The CHIME/FRB VOEvent Service

Real-time Alerts of CHIME Fast Radio Bursts

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On behalf of CHIME/FRB Collaboration

Welcome to an introduction to the CHIME/FRB VOEvent Service.
My name is Andrew Zwaniga, I am a research assistant at McGill University and will be presenting these materials on behalf of the CHIME/FRB Collaboration.
In this presentation you will learn about an alert system that publishes meta data in real-time for fast radio bursts observed with the CHIME telescope.

Outline

- Overview
- Subscriptions and event handling
- Real-time alerts
- Thresholds, data quality, and performance
- Post real-time alerts
- Conclusion

This presentation and materials referenced therein are intended for researchers in the FRB field who are interested in multi-wavelength follow-up of FRBs detected by CHIME. I will give an overview of the Service that CHIME/FRB operates towards that end, including details on how to use this subscription service. The meta data content of the alerts will be described but the listener should be advised that supplemental tutorials and resources are available on the CHIME/FRB public webpage. Finally, I will address the topics of thresholds and meta data quality, and plans for future post real-time alerts.

Overview

We begin with an overview of the CHIME/FRB VOEvent Service, which I refer to hereafter to as “the Service”.

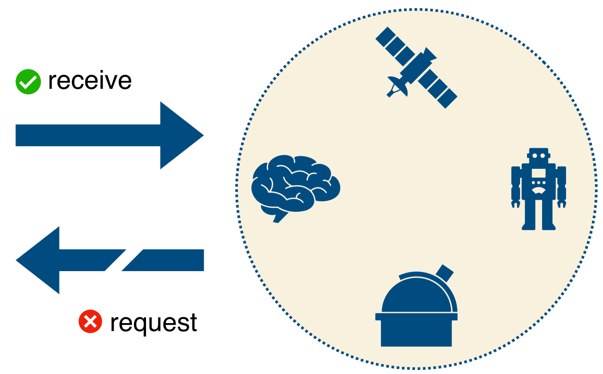
A Push Service

The Service is **push-based**: alerts are delivered to subscribers only once.

Contrast with **pull-based**: alerts cannot be requested from the Service.

Subscribers must plan their follow-up campaigns to be able to **take action at any given moment** while the Service is live.

Photo credit: CHIME Collaboration



The Service provides alerts of CHIME-detected FRBs through a subscription service that is push-based: subscribers can receive but not request alerts. For this reason, subscribers should plan to operate their follow-up campaigns to be trigger-based and content-aware. The next alert could come at any moment and will not be delivered more than once.

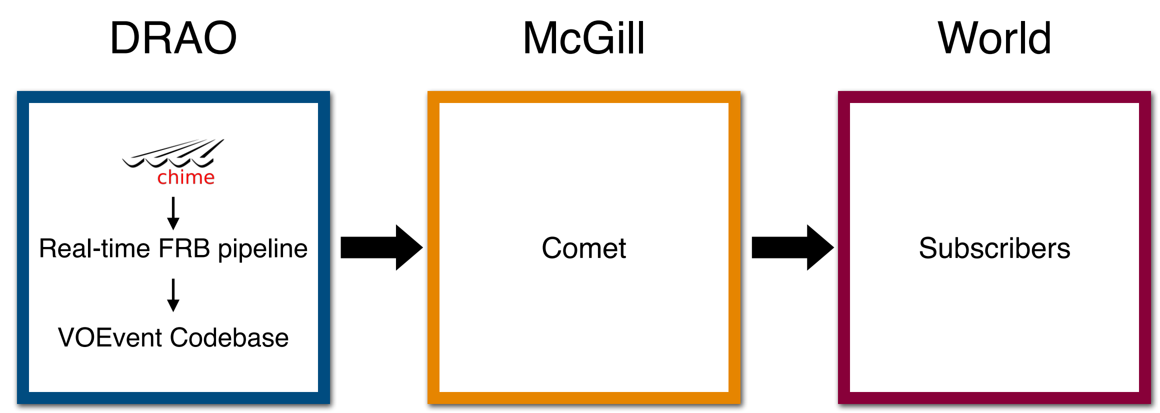
The CHIME/FRB VOEvent Service

As an overview of the Service, there are two stages before each VOEvent reaches the world. The CHIME telescope site at Dominion Radio Astrophysical Observatory (DRAO) near Penticton, British Columbia, Canada, houses all code and databases needed for creating the VOEvent from the meta data of the real-time FRB detection pipeline.

**** CLICK TO NEXT SLIDE ****

At McGill University in Montreal, Quebec, Canada, a service called Comet is ran to receive and broadcast VOEvents. From here, in principle any subscriber in the world can receive the VOEvent.

The CHIME/FRB VOEvent Service



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**** CLICK TO NEXT SLIDE ****

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Subscriptions and Alert Handling

If you are viewing this presentation, you likely are familiar with real-time alert services elsewhere in the astrophysical transients community. Moreover, if you are planning real-time follow-up of CHIME-detected FRBs, you may be well-versed in the specifics of CHIME and the FRB experiment. In this subsection, I will cut to the chase and detail the steps required to get started receiving and handling alerts from CHIME.

How to Subscribe to the Service

The Service is operated on a subscription basis and all new subscribers must submit basic information to facilitate delivery of VOEvents.

CHIME/FRB will collect user information and store it in a password-protected database located at the CHIME telescope site.

No passwords will be required or collected from the subscriber.

For complete transparency, the Service is operated on a subscription basis. This choice was made for both technical reasons regarding the underlying software architecture, and because it is amenable to usage tracking that will help CHIME/FRB better understand how its users make use of the Service and what the general outcomes are. Importantly, each subscription requires collecting of some user information, as explained in this subsection, but note that no passwords are required or collected from the subscriber.

How to Subscribe to the Service

Items that will be Stored by CHIME/FRB

Subscription requests can be made by filling this Microsoft Form.

1. Email address

- Email formatted VOEvents may be sent here.
- Changes, interruptions, or other important communications about the service will be sent here.
- Be sure to **check junk/spam folders** frequently to avoid missing important communications from the Service.

To set up a subscription, please fill out the Microsoft Form linked on the slide. Note this is also available on the CHIME/FRB public webpage. Six pieces of information are required for each subscription. Firstly, a valid email address to which emails may be sent including status updates or changes in the Service, and a human-friendly email version of the VOEvent. The email agent that represents the Service is a no-reply bot, so it is important to check one's spam or junk folders especially at the beginning of a new subscription period.

How to Subscribe to the Service

Items that will be Stored by CHIME/FRB

Subscription requests can be made by filling this Microsoft Form.

2. Name

- Subscriber’s name.
- This individual will be addressed in all email communications about the Service.

A name is also required, typically the owner of the email address provided in the previous step. Any communications about the Service will be addressed to this individual.

How to Subscribe to the Service

Items that will be Stored by CHIME/FRB

Subscription requests can be made by filling this Microsoft Form.

3. Institution or affiliation

- The name of the scientific collaboration to which the subscriber belongs; or,
- The name of the academic institution with which the subscriber is associated; or,
- Another recognized collaboration, experimental group, or research body.

The subscriber likely belongs to an academic institution or workplace or is affiliated with one of those. They may also have affiliations with scientific collaborations or research bodies. The subscriber should submit whichever one best reflects the nature of the follow-up campaign and any work that is being done on the basis of the VOEvent Service.

How to Subscribe to the Service

Items that will be Stored by CHIME/FRB

Subscription requests can be made by filling this Microsoft Form.

4. IP address of a VOEvent broker

- The **public** IP address where the subscriber's VOEvent broker will run.
- Only required if subscriber elects to receive XMLs.
- Use a **static** IP address wherever possible.
- Public IP addresses can be obtained with search engines and at the command line.

```
$ dig +short myip.opendns.com @resolver1.opendns.com

$ dig TXT +short o-o.myaddr.l.google.com @ns1.google.com
```


A full discussion of VOEvents and their XML format is still ahead in this presentation. This is the medium of the real-time alerts, and in order to receive it one must connect their VOEvent broker by submitting the IP address of the machine on which the broker runs. Selecting the machine to run the broker is an import step and the subscriber should ensure that the IP address of that machine is static. This slide includes instructions on how to obtain the IP address when working in a minimal linux environment (that is, without access to a GUI web browser from which addresses are also available).

How to Subscribe to the Service

Items that will be Stored by CHIME/FRB

Subscription requests can be made by filling this Microsoft Form.

5. Flag to receive XML version

- Answer **yes** to receive the VOEvent XML. It will be delivered to the VOEvent broker with the IP address as specified previously.
- Answer **no** to abstain from receiving the XML version of the VOEvent.

In combination with an IP address, the subscriber must indicate a flag to receive the XML version of the VOEvent. In case they do not provide an IP address, answering "No," is the only option.

How to Subscribe to the Service

Items that will be Stored by CHIME/FRB

Subscription requests can be made by filling this Microsoft Form.

6. Flag to receive email version

- Answer **yes** to receive an email formatted version of the VOEvent at the email address that was provided in part 1.
- Answer **no** to abstain from receiving email VOEvents.

Finally, a human-friendly email version of the VOEvent can be delivered to the subscriber. The latency of the email version may not compare well with that of the XML version, and in addition the email is not written to be machine friendly. Nonetheless, the subscribe can receive this at the email address they specified previously.

How to Receive CHIME/FRB VOEvents

Getting the machine-readable VOEvent XML

Step 1

Request to be added to the allow-list by filling this Microsoft Form.

Step 2

Install a VOEvent broker. **The remaining material assumes use of comet.**

Step 3

Assuming the IP address of the broker has been added to the allow-list, run the broker with the following command:

```
$ twistd -n comet --remote=chimefrb.physics.mcgill.ca
--local-ivo=ivo://test_user/test -print-event
```


Once the subscriber has filled the subscription form, a waiting period will ensue during which time CHIME/FRB will process the request. The subscriber is encouraged to consult references on VOEvent brokers if not already familiar. Note that the remainder of this presentation assumes the subscriber will use the existing Comet VOEvent broker solution that is available for use with Python. A link to Comet's documentation is provided on the slide. After the subscription request has been processed, the IP address provided in the form will be added to an allow-list, and the subscriber should make a few attempts to subscribe using the shell command shown on the slide. Importantly, the CHIME/FRB VOEvent broker is run from a domain called chimefrb.physics.mcgill.ca that is a network based at McGill University in Montreal, Quebec, Canada.

How to Receive CHIME/FRB VOEvents

Getting the email version of the VOEvent

Step 1

Request to be added to the allow-list by filling this Microsoft Form.

Step 2

Emails are sent to the address provided during the subscription process.

Notes

(1) **Monitor spam and junk** folders for messages from vo.event.sender@gmail.com, the dedicated CHIME/FRB VOEvent email agent.

(2) **Do not reply** to emails from vo.event.sender@gmail.com.

(3) Expect communications about the Service from the above address to be delivered to the email address you provided in the subscription form.

This slide lists reminders for receiving the human-friendly email version of the VOEvent. Most importantly, the subscriber should look for emails from an account called vo.event.sender@gmail.com. The subject line of these emails will be similar to “CHIME/FRB VOEvent” with the alert type included as well, either detection, subsequent, update, or retraction. We will cover those alert types ahead.

How to Parse CHIME/FRB VOEvents

Parsing the machine-readable VOEvent XML

Step 1

Become familiar with comet event handlers (documented here).

Step 2

Use an XML convenience library for extracting VOEvent meta data (voevent-parse).

Step 3

Obtain core CHIME/FRB meta data using a convenience function e.g.

voeventparse.get_grouped_params()

Step 4

Select meta data of interest from the above e.g. DM, SNR, sky location.

Setting up a Comet VOEvent broker to receive VOEvents from the Service is half of the work. The other half is developing code called an event handler in Comet's framework. Comet comes packaged with example handlers that can be used as a launchpad, as well as documentation (see link on the slide) for customizing event handlers. Each subscriber will have requirements unique to their follow-up campaign and event handling represents a non-trivial investment of time and effort. As Comet is a Python library, it is typically easy to get started with; moreover, there are convenience libraries such as voeventparse that make handling VOEvents simple, especially in combination with Comet. The standardized format of CHIME/FRB VOEvents makes developing a robust event handler intuitive. We will cover this standard format ahead, and in particular Step 4 above about selecting meta data of interest from the VOEvent.

How to Parse CHIME/FRB VOEvents

In need of further instruction?

Follow our Jupyter notebook tutorial!

Step 1

Go to the CHIME/FRB Open Data GitHub repository.

Step 2

Clone the repository to your machine and open this file with Jupyter:

chime-frb-open-data/cfod/utilities/chimefrb_voevent_tutorial.ipynb

Step 3

Complete the tutorial using the sample XML files that come with the repo.

While these slides and my commentary are a good place to start, it is recommended that subscribers consult the Jupyter notebook tutorial listed on our CHIME/FRB Open Data GitHub repository. The notebook gives an interactive walkthrough of a sample CHIME/FRB VOEvent XML, providing launch points and inspiration for how subscribers can handle VOEvents and select meta data of interest from them.

Real-time Alerts

In this section we introduce the VOEvent standard and its application to fast radio bursts. Those who are familiar with the standard are yet unlikely to be familiar with the more particular FRB VOEvent Standard and its further application to CHIME/FRB. This section serves a companion to the Jupyter notebook tutorial I described previously.

Virtual Observatory Events (VOEvents)

The VOEvent XML Standard is described by the IVOA here.

Key Features

- Machine readable representation of meta data, especially objects.
- Relies on XML, an existing object representation medium for web services.
- Standardizes reports of observations for virtually any domain.

Use Cases

- Gamma-ray Coordinates Network or Transient Alert Network (GCN/TAN) brings together instruments across the electromagnetic spectrum as they coordinate multi-wavelength observations of gamma-ray or X-ray targets with VOEvents.

For starters, VOEvents were first defined by the International Virtual Observatory Alliance (IVOA) as a useful medium for reporting on astrophysical transients. VOEvents are a useful medium because they are machine readable, rely on an existing Internet communication protocol, and present a standard that gives flexibility in WHAT to report but provides a common understanding among all users of HOW to report it. Other astrophysical transients such as gamma ray bursts, X-ray flares, and optical flares are being reported through VOEvents by for example the GCN/TAN, a conglomerate of over a dozen instruments across the spectrum.

FRB VOEvents

The FRB VOEvent standard was first defined in Petroff et al. 2017.

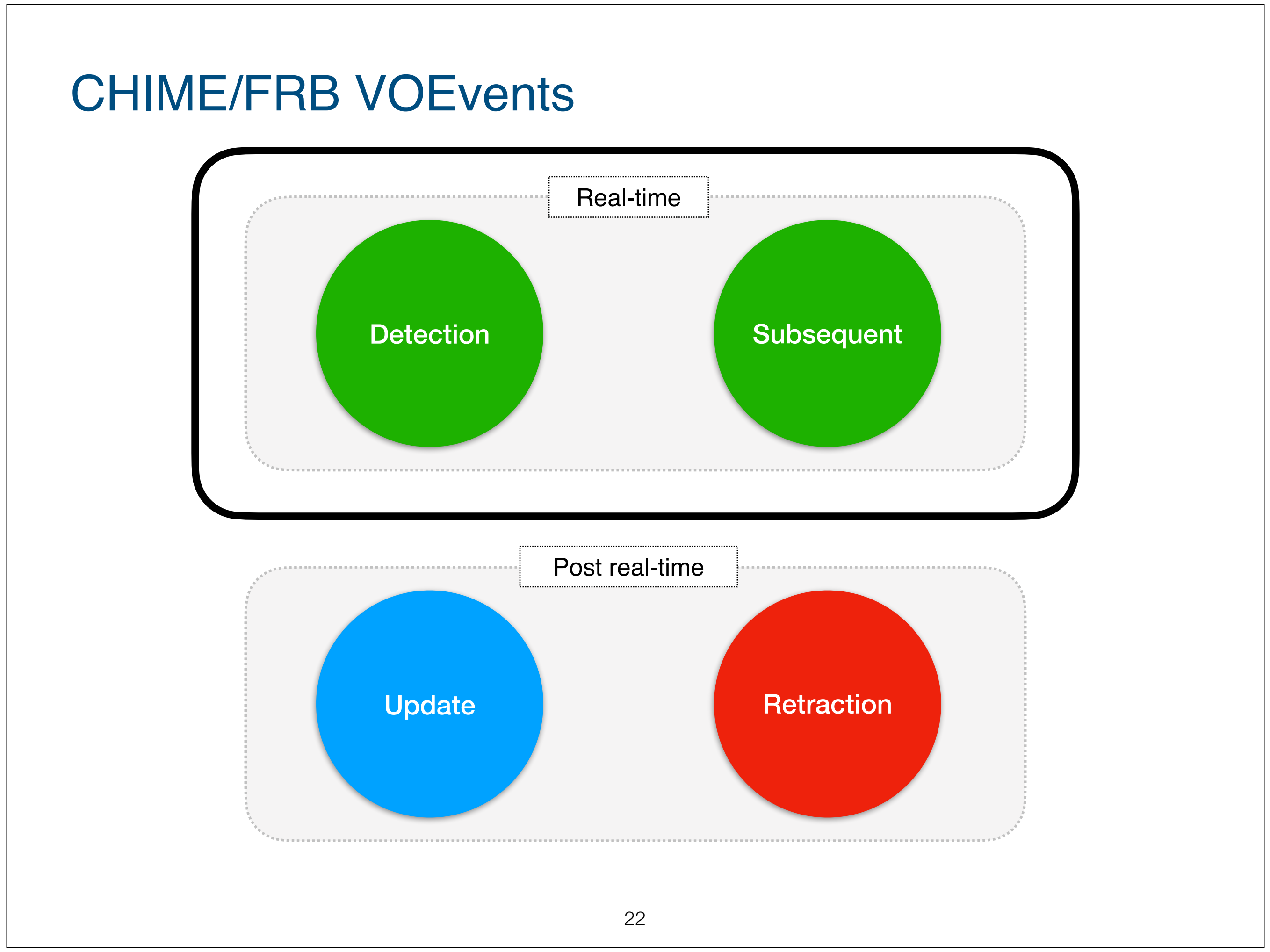
Key Features

- A new medium for reporting FRB observations in a machine-readable format.
- Prescribes four types of VOEvents for FRB observations.

Use Cases

- CHIME/FRB implements all four types, with some modifications and extensions.

The VOEvent Standard is amenable to expansion and indeed an FRB standard was first specified by Petroff et al in 2017. Beyond individual VOEvents, these authors also described four different types of VOEvents specifically for reporting on observations of fast radio bursts. These types are prescribed specifically for FRBs, some of which are known to repeat and so are the subject of special follow-up campaigns. CHIME/FRB adds further specificity to the FRB standard, as we look at next.



In the Petroff et al VOEvent Standard, four VOEvent types were defined. Each type has been configured for CHIME/FRB and further elaborated on. In this diagram, there are two classes of alerts: real-time, and post real-time. The real-time alerts both contain the same type of meta data, namely the header data from the real-time FRB detection pipeline - hence they are grouped together and both coloured green. The post real-time alerts are in a more developmental stage; they contain very unique types of meta data different than the real-time alerts, and different than each other. In this section, we focus on the real-time alerts.

CHIME/FRB Detection and Alert Criteria

A complete description of the real-time FRB detection pipeline is here [1].

All radio signals reaching the L2-L3 stage are assigned an **event number** and are referred to as Events.

If an Event satisfies the alert criteria it will be published as a VOEvent of one type:

- **Detection**, for a new FRB
- **Subsequent**, for an FRB associated with a known source

The **alert criteria** are:

- SNR >= 10; and
- Not associated with a known Galactic source; and
- Intensity and/or baseband callback data were requested.

Published VOEvents represent a **subset** of all FRB events that are detected and further processed by CHIME/FRB.

The VOEvent Service is triggered at the end of the real-time FRB pipeline. In that pipeline, data is organized into objects called Events, which may be published as VOEvents if they satisfy basic thresholds on the SNR. We do not publish VOEvents for data that has been associated with Galactic sources; and we only publish VOEvents when the dynamic spectrum (i.e. intensity data) capture has been requested. Since every VOEvent published should eventually be verified as an FRB or non-FRB at some point, we require that intensity data has been captured as a trigger condition for VOEvents. Depending on whether the Event in the pipeline was associated to a known FRB or not, the type of alert published is either detection or subsequent.

VOEvent XML Documents

The VOEvents are text documents styled in XML with a defined structure.

Click the **links** to go to the relevant slides.

Link →
Link →
Link →
Link →
Link →
Link →
Link →

```
<VOEvent […]>
  <Who>[…]</Who>
  <What>[…]</What>
  <WhereWhen>[…]</WhereWhen>
  <How>[…]</How>
  <Why>[…]</Why>
  <Citations>[…]</Citations>
</VOEvent>
```


Jupyter notebook tutorial.

The published VOEvent is just a text document styled in the mark-up language called XML. This language is used broadly across the Internet. In the following slides we cover the seven sections of a VOEvent XML for the special case of CHIME/FRB.

The `<VOEvent>` Section

IVORN

- **I**nternational **V**irtual **O**bservatory **R**esource **N**ame, similar format to a URL/URI, a unique identifying string for every VOEvent that uses ivo:// prefix.
- Example:

```
ivo://ca.chimenet.frb/FRB-DETECTION-
#2021-08-19-21:50:28.900992UTC+0000_7f17d982b325
```

role

- `“observation”` for detections of new or known FRBs.
- `“utility”` for measurement updates or retractions (post real-time).
- `“test”` for fake VOEvents that are meant to test that the Service is working.

Jupyter notebook tutorial.

Every VOEvent has a unique identifier called an IVORN. For CHIME/FRB, the IVORN is linked directly to an event number from the real-time pipeline. All real-time VOEvents represent an observation of an FRB, but future post real-time VOEvents will be considered utility alerts.

The <Who> Section

AuthorIVORN

- Shortened IVORN identifying CHIME/FRB as the author of the VOEvent.

Author → contactEmail

- Reach out here for questions about CHIME/FRB VOEvents.

Author → contactName

- Any communications via email can address this CHIME/FRB member.

Date

- Date and time when the VOEvent XML was created.

Jupyter notebook tutorial.

Every VOEvent should identify the agent that authored it. The Author IVORN is a special shortened kind of IVORN specifically representing CHIME/FRB. Within the Author details are an email address and a name that subscribers can reach out to for questions regarding the Service. Finally, in most cases the time of publication of the VOEvent will be within 10 to 15 seconds of the Event detection time.

The `<What>` Section

Overview

All relevant meta data for the observation is reported here as named parameters.

Values originate from the real-time FRB detection pipeline.

Observatory Parameters

- backend
- bandwidth
- bits_per_sample
- centre_frequency
- npol
- sampling_time
- tsys

Event Parameters

- dm
- dm_error
- event_no
- event_type
- known_source_name
- pipeline_name
- pos_error_semimajor_deg_95
- pos_error_semiminor_deg_95
- snr
- timestamp_utc
- timestamp_utc_error

advanced parameters

- dm_gal_ne_2001_max
- dm_gal_ymw_2016_max
- timestamp_utc_inf_freq
- timestamp_utc_inf_freq_error

Jupyter notebook tutorial.

The main meta data is contained in the aptly named “What” section. High level meta data parameters are reported like the dispersion measure, signal to noise ratio, and arrival time of the burst at both 400 MHz and at infinite frequency, after correcting for dispersion. The meta data get their values and uncertainties from the real-time pipeline, and are grouped into three categories.

The `<What>` Section

Observatory Parameters

- backend
- bandwidth
- bits_per_sample
- centre_frequency
- npol
- sampling_time
- tsys

backend

- Real-time FRB search backend produced these meta data.

bandwidth

- Nominal CHIME receiving bandwidth is 400 MHz (400 - 800 MHz).

bits_per_sample

- The raw intensity data consists of 16384 frequency channels at 0.983 ms cadence as 8-bit integers.

Jupyter notebook tutorial.

Several static data are reported in each VOEvent just as would be reported by any radio telescope. The bandwidth of the CHIME telescope is 400 MHz and in the dynamic spectrum the highest frequency resolution captured is 16384 channels sampled at about a 1 ms cadence.

The <What> Section

Observatory Parameters

- backend
- bandwidth
- bits_per_sample
- centre_frequency
- npol
- sampling_time
- tsys

centre_frequency

- Centre observing frequency of the CHIME band, 400 MHz.

npol

- CHIME antennas have 2 polarizations (dual).

sampling_time

- Real-time FRB search resolution is 0.983 ms.

tsys

- CHIME receiver noise temperature is 50 K.

Jupyter notebook tutorial.

The central observing frequency of the CHIME telescope is 600 MHz, so together with the bandwidth this implies the band is 400 to 800 MHz. Each antenna is dual-polarization, and the receiver noise temperature is an estimated 50 K. Note that these observatory parameters are not real-time estimates and are for reference only.

The <What> Section

Event Parameters

- dm
- dm_error
- event_no
- event_type
- known_source_name
- pipeline_name
- pos_error_semimajor_deg_95
- pos_error_semiminor_deg_95
- snr
- timestamp_utc
- timestamp_utc_error

dm

- Real-time (`bonsai` [1]) dispersion measure in cm^{-3} pc of the burst.

dm_error

- Real-time (`bonsai` [1]) dispersion measure uncertainty with one of five values: [0.404, 0.404, 0.809, 1.62 , 3.24] cm^{-3} pc.

event_no

- CHIME/FRB internal event number.
- Assigned at L2-L3 in the event registration process.
- Use this in all communications with CHIME/FRB regarding individual VOEvents.

Jupyter notebook tutorial.

Every real-time Event comes with a host of meta data and parameters, which are captured in this category. The DM estimate and its uncertainty comes directly from the highly optimized tree de-dispersion algorithm called bonsai. Every Event ends up in one of five possible bonsai trees, and each has a fixed uncertainty associated with it, with the highest tree having the largest uncertainty. Importantly, every VOEvent corresponds with a unique CHIME/FRB event number that is assigned from the real-time pipeline. This integer is a primary key in all of our databases and should be exclusively used when subscribers make inquiries about a VOEvent.

The <What> Section

Event Parameters

- dm
- dm_error
- event_no
- event_type
- known_source_name
- pipeline_name
- pos_error_semimajor_deg_95
- pos_error_semiminor_deg_95
- snr
- timestamp_utc
- timestamp_utc_error

event_type

- Real-time event classification based on comparison of DM with Galactic DM estimates.
- EXTRAGALACTIC or AMBIGUOUS.

Extragalactic: $DM - M > 5\sigma$
Ambiguous: $5\sigma \geq DM - M > 2\sigma$
Galactic: $2\sigma \geq DM - M$

where σ is the uncertainty in the DM measurement and M is given by

$$M = \max\{DM_{NE2001}, DM_{YMW2016}\}$$ [1]

Jupyter notebook tutorial.

The event type is a string indicating either a predicted extragalactic origin or ambiguous origin. These are classifications made in real-time that rely on a comparison of the DM of the event with two Galactic DM maps (NE 2001 and YMW 2016); the criteria for this are listed on the slide. An ambiguous origin implies that the DM compares closely with the expected Galactic DM along the line-of-sight. More details on the real-time classification are available in CHIME publications.

The <What> Section

Event Parameters

- dm
- dm_error
- event_no
- event_type
- known_source_name
- pipeline_name
- pos_error_semimajor_deg_95
- pos_error_semiminor_deg_95
- snr
- timestamp_utc
- timestamp_utc_error

known_source_name

- **Subsequent** alerts are published for detections of sources known both internally and publicly.
- The strength of association with the named source is measured by a probability.
- The probability of association with this source is reported in the <Why> section as the <Inference probability="…"> value in [0, 1].
- Some subsequent alerts may be associated with more than one known source; a probability is calculated for each, and only the most probable one is reported in the VOEvent.
- The known source name is either a TNS name, with format FRBYYYYMMDDx, or an internal CHIME/FRB **event number**.

An important stage of the real-time FRB pipeline involves a first estimate of known source association. An internal database of sources, some known publicly and others internal to CHIME/FRB, is cross-referenced with the DM and sky-position of the FRB. While in fact a list of possible associations is produced, the VOEvent contains only the most likely association, where the likelihood is estimated within a Bayesian framework. Sources in the public domain are reported with their Transient Name Server or TNS name, while as-yet unpublished sources from CHIME/FRB appear as event numbers only.

The `<What>` Section

Event Parameters

- dm
- dm_error
- event_no
- event_type
- known_source_name
- pipeline_name
- pos_error_semimajor_deg_95
- pos_error_semiminor_deg_95
- snr
- timestamp_utc
- timestamp_utc_error

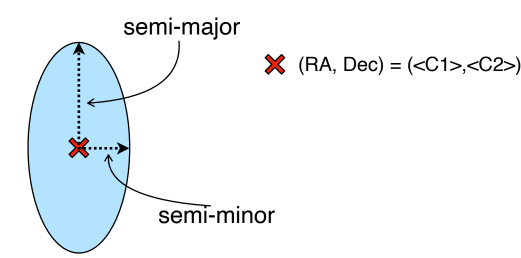
Important!

The error ellipse is not guaranteed to be axis-aligned with the local right ascension and declination directions.

pipeline_name
- Name of the pipeline that produced the results published in the VOEvent.

pos_error_semimajor_deg_95
- Error ellipse semi-major axis to 95% confidence in degrees.

pos_error_semiminor_deg_95
- Error ellipse semi-minor axis to 95% confidence in degrees.



Jupyter notebook tutorial.

Currently the real-time FRB pipeline is the only one that publishes VOEvents, but in the future other offline analysis pipelines will too.

That said, the best available localization for VOEvents is the real-time result that yields an elliptical sky region. Both the semi-minor and semi-major axes are published, however the orientation of the ellipse on-sky is not calculated in real-time. For this reason we publish the official localization of the real-time coordinates as the maximum of either axis, yielding a circle. This information is reported in the WhereWhen section ahead.

The <What> Section

Event Parameters

- dm
- dm_error
- event_no
- event_type
- known_source_name
- pipeline_name
- pos_error_semimajor_deg_95
- pos_error_semiminor_deg_95
- snr
- timestamp_utc
- timestamp_utc_error

snr

- Signal to noise ratio (SNR) of the detection beam.
- In the case of a multi-beam detection, the maximum SNR is reported.

timestamp_utc

- Detection time in UTC at 400 MHz after correction for dispersion, using the DM reported in the event.
- String formatted Pythonic `datetime` object with timezone info e.g. 2021-09-07 12:34:56.789000+00:00

timestamp_utc_error

- Uncertainty in the detection time, propagated from the uncertainty in the DM.
- Float number of seconds.

Jupyter notebook tutorial.

The published signal to noise ratio is the maximum of any synthesized beams that detected the burst. Multi-beam events are not uncommon, and they tend to produce larger uncertainties in the real-time localization. The event time is published as a Pythonic datetime object casted to a string, with an example shown on the slide. The arrival time is corrected for dispersion to the bottom of the CHIME band, 400 MHz. The uncertainty on this time is a float value in seconds and is propagated from the uncertainty in the DM.

The `<What>` Section

Advanced Parameters

- dm_gal_ne_2001_max
- dm_gal_ymw_2016_max
- timestamp_utc_inf_freq
- timestamp_utc_inf_freq_error

dm_gal_ne_2001_max

- Maximum Galactic DM along line of sight referenced from the NE 2001 model.

dm_gal_ymw_2016_max

- Maximum Galactic DM along line of sight referenced from the YMW 2016 model.

Jupyter notebook tutorial.

Within the real-time pipeline, two different Galactic electron density maps are consulted to classify an event as extragalactic, ambiguous, or Galactic. The Galactic DM along the line of sight to the real-time coordinates is reported for both the NE 2001 and YMW 2016 maps in this group.

The `<What>` Section

advanced parameters

- dm_gal_ne_2001_max
- dm_gal_ymw_2016_max
- timestamp_utc_inf_freq
- timestamp_utc_inf_freq_error

timestamp_utc_inf_freq

- Detection time in UTC at infinite frequency after correction for dispersion, using the timestamp at 400 MHz, the DM, and

$$k_{DM} = \frac{1.0}{2.41 \times 10^{-4}} \ \mathrm{cm}^3 \cdot \mathrm{s}^{-1} \cdot \mathrm{pc}^{-1}$$ [2]

- String formatted Pythonic `datetime` object.

timestamp_utc_inf_freq_error

- Uncertainty in the detection time, propagated from the uncertainty in the timestamp at 400 MHz and the uncertainty in the DM.
- Float number of seconds.

Jupyter notebook tutorial.

For convenience we also publish the arrival time at infinite frequency after correcting for dispersion delay using the well known conversion. The uncertainty is propagated from the value at 400 MHz and the uncertainty in the DM, and is reported as a float value in seconds.

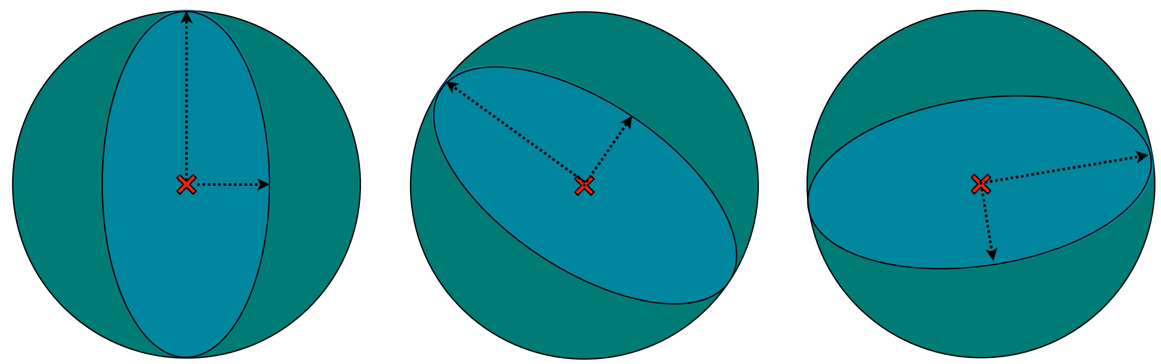
This concludes the list of meta data published in the What section.

The <WhereWhen> Section

Spatial (localization and coordinate system) and **temporal** (arrival time) information.

The real-time localization is reported as **a circle in equatorial coordinates**.

An elliptical localization is also available in the <What> section, representing a subset of the circular region (see possible scenarios below).



✖ (RA, Dec) = (<C1>,<C2>) [see Jupyter notebook tutorial]

Jupyter notebook tutorial.

The WhereWhen section contains the time and location of the VOEvent. CHIME/FRB VOEvents are reported in UTC-FK5 topocentric coordinates. The time of the event is set to the arrival time at 400 MHz, and the sky localization is a circular region, with radius equal to the maximum of the semi-major and semi-minor axes of the real-time localization ellipse.

The <How> Section

Currently contains a link to the CHIME/FRB public webpage: chime-frb.ca

As the public webpage evolves and expands, we may publish links to downloadable post real-time data products from the public webpage in the VOEvent.

Jupyter notebook tutorial.

The How section is lightly used but may expand in scope with future enhancements. Other VOEvent authors, such as the LIGO/Virgo Experiment, are known for publishing links to downloadable post processing data products. An example of this for CHIME/FRB might be a link to download the dynamic spectrum (i.e. intensity data).

The `<Why>` Section

The VOEvent Standard requires authors to publish an **importance** factor, a number from 0 to 1.

For observations of transient events, the number reflects the confidence in an astrophysical origin: 0 is lowest confidence, 1 is highest confidence.

The CHIME/FRB VOEvent Standard uses a real-time machine learning score from 0 to 1 to indicate this confidence, with an **internal threshold of 0.9.**

Additionally, a **probability** is reported *for subsequent alerts only* to indicate the likelihood of association with a known source.

Only the most likely association is reported, and the known source may be internal to CHIME/FRB or catalogued publicly.

- Integers of (e.g. 60792403, 183253678) are **CHIME/FRB event numbers.**
- Names formatted “FRB YYYYMMDDx” are **TNS names**.

Jupyter notebook [tutorial].

It is not typically enough to wait for the next VOEvent that has a DM and SNR that satisfies one’s observing campaign targets. One should also consider these important factors reported in the Why section. Firstly, the importance of the alert is a float value from 0 to 1 containing the score of a machine-learning classifier trained to distinguish RFI events (score of 0) from Astrophysical ones (score of 1). Internally we place a threshold of 0.9 before publishing a VOEvent.

The importance score on its own is enough for detection VOEvents. However, subsequent VOEvents also come with a probability value indicating the likelihood that the VOEvent is associated with the known source that is named in the event. The known source is named according to the following convention: any source known only to CHIME/FRB is published as an event number, while sources that are listed on the Transient Name Server are published with their TNS names.

The `<Citations>` Section

All VOEvents are citable in a basic way by their VOEvent IVORN.

Citations contain the VOEvent IVORN for a previous publication.

Subsequent VOEvent
- A **follow-up** observation that cites a previous detection.

Retraction VOEvent
- Offline **retraction** of a previous FRB, either detection or subsequent.

Update VOEvent
- Offline analysis results that **supersede** a previous detection or subsequent.

Jupyter notebook tutorial.

As with Astronomer's Telegrams, VOEvents are citable in a basic capacity through their VOEvent IVORN, which was discussed previously. In CHIME/FRB we make an effort cite our own VOEvents whenever a chain of subsequent detections occurs. Namely, any subsequent VOEvent is normally considered a follow-up of a previous detection from the associated source.

Because real-time VOEvents are not verified by a human until after publication, they may be classified as FRBs or non-FRBs and so warrant either a retraction VOEvent or an update VOEvent. These will be addressed in the final section of this presentation; but for completion, these VOEvents also cite the VOEvent that they are retracting or providing updated data on.

Thresholds, Data Quality, and Performance

At this stage, the subscriber should have an understanding of how to receive VOEvents and what the data contained therein represents. The subscriber should now be comfortable with receiving every VOEvent and parsing it to extract all of the data it contains. However, not every VOEvent will be relevant to one's observing campaign. This could be due to constraints or targets defined in the campaign, and/or by the quality of data provided in the VOEvent Service. In this section we discuss how to set thresholds on VOEvents, and the data quality and performance to expect from the Service.

Selecting Your Own Thresholds

Parameter	Data Type	Example Scenarios
dm	float	Low-DM targets →
event_type	str	Study AMBIGUOUS events only →
known_source_name	str	Trigger on specific repeating FRBs →
pos_error_semimajor_deg_95	float	Estimate chance coincidence probability for FoV →
pos_error_semiminor_deg_95	float	
snr	float	High-SNR low-DM targets for potentially nearby FRBs →
timestamp_utc	str	Trigger to search for temporal coincidences or afterglows →
timestamp_utc_inf_freq	str	
Right Ascension	float	Trigger on coordinates in observatory FoV →
Declination	float	

Table 1: Example thresholding scenarios for individual CHIME/FRB VOEvent meta data. Note that a general follow-up campaign will likely combine several scenarios into one. (Arrows link to a slide with more details on the parameter.)

Each follow-up campaign may be different, and in fact some observers may be learning from this presentation how to design their first or next campaign. In this table, the leftmost column lists the name and type of meta data from the VOEvent and an example where one might set thresholds as part of a follow-up scenario. For instance, consider a Target of Opportunity campaign in which an X-ray telescope must be given slew commands via telemetry to observe the next FRB that is reported by CHIME. In this case, getting the real-time sky coordinates and error region from the VOEvent and cross-referencing them with the telescope's slew time and FoV would be essential for planning a follow-up. A different scenario could be the follow-up of a repeating FRB source by radio telescopes at higher or lower frequency than CHIME. In this case, these radio observatories would point at the coordinates of a known repeating source and simply wait for a VOEvent from CHIME that is associated (strongly) with that source. The DM and timestamp information would also be relevant here.

Recommended SNR Thresholds

		Alert Type	Tier 1	Tier 2	Tier 3
Rate [day^-1]	FRB Candidates	Detection	0.88	0.94	1.04
		Subsequent	0.16	0.18	0.19
	Non-FRB Candidates	Detection	0.14	0.29	0.34
		Subsequent	0.00	0.00	0.00
			$SNR \geq 12$	$SNR \geq 11$	$SNR \geq 10$

Table 2: Average daily rate of VOEvents published between 17 June 2021 and 2 September 2021 (77 days). The rates are split by those events that were verified as FRBs (true positives) or non-FRBs (false positives) by humans **after** the VOEvent was published.

Besides scientific follow-up considerations, there may be important time and usage constraints for a given campaign. Namely, an observer may be interested in the next FRB published in a CHIME/FRB VOEvent, but they have limitations in the volume of alerts that can be handled. For instance, a Target of Opportunity campaign for an X-ray telescope following up FRBs may be limited to a certain number of ToO slews in the campaign. This is relevant because real-time VOEvents are published with a non-zero false positive probability — that is, a nonzero probability to be verified as a non-FRB candidate. The probability that a VOEvent is found to be a non-FRB generally decreases with the SNR. This table summarizes three tiers of SNR cuts that resulted in different mixes of FRB and non-FRB candidates, from a collection of recent VOEvents (a 77 day period from mid June to early September 2021). For detection VOEVents, the toughest cut (Tier 1) resulted in a ratio of FRB to non-FRB Candidates that is 2 times higher than the weakest cut (Tier 3). Note that for subsequent VOEvents, it happened that in this period there were not any false positives.

Alert Latency by Type

A basic latency measurement is defined as the difference in time between detection at 400 MHz and publication to the VOEvent Network.

Additional delays due to Internet traffic and routing between broadcaster and subscriber are **not accounted for**.

	Counts	Average Latency [s]	Standard Deviation [s]
Detection	149	12.42	3.92
Subsequent	19	12.99	3.07

Table 3: VOEvent latency by alert type between 17 Jun 2021 to 2 Sep 2021, reported as average and standard deviation over the 77 day period.

The latency of the VOEvent Service is closely tied to the overall latency of the real-time FRB pipeline, as evidenced by Table 3 that summarizes the latency for each alert type. The latency is defined by the time difference between the detection at 400 MHz and when the VOEvent was published to the broker (which then broadcasts to the broader Internet). The two alert types have consistent latency, which ranges from about 10 seconds to 15 seconds to one standard deviation. The time required for the broker to broadcast to other brokers managed by subscribers can vary with Internet traffic, the details of which are beyond the scope of this material.

Alert Latency by Verified Class

Figure 1: Latency of VOEvents published from 17 Jun 2021 to 2 Sep 2021. Post real-time human verification status is indicated by green for FRB Candidates and red for non-FRB Candidates. Most VOEvents are published with a latency of 10 to 20 seconds with respect to the detection at 400 MHz.

A different look at the alert latency as a function of human verification class (i.e. FRB or non-FRB) indicates that, on average, nothing special in the VOEvent Service yields a difference in processing time for true positives versus false positives.

Data Quality

The **importance** value of CHIME/FRB VOEvents is the best available real-time indication of data quality.

The value reflects a score in [0, 1.0] of the real-time machine learning classifier that attempts to distinguish two classes: Astrophysical, and RFI.

Internally a cut of 0.9 is applied before publishing a VOEvent, but subscribers are encouraged to **consider a higher cut of 0.98** to achieve a lower false positive rate.

Every real-time VOEvents contains one important measure of the data quality, namely the importance value. This is reported in the Why section, which has been previously addressed in this presentation. This value is actually a score given by a machine learning classifier that is run in real-time to classify events as either RFI or Astrophysical. Scores close to 1 indicate an Astrophysical event. While the Service publishes VOEvents for all events satisfying an importance of 0.9, a cut of 0.98 is further recommended for subscribers seeking a lower false positive rate.

Data Quality Factors

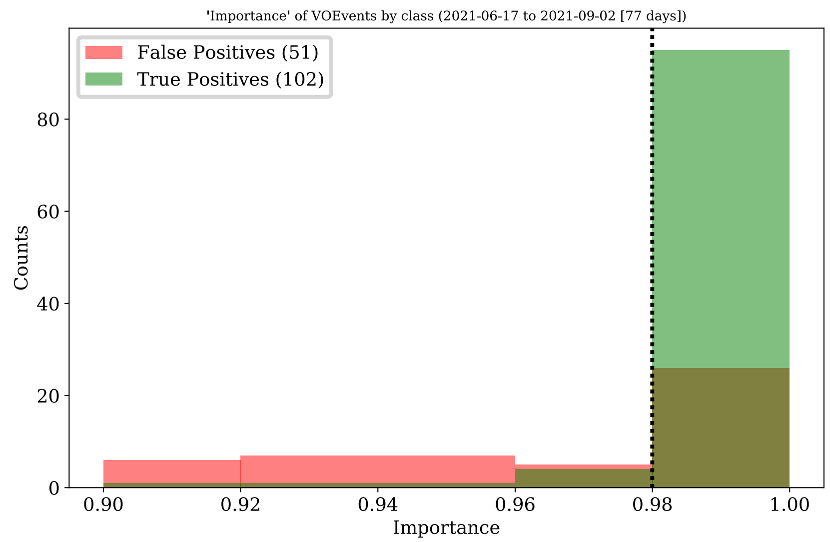


Figure 2: Importance value of VOEvents published from 17 Jun 2021 to 2 Sep 2021. Post real-time human verification status is indicated by green for FRB Candidates and red for non-FRB Candidates.

As shown in Figure 2, in a study of recent VOEvents (June 17, 2021 to Sept 2, 2021), placing a cut of 0.98 on the importance would have removed half of the false positives (shown in red) and retained 90% of the true positives (shown in green).

Misclassifications and False Associations

(1) RFI Contamination
- The real-time machine learning classifier has a non-zero false positive rate.

(2) Galactic Source Contamination
- Uncertainty of Galactic electron density maps (NE2001, YMW 2016).

(3) Incorrect Association with a Known FRB
- An event is detected and associated by chance with a known FRB.
- Tends to be more common for events detected in the $\delta \gtrsim 70°$ regime, related to the fact that CHIME has twice daily sky exposure in this range [2].

So far we have covered considerations for limiting the rate of false positives that a subscriber receives. The question remains — what are the false positives? The current real-time FRB pipeline is known to exhibit three behaviours that lead to them. RFI contamination from terrestrial RFI sources that sweep down in frequency in the CHIME band are a primary culprit. Galactic pulsars exhibit dispersed pulses but are only misclassified in regions of the sky where the Galactic DM maps are less accurate. Finally, associating events in real-time with known sources comes with its own set of challenges. The association algorithm is sensitive to the on-sky density of sources and the uncertainty in DM and position of a given event. For instance, a multi-beam event detected with the largest possible DM uncertainty at high declination could be associated with multiple other sources that have been detected there in the past, but for which none of them it is a true ssociation.

Real-time Localization Challenges

Single beam events are published with the sky coordinates of the beam centre.

(1) Side-lobe detection
- Off-meridian sensitivity of formed beams to **very bright events** results in a **side-lobe event**.

(2) SNR clipping
- Very bright multi-beam events lead to **clipping** of the max SNR.
- Clipping confuses the real-time localization algorithm, resulting in potentially bad central coordinates and error region.

The real-time localization has limited accuracy for very bright events, which usually present as very high SNR single or multi-beam events. Two separate causes are behind this. First, very bright events have the ability to trigger detections because of off-meridian sensitivity in the synthesized beams. In this case, the localization that would be published would refer to the centre of the synthesized beam which is referenced to its main lobe rather than side lobes that can be far from the meridian. Secondly, very bright events multi-beam events are processed in a way that can lead to clipping of the max SNR, which causes confusion when comparing the SNRs to the static synthesized beam model. Ahead we will look at examples of these effects.

Real-time Localization Challenges

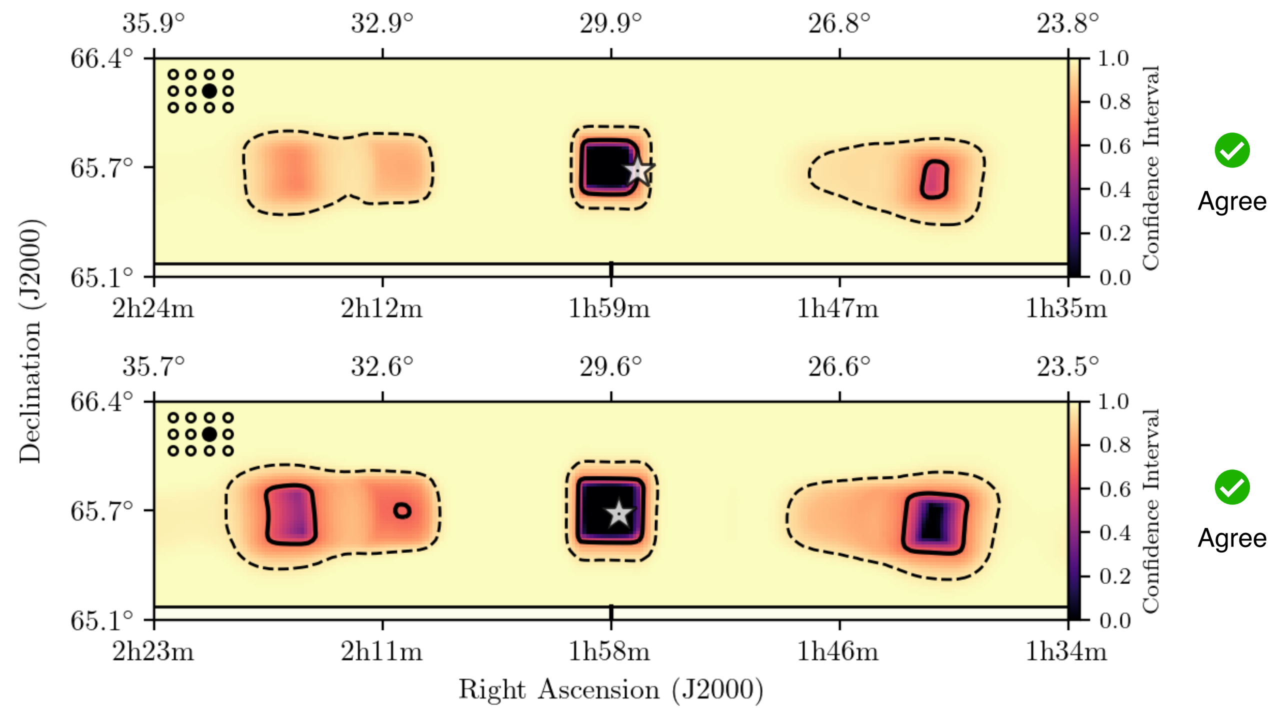


Figure 4: The true location of FRB 20180916B (star) is shown against the detection beam and its first side lobes, for two different events from the source. The method of pulsar analogues was used (see [3]) to produce the χ^2 surface and the 68% (solid) and 95% (dashed) confidence contours. The beam detection pattern is shown in the top left of each subplot. The beam centre is indicated by the black tick along the horizontal axis. The star and the black tick agree, indicating an accurate real-time localization. Figure courtesy of A. Josephy.

In Figure 4, the real-time localization of two events from FRB 20180916B were compared with an empirical model of the synthesized beams. The model was informed by the method of pulsar analogues, the details of which are available in a CHIME/FRB publication as listed in the references. The black tick on the horizontal axis indicates the sky coordinates that would have been published in a VOEvent for these two events. The true position of the FRB, which is known to good precision due to follow-up studies of the source, is indicated by the star. This figure shows that the real-time localization agreed with the true position, and that the event was detected in the main lobe of the detection beam.

Real-time Localization Challenges

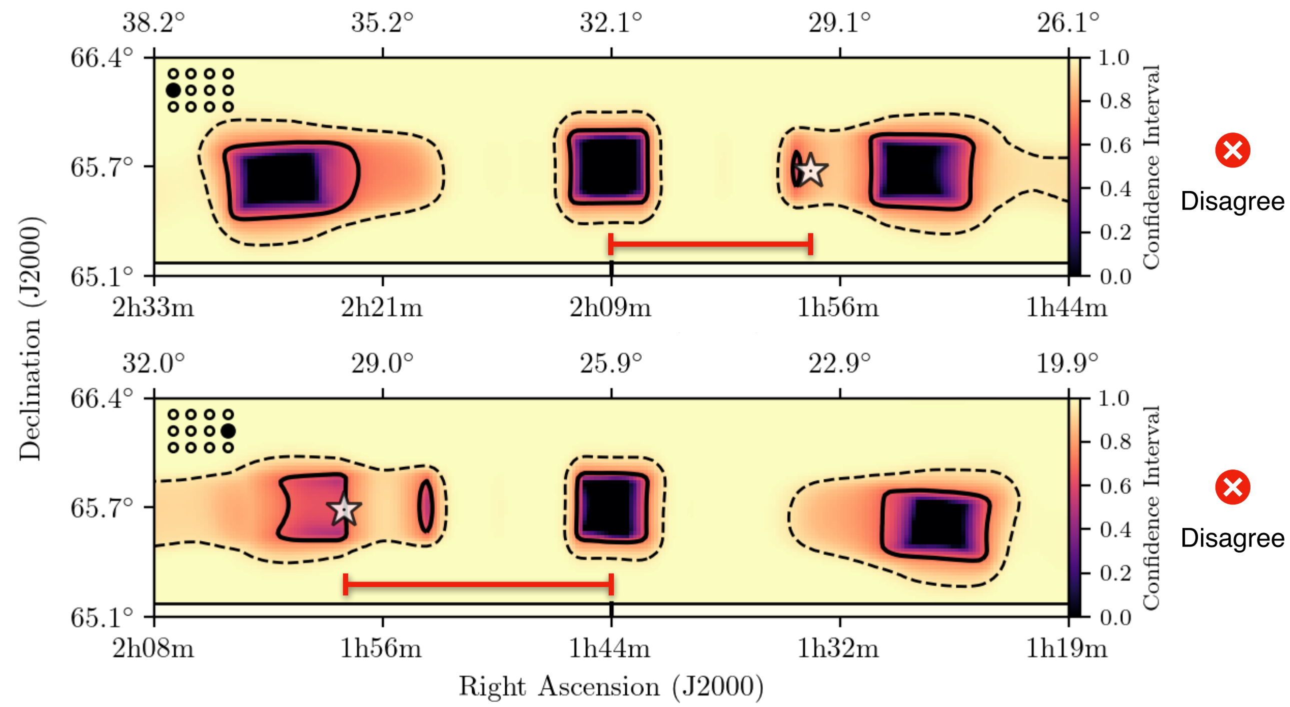


Figure 5: The true location of FRB 20180916B (star) is shown against the detection beam and its first side lobes, for two different events from the source, with contours colour scale, and all markings as in **Figure 4**. The disagreement between the star and black tick point to a side lobe detection. Figure courtesy of A. Josephy; see [3] for more details.

In Figure 5, two different events are shown in the same capacity as in Figure 4. The real-time sky-coordinates that would have been published in a VOEvent are the black tick on the horizontal axis. Because the true position does not agree with the black tick, this is evidence of a side lobe detection. Furthermore, it indicates that the real-time coordinates would have been misleading to follow-up observers, in both cases by more than 10 arc minutes in right ascension.

Service Outages and Downtime

Interruptions to the VOEvent Service should be expected and all follow-up observers should **design campaigns** with this consideration in mind.

Notifications of prolonged outages will be provided on a **best-effort basis via email** to the address provided during the subscription process.

Be sure to monitor **junk/spam** for important notices.

Upstream

- CHIME telescope up-time fluctuations:
  - Unplanned power or network loss
  - Planned upgrade cycles

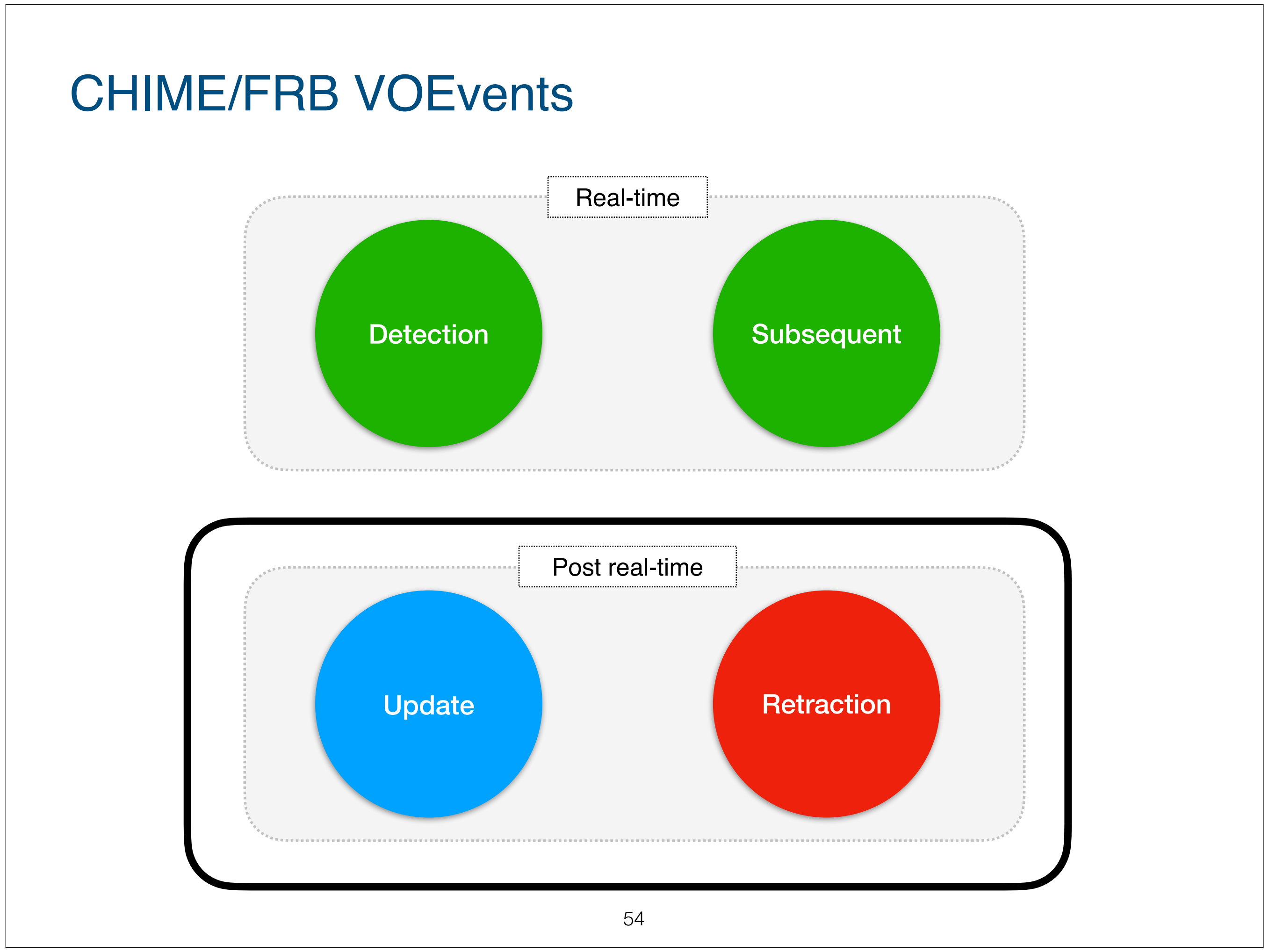
Downstream

- McGill Comet broker up-time fluctuations:
  - Unplanned power or network loss
  - Planned upgrade cycles

Limitations in the real-time localization are in the category of things that are out of the follow-up observer's control. Also in this category are limitations in the performance of the VOEvent Service. Outages, planned or unplanned, occur both upstream — in the CHIME telescope system and the CHIME/FRB experiment system — and downstream — with the Comet broker that runs at McGill University. Both cases result in downtime, and in the cases of prolonged outages we will provide a notification by email on a best-effort basis.

Post Real-time Alerts

In this final section we introduce two types of post real-time VOEvents that serve special purposes. Rather than reporting on observations of FRBs, these types of alert serve as revisions to previous alerts.



In revisiting this diagram, one can appreciate that the detection and subsequent VOEvents contain the same types of meta data and serve similar purposes. On the other hand, update and retraction VOEvents contain each different types of data and serve quite different purposes.

Real-time Alerts may be Retracted

Detection and subsequent VOEvents are subject to **retraction**, issued once per day.

Refer to the Jupyter notebook tutorial for further details.

The subscriber should **forego** planned follow-up of retracted alerts.

Retraction Scenarios

1. False positive due to RFI contamination
   - RFI mitigation is not perfect and is under iterated improvement.
2. Mis-association with known source (Galactic, or FRB)
   - Side lobe detections of bright pulsars e.g. the Crab Nebula pulsar.
   - Higher chance coincidence probability in certain sky regions ($\delta \gtrsim 70°$ [2]).

Starting with retraction VOEvents, these are being published in a basic capacity now to provide subscribers with a notice that a previous VOEvent was found to be a non-FRB. Following human verification, each day retractions will be published in bulk through special retraction VOEvents. Additional instruction on this can be found in the Jupyter notebook tutorial. At present there are two retraction scenarios. Firstly, RFI contamination is known to generate false positives in the real-time FRB pipeline, which end up published as VOEvents and later caught by humans. Secondly, both RFI contamination and true FRBs are capable of being falsely associated with known sources, either Galactic sources or known FRBs. The probability of chance coincidence in this scenario is not available in real-time, but the subscriber should understand that it exists and is likely non-zero.

Real-time Alerts may be Updated

The following represent **future enhancements** to the VOEvent Service.

Latency is hard to estimate but could be hours to days.

Update VOEvent #1: Transient Name Server (TNS) object name

- Published after successful submission to the TNS.

Update VOEvent #2: Miscellaneous post-processing analysis

- Maximum redshift from Macquart relation.
- Chance coincidence probability.

Update VOEvent #3: Intensity analysis

- Data products from analysis of the dynamic spectrum and intensity localization.

Update VOEvent #4: Baseband analysis

- Data products from analysis of the raw voltages and baseband localization.

Finally, if an event is verified as a true FRB by humans, it is sent off for post-processing with various analysis pipelines. Among the important results from these pipelines that are relevant to follow-up observers are improved localizations from intensity and baseband data analysis, as well as the official Transient Name Server designation for the event. The latency of these alerts is not currently known but in principle could be hours to days following the initial detection or subsequent VOEvent.

Conclusion

Summary

Questions that have been addressed in this presentation include:

1. What is the CHIME/FRB VOEvent Service?
2. How can I connect to the Service?
3. Where can I access additional help resources?
4. What is a VOEvent? What is an FRB VOEvent? How is CHIME/FRB using them?
5. What information is contained in a CHIME/FRB VOEvent?
6. I received a VOEvent from CHIME/FRB; how do I extract information from it?
7. How can I place thresholds on VOEvents that are meaningful for my follow-up campaign?
8. What thresholds does CHIME/FRB recommend for data quality?
9. How long will it take for me to receive a VOEvent after an FRB is detected?
10. I received a VOEvent from CHIME/FRB; how do I know if its a real FRB or not?
11. How accurate and precise are the localizations published in real-time VOEvents?
12. I have not received a VOEvent in a while; is there a problem with the Service?
13. What is next for the Service?

Stay Tuned for More!

Photo credit: CHIME Collaboration

References

[1] CHIME/FRB Collaboration, M. Amiri, K. Bandura, P. Berger, M. Bhard- waj, M. M. Boyce, P. J. Boyle, C. Brar, M. Burhanpurkar, P. Chawla, J. Chowdhury, J. F. Cliche, M. D. Cranmer, D. Cubranic, M. Deng, N. Denman, M. Dobbs, M. Fandino, E. Fonseca, B. M. Gaensler, U. Giri, A. J. Gilbert, D. C. Good, S. Guliani, M. Halpern, G. Hinshaw, C. Ho¨fer, A. Josephy, V. M. Kaspi, T. L. Landecker, D. Lang, H. Liao, K. W. Ma- sui, J. Mena-Parra, A. Naidu, L. B. Newburgh, C. Ng, C. Patel, U. L. Pen, T. Pinsonneault-Marotte, Z. Pleunis, M. Rafiei Ravandi, S. M. Ran- som, A. Renard, P. Scholz, K. Sigurdson, S. R. Siegel, K. M. Smith, I. H. Stairs, S. P. Tendulkar, K. Vand erlinde, and D. V. Wiebe. The CHIME Fast Radio Burst Project: System Overview. The Astrophysical Journal, 863(1):48, August 2018.

[2] Manchester and Taylor, 1975.

[3] CHIME/FRB Collaboration, B. C. Andersen, K. Bandura, M. Bhard- waj, P. Boubel, M. M. Boyce, P. J. Boyle, C. Brar, T. Cassanelli, P. Chawla, D. Cubranic, M. Deng, M. Dobbs, M. Fandino, E. Fonseca, B. M. Gaensler, A. J. Gilbert, U. Giri, D. C. Good, M. Halpern, A. S. Hill, G. Hinshaw, C. H¨ofer, A. Josephy, V. M. Kaspi, R. Kothes, T. L. Landecker, D. A. Lang, D. Z. Li, H. H. Lin, K. W. Masui, J. Mena- Parra, M. Merryfield, R. Mckinven, D. Michilli, N. Milutinovic, A. Naidu, L. B. Newburgh, C. Ng, C. Patel, U. Pen, T. Pinsonneault-Marotte, Z. Pleunis, M. Rafiei-Ravandi, M. Rahman, S. M. Ransom, A. Renard, P. Scholz, S. R. Siegel, S. Singh, K. M. Smith, I. H. Stairs, S. P. Tendulkar, I. Tretyakov, K. Vanderlinde, P. Yadav, and A. V. Zwaniga. CHIME/FRB Discovery of Eight New Repeating Fast Radio Burst Sources. The Astrophysical Journal Letters, 885(1):L24, November 2019.