critical. The often lively discussion addressed future directions for the virtual observatory time-domain facilities as a whole.

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