A Virtual Observatory Event Service for CHIME/FRB

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August 2020

A thesis submitted to McGill University in partial fulfillment of the requirements of the degree of Master of Science

DEDICATION

When I began this MSc journey, it was as if I had opened the door on an unlit hallway of twisting corridors: each aspect of the complex science and instrument I came to know was like a corner around which I thought I saw light but was met with a deeper pitch. It seemed like I was without a light of my own. Before too long, I discovered bright flashes issuing from every direction, bursts of encouragement and support from benevolent spirits not unlike the fast radio bursts that light up the sky. This cute analogy only came to me afterwards, but it is all the more reason to honour those spirits who guided me then, and who continue to do so now and forever. I first thank my loving and supportive parents and siblings who have always believed in my potential and drive to succeed. Finally, I am deeply grateful for Erin, who has stood by me true and honest, who has always held onto my umbrella with me, and who helps me see the rainbow hanging over my head. This MSc thesis is dedicated to *this* Family.

ACKNOWLEDGEMENTS

First I thank the McGill Space Institute for providing a place to work, learn, and enjoy 3 pm coffee and cookies, both individually and in collaboration with world-class research staff and students. Secondly, I thank the CHIME/FRB Collaboration, including especially members of the project office: Patrick Joseph “Jojo” Boyle, for helping me to cope with professional change, to manage my work-in-progress, and for holding me accountable for documentation; Shiny Brar, for providing tools and resources and mentoring me closely to design and implement the programming architecture in this thesis while maintaining coding practices; and Chitrang Patel, for his friendliness and contagious enthusiasm, especially during my first few months and during the migration of CHIME/FRB source names to the Transient Name Server, and his sound career advice. Thirdly, I thank the team at the Transient Name Server (TNS) lead by Eran Ofek and Ofer Yaron for their collaboration on the FRB naming convention that CHIME/FRB has adopted and which is expected to continue as the internationally-recognized standard for this transient phenomenon. Fourthly, thanks to my friends and fellow students Marcus Merryfield, Rafael Fuentes, Bridget Andersen, and Simon Guichandut, for their companionship and moral support, and who made living in Montréal fun. Finally, my sincere thanks to my thesis supervisor Vicky Kaspi, who is a continual source of energy and enthusiasm for doing good, interesting and groundbreaking science; who believes in her students potential to succeed and does not fail to find opportunities for them to showcase their work; and who diligently and gracefully kept our large research group moving forward during the COVID-19 pandemic.

ABSTRACT

Fast radio bursts (FRBs) are extremely energetic radio transients that appear to originate from cosmological distances. These millisecond duration blasts of Jansky level energy remain unexplained amidst a diverse family of plausible models. An observation of an FRB in coincidence with a detection of an X-ray, optical, or gravitational wave transient signal would represent a breakthrough in this field by constraining the model space, and therefore a mechanism for coordinating FRB follow-up is crucial to advancing their study. Presently, a suite of automated observatories communicate over the Internet by exchange of Virtual Observatory Events (VOEvents). What remains is to establish a service that (1) connects an FRB instrument to this network to produce VOEvent packets of newly detected FRBs in real-time and (2) translates received VOEvents into multi-wavelength sources of interest to correlate with real-time FRB observations. The Canadian Hydrogen Intensity Mapping Experiment (CHIME) is a transit radio telescope monitoring the entire Northern sky and detecting multiple FRBs per sidereal day. The CHIME/FRB instrument searches in real-time for FRBs, classifying incident dispersed radio signals through a multi-level pipeline in typically under a minute, the final level of which can trigger the novel CHIME/FRB VOEvent Service. Four different types of VOEvents can be published by the Service in order to report real-time detections of new and repeating FRBs, with a unique FRB name assigned by the Transient Name Server (TNS) and updated measurements following in update VOEvents. This MSc thesis covers the scientific motivation for and software implementation of the CHIME/FRB VOEvent Service.

ABRÉGÉ

Les sursauts radio rapides ("fast radio bursts", FRBs) sont des transitoires radio extrêmement énergétiques qui semblent provenir de distances cosmologiques. Ces explosions d'une durée d'une milliseconde d'énergie de niveau Jansky restent inexpliquées parmi une famille diversifiée de modèles plausibles. Une observation d'un FRB en coïncidence avec une détection d'un signal transitoire de rayons X, optique ou d'onde gravitationnelle représenterait une percée dans ce domaine en contraignant l'espace modèle, et donc un mécanisme de coordination du suivi de FRB est crucial pour progresser leur étude. À l'heure actuelle, une suite d'observatoires automatisés communique sur Internet par l'échange d'événements d'observation virtuelle (VOEvents). Il reste à établir un service qui (1) connecte un instrument FRB à ce réseau pour produire des paquets VOEvent de FRB nouvellement détectés en temps réel et (2) traduit les VOEvents reçus en sources d'intérêt multi-longueurs d'onde à corréler avec le temps réel. L'expérience canadienne de cartographie de l'intensité de l'hydrogène (CHIME) est un radiotélescope de transit qui surveille tout le ciel nordique et détecte plusieurs FRB par jour sidéral. L'instrument CHIME/FRB recherche en temps réel les FRB, classant les signaux radio dispersés incidents à travers un pipeline à plusieurs niveaux en généralement moins d'une minute, dont le niveau final peut déclencher le nouveau Service VOEvent par CHIME/FRB. Quatre types différents de VOEvents peuvent être publiés par le Service afin de signaler les détections en temps réel de FRB nouveaux et répétitifs, avec un nom de FRB unique attribué par le Transient Name Server (TNS) et des mesures mises à jour suite à la mise à jour VOEvents. Cette thèse de maîtrise couvre la motivation scientifique et la mise en œuvre logicielle du Service VOEvent par CHIME/FRB.

CONTRIBUTION BREAKDOWN

Design and specification of the CHIME telescope together with the CHIME Fast Radio Burst (CHIME/FRB) experiment was a massive undertaking that precedes this MSc thesis. The hardware and software that support the cosmology, fast radio burst, and pulsar research programs were and continue to be the product of a team of scientists and engineers. The bulk of Chapter 2 is written with recognition of and appreciation for these individuals who are authors on the various CHIME Collaboration or CHIME/FRB Collaboration papers cited there. Chapter 3 is a description of the pre-existing Virtual Observatory Event (VOEvent) XML medium and Network that is a product of the International Virtual Observatory Alliance. The author's use of these in `python` has been enabled largely by John Swinbank, maintainer of the open-source Comet VOEvent broker, who the author communicated with over email on several occasions to coordinate the addition of a feature in Comet that helps developers with continuous integration of event handlers. Sections 4.3 - 4.5 contain original work that rests on software frameworks in the L4 and FRB Master backend modules for which core functionalities were largely developed by Shiny Brar, Davor Cubranic, and Chitrang Patel. The L4 header that is used to create the detection-type VOEvent contains meta data from the entire real-time FRB search pipeline. The primary contributors for each level of the pipeline are: Kendrick Smith, Dustin Lang, Masoud Refiei Ravandi, Utkarsh Giri, and Alex Josephy for L1 (§2.3.2); Shriharsh Tendulkar, Emmanuel Fonseca, Paul Scholz, Shiny Brar, Ziggy Pleunis, Chitrang Patel, and Alex Josephy for L2/L3 (§2.3.3 & 2.3.4); Davor Cubranic, Michelle Boyce, and Chitrang Patel for L4 (2.3.5). The overall efforts were coordinated by Victoria Kaspi (Principal Investigator) and Patrick Boyle (Project Manager). Sections

5.2 - 5.4 contains original work that rests on code for using the beam model that was developed largely by Paul Scholz, and an algorithm for finding the beam in which a given celestial coordinate is found at a given UTC moment that is based on an algorithm developed by Pragya Chawla.

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CHAPTER 1
Introduction to Fast Radio Bursts

1.1 The Fast Radio Burst Phenomenon

Fast radio bursts (FRBs) are an emergent class of astrophysical transients that represent a major and unexpected astronomical discovery. At least three factors contribute to their special classification among previously known transients: the pulse duration and brightness; the all-sky rate of FRB sources; and the process of evaluating the distance to an FRB source. Each of these is connected intimately to the phenomenon and to the observatory that detects them. Furthermore, each quality is related to the other in a way that makes FRB science interesting, involved, and a modern challenge. FRBs are short bright bursts of radio emission. The pulse typically lasts on the order of 1 to 10 milliseconds or less and is detected with a peak flux on the order of 1 to 10 Janskys or more. The shortest bursts are unresolved by many radio telescopes, in which case the integrated flux over time, cf. fluence, is measured instead.

The FRB phenomenon has been reviewed several times in recent years by a number of established authors. In order of both length and when they were written, one can consult [39] for a short review; [21] for a longer review; and finally, for an explicit and involved review, with expanded discussions dedicated to both early CHIME era FRB sources and contending FRB models, see [35].

The duration and brightness of FRBs suggests two important inferences:

1. The emitting region is small, either compact or a sub-region of a larger object.

2. The emission is a coherent process, as opposed to an incoherent one from a thermalized medium.

In the first case, the light-crossing time of the emitting region cannot be too large, otherwise the emitted radiation will originate in spatially distinct locations and thus have a large window of arrival times, therefore constituting a pulse longer in duration. Without invoking relativistic motion of any bulk material involved, the duration Δt in milliseconds relates to the emission region size Δr via $c\Delta t \sim \Delta r$. A rough estimate therefore suggests the emission region is 1 ms $\times$ 10^{10} cm s^{-1} = 10^7 cm.

In the second case, the brightness temperature for Jansky-level flux received at a telescope is typically $T \sim 10^{37}$ K, unreasonably large for any thermal black body or even particle with the corresponding energy $k_{\rm B}T$ where k_B is the Boltzmann constant in J/K. The implication is that the emission involves some bulk ejecta, the particles of which emit radiation coherently.

In Figure 1–1, the dynamic spectrum of an FRB is shown. The most salient observational feature is the inverse relationship between the arrival time and the observing frequency (more on this in §1.2), which is now understood as a physical effect that occurs during the propagation of the radio signal and is not intrinsic to the source or to the detecting instrument. (But see [22] that presented a thorough consideration of alternative hypotheses, including the possibility that the characteristic delay was native to the progenitor, or that the FRB was in fact a terrestrial atmospheric effect.)

1.2 Discovery of a Cosmological FRB Population

The first FRB was discovered in a single pulse search on archival observations of the Small Magellanic Cloud (SMC) by the Parkes radio telescope at 1.4 GHz [24]. The so-called "Lorimer burst" superficially resembled bursts well known to the study of a class of Galactic radio transients called pulsars,

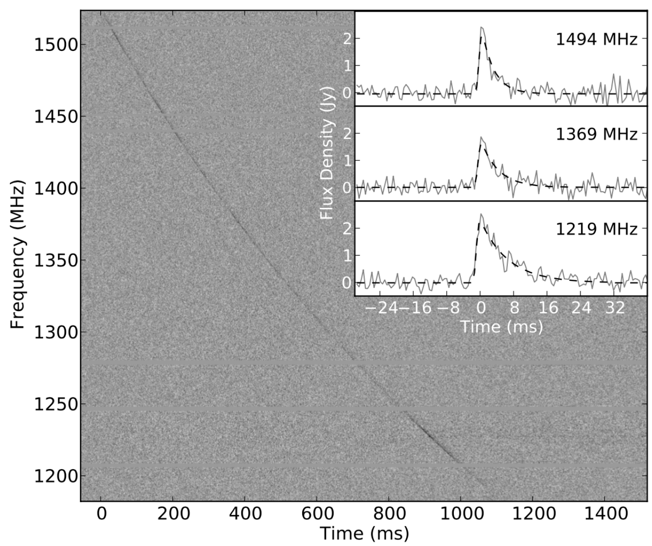

Figure 1–1: The dynamic spectrum of a fast radio burst, usually called a "waterfall" plot, without de-dispersion applied. On the Y-axis is the frequency, with the central observing frequency in the ~ 1 GHz range, while the X-axis is the time measured relative to the arrival time of the highest frequency recorded in the burst. The higher frequencies arrive ahead of the lower frequencies owing to the dispersion effect in Equation 1.9 that admits a measurable quantity called dispersion measure (DM). Inset: Waterfall plots are normally presented after removing the dispersion effect. Each panel is a selected sub-band from the full frequency data of the burst that has been de-dispersed. The peak of each pulse is aligned with $t = 0$. Taken from Figure 2 in [51].

rapidly rotating neutron stars formed from the collapse of a massive star. However, the excitement was three-fold: the burst was incredibly bright at nearly 30 Jy and extremely short, under 5 ms, but moreover there was a good reason to believe that it originated outside the Galaxy.

Support for the extragalactic origin rested largely on the fact that cold plasma in the Galactic interstellar medium and intergalactic medium containing free electrons presents an ambient material through which electromagnetic radiation is dispersed. Namely, the "Lorimer burst" was found to exhibit dispersion that could not be explained by Galactic material alone, according to the measurement of an observable parameter in the burst called dispersion measure (DM). Using [15] as a reference the dispersion of radio waves can be derived. Working in CGS units, let ω be the angular frequency in rad s^{-1} and k be the wavenumber in cm^{-1} of a propagating wavefront. The angular frequency ω_e attributed to the electrons in the plasma has an effect on the dispersion relation given by

$$\omega^2 = \omega_e^2 + c^2 k^2 \tag{1.1}$$

where c is the speed of light in cm s^{-1}. This electron angular frequency can be written (section 11.2 in [15])

$$\omega_e^2 = \frac{4\pi n_e e^2}{m_e} \tag{1.2}$$

where n_e is the electron number density in cm^{-3}, e is the elementary charge in coulombs (C), and m_e is the electron mass in grams (g). In the radio wavefront, the group velocity v_g in cm s^{-1} depends on wave frequency $\nu = \omega/2\pi$ via

$$v_g(\nu) \equiv \frac{\partial \omega}{\partial k} = c\sqrt{1 - \frac{\omega_e^2}{\omega^2}}. \tag{1.3}$$

The time required for the group to traverse a distance L in cm is

$$t(\nu) = \int_0^L \frac{1}{v_g(\nu)} dl = \int_0^L \frac{1}{c}\Big(1 - \frac{\omega_e^2}{\omega^2}\Big)^{-1/2} \tag{1.4}$$

Under typical astrophysical conditions, the electron number density is in the range 10^{-4} cm^{-3} to 10^4 cm^{-3} which places the plasma frequency $\nu_e = \omega_e/2\pi$ far below the GHz observing band for FRBs, so that in Equation 1.4 we can approximate $(1-x)^n \approx 1 - nx$:

$$t(\nu) \approx \int_0^L \frac{1}{c}\Big(1 + \frac{1}{2}\frac{\omega_e^2}{\omega^2}\Big) d\ell \tag{1.5}$$

$$t(\nu) - t(\infty) = \frac{e^2 \cdot \text{ parsec}}{2\pi m_e c} \frac{1}{\nu^2} \cdot \int_0^L n_e(l) d\ell \tag{1.6}$$

This shows that the arrival time of frequency ν relative to infinite frequency (∞) depends on a constant

$$K = \frac{e^2 \cdot \text{ parsec}}{2\pi m_e c}, \tag{1.7}$$

which in [25] is quoted as 4.149 GHz^2 cm^3 pc^{-1} ms, and the integrated electron number density $n_e(\ell)$ along the path described by $d\ell$. The latter is given the name dispersion measure (DM) and is written

$$\text{DM} = \int_0^L n_e(\ell) d\ell \tag{1.8}$$

with units of cm^{-3} pc, as per the units of the constant K. Rearranging Equation 1.6, the DM relates the time delay Δt between two frequencies ν_1 and ν_2 with $\nu_1 < \nu_2$ via

$$t_1 - t_2 \equiv \Delta t = K \cdot \text{DM} \cdot \Big(\frac{1}{\nu_1^2} - \frac{1}{\nu_2^2}\Big). \tag{1.9}$$

Knowing n_e within and beyond the Galaxy is crucial to the study of FRBs, as explained next.

Dispersion explains the inverse relation in Figure 1–1, but moreover it affects all radio signals propagating through the Universe. Owing to the large number of Galactic radio pulsars that have been catalogued all over the sky for the past 50 years, the DM along a selection of sight-lines through the Galaxy has been conglomerated into two maps of free-electron density in the Galaxy, in effect giving an all-sky DM map. These are the NE 2001 [14] and YMW 2016 [57] models. By subtracting the maximum integrated free-electron content along the source-observer line-of-sight from the measured DM of a new radio signal, the DM excess is obtained. For FRBs this DM excess is too large to believe the progenitor is a source in the Galaxy.

The measured DM of the Lorimer burst was 375 cm^{-3} pc, far in excess of the predicted 25 cm^{-3} pc for the line-of-sight to the source, and was localized to a region 3° south of the SMC, at which Galactic latitude all known Galactic pulsars did not have DMs larger than the FRB value [24]. From where the excess DM came remained unanswered. Three options were plausible:

1. The DM is largely intrinsic to the immediate environment of the progenitor (e.g. a dense ambient nebula).
2. The DM is largely contributed by the line-of-sight through the host galaxy of the progenitor.
3. The DM is largely contributed by the intergalactic medium (IGM).

Option 1 could allow the source to be Galactic, as dense Galactic nebulae are not uncommon, or extragalactic. But conceivably, each option could keep the source outside the Galaxy, in which case the distance estimate increased enormously from option 1 through 3. The distance estimate hinged on estimates of the free-electron content in the IGM and for which a DM-redshift relationship was claimed ([18], [17]). Option 3 led to the most extreme conclusion, allowing the source to be up to $z = 0.3$, a corresponding luminosity distance over 1 Gpc. Despite these and other arguments presented in the discovery study [24], the FRB phenomenon awaited corroboration around the world for other telescopes to detect similar sources.

1.3 Corroboration from Multiple Observatories

Four additional FRBs were found from the High Time Resolution Universe (HTRU) survey undertaken again with the Parkes radio telescope, with DMs in the range $553 - 1103$ cm^{-3} pc [51] all of which were unexplained by Galactic DM contributions. Soon after came the discovery of an FRB with the Pulsar ALFA survey conducted with the Arecibo radio telescope in Puerto Rico [46] also at 1.4 GHz. With a new telescope on the playing field, and following two thorough investigations ([36], [22]) that separated a true population of FRBs in the Parkes data from terrestial signals, including impostors produced by the magnetron of a microwave oven being interrupted prematurely at lunch time [36], FRBs were accepted as a new class of astrophysical transients.

The inferred all-sky rate exacerbated the contention with other known transients. Gamma-ray bursts (GRBs) were shown to be at least 1000 times less numerous in the sky than FRBs [51]. An independent study of volumetric rates of known transients (Table 2 in [22]) underlined the mismatch in volumetric rate of FRBs against other known transients. The conclusion of [22] was that, without invoking multiple classes of FRB progenitors, only one transient could accommodate the high rate of up to ~ 1000 per sky per day [23]: soft-gamma repeaters (SGRs).

It turned out that the Arecibo-discovered FRB [46] exhibited repetition and became the first known repeating source [43]. The possibility that multiple FRB progenitor classes exist looked promising: the previously known singleton bursts that had not been observed to repeat were compatible with cataclysmic cosmic explosions, while of course a repeating source could not be explained by an annihilation like this.

The "repeater" - one of two monikers that did not age as well as the formal name FRB 121102 once CHIME/FRB reported a swathe of repeaters (Chapter 2) - was cross-referenced with available multi-wavelength observations from the *Swift* and *Chandra* X-ray telescopes which did not report any significant associations [42]. However, optical spectrograph observations with the Gemini North telescope on Mauna Kea, Hawai'i, based on a precise localization of FRB 121102 [27], revealed the host galaxy of the source to be a low-metallicity, star-forming dwarf galaxy at a redshift of $z \sim 0.2$. This exciting first localization and host identification, along with the basic fact that repeating FRBs exist, linked FRBs back to neutron stars again, owing to the astrophysical association of young massive stars, neutron stars, and star-forming galaxies. At the same time, a single host association was not enough to be broadly representative of the FRB population.

With the discovery of a repeating FRB, multi-wavelength follow-up campaigns could look forward to the discovery of more repeating sources and reports of active periods. Indeed, FRB 121102 had been shown to exhibit clusters of bursts in time, with several detected in the span of a few minutes [42]. In retrospect the time was just right for a guiding observatory to come along, one that would have daily exposure to a large sky area, providing a constant source of new FRBs and regularly monitoring any repeating sources for active periods. That the CHIME telescope began construction and pre-commissioning to detect FRBs in real-time by monitoring the entire Northern sky every day is not a coincidence; and in keeping with the theme of this MSc thesis, the next sections underlines the benefits of such a real-time search, by summarizing the variety of FRB progenitor models and the need for a real-time automated telescope to conduct a survey yielding not just a few bursts and a single repeater but a population of FRBs.

1.4 Recent Advances

The fast radio burst (FRB) population has grown rapidly in the past two years. The study of singleton bursts, repeating sources, and even a repeating source with a measured period, has been accelerated during this time by the commissioning of a novel radio telescope, the Canadian Hydrogen Intensity Mapping Experiment (CHIME). While the CHIME fast radio burst (CHIME/FRB) search has yielded hundreds of new singleton FRBs, and presently maintains an online public bulletin for recent activity from 18 CHIME-discovered repeating sources[1] , the FRB population remains unexplained by any single mechanism or progenitor.

For the majority of its existence, the FRB research field was teeming with enough theoretical models to rival the number of known FRB sources, a fact which nearly every observational paper in the field would poke at. However, through CHIME/FRB the tables have turned quite dramatically. The CHIME era of fast radio burst research, with detections of several new FRBs each day, and daily monitoring of repeating sources for subsequent activity, brings with it a promising opportunity to seriously constrain the space of FRB models via multi-wavelength follow-up observations. The most remarkable and very recent instance of this is the detection of an FRB in temporal coincidence with an X-ray burst both consistent with a Galactic source called SGR 1935+2154,

[1] `https://www.chime-frb.ca/repeaters`

a result that has been submitted to *Nature* [49]. This represents a major advancement and throws into sharp relief the necessity to push forward with additional multi-wavelength FRB studies, a challenge that is neatly met through low-latency follow-up observations addressed next.

1.5 The Case for Follow-up Observations

The low-latency follow-up domain has remained largely unexplored for fast radio bursts. FRBs have a higher all-sky rate than any other class of astrophysical transient [22], with an estimate of up to ~ 1000 sky^{-1} day^{-1} [51], and no preferred sky distribution. Therefore, multi-wavelength observatories (X-ray telescopes and optical telescopes for example) seeking to follow-up an FRB detection would in principle need to track the sky coverage of the radio telescope contemporaneously. However, even under those conditions, the dispersion delay (Equation 1.9) makes the most prompt observations difficult because the radio signal takes time to be fully received and identified before it can produce an alert for follow-up observatories.

Nonetheless, a real-time public alert system with machine-readable FRB detection reports (the CHIME/FRB VOEvent Service, Chapter 4) has been developed in attempt to solve this. The motivation for this automated follow-up regime is supported on the grounds that many FRB progenitor models are sensitive to detecting counterparts to the FRB emission.

Namely, with FRBs being perhaps the most unexpected astrophysical discovery in recent decades, theorists in the field have brought to light FRB progenitor models that together sample seemingly every corner of astrophysics. The FRB Theory Catalogue[2] is a useful one-stop-shop to consult the predicted counterparts from these many models across the electromagnetic spectrum,

[2] `https://frbtheorycat.org`.

and into the multi-messenger spectrum as well. The following are expected to produce at least one of X-ray, gamma-ray, optical, and/or gravitational wave signals in addition to the FRB signal.

- neutron star collapsing to a quark star [45]
- binary merger of black hole with black hole [58] or neutron star [31]
- binary neutron star merger [53]
- young magnetar born in compact binary merger event [28]
- magnetar wind interacting with an ambient nebula via single flares [38]

1.6 Thesis Overview

The remaining chapters in this MSc thesis are structured as follows. In Chapter 2 the CHIME telescope is introduced with a summary of the detection principle, from the receiving antennae to the computationally intensive FRB search software, and the recent accomplishments made with CHIME in the study of FRBs. In Chapter 3 we describe an online network of robotic telescopes that communicate in real-time as a single multi-wavelength virtual observatory. In Chapter 4 we reach the heart of this MSc thesis, namely the efforts to broadcast real-time public alerts for FRBs detected with CHIME/FRB. In Chapter 5 we describe efforts to receive similar real-time public alerts from other observatories and instruments. Finally in Chapter 6 we summarize, suggest future work, and outline task lists for continuing work on the CHIME/FRB VOEvent Service.

CHAPTER 2
The CHIME/FRB Era: Fast Radio Bursts in Real-Time

2.1 The CHIME Telescope and Upgrades for FRB Search

The Canadian Hydrogen Intensity Mapping Experiment (CHIME) is a radio telescope located at the Dominion Radio Astrophysical Observatory (DRAO) in Penticton, British Columbia, Canada, pictured in Figure 2–1. In 2018 the CHIME/FRB Collaboration published a project overview paper in which the telescope and the CHIME Fast Radio Burst (CHIME/FRB) experiment is exposed in good detail [10]. The reader is invited to consult this for details beyond the scope of this MSc thesis.

CHIME is a transit telescope: there are no moving parts. It consists of four 20 m $\times$100 m static parabolic cylindrical dishes composed of a galvanized steel mesh suitable for reflecting radio waves in the decimetre wavelength. The symmetry axis of each cylinder is aligned North-South and the cylinders are spaced East-West. Along each of the axes are 256 dual-polarization feeds for a total of 2048 signal paths, sensitive to the observing frequency band of 400 to 800 MHz.

As the Earth rotates about its axis, the CHIME meridian sweeps out the entire Northern sky from a declination of $\sim -10^\circ$ to 90°. The field-of-view of CHIME is $\sim 110^\circ$ in the North-South direction; in the East-West direction this is $\sim 2.5^\circ$ at the bottom of the CHIME receiving frequency band, 400 MHz, but $\sim 1.3^\circ$ at the top of the CHIME band, 800 MHz. This makes for an overall field-of-view of approximately 200 deg^2. Since the DRAO site is located at a latitude of $49^\circ 19' 14''$, CHIME has exposure to a region of the circumpolar sky

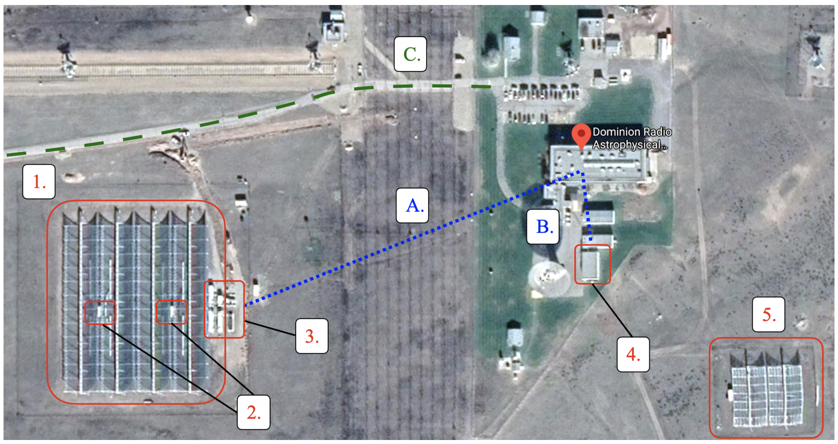

Figure 2–1: An aerial view of the DRAO site obtained from satellite images, copyright Google Maps 2020: 1. The four parabolic cylindrical reflectors of the CHIME telescope aligned along local North-South and spaced East-West; 2. East and West (left to right) receiver huts containing the CHIME F-engine; 3. Industrial shipping containers ("sea-cans") retrofitted to house the 256 GPU nodes representing the CHIME correlator, and the 130 CPU nodes representing the L1 system (128 nodes), and the L2 and L3 (together in one node) system; 4. VSOP room containing receiver nodes for CHIME, the L4 node, the FRB analysis nodes, the intensity and baseband archive nodes, and internal-to-external communication gateways; 5. The Pathfinder telescope. A. Underground network link from GPU huts to VSOP room; B. Network VSOP link; C. Observatory Access Road

above a certain declination that was reported in [13] to be $\sim 70^\circ$ (see later Figure 5–4 for a visual aid).

CHIME is a software telescope: the novelty of the instrument is owed to its powerful correlator that correlates digitized and channelized frequency data received from each of the 2048 signal paths with every other path in real-time to map the Northern sky. The original science objective for CHIME was to map the baryon acoustic oscillation signal from the neutral hydrogen $\lambda = 21$ cm radio signal over redshift $z = 0.8 - 2.5$, a time in the cosmic past at which dark energy began to dominate the expansion of the Universe [32]. The CHIME/FRB experiment was created in recognition of the wide bandwidth, high sensitivity, and powerful correlator possessed by CHIME, all excellent starting points for a dedicated search for fast radio bursts in the CHIME sky.

The CHIME/FRB instrument harnesses the upgraded CHIME correlator to obtain a sampling resolution of 0.983 ms and $16,384$ frequency channels, enhanced from the 20 s integration time and 1024 channels. Firstly, the ~ 1 ms time resolution allows the FRB search to at least meet the timescale of millisecond FRBs. While the native 2.56 μs CHIME resolution would give excellent resolution, the resulting data rate would present data-wrangling problems. Secondly, the improved frequency channel size helps to mitigate intra-channel smearing, an effect due to dispersion of radio frequencies (§1.1) that spreads out the intensity of a radio signal within a frequency channel according to the dispersion effect (Eq. 1.9) due to the non-infinitesimal width of digitized channels. Without this, the FRB signal would not be detectable amidst the radio interference background to which the CHIME telescope is inescapably exposed.

2.2 CHIME/FRB Accomplishments

Nearly two years have passed since CHIME/FRB began its pre-commissioning operations, a time during which the FRB search began in earnest while configuration changes to the real-time FRB search pipeline (§2.3) were being made to respond to first results. In other words, the past two years have been a somewhat unstable time. The instrument was expected to detect between 2 and 42 FRBs each day, despite that previous searches at low frequencies - by ARTEMIS [20] (145 MHz), the Murchison Wide-field Array [41] (182 MHz), and the Green Bank Northern Celestial Cap Pulsar Survey (350 MHz) [9] - had not found any FRBs. As of today, many hundreds of FRBs have been detected with CHIME/FRB, averaging 2-3 per day during periods of stable operation, and the following sub-sections summarize the landmark results that have come along the way to obtaining this sizable population. Overall, the results show that CHIME/FRB is delivering a steady supply of both new singleton FRBs, new repeating sources, and subsequent bursts from these repeaters, facts which lend promise for low-latency multi-wavelength follow-up of CHIME/FRB sources as they are published via the CHIME/FRB VOEvent Service (Chapter 4).

2.2.1 The First FRBs Down to 400 MHz

While the CHIME/FRB instrument was undergoing routine upgrades to the FRB search software, 13 bursts were detected in the CHIME band with some bursts extending in frequency structure down to 400 MHz. The bursts showed diverse spectral and temporal properties (Figure 2–2) and were detected over a range of DMs, with one being the lowest DM source of any FRB known at the time and therefore interesting as a potentially nearby source. Besides demonstrating a proof-of-concept for the CHIME/FRB experiment, this result confirmed the existence of a population of repeating FRB sources by reporting a new source known then by the name FRB 180814.J0422+73 but which is now called FRB 20180814A according to the recently adopted internationally-recognized Transient Name Server convention[1] (§4.3.5). Details on the analysis methods, including measurements of the burst morphology and FRB all-sky rate estimates are in the full publication [12] and the full 16k frequency channel data are publicly available[2] .

2.2.2 Multiple Repeaters and a Periodic Source

CHIME/FRB has since proven to be an excellent resource for observing and discovering repeating sources. In the year that followed its first discoveries, CHIME/FRB yielded four separate publications: first, the detection of FRB 121102 [19]; second, the detection of a new repeating source FRB 180814.J0422+73[3] [11]; and thirdly, a total of 17 additional repeating sources split over two releases [13] and [16]. The diversity among the repeating sources is not to be overlooked. Both morphological differences and similarities in their frequency and temporal structure are apparent. Especially salient among the CHIME/FRB population is the so-called downward-drifting sub-structure seen. Among the population is a source named 180916.J0158+65[4] that continues to be detected regularly by CHIME/FRB with a measured period of 16.35 days [50]. This landmark result came following cooperation with external collaborators that enabled the FRB source to be localized to a nearby

[1] `https://wis-tns.weizmann.ac.il/`.

[2] `https://chime-frb-open-data.github.io/`.

[3] FRB 20180814A.

[4] FRB 20180916B.

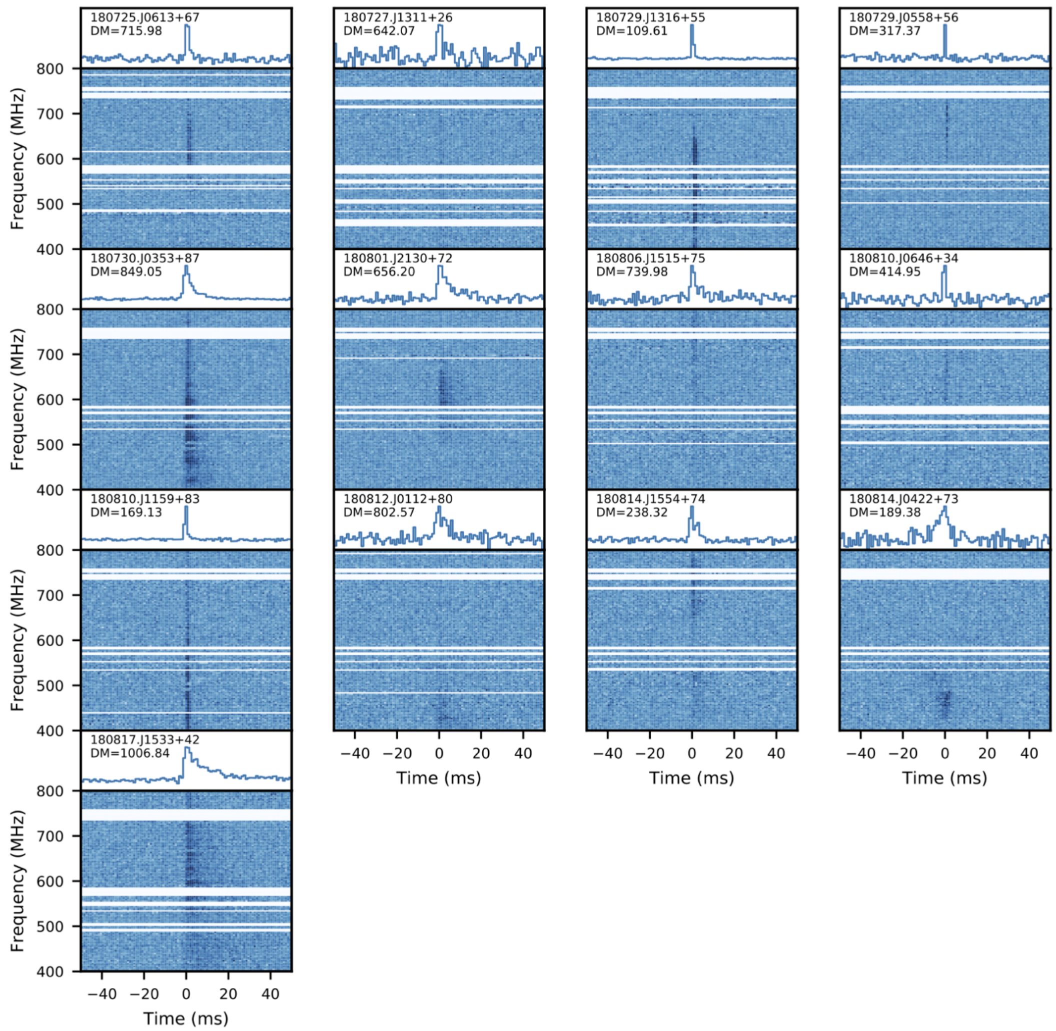

Figure 2–2: These 13 sub-plots represent individual FRBs detected with CHIME/FRB and reported in [12] as Figure 1. Each is the dynamic spectrum intensity data that has been corrected for dispersion according to the DM value reported in each sub-plot. Each individual sub-plot is usually called a "waterfall" plot, where the darkness of each pixel (blue, in colour) is proportional to the signal-to-noise ratio of the detection within a given frequency-time bin (Y and X axes, respectively). White horizontal stripes indicate excised frequency channels that are masked where terrestrial radio frequency interference (RFI) prevents any signal extraction. The top panel in each sub-plot is a time-series constructed from the sum over frequency channels in each time bin.

($z = 0.0337 \pm 0.0002$) spiral galaxy via observations of the CHIME/FRB coordinates with the European Very Long Baseline Interferometry (VLBI) Array [26].

Furthermore, the activity of each repeating source is tracked in semi-real-time through the manual update of a publicly accessible web page[5] . While this web page currently functions as a public bulletin, it requires active human agents in the community to monitor the website for updates. A major application of the work of this MSc thesis is to provide activity updates on these CHIME/FRB repeating sources in real-time using the machine-readable messages that will be distributed by the public alert system (the CHIME/FRB VOEvent Service, Chapter 4), a significant upgrade for observing campaigns with multi-wavelength observatories.

2.2.3 A bright millisecond radio burst from a Galactic Magnetar

The most recent CHIME/FRB result is still in the review process but has been submitted to *Nature* [49]. The reader can consult the paper for details beyond the scope of this thesis. It describes the 28 April 2020 detection of a bright millisecond radio burst with CHIME/FRB that was detected far from the CHIME meridian (Figure 2–3). The radio data exhibits two bursts within the time window of the CHIME/FRB observation, the peaks of which are separated by $\sim$ 29 ms. The frequency structure of the bursts indicates that the detection occurred in the far side lobes of the CHIME telescope. A localization procedure, following a Markov Chain Monte Carlo (MCMC) optimization routine, was used to determine the sky origin of the CHIME/FRB detection by searching a box of size $108^\circ \times 10^\circ$ (North-South by East-West, respectively) centred on the detection beam having the highest SNR in the

[5] `https://www.chime-frb.ca/repeaters/`.

event. The fitted celestial coordinates $(\alpha, \delta) = (293.9^\circ,\ 22.1^\circ)$ were assigned a systematic uncertainty of 1°, with the express understanding that the MCMC localization routine will be published in an upcoming paper and until then remains under continual development. Importantly, to within 0.3° these coordinates are consistent with a known Galactic source called SGR 1935+2154. Here, SGR means soft-gamma repeater and reflects the repeated detection of short-gamma ray bursts (SGRBs) from the source.

The association of the CHIME/FRB radio burst with SGR 1935+2154 is supported by the fact that this source was exhibiting a period of unusually bright X-ray activity, as reported in measurements made with the *Swift* Burst Alert Telescope (BAT) [34]. Together with the spatial association, there are strong reasons to believe the radio activity is uniquely caused by SGR 1935+2154. Curiously, the SGR source had entered an active period as early as November 2019, emitting many dozens of X-ray bursts and gamma ray bursts (GRBs) since then, but no matching radio activity was detected with CHIME/FRB during that time [49].

SGR 1935+2154 is widely believed to be a magnetar (a highly-magnetized neutron star) for which FRB models have been closely studied and largely found to agree with FRB observations. On the other hand, the energetics of the radio burst in the CHIME band were measured to be $\sim 10^{34}$ erg [49], a curious three orders of magnitude larger than any known radio burst from other magnetar sources. Nonetheless, it is the first indication in the study of FRBs of a bridge between the Galactic magnetar population and the cosmological FRB population.

The real-time public alert system to be described in this MSc thesis was not active and therefore played no role in communicating the CHIME/FRB

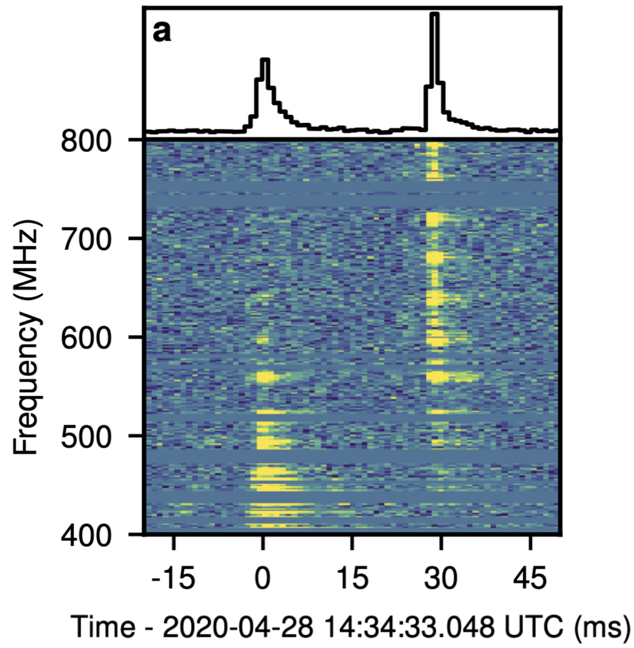

Figure 2–3: The de-dispersed dynamic spectrum of a bright millisecond radio burst from SGR 1935+2154 detected with CHIME/FRB. Two bursts have been captured in the same FRB search time window, with a separation of 30 ms. **Bottom panel:** The colour scale here is normalized to the total intensity, with yellow indicating high SNR and dark blue indicating low SNR. Horizontal strips of blue indicate channels excised by RFI masking algorithms and set to the median intensity. **Top panel:** The time series produced by integrating across all frequency channels, with $t = 0$ indicating the burst arrival time at 400 MHz.

discovery of radio bursts from SGR 1935+2154. The timestamp and sky localization of CHIME/FRB discoveries are key ingredients in the exchange of new radio activity from known and unknown sources between CHIME/FRB and X-ray observatories; the activity from SGR 1935+2154 provides an example of a situation where publishing such information in real-time would expedite and nourish the science of joint radio and X-ray studies of sources like this one. Collaborations between CHIME/FRB and X-ray observatories are ongoing to determine more precisely what science can be done, using among other things the SGR 1935+2154 discoveries as a source of inspiration.

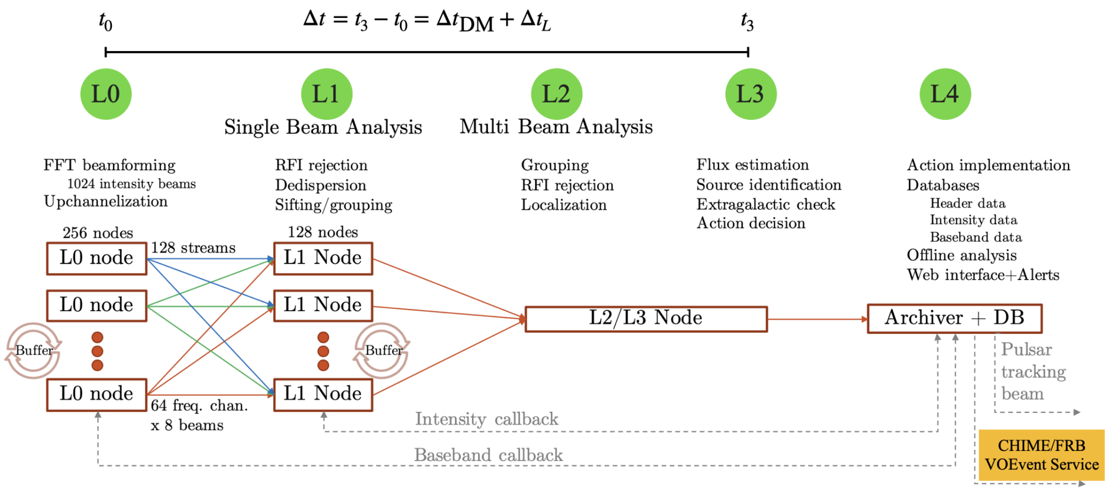

Figure 2–4: The FRB search pipeline is a 1 + 4 stage process that consists of beam-forming (L0); per-beam de-dispersion analysis and event header formation (L1); multi-beam assembly of L1 events into a single L2 event (L2); extragalactic source identification and further action specification yielding an L3 event (L3); and finally, action implementation and database archiving to accommodate offline processing and web service interface for user access and the public alert system that is the product of this MSc thesis (L4). The latency in the real-time pipeline comes from Δt_{DM} being the time required to receive the entire pulse of a dispersed radio signal with a given DM, plus the latency of the L1-L3 processes that typically require $2-3$ s. For a burst of DM 1000 cm^{-3} pc the value of Δt_{DM} is about 24 s (Eq. 1.9). This is modified from Figure 4 in [10] with added notes.

2.3 FRB Search Pipeline Overview

With the accomplishments of the CHIME/FRB experiment in mind, it remains to describe how they were made. CHIME/FRB is a real-time fast radio burst search pipeline that is organized into four processing stages labelled L1 through L4, with the preliminary digitized and channelized frequency data from the CHIME correlator represented as an initial stage, L0. Here we cover each stage in brief, and the reader is reminded that more details are available in [10]. Figure 2–4 is a visual aid to guide the reader through the flow of the pipeline.

2.3.1 L0: Beam-forming

The real-time FRB search pipeline first receives a "picture" of the radio sky overhead of the CHIME telescope as captured by the beam-forming process completed by the correlator. This is a grid of 1024 elliptical regions within the CHIME primary beam that extends North-South ($\sim 110°$) and East-West ($\sim 1.3 - 2.5°$)[6] . These 1024 regions represent the radio-frequency sensitivity of the telescope to sources in the sky (in the CHIME band) and are what allow a basic localization of any detected signal. All subsequent processing refers to these 1024 "beams," terminology that comes from the beam-forming process [33]. The 1024 beams are formed on the sky in four columns aligned North-South of 256 rows aligned East-West as illustrated in the graphic in Figure 2–5.

2.3.2 L1: Per-beam De-dispersion and Search

An attempt is made on each of the 1024 beams to identify an FRB-like signal by investigating trial de-dispersion up to $13,000$ cm^{-3} pc applied to the radio frequency data. The de-dispersion is handled by a novel algorithm called `bonsai` that is special in its ability to overcome memory bottlenecks and dispersion delay approximations that are typical hurdles in modern dispersion algorithms. Analysis results for each beam are saved into their own packet called the L1 event or sometimes L1 header, that includes information such as the measured DM, the on-sky pointing of the centre of the beam (in right ascension and declination), the arrival time of any radio signal in that beam at 400 MHz, and importantly the signal-to-noise ratio (SNR) in that beam.

[6] The beam width is larger at 400 MHz than at 800 MHz.

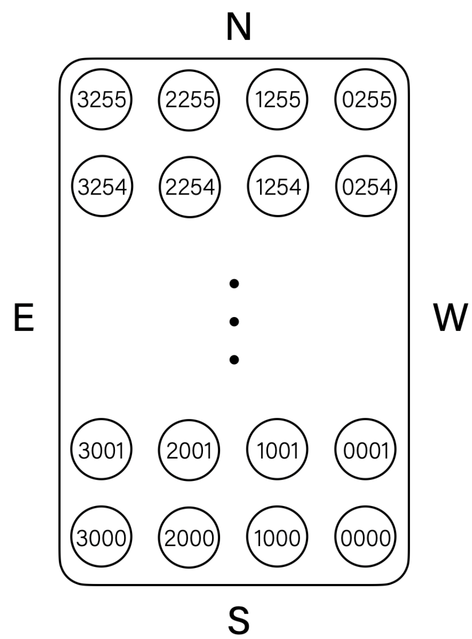

Figure 2–5: An illustration of the CHIME formed beams of which there are 1024 that result form the beam-forming process [33]. The convention is to number individual beams from the bottom right corner (South-West) starting at 0 and increasing to 255 along a North-South column. The rows are arranged East-West and by convention the beams are numbered with four digits in which the first digit (thousands column) indicates the beam column - in the first beam column, this digit is 0 and in the second it is 1. This schematic is for illustration only and the beam sizes and spacing is not to scale.

2.3.3 L2: Multi-beam Grouping and RFI Mitigation

Simultaneous L1 events are grouped by DM and detection time, yielding an L2 event that represents one or more beams. This data packet is passed to a machine learning algorithm that classifies it on a scale from 0 (RFI) to 10 (astrophysical). This grouping procedure also permits a basic localization called the L2 localization that is represented in the header as a central coordinate and semi-major and semi-minor axes for an on-sky ellipse closest to the beam that had the highest detected SNR in the (possibly multi-beam) event.

2.3.4 L3: Galactic Inferences and Action Specification

The L2 event contains enough information now to classify the data packet as one of four types: Galactic, ambiguous, extragalactic, or RFI. This is based on comparing the DM of the L2 event with the maximum Galactic DM predicted by the NE 2001 [14] and YMW 2016 [57] models. The maximum is calculated based on the line-of-sight to the sky coordinates from the L2 localization. If σ is the combined statistical and systematic uncertainty in the DM measurement process for the L2 event, and $M = \max(\mathrm{DM}_{\mathrm{NE}}, \mathrm{DM}_{\mathrm{YMW}})$ the classification at L3 is as follows:

- extragalactic: $\mathrm{DM} - M > 5\sigma$
- ambiguous: $5\sigma \geq \mathrm{DM} - M > 2\sigma$
- Galactic: $2\sigma \geq \mathrm{DM} - M$

The two Galactic DM models are known to disagree at certain sky-locations. An ambiguous (in the sense just defined) FRB source could conceivably be Galactic or nearly adjacent to the Galaxy. Apart from this DM-checking procedure, a simultaneous procedure evaluates the DM and sky-position of the L2 event against a catalogue of known sources (Known Source DataBase, KSDB[7]) that is embedded in the real-time pipeline and undergoes updates on a cadence of ~ 1 hr to include especially newly human-verified FRB sources[8] . This is the mechanism upon which real-time identification of repeating sources takes place. If the DM and sky position are sufficiently close to a known source, the name of that source is added to what is now the L3 event. Otherwise the known source name is left blank[9] .

The L3 stage also handles making logical inferences on the content of the L2 event plus the source classification and known source identification steps. A set of action rules are hosted as configurable files to be consulted in real-time, consisting of logical statements. Flags are raised wherever the statements evaluate true, and this is crucial for instructing the next stage, L4, for what actions to implement. Among these action rules is one which defines thresholds triggering the CHIME/FRB VOEvent Service, which in some places is referred to by its legacy name "Alert Community." At the time of writing, the rules for the Service are summarized in Table 2–1[10] .

2.3.5 L4: Web, Database, and Offline Service Integration

The final stage evaluates the action rules that were specified and gathered in the L3 event. L4 is best described as a database and web server integration layer that provides three core services.

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[7] Author's abbreviation.

[8] Human verification is handled offline at L4.

[9] In Chapter 4 we describe how this triggers the release of a special alert for known repeating sources.

[10] A similar table is available to CHIME/FRB collaboration members at the password-protected FRB-Web portal.

Source Category Type	Source Type Name	Rule
Unknown Source	Extragalactic	SNR ≥ 8.5
Unknown Source	Ambiguous	SNR ≥ 8.5
Known Source	Known-FRB	SNR ≥ 8.0

Table 2–1: The real-time rules for triggering the CHIME/FRB VOEvent Service (Chapter 4). The rules are managed at the L3 stage of the real-time FRB search pipeline and are appended to the L2 event as part of forming the L3 event, though they are not implemented until the L4 stage. When all three conditions in each row are satisfied, a Boolean flag called `"ALERT_COMMUNITY"` is raised (set to `True`). As an example, the first row indicates that an event classified as an unknown source and classified as extragalactic needs to be detected with a signal-to-noise ratio at least 8.5 to raise this flag.

- Communicate with external processes for handling desired actions in the L3 event, including the public alert system.
- Request captures of the intensity and baseband (raw voltage) data from upstream pipeline and telescope processes.
- Store the L4 event containing L3 event data plus results of implemented actions, providing database layers for human and graphical web viewers to access and process L4 events offline.

L4 handles service integration and interface in many respects, importantly connecting humans to the results of the real-time FRB search pipeline. Human verification is an integral part of the scientific process that identifies FRBs that may or may not be among the L4 events. That is, the false-positive rate is nonzero at the end of the real-time pipeline, such that humans are required to distinguish true FRBs from bursts from known Galactic sources and RFI contamination that masquerades as an FRB-like signal. Because the performance of machine learning algorithms determine the output of the real-time pipeline, false-positives are an ongoing antagonist for the public alert system, an issue that will be addressed in Chapter 4.

2.4 Latency of the Real-time FRB Pipeline

The description of any real-time process is incomplete without a measure of the latency from start to finish, particularly when time-sensitive offline processes depend on it. In Chapter 4 it will be made clear exactly how the public alert system integrates into L4, however for now one can picture the best-case scenario: a radio signal reaches the CHIME antennae and passes all the way through the FRB pipeline up to L3, where the `"ALERT_COMMUNITY"` flag is raised. Up to here, the latency accrued is equal to

$$\Delta t_{\mathrm{L3}} = \Delta t_{\mathrm{DM}} + \Delta t_L \tag{2.1}$$

where Δt_{DM} is equal to the time required for the dispersed radio signal to completely arrive in the CHIME band (Eq. 1.9), and Δt_L is the nominal latency of the stages L0 through L3, which is about $2-3$ s. Naturally, Δt_{DM} depends on the radio signal itself, in particular the bandwidth of the pulse and its DM. From Eq. 1.9 one can see that a broadband pulse in the CHIME band with a DM of ~ 130 cm^{-3} pc requires ~ 3 s to be received at 400 MHz. Taking a sample of random lines-of-sight through the Galaxy, the average maximum DM along a line-of-sight through the Galaxy is at least 200 cm^{-3} pc according to the NE 2001 model (Figure 11 in [14]), and hence any broadband extragalactic FRB detected with CHIME/FRB will result in $\Delta t_{\mathrm{DM}} \gtrsim 3$ s. Therefore, the latency of the real-time FRB pipeline is dominated by the DM delay.

2.5 CHIME/FRB Can Provide a Steady Supply of Multi-wavelength Targets

It cannot be overlooked that CHIME/FRB is in a superior position to provide the astrophysical community with the largest daily volume of new FRBs and subsequent bursts from repeating FRBs. The event rate of 2-3

FRBs per day in combination with regular exposure to repeating FRB sources, including the periodic FRB 20180916B, indicates that multi-wavelength observatories can expect up to multiple FRB targets per day to pursue, at least in the Northern sky from $\sim -10^\circ$ in declination and upwards.

CHAPTER 3
Virtual Observatory Events (VOEvents)

3.1 Introduction

To enable rapid multi-wavelength follow-up of any new astrophysical transient, a key ingredient is a standardized reporting format for these observations that can be handled by a computer program and have arbitrary actions executed upon it. To specify this further, one can imagine a general framework that breaks down as follows.

1. A medium in which reports of such events can be published.
2. A network over which the reports can be distributed.
3. An entry point to the network to provide broadcasts and/or subscribe to broadcasts of these reports.

Together, these three parts should allow any observatory or instrument to produce, disseminate, and receive reports of observations of any transient in a consistent and transparent format. Specifying this standard for FRBs is a specific task (Chapter 4) that can be circumscribed in a more general framework.

Fortunately there exists such a framework that is already well-established. The International Virtual Observatory Alliance (IVOA)[1] maintains a recommendation for how to report on observations of transient phenomena across the electromagnetic spectrum in the form of the Virtual Observatory Event (VOEvent) standard. The name reflects the ambitious vision of a single virtual

[1] `http://ivoa.net/`.

observatory that is a conglomerate of any and all observatories on Earth (or in orbit). By coordinating in real-time via exchange of VOEvents, such a monolithic network could in principle observe individual astrophysical transients in coordination and obtain coverage across the electromagnetic and multi-messenger spectrum.

The VOEvent standard is intended solely for messages that are distributed across the dedicated VOEvent Network. As a general framework, the experience of publishing, broadcasting, and receiving VOEvents is intended to resemble browsing the World Wide Web. That is, connecting an observatory allows one to send and receive observations of transients from around the world as if they are originating locally, just as web pages stored on servers around the world seem to originate from the local machine. In the CHIME/FRB context the most important feature of VOEvents is that they provide a standard format that can be distributed to any machine around the world and act as a trigger for observatories that span the electromagnetic and multi-messenger spectrum.

3.2 Methods: The VOEvent Medium

The VOEvent standard was most recently updated in [44]. A VOEvent is a specialized XML[2] document that allows one to encode scientific meta data, along with descriptions for what the data represent and what inferences have been or could be drawn from an observation, into a text-like document that is machine readable (in object-oriented programming languages, each document is an object). XML documents are an established format applied broadly across the Internet. As a communication medium in astronomy, a document based on XML is far more suitable to be handled by a program in

[2] `https://www.w3.org/TR/xml/#sec-intro`.

comparison with, e.g., a plain text document, the parsing of which would need to be handled on a case-by-case basis on account of varying syntax, style, and language. Convenient libraries for parsing XML exist in most programming languages, including `python`[3] . Moreover, the special case of VOEvent XML documents can be parsed with further abstraction from the technicalities of XML using available wrapper libraries in `python` e.g. `voevent-parse`[4] [47].

The VOEvent standard is a recommendation on *how* to report the meta data of an observation, rather than *what* specifically to report. The flexibility in content accommodates different observation specifications; on the other hand, the rigidity in the structure ensures a level of uniformity compatible across platforms (i.e. programming languages and operating systems).

A VOEvent XML is written to disk as a `.xml` file and can be opened in any text or code editing environment, similar to `html` documents. Several resources online give more complete details of the syntax of XML documents than can be covered here. The reader can also obtain many examples of VOEvent XMLs by following tutorials for the VOEvent database called `voeventdb.remote` maintained by the 4 Pi Sky group[5] . Within the VOEvent XML, there may be up to seven IVOA-recommended sections within the document that neatly breakdown the who, what, where, when, why, and how aspects of the observation. In the following, *author* will refer to the human(s) that decide on the content of the VOEvent, and *agent* will refer to the system(s) that assemble the VOEvent XML. Furthermore, text written in `monospace` font indicates names of variables, attributes, or parameters featured in VOEvent XML documents.

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[3] `https://lxml.de/`.

[4] `https://voevent-parse.readthedocs.io/en/latest/index.html`.

[5] `https://4pisky.org/voevents/`.

3.2.1 `<VOEvent>` Header

All VOEvent XMLs begin with this header that lays out the following basic information.

- The `version`, which for recent VOEvents will be `2.0` as this is the current release version of VOEvents [44].
- The `role`, which will be one of either `"observation"`, `"utility"`, or `"test"`.
- The `ivorn`, meaning the International Virtual Observatory Resource Name (IVORN).

The `version` is crucial for both the library that parses the VOEvent XML and the VOEvent Network. The `role` can take one of three values, and allows an author to consider publishing `"test"` VOEvents that might be part of a continuous integration process as the author develops new versions of a VOEvent XML template; `"utility"` VOEvents that may only be useful for telemetry purposes for orbital observatories; and `"observation"` VOEvents that uniquely specify an astrophysical purpose. Lastly, the `ivorn` is a unique identifier that is usually formatted similar to a URL but does not link to any web page, and that is unique insofar as two unique VOEvents should never have the same IVORN. IVORNs may be customized but must begin with the prefix `ivo://` and are often followed by a reversed Domain Name System (DNS) identifier for an observatory's main web page.

3.2.2 `<Who>` Header

The identity of the author that is responsible for the VOEvent XML is contained between the tags `<Who>` and `</Who>`. Sub-headings here often include the following.

- A `<Description>`, to give a human-readable name to the agent that produced the VOEvent.

- An `<AuthorIVORN>` to give the agent its own IVORN, usually similar to the `ivorn` previously mentioned but only needs to be unique to each agent.
- A `<Date>` with the UTC timestamp when the VOEvent was created, not when the observation was made.
- An `<Author>` that can have two further sub-headings identifying the human maintainer of the VOEvent agent: `<contactEmail>` and `<contactName>`.

3.2.3 `<What>` Header

Any meta data that are crucial to specifying the environment in which the observation was made should be reported here. The VOEvent author is expected to provide any and all such information as it pertains to the sky conditions, presence of celestial bodies in the field of view e.g. the Sun or Moon that may degrade the observation quality, fit parameters of any analyses performed to report on the localization in space and time, and system parameters of the instrument that obtained the measurements, in addition to all the measured parameters of the astrophysical event itself. Each meta datum is enclosed in a header called `<Param>`. Several such data can be grouped by `<Group>` headers that can be given a `name` to collect observatory parameters and separate them from astrophysical event parameters, for example.

3.2.4 `<WhereWhen>` Header

This section is reserved for coordinates, pertaining to those of the observatory (terrestrial or orbital), and those of the transient observation that was made. The astrophysical coordinate system and the time system must be specified. An example follows below in Figure 3–1.

```xml
<WhereWhen>
  <ObsDatLocation>
    <ObservatoryLocation id="CHIME lives at DRAO">
    <ObservationLocation>
      <AstroCoordSystem id="UTC-FK5-TOPO">
      <AstroCoords coord_system_id="UTC-FK5-TOPO">
        <Time unit="s">
          <TimeInstant>
            <ISOTime>2020-01-01T00:00:00.000000<ISOTime>
          </TimeInstant>
        </Time>
        <Position2D unit="deg">
          <Name1>RA</Name1>
          <Name2>Dec</Name2>
          <Value2>
            <C1>0</C1>
            <C2>0</C2>
          </Value2>
        <Error2Radius>0</Error2Radius>
        </Position2D>
      </AstroCoords>
    </ObservationLocation>
  </ObsDataLocation>
</WhereWhen>
```

Figure 3–1: All VOEvent XMLs must have the `<WhereWhen>` section in order to communicate the coordinates of the observatory and the observation in both space and time. In this example, a hypothetical observation occurred at midnight UTC on January 1, 2020. The sky-coordinates are right ascension 0° and declination 0°, represented by the values of the `<C1>` and `<C2>` parameters, respectively. These are the centre of a circular localization region on the sky of radius 0° as specified by `<Error2radius>`.

```xml
<Inference probability="0.9">
  <Name>Interference Mitigation</Name>
  <Concept>Probability of astrophysical origin</Concept>
</Inference>
```

Figure 3–2: An example of a scientific inference that could be reported in the `<Why>` section. Here, the VOEvent author reports a probability of 90% that the observation is astrophysical in origin, and not produced by interference. This is a general use case that could be realized for radio telescopes, for gravitational wave detectors, or for ultra-sensitive underground cosmogenic neutrino detectors, to name only a select few.

3.2.5 `<Why>` Header

This section is optional, though recommended as a way to provide one or both of (1) a measure of the confidence (via probability) that the observation is astrophysical rather than background noise from the sky or terrestrial interference; and (2) an indication of the scientific importance to help recipients of the VOEvent decide whether to take any follow-up actions. Some VOEvent authors may choose to report all of their observations down to a certain sensitivity or credibility threshold, as determined by their instrument rather than by the scientific relevance for the general observer, in which case the importance flag and probability measure here can play a critical role for the subscriber. VOEvent authors that operate this way help to serve all possible subscribers, including both those interested in sub-threshold observations and those awaiting only the most credible (e.g. "brightest") observations. The VOEvent author should use the `importance` attribute to give a score from 0 to 1 as a measure of whether another observer should take action, and the `probability` should be assigned from 0 to 1 in accordance with a scheme that measures how likely the observation is astrophysical in origin. General scientific inferences made from the observation can be reported by the author using the `<Inference>` sub-heading as in Figure 3–2.

3.2.6 `<How>` Header

This section is optional, though recommended as a means of describing how the meta data that are reported in `<What>`, `<WhereWhen>`, and `<Why>` were measured or evaluated. In real-time systems that analyze the observational data and prepare the meta data for the VOEvent, there may be one or more data analysis pipelines that are used, which in turn can depend on e.g. parallel suites of analytic algorithms and machine learning classifiers. The author is recommended to report precisely what such analysis was performed especially if it has a public or even an internal name. Moreover, using the `<Reference>` heading, the VOEvent author can provide links to additional resources that can be downloaded for automated processing. Note that unlike emails, the VOEvent standard does not support attaching files to the XML document and therefore all such content must be provided by resource links, the content of which must be hosted elsewhere. As an example, the LIGO/Virgo Collaboration demonstrates the usage of machine-readable links in their VOEvents (see §3.4).

3.2.7 `<Citations>` Header

This section is optional, though in principle its effective usage by all observatories exchanging VOEvents over the VOEvent Network is perhaps the most ambitious aspect of the IVOA's vision of a single, global virtual observatory. Here the author of a follow-up observation to a previously issued VOEvent should at minimum cite that VOEvent, and, wherever practical, all previously issued VOEvents representing the original observation. This is done by recording the VOEvent IVORN of the original observation (Figure 3–3) within the current VOEvent. If used widely and properly, this paradigm would imply that a randomly selected VOEvent could have both citations (VOEvents to which it refers) and references (VOEvents that refer to it), creating a web of

```
<Citations>
  <EventIVORN cite="supersedes">
  ivo://ca.chimenet.frb/FRB-DETECTION-#2020-01-01
  </EventIVORN>
</Citations>
```

Figure 3–3: An example of a `<Citations>` header used in a VOEvent that refers to a previous VOEvent directly by its IVORN. For this reason, every VOEvent must have a unique IVORN to avoid confusion between two possibly unrelated observations. In this case, the VOEvent containing this particular segment is published as an *update* to a previous VOEvent that was published under the IVORN `ivo://ca.chimenet.frb/FRB-DETECTION-2020-01-01`. This is communicated by the keyword `cite="supersedes"`.

linked observations of transient phenomena. Along an orthogonal axis, citations are also an effective tool for a VOEvent author to publish a continually revised observation: an initial VOEvent published in real-time with moderate uncertainties in sky localization and other meta data can be followed by a chronology of multiple updates, each having revised estimates obtained from improved offline analyses applied to the original data, and carrying a continually growing chain of citations.

3.3 Methods: The VOEvent Network

The VOEvent medium represents a full solution for exchanging reports of real-time and follow-up observations when combined with the VOEvent Network. As illustrated in Figure 3–4, VOEvents are exchanged between perpetual services called VOEvent brokers. Under normal circumstances, an author will create a VOEvent XML document locally, using software that translates their observational meta data into the schema, and then publish it to a VOEvent broker. By default, this broker will broadcast the VOEvent and it will be received by all other brokers connected to the Network. Again by default, any other brokers in the Network will receive the VOEvent and re-broadcast it. This ensures both fast coverage across the Network, and it avoids single-point failures. Namely, if a single broker drops out, the VOEvent will still be broadcasted everywhere. Brokers are equipped with a long-term memory of previously-seen VOEvents, each one identified by their unique IVORN, and are instructed to never broadcast such VOEvents, thus avoiding duplication. In this way, no loops are formed within the Network, and hence it can be thought of as a directed acyclic graph (DAG).

Beyond this basic description, the behaviour of individual VOEvent brokers can be customized. Software solutions for VOEvent brokers are available in common programming languages, including the Comet VOEvent client [48], a complete open-source VOEvent broker solution written in `python` that provides publishing, broadcasting, and subscribing capabilities. Comet allows one to operate a VOEvent broker perpetually at a command-line interface to fulfill any and all of these three roles simultaneously. In the following three subsections we briefly describe each role as it applies to any VOEvent broker.

3.3.1 Publishing

A VOEvent broker configured in publish-mode will only accept VOEvents constructed according to the current IVOA VOEvent schema [44]. To do this in `python`, the `voevent-parse`[6] [47] library provides both a user-friendly wrapper of the underlying XML requirements and additional helper functions to create the seven VOEvent headers described in §3.2.1 - 3.2.7. In publish-mode, the local broker accepts the VOEvent but does not distribute it to any other brokers in the VOEvent Network.

[6] `https://voevent-parse.readthedocs.io/en/latest/index.html`.

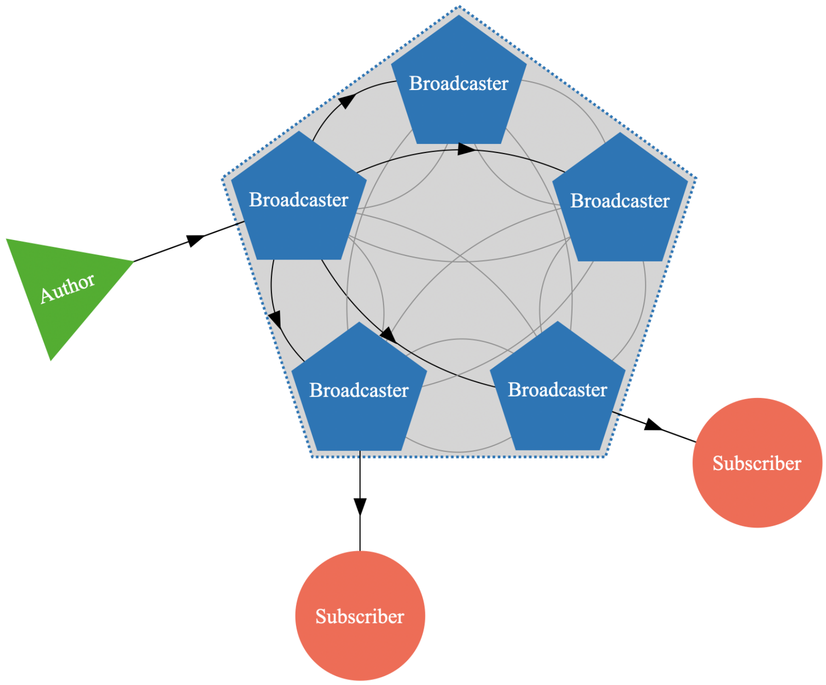

Figure 3–4: The VOEvent Network consists of VOEvent brokers that each have a static IP address according to their local Internet connection. Brokers can be configured to operate in one or more of three roles simultaneously: publish, broadcast, and subscribe. An author (green triangle) that produces VOEvents typically runs a broker locally as both a publisher and broadcaster in order to spread their VOEvents through the Network. Other brokers in the Network (blue pentagon) by default will re-broadcast all incoming VOEvents. Clients wishing to receive VOEvents (red circle) can run a broker in subscribe-mode. Apart from blocking malformed VOEvents that do not conform to the VOEvent XML schema laid out by the IVOA, brokers also keep a list of previously received VOEvents by their IVORNs to prevent spreading duplicates across the Network. This is illustrated by the black arrows that show a VOEvent spreading without forming an infinite loop within the Network. In principle, each broker is connected to every other broker to ensure that the Network survives a single-point failure (where one broker drops out). Publishing and subscribing brokers can be made to submit and receive VOEvents, respectively, from specific brokers by specifying that broker's IP address.

3.3.2 Broadcasting

In broadcast-mode, a VOEvent broker will broadcast any VOEvents it receives to the VOEvent Network. In publish-mode, the VOEvent can originate from a local author, while in subscribe-mode the VOEvent can originate from a remote author or broker. Any VOEvent broker is assigned an IP address according to the local Internet connection and it presents that IP address to the VOEvent Network to be visible to other brokers. Furthermore, it is possible to specify a list of fixed IP addresses for a broker, called a white-list, each of which is permitted to receive the broadcast of that broker. On one hand, restricting the allowed recipients of a VOEvent interferes with the complete connectivity illustrated in Figure 3–4. On the other hand, it allows the human developer who is deploying the broker to control who can subscribe to their broker during testing or continuous integration phases.

3.3.3 Subscribing

As a subscriber, a VOEvent broker running on one's local machine is initialized with one or more IP addresses that identify the remote VOEvent broker(s) from which broadcasts will be accepted for publication by the local broker. In combination with broadcast-mode, a VOEvent broker that subscribes to others represents one of the nodes in Figure 3–4 that has multiple arrows impinging on it. Otherwise, in subscribe-mode only, the broker is a terminal node.

3.3.4 Event Handling

VOEvent brokers come equipped with the capacity to execute arbitrary programs on VOEvents that are received, a task called event handling. This is where scientifically meaningful activities enter, and the utility of the general VOEvent framework is realized. The event handler is just an executable script that is attached to the broker and launched in a separate thread upon receipt of a VOEvent. In Comet [48] the capacity to implement arbitratry plugins as event handlers is straightforward[7] . A common VOEvent handling framework involves an event handler that contains only action rules and contacts independent processes to handle implementing those actions. A simple use case is one in which a guiding observatory with a wide field-of-view is accompanied by multi-wavelength observatories that are already pointing somewhere in that field-of-view. As the follower-observatories handle VOEvents about a detection from the main instrument, they refine their pointing to the uncertainty region contained in the detection. The capacity for CHIME/FRB to be the guiding instrument in a special case of this example is discussed in Chapter 4. On the other hand, Chapter 5 describes the event handling of VOEvents by a dedicated CHIME/FRB VOEvent broker for related possible multi-wavelength observations.

3.4 Examples

The VOEvent standard works well when both real-time and semi real-time analyses are carried out on observations and are reported incrementally through VOEvents. Using citations to previous VOEvents, one author can produce an initial VOEvent to be broadcasted with low latency, containing preliminary measurements and estimates, and then follow this with an updated VOEvent refining these. In parallel, receivers of the initial VOEvent can act on the low-latency alert to trigger their observations. In the case of a multi-wavelength detection, receivers can (1) report on their results in a VOEvent that cites the initial one and (2) wait for the updated VOEvent from the original author that will allow for deeper inferences about the likelihood of the coincident detection being related.

[7] `https://comet.transientskp.org/en/stable/handlers.html`.

Before describing in Chapter 4 how the scientific community can expect to participate in such multi-wavelength campaigns through the CHIME/FRB VOEvent Service, it is instructive to look at an example. The LIGO/Virgo Collaboration hosts an online public archive[8] for VOEvents published in connection with gravitational wave transients observed by one or more of the Hanford, Livingston, or Virgo detectors. These VOEvents are a good model for other authors that operate observatories that perform both real-time and offline analysis. LIGO/Virgo makes exemplary use of the most powerful feature of publishing VOEvents, namely the citations. As an example the following link[9] redirects to a particular LIGO/Virgo VOEvent that reports on the updated analysis on an observation of a gravitational wave (GW) transient from a binary black hole merger event. This particular VOEvent functions as a reference for the VOEvent schema, especially the content and organization of meta data in the `<What>` section. Additionally, one can appreciate the utility of the `<Citations>` section that is used heavily by LIGO/Virgo. Namely, this VOEvent represents the last in a chain of VOEvents, each which successively cites a previous VOEvent in a chain of three different types: preliminary, initial, and update. Lastly, while the `<WhereWhen>` section does not contain any sky coordinates for the GW transient, this VOEvent serves to exemplify how such information can be delivered instead in the form of a link to a downloadable sky localization map. In the `<What>` section, the `<Group>` called `"GW_SKYMAP"` contains a `<Parameter>` called `"skymap_fits"` that links

[8] Select "VOE" under any of the events listed at `https://gracedb.ligo.org/superevents/public/O3/`.

[9] `https://gracedb.ligo.org/api/superevents/S200224ca/files/S200224ca-4-Update.xml,0`.

directly to a specially formatted file that LIGO/Virgo uses for communicating its localization regions for follow-up efforts.

CHAPTER 4
CHIME/FRB VOEvents

4.1 Introduction

The primary work of this MSc thesis is the application of the VOEvent medium (Chapter 3) to the reporting of newly detected fast radio bursts with the CHIME/FRB instrument. Plans for a real-time public alert system were originally announced in [10], although this MSc thesis is the first work to be made specifically on the topic. Moreover, the average event rate of $\sim 2-3$ FRBs per day detected by CHIME/FRB means that such a real-time alert system will provide machine-readable alerts of multiple FRBs each day, the first of its kind in the world. In this chapter we describe four types of CHIME/FRB VOEvents and the framework used to orchestrate producing and publishing a stream of these VOEvents to the VOEvent Network.

4.2 Related Work

As illustrated in Chapter 3, VOEvents are a flexible, general framework for *how* to report on detections of transient astrophysical phenomena across the electromagnetic spectrum; but, a key ingredient for each frequency range or observing instrument is the development of a prescription to be followed on *what* to report. Prior to this MSc thesis, such a recommendation was made by [37] as to what details of an FRB detection should be considered essential to report in a VOEvent, and how to format those details according to the VOEvent standard. The FRB VOEvent standard suggested there is intended for general use by dedicated FRB observatories and campaigns.

In particular, the work in [37] goes beyond a recommendation for how to coherently assemble FRB observational data into a VOEvent. It prescribes four types of FRB VOEvents that together address the need to both report detections of new FRBs and report detections of bursts associated with previously detected FRBs, both which may be based on low-latency or otherwise preliminary results from a real-time pipeline that are later refined by offline analysis pipelines. There are at least two takeaways from [37]. Firstly, the mechanics of VOEvents are suitable for the population of FRB observations expected to continue coming online in coming years. Secondly, the VOEvent standard has already been deployed successfully for astrophysical transients in, for example, the GRB community. One of the authors of [37] maintains a GitHub repository[1] offering templates for the recommended four types of FRB VOEvents, an accessible starting point for members of the FRB community to collect ideas for their own real-time FRB VOEvent service.

4.3 Methods

The four FRB VOEvent types proposed in [37] have been contextualized for the CHIME/FRB project. Some modifications have been made in order to bring these into harmony with how CHIME/FRB orchestrates real-time and offline analysis of newly detected FRBs. Here we present the CHIME/FRB VOEvent Service (yellow box in Figure 2–4) that accomplishes the task of authoring and publishing CHIME/FRB VOEvents. The Service is coordinated through the combination of three parts, illustrated in Figure 4–1, all of which were written in `python` and make use of both built-in and open-source libraries.

1. A module in the L4 pipeline environment called `VOEventSender` that passes the L4 header onward according to action rules assigned at L3.

[1] `https://github.com/ebpetroff/FRB_VOEvent`.

2. A selection of API[2] endpoints in a module called FRB Master for performing translation of L4 headers and intensity/baseband analysis results into VOEvent XMLs, all of which are accessible by the L4 module, asynchronous offline pipelines, and web servers used by human agents in CHIME/FRB.
3. A containerized service called FRB VOE that perpetually runs a Comet [48] VOEvent broker and an email client for outgoing VOEvents.

The choice to divide the CHIME/FRB VOEvent Service into three separate pieces means that three separate GitHub repositories need to be maintained in step with one another, and that there are three opportunities for single-point failures. On the other hand, the process of producing and publishing a CHIME/FRB VOEvent remains transparent and easier to debug than having a single unwieldy module, as issues can be logically narrowed to one of these mutually-exclusive components. Furthermore, the Service must be accessible by both the real-time pipeline and offline analysis pipelines, necessitating that the major tasks of VOEvent preparation and publication be neatly separated from each other.

4.3.1 L4 `VOEventSender` Module

The L3 header received at the L4 stage of the real-time pipeline contains the `"ALERT_COMMUNITY"` Boolean flag, with positive instances defined in Table 2–1. This triggers the `VOEventSender` module to extract meta-data from the L4 header and form a JSON[3] document that conforms to a predefined

[2] An Application Programming Interface (API) can be described as a way to organize algorithms that are accessible through a standardized path, typically specified by a URL-like token and commonly used to provide controlled, one-off, and asynchronous access to algorithms and databases.

[3] `https://www.json.org/json-en.html`.

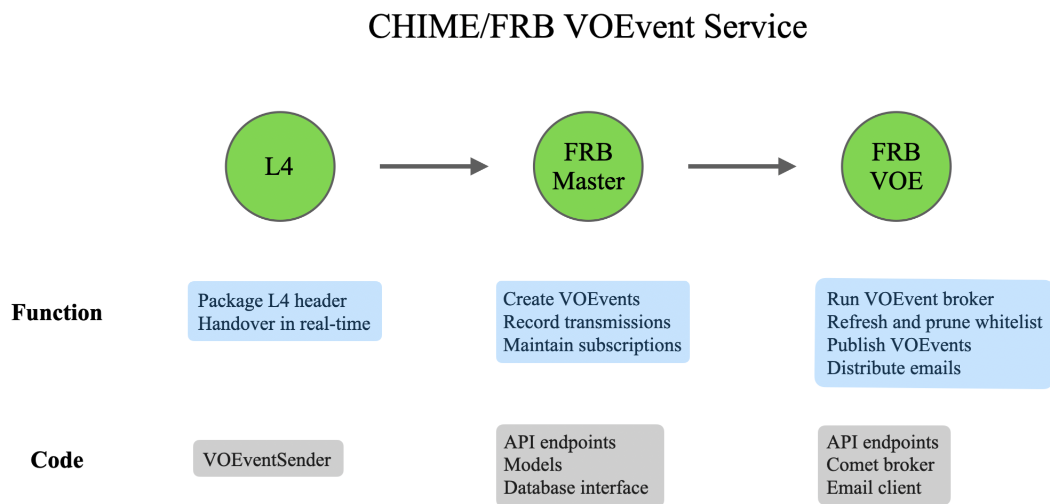

Figure 4–1: The CHIME/FRB VOEvent Service consists of three mutually-independent modules that are maintained in separate code repositories. The L4 module runs on its own computing node and maintains contact with the later two stages over the local network via HTTP requests. The API endpoints in the FRB Master module can be contacted by both the L4 module and the third module, FRB VOE, allowing the VOEvent transmission record-keeping database and the VOEvent subscription database to be read from and written to asynchronously. The Comet VOEvent broker [48] runs inside the FRB VOE module and can be contacted through API endpoints with VOEvent XMLs to be published to the VOEvent Network.

Name	Description
`event_id`	CHIME/FRB event number
`timestamp_utc`	UTC detection time at 400 MHz
`event_type`	`"GALACTIC"`, `"EXTRAGALACTIC"`, or `"AMBIGUOUS"`?
`known_source_name`	Name of known source, if identified
`known_source_rating`	Probability of known source association
`ra`	Right ascension (J2000) in decimal degrees
`dec`	Declination (J2000) in decimal degrees
`pos_error_semimajor_deg_95`	L2 header localization semi-major axis to 95% confidence limit
`pos_error_semiminor_deg_95`	L2 header localization semi-minor axis to 95% confidence limit
`dm`	Dispersion measure in pc cm^{-3}
`dm_error`	DM uncertainty in pc cm^{-3}
`combined_snr`	Detection beam signal-to-noise ratio
`dm_gal_ne_2001_max`	Max LOS[a] Galactic DM (NE 2001)[b]
`dm_gal_ymw_2016_max`	Max LOS Galactic DM (YMW 2016)[c]
`rfi_grade_level2`	RFI contamination score
`dispersion_smearing`	Dispersion smearing
`dispersion_smearing_error`	Dispersion smearing uncertainty

Table 4–1: These meta data are extracted from the L4 header by the `VOEventSender` and are required by the next stage in order to properly form a VOEvent XML. The Name column identifies variables as they exist within the CHIME/FRB L4 header. Notes: [a] line-of-sight. [b] NE 2001 Galactic DM model [14]. [c] YMW 2016 Galactic DM model [57].

model (Table 4–1) expected by the next stage of the process. The latency introduced by this first of three stages is negligible compared to the latency already accrued during the previous real-time stages (see §2.4).

4.3.2 FRB Master Backend

Coordinating and distributing computing resources to various analysis tasks is the broad responsibility of the FRB Master system, a name that refers to a backend suite of algorithms and modules that are available through

HTTP requests[4] to offline analysis pipelines. FRB Master handles requests asynchronously and provides a reliable environment to host the next stage of the VOEvent Service: translation. The input to this second stage in the VOEvent Service is the JSON payload from the `VOEventSender`, while the output is a fully-formatted VOEvent XML document and the text body of an email that are ready to be published.

Aside from hosting API-accessible algorithms, the FRB Master module provides an interface to database tables that are a key ingredient in storing and accessing meta data for various offline analysis tasks, including intensity and baseband data analysis. The CHIME/FRB VOEvent Service relies on two tables here, one for tracking transmission records of outgoing CHIME/FRB VOEvents, and one for keeping a list of CHIME/FRB VOEvent Service subscribers.

Figures A–1 and A–2 show two different examples of transmission records that each relate to two unique, hypothetical CHIME/FRB detections. Importantly, these transmission records are indexed by their CHIME/FRB event number, an internal identifier that is assigned to every L3 header in the process that transforms it to an L4 header. This means that for new detections identified by the real-time FRB detection pipeline and saved as L4 headers, a new entry like Figure A–1 or A–2 is made with the `"id"` corresponding to the CHIME/FRB event number. The `"record"` field is populated as a list of individual entries that grows as every new CHIME/FRB VOEvent linked to the event number is produced.

Figure A–3 shows an example of a database entry representing a subscription to the VOEvent Service. As mentioned in Chapter 3, the default

[4] `https://requests.readthedocs.io/en/master/`.

behaviour of a given VOEvent broker is to allow any other VOEvent broker to subscribe to and receive VOEvents from the former; however, in the formative stages of the CHIME/FRB VOEvent Service, it has been deemed essential to place limitations on who can subscribe to the Service. The reason for this is two-fold: in the foremost, the individual software modules of the Service need time to mature and be tested for corner cases that are not easily discovered except while running live; secondly, the Service is intended to produce VOEvents for all L4 headers[5] , and therefore releasing VOEvents to the entire community is contingent on a solid understanding of the false positives issuing from the real-time FRB detection pipeline. Subscriptions are maintained through a database consisting of entries like Figure A–3, wherein IP addresses and email addresses permitted to receive CHIME/FRB VOEvents are stored.

4.3.3 FRB VOE Container

The final stage of the CHIME/FRB VOEvent Service handles publishing the VOEvent XML to the VOEvent Network and distributing an email formatted copy. This is accomplished by running a Comet [48] VOEvent broker as a background process within a Docker[6] container that can be contacted via its own API endpoints. In this way, the VOEvent broker runs perpetually, awaiting fully-formatted VOEvents to arrive through an HTTP request from the previous stage. Simultaneously, an automated one-time sign-in to a dedicated account `vo.event.sender@gmail.com` is performed to distribute an email copy of the VOEvent XML through the simple mail transfer protocol[7] .

[5] Subject to the trigger conditions in Table 2–1.

[6] `https://github.com/docker`.

[7] `smtplib`; see `https://docs.python.org/3/library/smtplib.html`.

Because the trigger received by the VOEvent broker from the module in the FRB Master backend is handled as an HTTP request[8] , a response is returned to FRB Master containing an indication of whether the VOEvent was successfully published to the Network. This updates the database of transmission records, reflecting (1) the UTC time at which the VOEvent was published in the `"timestamp_utc"` field and (2) the IVORN of the VOEvent in the `"message_ivorn"` field (e.g. Figure A–1).

Presently, the CHIME/FRB VOEvent broker is configured to run in publishing and broadcasting mode with restrictions placed on what other VOEvent brokers can subscribe. This is managed by regularly pruning the subscriber database previously described, removing the expired subscriptions from the white-list of IP addresses that every VOEvent broker can be equipped with. In the same way, the list of valid email addresses is updated, and this pruning is currently handled manually by submitting an API request to the CHIME/FRB VOEvent Subscribers module in the FRB Master backend with the current date and time to which all expiration dates are compared. As the CHIME/FRB VOEvent Service matures, the conditions for removing the subscription white-list and opening the VOEvents to arbitrary subscribers will be progressively met (§4.5).

4.3.4 Four Types of CHIME/FRB VOEvents

The previous three sub-sections (§4.3.1 - 4.3.3) describe the transformation of meta data for an FRB detected by the real-time pipeline into a VOEvent XML, representing two of four possible *types* of CHIME/FRB VOEvents: detection, subsequent, update, and retraction. These four types apply the prescription [37] for FRB VOEvents in general to the context of CHIME/FRB,

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[8] `https://requests.readthedocs.io/en/master/`.

and here we illustrate them by way of individual use cases. As a primer, the four types can be thought of as VOEvent sub-streams according to their IVORNs. The default IVORN format for CHIME/FRB VOEvents is shown in Item 4.1 with the components detailed below:

$$\texttt{ivo://ca.chimenet.frb/}\{1\}\texttt{-}\{2\}\texttt{-\#}\{3\}\_\{4\} \tag{4.1}$$

1. For retraction-type VOEvents, this is set to `OBS` to indicate that the VOEvent is not a report of a detection or measurement of an FRB but rather a remark about one. Otherwise, it is set to `FRB`.
2. The VOEvent type appears in capital letters as one of `DETECTION, SUBSEQUENT, UPDATE, RETRACTION`.
3. A timestamp referenced to UTC indicating the `"timestamp_utc"` field (Table 4–1) for detection- and subsequent-type VOEvents; for update-type this is a timestamp of when the offline analysis was completed; and for retraction-type this is the timestamp of when the human agent issued the VOEvent.
4. A random 12-digit hexadecimal value obtained as a universally unique identifier (UUID) as a safety measure to ensure that IVORNs are unique.[9]

Detection-type

This is the primary CHIME/FRB VOEvent type. Every CHIME/FRB event satisfying the criteria in Table 2–1 is published in a detection-type VOEvent, with the VOEvent meta data originating from the L4 header (Table 4–1). The following summarizes the three major pieces of information that are communicated in the detection-type VOEvent.

[9] UUID in `python`: `https://docs.python.org/3/library/uuid.html#`.

- Localization: the L2 process produces a localization that is an ellipse on the sky with the central coordinate specified in right ascension and declination (decimal degrees) along with semi-major and semi-minor axes. In a multi-beam event the L2 process can yield multiple such ellipses, in which case the parameters for the ellipse closest to the beam with the highest SNR in the event is reported. (See also section 4.4 in [10].)
- DM: the DM is determined from the tree dedispersion algorithm called `bonsai` with an error in the range of 1.62 pc cm^{-3} to 25.84 pc cm^{-3} [10], provided alongside the maximum Galactic DM estimates along the line-of-sight represented by the above localization from the NE 2001 [14] and YMW 2016 [57] models. (See also section 4.3 in [10].)
- RFI contamination: a score from 0 to 10 is assigned on the basis of a machine learning algorithm, trained to score a true astrophysical signal with 10 and a true RFI signal with 0. (See also section 4.8 in [10].)

Subsequent-type

The subsequent-type is reserved for L4 headers that represent detections associated with known sources, including those listed in published catalogues as well as internal FRB sources that have been identified by CHIME/FRB but not yet published. The same information in the detection-type is provided here, with the addition of a name for the known source and a probability of association of the named source. Presently only the source with the highest probability, among all that are associated under the current scheme of Bayes factors (section 4.5 in [10]), is reported; however it is not guaranteed that this probability is 1, and the value of the `"known_source_rating"` in the L4 header reflects this. An additional algorithm is also run to obtain the IVORN of the first detection- or subsequent-type VOEvent that was produced about the source to which the current VOEvent refers, citing this in the `<Citations>` VOEvent header.

Update-type

Following the release of the real-time L4 header data through the detection- or subsequent-type VOEvent, offline analysis pipelines are able to analyze the intensity data and, if it was acquired, the baseband data. (For more on baseband data, see also section 5.3 in [10].) Presently the exact measured parameters that will be included in the `<What>` header of the update-type VOEvent is under review and subject to change, but it is likely to include some or all of the items listed in Table 4–2. The VOEvent Service is designed to support publishing separate update-type VOEvents for arbitrarily many offline analysis pipelines, with each one citing the IVORN of the original detection- or subsequent-type VOEvent for the L4 header.

Apart from supplying updated measurements of the radio burst parameters, the update-type VOEvent published with intensity or baseband data is essential for providing subscribers with an improved sky localization. While the detection-type contains the output of the L2 localization from the real-time pipeline, the intensity and baseband analysis pipelines each independently obtain a localization, using the intensity of the received electric field and the raw voltages, respectively. Currently the action rules in the L3 system are configured to trigger the CHIME/FRB VOEvent Service whenever the intensity callback procedure [10] is performed, but these conditions are not as strict (in terms of the SNR required to for a trigger) as for the baseband callback. Therefore, update-type VOEvents with intensity localization will follow the detection-type, but the baseband analysis may not always be provided this way.

Name	Description	Pipeline
redshift_inferred	Redshift estimate	L
redshift_host	Redshift of host galaxy, if known	L
dm_index	Power law index in DM relation	I
scattering_timescale	Scattering timescale in ms	I
scattering_index	Measured scattering power law index	I
spectral_index	Measured spectral power law index	I
fluence	Measured radio fluence in Jy ms	I
flux_calibrated	Calibrated flux measurement in Jy	I
linear_pol	Linear polarization as %	B
circular_pol	Circular polarization as %	B
rm	Rotation measure in rad m^{-2}	B

Table 4–2: The names of parameters as they appear as `<Param>` items under the `<What>` header in the CHIME/FRB update-type VOEvent, along with short descriptions and the offline analysis pipeline that produces their values. "L" stands for a planned low-latency pipeline that carries out analysis not included in the real-time system but also logically separate from dedicated intensity "I" and baseband "B" analysis pipelines. In addition, the update-type VOEvent will also include the uncertainty on each parameter with naming scheme `*_error` where `*` indicates the parameter name.

Retraction-type

Especially during the formative stages of the CHIME/FRB VOEvent Service, there may be reason to retract a previously issued VOEvent. The real-time pipeline relies on a mix of search algorithms and machine learning classifiers for which the false positive rate is non-zero, and therefore it is possible that detection-type VOEvents will be published about bursts that are non-FRBs. Additionally, the algorithm that assigns the `known_source_name` name and `known_source_rating` to a new burst operates on probabilities and has been seen to falsely associate new bursts with previously known FRB sources. In such a case, a subsequent-type VOEvent will be published about an association between a known FRB source and a new FRB that are later found, following human verification, to not actually be associated. These two scenarios are anticipated to dominate the use cases for the retraction-type VOEvent.

The retraction-type VOEvent contains no meta data, measured parameters, or localization. It has only a citation to the VOEvent that is to be retracted. Subscribers are therefore expected to follow the CHIME/FRB VOEvent stream closely for reports of detections and the possibility of a retraction that could be cause to abandon a follow-up search that is scheduled or perhaps underway, or that in general would be needed to properly interpret the results of a follow-up detection/non-detection.

4.3.5 Official FRB Naming Scheme

A key ingredient in the sharing of new CHIME/FRB detections to the wider astrophysical community through VOEvents is the use of a coherent and transparent FRB naming system. The CHIME/FRB Collaboration has officially adopted the naming scheme FRB YYYYMMDDx, specifying the year (YYYY) month (MM) and day (DD) plus a string (x) of up to three Latin uppercase letters, and will officially acquire these names through the Transient Name Server (TNS)[10] .

This FRB naming scheme is expected to become the first international standard for FRBs. Naming transient astrophysical events has historically played both a tangible scientific role and an intangible "cultural" role in astrophysics, and the FRB naming scheme was selected to embrace both of these. The scheme allows for up to 17576 names to be assigned in a single UTC day with the letter string ranging from A to ZZZ, so that each FRB name is unique, memorable, and not a burden to have to repeat twenty or more times in, say, a 10-minute lunchtime presentation to colleagues. The scheme has already seen informal usage in the FRB community. It is not dissimilar to what has been done for other transients, including gamma ray bursts (e.g. GRB 170817A [6])

[10] `https://wis-tns.weizmann.ac.il/`.

and gravitational waves (e.g. GW190814 [1]), and was developed via consultation between the CHIME/FRB Collaboration and other leading FRB experts from around the world. As CHIME/FRB will soon publish a backlog of hundreds of FRBs, and will continue to detect a projected $\sim 2-3$ FRBs each day, it represents a leading source of new FRBs, all the more reason to ensure that the CHIME/FRB naming scheme is amenable to the community.

Despite this, CHIME/FRB will be just one of many sources of FRBs around the world, necessitating a third party that maintains and distributes the names. The TNS is the responsible agent that provides this service over the Internet. Using API and sample `python` scripts available on the TNS web page[11] , obtaining the name for a new FRB in real-time has been made possible. Currently all previously published FRBs from CHIME/FRB ([12], [11], [50], [13], [16]) are available to the public on the TNS with official TNS names. In an upcoming CHIME/FRB publication we will reveal official TNS names for hundreds of new FRBs, with a long-term plan of integrating automatic submission to the TNS with the internal FRB candidate identification procedure and VOEvent Service. The bulk submission of CHIME/FRB detections to the TNS, including early testing of the beta TNS FRB hosting software and validation of the results, was a major task carried out by the author during this MSc thesis.

While acquiring a TNS name can in principle be done with low-latency ~ 1 s, the prospect of including the name in the CHIME/FRB detection- or subsequent-type VOEvent faces the concern of the possibility of false positives from the real-time pipeline. As previously discussed, retraction-type VOEvents are available in this case, but an additional request to the TNS

[11] `https://wis-tns.weizmann.ac.il/content/tns-getting-started`.

to delete the name of the FRB would also be required. This is unnecessarily disruptive to both users and maintainers of the TNS, therefore the decision has been made to acquire the TNS name through a low-latency offline process that runs after the L4 header data has passed human verification by the CHIME/FRB Collaboration. At this point an update-type VOEvent will be released with the TNS name that uniquely maps to the CHIME/FRB event ID contained in the L4 header for the original detection-type VOEvent. Figure 4–2 illustrates the workflow for obtaining the TNS name in the context of the real-time pipeline, human verification, and CHIME/FRB VOEvent Service.

In the category of situations where a new FRB candidate from the real-time detection pipeline is falsely associated with a previously known FRB source (internal to CHIME/FRB or otherwise), there is the possibility that this is realized only after human verification has already occurred and the TNS name has therefore been retrieved. Within the human verification workflow, the frequency of such occurrences has been small but non-zero. Through the CHIME/FRB VOEvent Service, this could mean that candidates are submitted to the TNS that are actually mis-classified Galactic sources. This is certainly a non-trivial concern with an equally non-trivial solution. However, both the online algorithms that help human agents decide whether to associate real-time candidates with previously known Galactic sources, and the training of CHIME/FRB Collaboration members in this task, are constantly improving. In the future, the frequency of CHIME/FRB entries in the TNS that are in fact Galactic candidates should steadily decrease, and these ideally rare occurrences can be treated on a case-by-case basis.

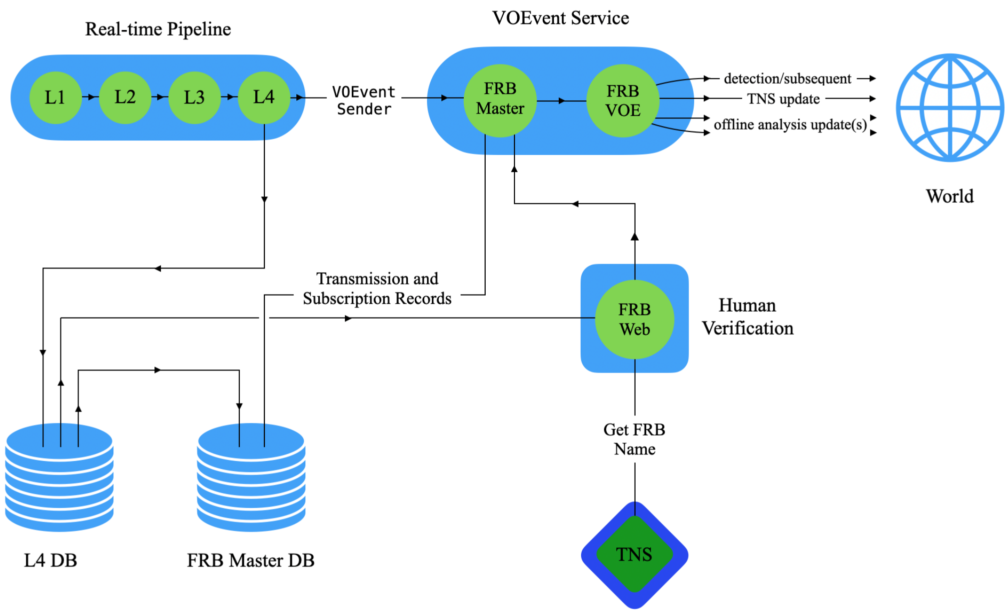

Figure 4–2: The CHIME/FRB VOEvent Service in the context of the real-time pipeline, human verification of L4 headers, and Transient Name Server (TNS) interface. Connections illustrate the exchange of information between modules: arrows indicate a one-way exchange while otherwise the exchange can go both ways. Human verification of L4 headers is handled through viewers hosted on FRB Web that allow CHIME/FRB Collaboration members to validate events retrieved from the L4 database. The FRB Master backend maintains databases with selected data from the L4 database, in addition to the databases for VOEvent records. The TNS name is acquired only after human verification of L4 header data and is not included in the detection- or subsequent-type VOEvent. Instead it follows in an update-type VOEvent that is separate from those provided by offline analysis pipelines. Because the TNS (in darker colours) is not maintained by the CHIME/FRB Collaboration, acquiring the TNS name after human verification prevents any incident that would require retracting a TNS submission. The interface with the TNS is handled programmatically through API and involves both a submission and query process to validate the name that is retrieved and match it uniquely to a CHIME/FRB L4 header.

4.4 Examples

Here we give examples of the current format and content of each of the VOEvent sections (§3.2.1 - §3.2.6) for CHIME/FRB VOEvents to illustrate their compliance with the IVOA VOEvent 2.0 recommendation [44] and their commonalities with the prescription given in [37]. Note that creating and reading compliant VOEvent XML documents is transparent using the `voevent-parse`[12] [47] module in `python`.

4.4.1 `<VOEvent>` Header

All four types of CHIME/FRB VOEvents share the same format for the `<VOEvent>` header, with the only difference being the IVORN within it (see Item 4.1). A sample is shown in Figure A–4.

4.4.2 `<Who>` Header

Similarly, the `<Who>` header contains the same information across all four CHIME/FRB VOEvent types. A sample is shown in Figure A–5.

4.4.3 `<What>` Header

The `<What>` header consists of `<Param>` objects arranged under three `<Group>` sub-headers labelled by `observatory`, `event`, and `advanced`, shown in Figures A–6, A–7, and A–8, respectively.

4.4.4 `<WhereWhen>` Header

See Figure 3–1 for a sample. The format and content is identical among the four VOEvent types, excluding the retraction-type that does not contain coordinates.

[12] `https://voevent-parse.readthedocs.io/en/latest/index.html`.

4.4.5 <Why> Header

This section is used to report on the significance of the CHIME/FRB VOEvent, the precise quality definition of which varies between the four different VOEvent type. In the case of detections of new FRBs, either singletons or bursts from known sources, subscribers should interpret the `importance` flag as a measure of the likelihood that the data represent an astrophysical source, as the value is derived from from the `rfi_grade_level2` parameter from the L4 header. Meanwhile, the `importance` is set to 1 for both update and retraction to ensure that the subscriber does not miss the alert. The reasons are that (1) some subscribers may perform further advanced or targeted searches on the basis of the updated localization expected in the update-type; and (2) all subscribers should abort planned observations, or update their inferences of observations that have already been made prior to receiving the retraction, when a retraction is issued. See Figure A–9 for a sample.

4.4.6 <How> Header

This short section is expected to be more useful as more CHIME/FRB data moves into the public domain. It is designed to provide links to additional resources that are both human and machine-readable. It will eventually provide a link using the `<Reference uri="">` header to the CHIME/FRB public web page specific for the source to which the meta data in the subsequent-type or update-type VOEvent is associated[13] , but only for repeat bursts from CHIME/FRB sources that have already been made public (either through CHIME/FRB publications or otherwise). Furthermore, the arbitrarily many analysis pipelines that can report update-type VOEvents will be identified properly using the `<Description>` header here.

[13] `https://www.chime-frb.ca/repeaters`.

4.5 Conclusion and Future Work

The CHIME/FRB VOEvent Service is positioned to contribute to a leap-forward in the science of multi-wavelength follow-up of new FRBs, both from new sources and from known repeating sources. The initial detection- or subsequent-type VOEvent can be leveraged as a real-time trigger for observatories that are represented via their own VOEvent broker that is subscribed to the Service. Likewise, update-type VOEvents can serve to inform the subscriber of an improved sky localization for a more accurate and more precise search for the origin of the source. Alternatively update-type VOEvents could provide improved measured parameters that may qualify the burst as a target of interest for special campaigns seeking low DM FRBs, on- or off-Galactic plane sources, scattered bursts, repeating sources, and known Galactic sources such as the very recent discovery of a millisecond radio burst from the magnetar SGR 1935+2154 [49], to name a few examples.

That said, the Service is not yet operating at its design capacity. The following timeline should be considered flexible. The Service is scheduled to be deployed in stages, with detection- and subsequent-type alerts coming online first, and representing the largest technical hurdle to overcome. Revisions to the content of these alerts could take place at every stage of the deployment, including but not limited to initial testing within CHIME/FRB, opening the alerts to collaborators that have arranged a memorandum of understanding (MoU) with CHIME/FRB, and of course the broader public when the time comes.

1. Mid-November 2020: Complete internal code review of L4, FRB Master, and FRB VOE components with assistance from the CHIME/FRB Project Office.

2. Late November 2020: Deploy the detection- and subsequent-type alerts, restricted to CHIME/FRB only, and complete testing and monitoring of all published VOEvents within at least one week of *normal* real-time FRB pipeline performance.
3. Mid-December 2020: Complete up to two weeks of testing and monitoring with subscriptions open to specific external collaborators that have signed an MoU in connection with projects designed for early-stage CHIME/FRB VOEvent usage.
4. January 2021:
   - Have a complete suite of monitoring tools that can integrated to the normal FRB pipeline monitoring regime, made user-friendly for all CHIME/FRB members to distribute the responsibility of checking outgoing communications.
   - Deploy retraction-type, TNS update-type, and quick analysis update-type VOEvents, including integration with the FRB pipeline monitoring regime.
5. February 2021: Work with CHIME/FRB offline analysis working groups to integrate human-triggered update-type VOEvents that can report improved intensity and baseband analysis results.
6. March 2021: Evaluate the overall performance of the VOEvent Service during the Winter data collection run for CHIME/FRB. Assemble key metrics, including data quality and monitoring, and prepare a briefing that can be used and hosted online for the general astrophysics community to consult, aiding decisions for all public experiments and observatories to engage in follow-up campaigns through the CHIME/FRB VOEvent Service.

The detection- and subsequent-type alerts are well-positioned to come online first, as all the infrastructure needed for this has been presented in this chapter. The subscription side of the Service will be updated manually at first, with subscriptions being kept internal to the CHIME/FRB Collaboration while the Service is monitored for performance issues and corner cases that occur during live run-time. Following this, these two VOEvent types will be released to the community, along with the retraction-type, by opening subscriptions to the community using the model in Figure A–3.

Update-type VOEvents can be expected to come online still more incrementally. The infrastructure for handling input from the various offline analysis pipelines is in place, including basic models for what meta data is required as output from them for the update-type VOEvent. While the suite of CHIME/FRB offline analysis pipelines has progressed enormously during the course of this MSc thesis work, in an upcoming CHIME/FRB publication containing many hundreds of FRBs the output of those pipelines will be put under the scrutiny of the astrophysical community. Further internal review and processing of that feedback will be insightful for how to report the offline analysis output in the update-type VOEvent, in the context of those parameters listed in Table 4–2. Lastly, some decisions are underway as to how to coordinate the separate modules that represent the broad tasks handled by the intensity and baseband pipelines, so that they each can report coherently to the API endpoint in the FRB Master module (Figure 4–1) that assembles the update-type VOEvent XML.

Subscribers pursuing CHIME/FRB detections for low-latency follow-up can expect the latency of the detection- and subsequent-type VOEvents to be dominated by (1) the latency of the real-time pipeline plus (2) transit time through the VOEvent Network. The stages illustrated in Figure 4–1 have not been measured and tested for speed, allowing only qualitative statements at best to be made. However, the modules were built with `python` libraries that were selected for being fast, lightweight, versatile implementations for multi-processing and asynchronous handling. Namely, the FRB Master module relies on `sanic`[14] that is designed for speed and efficiency. The FRB VOE module uses the Comet [48] VOEvent broker that is designed for speed in broadcasting published VOEvents. From there, the VOEvent Network latency is dominated by the path from the IP address of the CHIME/FRB VOEvent broker to the IP address of the subscriber's VOEvent broker. An end-to-end measurement of the latency from the real-time pipeline to publishing on the VOEvent Network is a worthwhile future endeavour.

This connects with a final remark about the monitoring of the CHIME/FRB VOEvent Service. Future work should include specifying metrics to represent quality and performance. The most basic aspects to monitor include the daily count of CHIME/FRB VOEvents of each type that are published, how these numbers compare to the incoming events processed by CHIME/FRB Collaboration members during human verification, and the latency from the L4 `VOEventSender` to the FRB VOE module (Figure 4–1). However, as the Service matures there will be new features to monitor. For instance, the meta data reported in each of the four VOEvent types may undergo small revision or expansion over time. Plus, as an aid to subscribers that are each expected to prepare their own event handling module (§3.3.4) suitable for CHIME/FRB VOEvents, it will be convenient to supply test versions of all four VOEvent types that evolve in step with their deployments of changes to their live counterparts. In this way, the subscriber's event handling code is less likely to break

[14] `https://sanic.readthedocs.io/en/latest/`.

at an inopportune moment when a new CHIME/FRB detection is published as the latest detection-type format. That said, it remains to specify a framework for publishing these test versions and monitoring their publication alongside the live counterparts of CHIME/FRB VOEvents for quality assurance.

In conclusion, the CHIME/FRB VOEvent Service is built with open source software that can and should be adapted for observatories around the world to bring them into the VOEvent Network. The quest to understand fast radio bursts begins and ends with the global sharing of knowledge, and CHIME/FRB is positioned to catalyze the process as a provider of new targets that can be automatically selected for follow-up by real-time observatories the world over.

CHAPTER 5
GCN VOEvents

5.1 Introduction

5.1.1 GCN VOEvent Sub-streams

Virtual Observatory Events (VOEvents; Chapter 3) are currently being published by several observatories and broadcasted by a single VOEvent broker that forms part of the Gamma-ray Coordinates Network or Transient Astronomy Network (GCN/TAN)[1] , in connection with activity from new and known astrophysical transients. As illustrated in Figure 5–1, the GCN/TAN presently consists of a collection of mostly X-ray and gamma-ray observatories aboard scientific satellites. However, there are two exceptions to this. First, there are two instruments aboard the International Space Station (ISS) that orbits the Earth at an altitude of about 408 km, namely the CALorimetric Electron Telescope (CALET) that functions to detect high energy cosmic rays (in addition to gamma-rays), and the Monitor of All-sky X-ray Image (MAXI) instrument. Secondly, the Laser Interferometer Gravitational wave Observatory and Virgo Collaboration (LIGO/Virgo) reports candidate gravitational wave events from binary mergers of compact stellar remnants that are detected by one or more of three ground-based laser interferometers.

The purpose of GCN/TAN is to distribute real-time alerts by way of publishing VOEvents through a single dedicated VOEvent broker, in connection

[1] `https://gcn.gsfc.nasa.gov/about.html`.

with gamma-ray burst (GRB) locations, images, spectra, and light curve measurements, all which have been collected by one or more of the observatories pictured in Figure 5–1. GCN VOEvents follow the IVOA VOEvent recommendation 2.0 [44] with each observatory publishing under a unique author IVORN (§3.2.1). The published VOEvents of each author therefore represent a separate sub-stream within the GCN stream, and at the time of writing there are at least 12 active GCN VOEvent sub-streams, as listed in Tables 5–1 and 5–2.

Individual event IVORNs for GCN VOEvents follow the format in Item 5.1.

`ivo://nasa.gsfc.gcn/{1}#{2}_{3}` (5.1)

In place of the numbered components in Item 5.1, one can consult Tables 5–1 and 5–2 and substitute the following:

1. The string in the "Sub-stream" column.
2. One of the strings listed under the "Packet Label" column for the corresponding sub-stream.
3. A string that for most sub-streams is a date-time string in the format `2020-05-03T12:34:00.00`, or a trigger ID found in the top-level `<Param>` called `"TrigID"`, or concatenation of the two.

As an example, a recent IVORN for a GCN VOEvent published under the sub-stream for the BAT (Burst Alert Telescope) aboard the *Swift* satellite, in connection with an observation of X-ray activity from the Galactic magnetar SGR 1935+2154, is listed in Item 5.2.

`ivo://nasa.gsfc.gcn/SWIFT#BAT_Known_Pos_-1856436910-230` (5.2)

In the example of Item 5.2, the final component of the IVORN is `-1856436910-230` and it contains the value of the top-level `<Param>` named `"TrigID"` in the

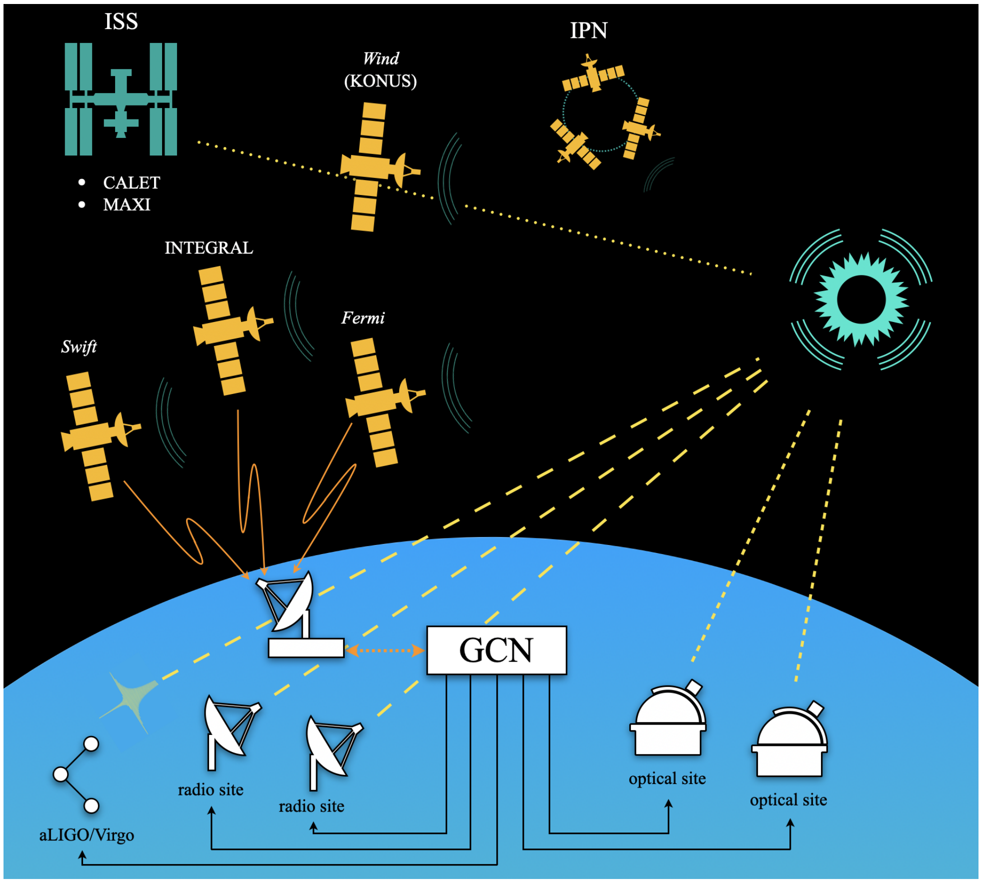

Figure 5–1: An illustration of the GCN/TAN adapted from the version available from the GCN landing page at `https://gcn.gsfc.nasa.gov/`. This updated illustration was prepared by the author to show only the observatories that currently publish VOEvents through the GCN VOEvent broker. The GCN largely consists of X-ray and gamma-ray observatories aboard scientific satellites in orbit about the Earth or in geo-lunar orbit or distributed through the solar system, such as the InterPlanetary Network (IPN). The GCN represents a coordinated effort for simultaneous multi-wavelength observations of astrophysical transients with as many as possible of the observatories depicted, including the (unnamed) optical, radio, and multi-messenger observatories on the surface of Earth. Pictured is an artistic rendering of the GCN in action during transient activity from a hypothetical source. Each observatory shown has the capacity to submit observational meta data that is formatted into a VOEvent XML through internal processes and published to the VOEvent Network through a single VOEvent broker with IP address `45.58.43.186`. As an example, the *Swift* satellite publishes a variety of VOEvent XMLs through the GCN VOEvent broker, some of which represent new observations while others simply report the current or upcoming target sky coordinates.

VOEvent XML, namely `-1856436910`. Meanwhile the string `-230` is not communicated anywhere else in the VOEvent XML and could conceivably serve as an internal index or a randomly selected integer to maintain uniqueness during a high VOEvent publication rate from the `SWIFT` sub-stream.

From these two tables, it is evident that the GCN VOEvent broker publishes a large volume of VOEvents. Importantly, some of the packet types (Tables 5–1 & 5–2) are published in two further sub-streams with one of each of the `"observation"` and `"test"` attributes that are configured in the `<VOEvent>` header (§3.2.1). This is the case even for those in which the packet label does *not* contain the string `"Test"` (or some equivalent). While slightly confusing, this follows the common practice recommended by the IVOA [44] for a VOEvent author to provide a test version of every VOEvent they intend to publish, so that subscribers can know what to expect for true observations.

However, even among those GCN VOEvents published in connection with true observations, not all of the packet types contain sky coordinates for *detections* of astrophysical transients. Some packets are used solely to communicate links to archival resources that may support a detection published in a preceding VOEvent. As an example, the *Swift* satellite publishes a sequence of messages that allow the recipient to track the observatory from target request, to target selection, to slew pointing, and finally (possibly) to detection report. Namely, the next immediate bore-sight pointing coordinates are published through packet `83`; its current pointing coordinates via packet `103`; the coordinates of a detection (with some confidence via the `importance` and `probability` flags, §3.2.5) via packets `61,84,140` and `141`; and observed light curves and spectra as measured by the X-ray Telescope (XRT) (via packets `67`, `68`, `69`, and `70`) and Ultra-Violet and Optical Telescope (UVOT) (`72`, `73`,

Sub-stream	URL	Packet Type	Packet Label
gwnet/LVC	lvc	150	Preliminary
		151	Initial
		152	Update
		164	Retraction
INTEGRAL	integral	51	Point_Dir
		52	SPIACS
		53	Wakeup_Pos
		54	Refined_Pos
		55	Offline_Pos
		56	Weak_Pos
Fermi	fermi	110	GBM_Alert
		111	GBM_Flt_Pos
		112	GBM_Gnd_Pos
		115	GBM_Fin_Pos
		119	GBM_Test_Pos
		124	LAT_Test_Pos
		125	LAT_Monitor
		128	LAT_Offline_Pos
		129	Point_Dir
		131	GBM_SubThresh
MAXI	maxi	134	Unknown_source_Pos
		135	Known_source_Pos
		136	Test_Pos
AGILE	agile	105	A_MCAL_Alert
		109	SA_Test_Pos
MOA	moa	139	Lensing_Event
IPN	ipn	31	Raw
KONUS	konus	59	Lightcurve
CALET	calet	160	GBM_Flight_Lightcurve
COUNTERPART	counterpart	45	Position

Table 5–1: All currently active GCN VOEvent sub-streams, namely those that published a VOEvent at least as recently as April 28 2020. Except for the LIGO/Virgo Collaboration, represented by `gwnet/LVC`, each of the entries in the Sub-stream column should be appended to the GCN VOEvent broker author IVORN, namely `ivo://nasa.gsfc.gcn/`. By replacing what is listed under the URL column for the `*` in `https://gcn.gsfc.nasa.gov/*.html` one can access the GCN help page for the respective sub-stream. Each sub-stream issues potentially several different types of VOEvents that are codified by their GCN packet type and packet label. The packet type is represented in all GCN VOEvent XMLs as a top-level `<Param>` called `Packet_Type`. The packet label forms part of the event IVORN for the VOEvent issued under the corresponding packet type, according to Item 5.1. (Continued in Table 5–2)

Sub-stream	URL	Packet Type	Packet Label
AMON	amon	159	TEST_Event
		173	ICECUBE_GOLD_Event
		174	ICECUBE_BRONZE_Event
SWIFT	swift	46	FOM_Obs
		47	SC_Slew
		61	BAT_GRB_Pos
		63	BAT_Lightcurve
		64	BAT_Scaledmap
		65	FOM_Obs
		66	SC_Slew
		67	XRT_Pos
		68	XRT_Spec
		70	XRT_Lightcurve
		71	XRT_Nack_Pos
		72	UVOT_Image
		73	UVOT_SrcList
		77	XRT_Proc_Spec
		79	UVOT_Proc_Image
		80	UVOT_Proc_SrcList
		82	BAT_GRB_Test_Pos
		83	Point_Dir
		84	BAT_Trans_Pos
		97	BAT_QuickLook_Pos
		103	Actual_Point_Dir
		140	BAT_SubSubThresh_Pos
		141	BAT_Known_Pos

Table 5–2: Continuation of Table 5–1; see the caption there for more details.

79, and 80). In Table 5–3 we highlight details of all the observatories that publish VOEvent sub-streams through the GCN.

5.1.2 GCN Circulars

The GCN/TAN has recently served as an important platform for comparing CHIME/FRB detections of new FRBs against recently reported (but unpublished) multi-wavelength counterpart activity of astrophysical transients; but this has not yet been achieved through VOEvents. In a recent CHIME/FRB paper [49] the detection of a bright millisecond radio burst with CHIME/FRB from the Galactic magnetar SGR 1935+2154 was published, and a hard X-ray/soft gamma-ray burst was detected by the INTEGRAL SPI-ACS and IBIS instruments [30], the Konus-*Wind* satellite [40], and the *Insight*-HXMT instrument [59]. Additionally, in November 2019 X-ray activity was reported from this source by the *Swift*-BAT and the *Fermi*-GBM (Gamma-ray Burst Monitor) at times when the source's sky coordinates were above the CHIME/FRB horizon, though no FRB counterparts were detected with CHIME/FRB at those times [49]. The X-ray and gamma-ray observations were all reported and archived through the GCN Circulars, an alert service that runs parallel in some sense to the GCN VOEvent service[2] . GCN Circulars are intended to be received and parsed by a human and are usually delivered through email. GCN VOEvents are essentially the machine-readable equivalent of this.

[2] Recent GCN Circulars are indexed by a 5-digit integer at `https://gcn.gsfc.nasa.gov/gcn3_archive.html`. For example, 27667 is a Konus-*Wind* detection of SGR 1935+2154.

Name	Where	Instrument(s)	Observing Targets
aLIGO/Virgo	Terrestrial	Hanford, WA (H1) Livingston, LA (L1) Cascina, Italy (V1)	0.01 – 10 kHz [a]
INTEGRAL [b]	Satellite	SPI IBIS JEM-X OMC	18 keV – 8 MeV 15 keV – 10 MeV 3 – 35 keV 500 – 600 nm
Fermi [c]	Satellite	GBM LAT	$\sim$ 1 keV – 30 MeV 20 MeV – 300 GeV
MAXI [d]	ISS	GSC SSC	2 – 30 keV 0.5 – 12 keV
AGILE [e]	Satellite	GRID Super-AGILE MC	30 MeV – 50 GeV 10 – 40 keV 0.25 – 200 MeV
MOA	Terrestrial	UCMJO [f]	1.8 m reflector
IPN [g]	Solar System	Multiple	Multiple
KONUS	Satellite	NaI detectors	$\sim$ 10 keV – 10 MeV [h]
CALET	ISS	CGBM	$\sim$ 7 keV– $\sim$ 20 MeV [i]
AMON [j]	Multiple	Multiple	EM, multi-messenger
Swift [k]	Satellite	BAT XRT UVOT	15 – 150 keV 0.2 – 10 keV 170 – 650 nm

Table 5–3: Observing targets of observatories that publish VOEvent substreams through the GCN VOEvent broker, listed in the same order as in Tables 5–1 & 5–2. Notes: [a] Together the three aLIGO/Virgo instruments can detect gravitational waves in this frequency range [29]. [b] Ref. [54]. [c] Ref. [3]. [d] Ref. [5]. [e] Ref. [55]. [f] University of Canterbury Mt. John Observatory (UCMJO) is used for Microlensing Observations in Astrophysics (MOA), a research collaboration between Japan and New Zealand. [g] The InterPlanetary gamma-ray burst timing Network (IPN) publishes VOEvents reporting the timestamp of corroborated observations of a GRB by up to 14 observatories, including *Ulysses*, Mars *Odyssey*, KONUS *Wind*, and others already listed in this table [4]. [h] Ref. [52]. [i] CALET is a cosmic ray detector [56]. *j* The Astrophysical Multimessenger Observatory Network (AMON) [7] currently publishes VOEvents from the IceCube neutrino observatory. [k] Ref. [2].

5.1.3 Handling GCN VOEvents

To subscribe to the GCN VOEvent broker, one can run a local VOEvent broker in subscribe mode (§3.3.3) after installing one of a few options for VOEvent broker software. In `python` the Comet [48][3] library is straightforward and provides a full solution for VOEvent brokers. The GCN VOEvent broker exists with IP address `45.58.43.186` and one can issue the command in Item 5.3 at the prompt on their local machine to subscribe to it. Note that `--print-event` is a command to run an event handler that comes installed with the Comet release; it will print every VOEvent XML that the broker receives to the standard output.

```
twistd -n comet --subscribe=45.58.43.186 --receive --print-event
```

(5.3)

Within Comet it is straightforward to develop event handlers (§3.3.4) that function as simple plug-ins for the Comet VOEvent broker. In the absence of an event handler, the local broker will receive GCN VOEvents without performing any actions. Developing a custom event handler[4] is straightforward when using the existing default handlers as a template. In §5.2 we describe a custom event handler used to perform actions on GCN VOEvents and translate the received sky coordinates into the observational context for CHIME/FRB.

5.1.4 Archival GCN VOEvents

While developing a custom event handler for GCN VOEvents it is useful to have test VOEvent XMLs to work with. As seen in Tables 5–1 & 5–2,

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[3] The procedure for installing Comet can be found at `https://comet.transientskp.org/en/stable/`.

[4] `https://comet.transientskp.org/en/stable/handlers.html`.

most sub-streams have a dedicated packet type for a test VOEvent, and some packets are published in a format having `role="test"`, in addition to the `role="observation"` format. These test packets are published periodically by the GCN VOEvent broker and not all in one sequence. Continuous integration of a custom event handler can be handled smoothly by instead making use of archival GCN VOEvents. These are stored in a database that is accessible through a `python` module called `voeventdb.remote` that is maintained by the 4 Pi Sky group[5] . Here, full VOEvent XMLs are stored and indexed by their event IVORN. Tables 5–1 & 5–2 become particularly useful here, as within `voeventdb.remote` it is straightforward to filter VOEvents by sub-stream (e.g. `"nasa.gsfc.gcn/SWIFT"`) and obtain a list that can be further narrowed by selecting VOEvent XMLs for which the top-level `<Param>` called `"packet-type"` matches the desired numerical value.

5.2 Methods

5.2.1 Custom GCN VOEvent Handlers

Two custom event handlers have been specified, designed, and implemented within the default Comet [48] installation. At the time of writing the event handling code has yet to be integrated to the CHIME/FRB VOEvent Service (Chapter 4), though the intent is to run the CHIME/FRB VOEvent broker in both broadcast *and* subscribe mode (§3.3.3) while deploying these event handlers. These two event handling classes are (1) `GRBReceiver`, for performing actions on GCN VOEvents that are published in connection with detections of astrophysical transients thought to be gamma-ray bursts; and (2) `LVCReceiver`, for performing actions instead on VOEvents issued by the aLIGO/Virgo Collaboration through the `gwnet/LVC` stream, about detections

[5] `https://4pisky.org/voevents/`.

of gravitational wave (GW) transients from compact binary mergers in the local Universe. Importantly, the sky localization of a GW transient from aLIGO/Virgo is published with a URL in the VOEvent to a downloadable full-sky map (§3.4) and is *not* found in the `<WhereWhen>` header (§3.2.4). This is the main difference between how the two event handlers operate.

Figure 5–2 is a block diagram intended to illustrate the operation of both the `GRBReceiver` and `LVCReceiver`. The event handler is given a recently received VOEvent XML as a pythonic object, and the subsequent handling process can be summarized in the following steps.

1. Extract the GCN VOEvent sub-stream and GCN packet-type (Table 5–1), the role (§3.2.1), and any name or special identifiers for the burst or source that may be published in the VOEvent.
2. Discard test VOEvents, slewing notices, and VOEvents otherwise referring to activity from identified sources that are not relevant (currently or absolutely) to CHIME/FRB.
3. Extract the central sky coordinates on which the circular localization region is centred (for GRB-related transients) and the UTC timestamp as the spacetime coordinates of the event[6] . (The `GRBReceiver` and `LVCReceiver` behave very differently at this step.)
4. Check whether the spacetime coordinates are (1) above the local horizon (Figure 5–3) for the CHIME telescope, (2) within the CHIME primary beam (Figure 5–4), and/or (3) within one of the CHIME/FRB formed beams (§2.3.1).

[6] While no attempt is made to sample coordinates from the localization region, either in the case of the GRB error circle or the complicated error regions reported by aLIGO/Virgo, this is certainly an avenue for future work.

5. Compile a human-readable text message containing some information from the VOEvent, together with results of the computations performed on the meta data contained within, and relay it to a human audience.

The `GRBReceiver` and `LVCReceiver` are written in `python` as classes that were modelled after the default Comet event handlers. The author collaborated with the maintainer of the Comet GitHub repository to introduce additional features to the current Comet release[7] that make it easier to run event handlers as plug-ins at the command line of a local machine as shown in Item 5.3 and continuously integrate new changes to event handlers. After cloning the GitHub repository for Comet into a folder called `Comet`, the following procedure for developing the event handlers was conducted.

- Under `Comet/comet/plugins` two new classes `GRBReceiver` and `LVCReceiver` were defined and saved in `grb_receiver.py` and `lvc_receiver.py`, respectively, using the default `eventprinter.py` handler as a model.
- Functions similar to those illustrated in Figure 5–2 were written for the two custom event handlers.
- Integration and testing with the base Comet installation were checked by running Items 5.5 at the command line in the `Comet` folder. Comet is already set up to test new event handlers in a standard way and these lines will throw run-time and compilation errors that must be resolved before the event handler runs smoothly with the VOEvent broker.

```
Comet user$ python setup.py install        (5.4)
Comet user$ trial comet                    (5.5)
```

[7] `https://github.com/jdswinbank/Comet`.

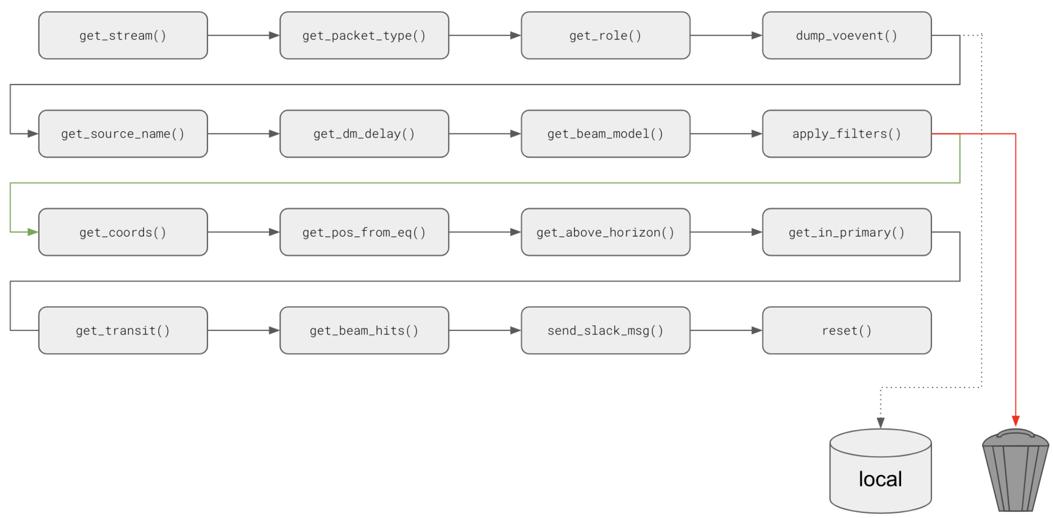

Figure 5–2: An algorithm representing an event handler (§3.3.4) to be used with a Comet [48] VOEvent broker running in subscribe mode (§3.3.3) for handling incoming VOEvents from the GCN VOEvent broker that broadcasts with IP address `45.58.43.186`. The algorithm is constructed from functions (blocks) that are called in a definite order (arrows). The event handler is written in `python` as a class. The input to the algorithm is an object form of the VOEvent XML obtained using the `voevent-parse` [47] library in `python`. The meta data in the GCN VOEvent is used to perform several computations, including making inferences about the visibility of the sky coordinates in the context of CHIME/FRB. A copy of the VOEvent XML is saved to a local directory to keep recent examples of each GCN packet type. The `apply_filters()` step discards VOEvents according to selection criteria relevant for CHIME/FRB. A human-readable text message is compiled containing a subset of the VOEvent meta data together with the results of these computations and is relayed to a CHIME/FRB Collaboration Slack channel for members to stay abreast of important GCN VOEvents. Finally, the event handler is `reset()` to clear its internal state that is modified during the workflow.

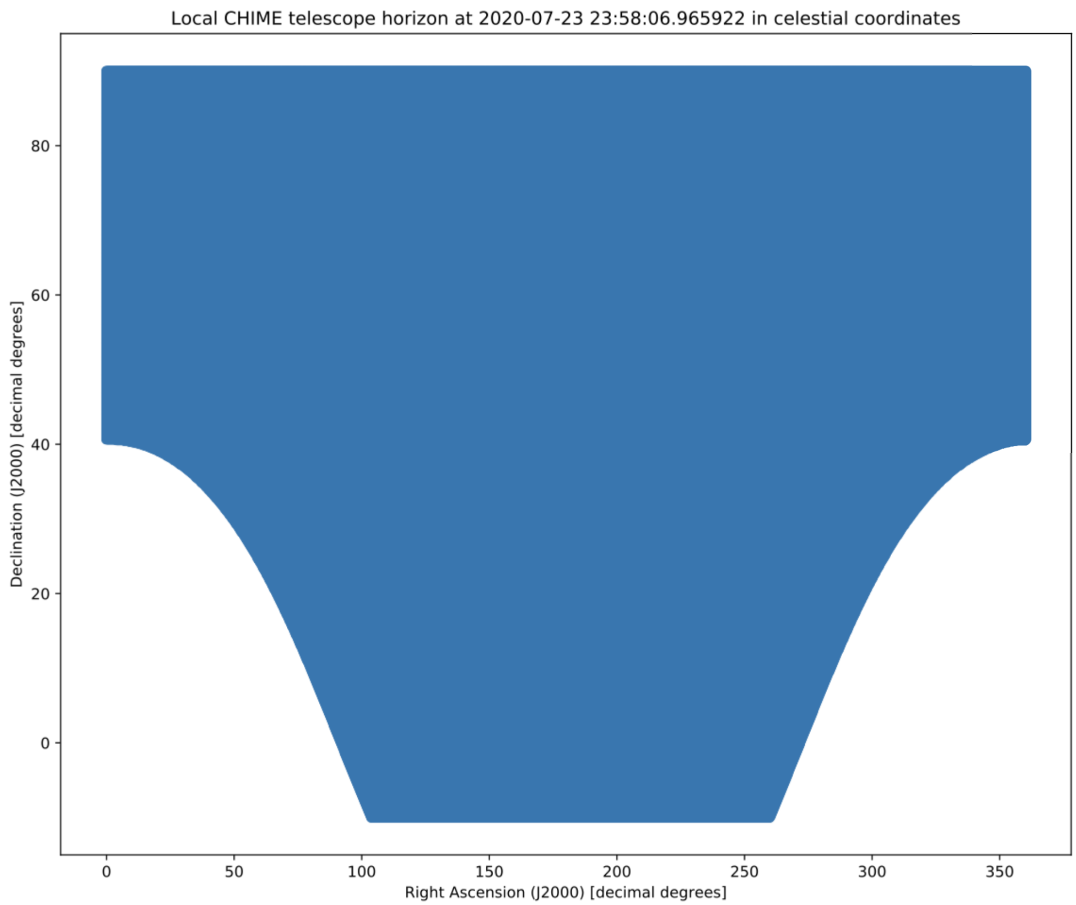

Figure 5–3: A fine rectilinear grid of celestial coordinates in right ascension $\alpha \in (0°, 360°)$ and declination $\delta \in (-10°, 90°)$ is formed from 10^6 equally spaced points in (α, δ) space. Blue points are plotted at grid positions where the corresponding coordinate is above the local horizon relative to the CHIME telescope's meridian at a given UTC moment. On a given day, as time advances from midnight UTC to the next day, the white region moves from left to right in this plot. (Note that $\alpha = 0°$ and $\alpha = 360°$ are equivalent in celestial coordinates.) In handling GCN VOEvents, the coordinates published in each VOEvent along with their UTC detection time are consulted against the algorithm that produced this plot, whose output is `True` or `False` depending if the coordinate belongs to the blue region corresponding to the UTC time. The algorithm that produced this plot was developed by CHIME/FRB Collaboration members (not the author) and has been used in publications including recently [49] for checking whether reported astrophysical transients occurred within the CHIME horizon at their specified times.

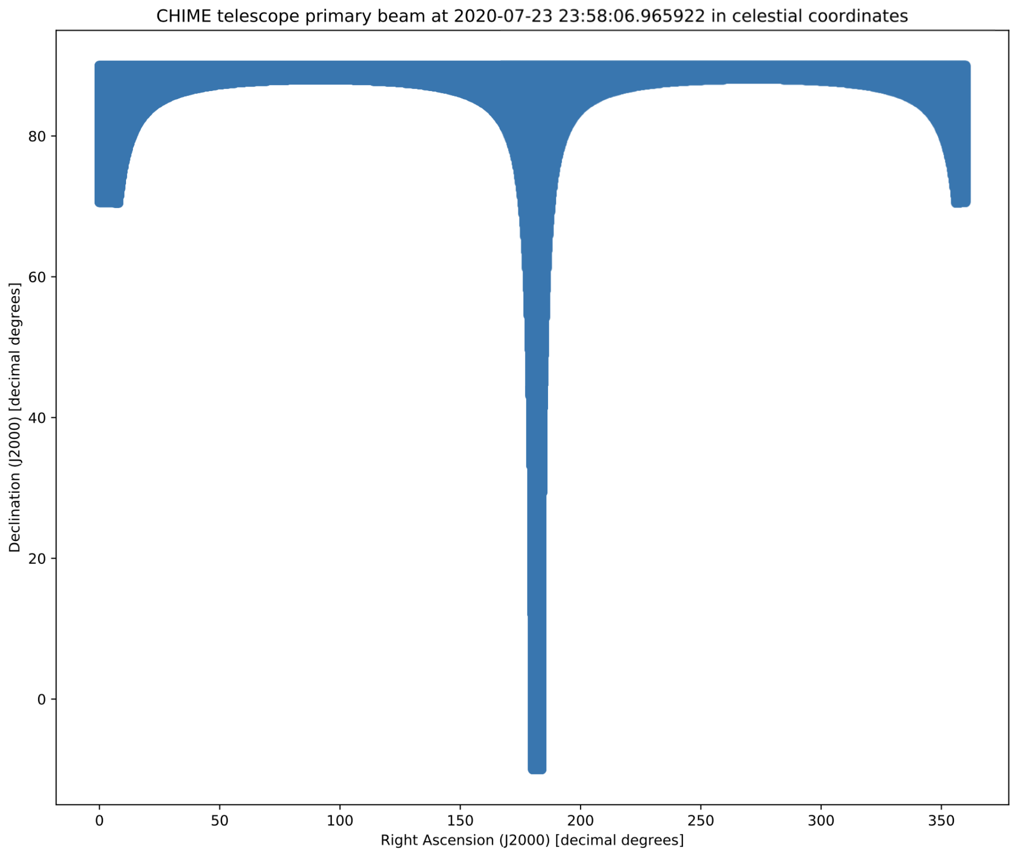

Figure 5–4: Similar to Figure 5–3, a fine rectilinear grid of celestial coordinates in right ascension $\alpha \in (0°, 360°)$ and declination $\delta \in (-10°, 90°)$ is formed from 10^6 equally spaced points in (α, δ) space. Blue points are plotted at grid positions where the corresponding coordinate is considered to be within the maximum sensitivity region for the CHIME primary beam model [10]. On a given day, as time advances from midnight UTC to the next day, the white region moves from left to right in this plot. (Note that $\alpha = 0°$ and $\alpha = 360°$ are equivalent in celestial coordinates.) This plot illustrates the meaning of a sky coordinate being "in the primary beam". The central blue region is essentially symmetric about the CHIME meridian at the given UTC moment, and the primary beam extends beyond the North celestial pole at $\delta = 90°$ which explains the second blue region that is split across $\alpha = 0° \equiv 360°$ and which cuts off around $\delta \sim 70°$. This illustrates the fact that CHIME has double exposure to the circumpolar sky above $\delta \sim 70°$ [13]. A precise description of the shape of this plot is outside the scope of this thesis, and the algorithm that generated the blue regions was not developed by the author; rather, it is based on the existing beam model that has been developed by members of the CHIME/FRB Collaboration, the CHIME Collaboration, and colleagues who worked on the CHIME Pathfinder instrument [8], and has been used heavily in CHIME/FRB publications for sensitivity and exposure estimates ([12], [19], [11], [13], [16]).

5.2.2 Filtering GCN VOEvents

The selection criteria for GCN VOEvents that are relevant to the CHIME/FRB experiment are applied to incoming VOEvents in the `apply_filters()` method (Figure 5–2). At the time of writing, GCN VOEvents with packet type among `51`, `52`, `83`, `103`, `110`, or `129` (Tables 5–1 & 5–2) are discarded. These types contain either only test information, or slewing information, and therefore no information on new transients that have been detected. Furthermore, packet type `141` from the *Swift*-BAT represents detections from known sources. This includes interesting targets like SGR 1935+2154 (see recent CHIME/FRB detection in [49]) labelled as `"sgr1935p2154"` in the *Swift*-BAT source catalogue[8] , but which also includes sources that have a very high event rate in *Swift*-BAT and which are not interesting to CHIME/FRB presently. For this reason, when handling packet type `141` the event handlers acquire the source name from the `Name` attribute under `<Inference>` in `<Why>` (§3.2.5) and will discard VOEvents published under the names `"Crab"` and `"Cyg_X-3"`, which indicate the supernova remnant at the centre of the Crab Nebula (NGC 1952) and Cyg X-1, a Galactic X-ray source in the Cygnus constellation.

5.2.3 Handling Gamma-ray Transients

All sub-streams (Tables 5–1 & 5–2) in GCN publish VOEvents related to detections of gamma-ray or X-ray transients, towards coordinating multi-wavelength follow-up of gamma-ray bursts (GRBs), except for `gwnet/LVC`. Therefore this sub-section applies to the majority of GCN VOEvents. The main difference is that the localization region in these VOEvents is specified

[8] The full *Swift*-BAT known source catalogue is available at `https://github.com/lanl/swiftbat_python/blob/master/swiftbat/catalog`, a very useful resource for handling GCN VOEvents of packet type `141`.

as a circle in celestial coordinates (right ascension and declination) in the `<What>` section (§3.2.3). If the central coordinate in localization circle has a declination less than $-10°$ the transient is considered out of the field-of-view for CHIME/FRB (§2.1), so the VOEvent is discarded. Otherwise, if all previously mentioned filter criteria are met, Figure 5–2 shows that the next step is to translate the sky coordinates and detection timestamp into the local coordinate system for the CHIME telescope via `get_pos_from_eq()`. The result is a coordinate (x, y) that is one-to-one with a celestial coordinate in right ascension $\alpha \in (0°, 90°)$ and declination $\delta \in (-10°, 90°)$, a correspondence obtained through the use of the beam model (Figure 5–5). The algorithm that performs this calculation was developed by other CHIME/FRB Collaboration members. Furthermore, the beam model relies on CHIME beam studies done with the CHIME Pathfinder [8], and it has been used extensively in estimates of exposure and sensitivity of the CHIME/FRB experiment in published works ([12], [19], [11], [13], [16]).

The central celestial coordinates of the VOEvent, along with the UTC timestamp, are used to assess whether the transient occurred at a sky-position that was above the CHIME horizon at the reported time. As an illustration, one can look at Figure 5–3, in which the blue region changes as a function of the detection time and indicates celestial coordinates that are above the CHIME horizon. On the other hand, the corresponding local coordinates are evaluated against a different algorithm to determine if the transient occurred within the CHIME primary beam. As an illustration, one can similarly look at Figure 5–4, in which the blue region again changes as a function of the detection time and indicates celestial coordinates that are within the CHIME primary beam. The important result is whether the central coordinates are

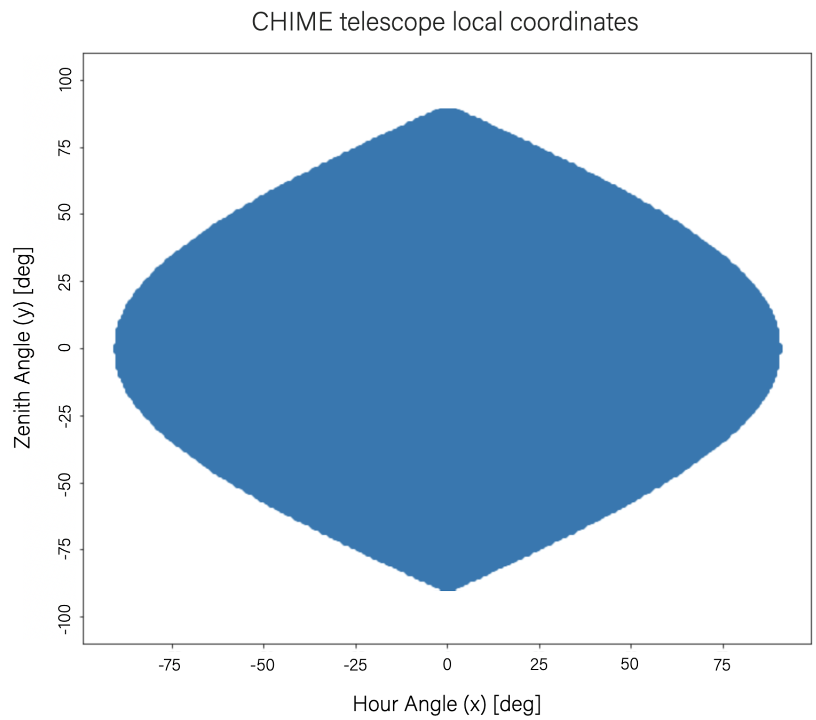

Figure 5–5: The local coordinates system for the CHIME telescope is described by (x, y) for which there is a unique correspondence with right ascension α and declination δ, via the beam model, at every given UTC moment. Here, x is an hour angle in degrees measured relative to the CHIME meridian, while y is a zenith angle in degrees measured relative to the local zenith. A fine grid in (x, y) is plotted with blue markers to indicate the relationship between hour angle and zenith angle. The correspondence $(x, y) \leftrightarrow (\alpha, \delta)$ is used by the `GRBReceiver` and `LVCReceiver` event handlers to determine if the sky coordinates of a transient published in a GCN VOEvent are within the CHIME primary beam; the calculation enters into the handling routines at the `get_pos_from_eq()`, a shorthand for "get CHIME local position from equatorial/celestial coordinates". We take $x \in (-2, 2)$ and $y \in (-60, 60)$ as a working definition for maximum sensitivity to a sky coordinate with the CHIME primary beam. The details of that choice and moreover the mathematical description of the blue region are beyond the scope of this thesis; however this choice and the beam model that informs this choice have both been used extensively in CHIME/FRB publications for sensitivity and exposure calculations (e.g. [12]).

above the CHIME horizon or not, and whether they are in the CHIME primary or not.

Moreover, it is scientifically meaningful to allow for a delay between the detection time of the transient published in the GCN VOEvent and any possible *contemporaneous* radio counterpart that might be detected by CHIME/FRB, in accordance with the unknown dispersion delay accrued by radio waves as they propagate from the source to the telescope. We allow for this unknown dispersion delay, according to Equation 1.9 evaluated at infinite frequency i.e. $\nu_1 = 400$ MHz and $\nu_2 \to \infty$, through a set of possible DM values from 0 cm^{-3} pc up to 4000 cm^{-3} pc. This upper bound is arbitrarily selected but is well within the upper CHIME/FRB search limit of $13,000$ cm^{-3} pc at L1 (§2.3.2). For the range of DM values in $(0, 4000)$ cm^{-3} pc we repeat the CHIME horizon and CHIME primary checks described in the previous paragraph on the celestial coordinates of the VOEvent, inputting now the published detection time of the transient *plus* the dispersion delay time. The addition is consistent with the notion that any radio counterpart signal would be delayed in time relative to the reported GCN VOEvent transient. Note that this delay has only to do with the physics of radio wave propagation (§1.2) and has no connection with any additional delays that have been theorized regarding astrophysical engines that can produce both GRB and FRB emission (§1.5).

The beam model is also used to calculate (1) whether the published VOEvent coordinates occurred within one of the CHIME formed beams (§2.3.1) at the detection time plus dispersion delay; (2) the UTC time when the nominal coordinates will transit the CHIME meridian; and (3) which of the formed beams the coordinates will move through during the transit. The algorithm for calculating the transit is part of the beam model code developed by other CHIME/FRB Collaboration members. On the other hand, the algorithm for determining any coincidences of the transient coordinates with the formed beams is the same that has been used in exposure calculations in other CHIME/FRB publications (e.g. [12]). Namely, the formed beams are drawn as a grid of ellipses on the sky with widths determined from the frequency-dependent beam model referenced to 600 MHz, and the question is asked in which beam do the transient sky coordinates fall (if any; see Figure 2–5).

5.2.4 Handling Gravitational Wave Transients

The GCN VOEvents published through the `gwnet/LVC` sub-stream (Table 5–1) represent candidate detections of gravitational wave (GW) transients published by the aLIGO/Virgo Collaboration. Below are the four defining features of aLIGO/Virgo VOEvents that are relevant to any search for multi-wavelength counterpart signals. (See §3.4 for an example.)

- The coordinates are provided as an all-sky map showing the localization region and corresponding confidence of regions in the sky map. Currently this is found in a `<Param>` named `"skymap_fits"` in the `<Group>` named `"GW_SKYMAP"` in the `<What>` section (§3.2.3).
- Up to the three GW detectors in Hanford, WA (H1), Livingston, LA (L1), or Virgo in Cascina, Italy (V1), may have been involved in detecting the signal. Currently this is in the `<Param>` named `"Instruments"` in the `<What>` section.
- The transient is classified according to a five-fold scheme with probabilities stored as values of `<Param>` within the `<Group>` called `"Classification"` in `<What>`. The classes are either a `"Terrestrial"` event, or a merger of two compact stellar remnants, with some probability for each of four classes. These classes include: binary neutron star (`"BNS"`); binary black hole (`"BBH"`); neutron star/black hole (`"NSBH"`); or a merger of

two objects in which one has a mass between 3 and 5 solar masses called `"MassGap"`.

- The false-alarm rate (FAR) of the transient detection is provided in a `<Param>` named `"FAR"` also in `<What>`.

The handling of aLIGO/Virgo VOEvents is far more complicated, and therefore the process to be described here is equally less mature, than for the GRB-related VOEvents from GCN. The current handling is executed with the `LVCReceiver` class and does not attempt to perform the same treatment with the coordinates reported in the all-sky map as is done with the central coordinates reported for the GRB-related VOEvents. In principle the same treatment could be done but is even then only practical for the GW transients that are "well-localized"[9] [10]. The localization is the largest barrier to handling GW transients; namely the all-sky localization can be very complicated and enormous, such that even the field-of-view of CHIME/FRB ~ 200 deg^2 [10] covers at best a small fraction of the GW localization region.

Therefore, the current prescription is to simply acquire the UTC timestamp of the GW transient from the `<WhereWhen>` section (§3–1). The human-readable message (Figure 5–7) can then be used by CHIME/FRB Collaboration members during normal experiment monitoring to cross-reference with incoming detections made with CHIME/FRB. The workflow for this has potential for refinement and will be expanded on in §5.4.

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[9] See `https://gracedb.ligo.org/apiweb/superevents/S190814bv/files/LALInference.v1.png,0` for a "well-localized" transient.

[10] See `https://gracedb.ligo.org/apiweb/superevents/S190425z/files/LALInference.png,0` for a very complicated localization.

5.3 Example of Results

At the time of writing, the useful output of both the `GRBReceiver` and `LVCReceiver` event handlers is a human readable text-message that is posted to a dedicated internal CHIME/FRB Collaboration Slack channel[11] containing a selection of the meta data and their descriptions or inferences from the received VOEvent together with the calculations or computations carried out by either event handler. The purpose of these messages is to allow interested members of the CHIME/FRB Collaboration to stay abreast of GCN VOEvents that may be published in connection with new astrophysical transients relevant for multi-wavelength FRB researches.

An example of the output of `GRBReceiver` on a GCN VOEvent published by *Fermi*-GBM is shown in Figure 5–6, while an example of the output of `LVCReceiver` on a GCN VOEvent published by aLIGO/Virgo is shown in Figure 5–7.

5.4 Conclusion and Future Work

In conclusion, this Chapter presents the GCN/TAN as a reliable source of low-latency alerts regarding detections of new and known sources via transient gamma-ray, X-ray, and gravitational wave activity as published in the VOEvent XML schema and distributed over the VOEvent Network. Many online resources for the GCN, especially regarding the VOEvent and Circulars communications, are obviously in need of modernization. It is the author's ambition that Figure 5–1 and Tables 5–1 & 5–2 will prove much more accessible to the reader. Additionally, the volume of different instruments and

[11] CHIME/FRB Collaboration members can join the `#gcn-voevents` and `#voevents` channels.

```
Observatory          : FERMI
Instrument           : Fermi Satellite, GBM Instrument
Produced             : 2020-05-24 05:05:17 UTC (latency = + 00:01:16)
Event IVORN          : ivo://nasa.gsfc.gcn/Fermi#GBM_Gnd_Pos_2020-05-24T05:04:00.36_611989445_0-779
GCN Packet Type      : 112 (GBM_Gnd_Pos, observation)
Source Name          : None or Unknown
Explanation (1)      : process.variation.burst;em.gamma
Explanation (2)      : The Fermi-GBM location of a transient.

Localization         : (RA, DEC) = (201.88, 65.22) +/- 3.02 deg
Time                 : 2020-05-24 05:04:00.360000 UTC
Coord System         : UTC-FK5-GEO
Importance           : 0.5 (scaled 0 to 1)
Energy Band          : (None, None)
Flux                 : (None, None)
Timescale            : (None, None)

Links                : http://gcn.gsfc.nasa.gov/fermi.html
Contact              : Julie.E.McEnery@nasa.gov (Julie McEnery)
Citations            : None (None)

CHIME/FRB Visibility

      DM Delay Time [UTC]        x        y  ^ Horizon In Primary In Beams         Transit Time [UTC]          Transit Beams
    0.00  05:04:00.360000    -1.45    15.83       True       True       [] 2020-05-24 05:17:37.998528 [167, 1167, 2167, 3167]
   50.00  05:04:01.656562    -1.45    15.83       True       True       [] 2020-05-24 05:17:39.295090 [167, 1167, 2167, 3167]
   81.36  05:04:02.469832    -1.45    15.83       True       True       [] 2020-05-24 05:17:40.108360 [167, 1167, 2167, 3167]
  132.40  05:04:03.793226    -1.45    15.83       True       True       [] 2020-05-24 05:17:41.431754 [167, 1167, 2167, 3167]
  215.44  05:04:05.946718    -1.44    15.83       True       True       [] 2020-05-24 05:17:43.585246 [167, 1167, 2167, 3167]
  350.58  05:04:09.450991    -1.44    15.83       True       True       [] 2020-05-24 05:17:47.089519 [167, 1167, 2167, 3167]
  570.48  05:04:15.153321    -1.43    15.83       True       True       [] 2020-05-24 05:17:52.791849 [167, 1167, 2167, 3167]
  928.32  05:04:24.432440    -1.41    15.82       True       True       [] 2020-05-24 05:18:02.070968 [167, 1167, 2167, 3167]
 1510.61  05:04:39.531893    -1.38    15.82       True       True       [] 2020-05-24 05:18:17.170421 [167, 1167, 2167, 3167]
 2458.13  05:05:04.102486    -1.34    15.82       True       True       [] 2020-05-24 05:18:41.741014 [167, 1167, 2167, 3167]
 4000.00  05:05:44.085000    -1.27    15.82       True       True       [] 2020-05-24 05:19:21.723528 [167, 1167, 2167, 3167]
```

Figure 5–6: A human-readable text message designed to be posted on the CHIME/FRB Collaboration Slack channel `#gcn-voevents`. The text contains information meta data from a GCN VOEvent, together with inferences and computations made on that meta data, that was published under the `Fermi` sub-stream with packet type `112` and packet label `GBM_Gnd_Pos`. The VOEvent reported a burst from an unknown source localized to a circular region in celestial coordinates given by $(\alpha, \delta) = (201.88°, 65.22°) \pm 3.02°$ as observed by the *Fermi* Gamma-ray Burst Monitor (GBM) at 05:04:00.360000 UTC on 2020 May 24. The latency between the detection time and the VOEvent publication time was about 1 minute and 16 seconds. The appended table calculates the time at which one could expect a contemporaneous radio signal according to the delay introduced by a range of unknown dispersion measure (DM) values (Equation 1.9). For every DM value, the coordinates (x, y) in the CHIME local coordinates (Figure 5–5) are calculated and Boolean flags indicate whether the coordinates are above the CHIME horizon (Figure 5–3); are within the CHIME/primary beam (Figure 5–4); or are within any of the formed beams (§2.3.1). Further, the time at which the coordinates will transit the CHIME meridian are shown and the formed beams through which the coordinates will move as the Earth rotates are shown. Only the central coordinates $(201.88°, 65.22°)$ are evaluated within the CHIME coordinate system and no attempt is made to sample from the circular error region. In the "In Beams" column, empty square brackets `[]` indicate that the central coordinates were not within any of the formed beams, a result of "gaps" between the the elliptical beams that are an artefact of evaluating the frequency-dependent beam sensitivity model at 600 MHz.

```
Observatory          : LIGO/Virgo Collaboration
Instrument           : Candidate gravitational wave event identified by low-latency analysis
Produced             : 2020-06-05 21:08:36 UTC (latency = + 00:12:43)
Event IVORN          : ivo://gwnet/LVC#MS200605u-3-Initial
GCN Packet Type      : 151 (Initial, test)
Source Class         : BNS (1.0)
Explanation (1)      : MS200605u (Initial)
Explanation (2)      : H1,L1

Localization         : Sky-map analysis coming soon!
Time                 : 2020-06-05 20:55:52.780387 UTC
Coord System         : UTC-FK5-GEO
Importance           : False Alarm Rate is 9.11e-14 (1 per 348050.03 years)

Links                : https://gracedb.ligo.org/superevents/MS200605u/view/
Contact              : Unaccessible 'Who.Author.contactEmail': no such child: contactEmail (LIGO Scientific Collaboration and Virgo
Collaboration)
Citations            : 2-Preliminary | 1-Preliminary | (Initial localization is now available)

CHIME/FRB Visibility:
Coming Soon!
```

Figure 5–7: A human-readable text message designed to be posted on the CHIME/FRB Collaboration Slack channel `#gcn-voevents`. The text contains information meta data from a GCN VOEvent, together with inferences and computations made on that meta data, that was published under the `gwnet/LVC` sub-stream with packet type `151` and packet label `Initial`. The VOEvent is a test published by the aLIGO/Virgo Collaboration that has the same content and structure that a real observation published under this packet type would have. The VOEvent reported a fake GW transient detected by the Hanford (H1) and Livingston (L1) detectors at 20:55:52.7803887 UTC on 2020 June 5, and the VOEvent was published to the VOEvent Network approximately 12 minutes later. The observation was classified as a binary neutron star (BNS) merger with probability 1.0. The Grace ID for this fake event is MS200605u and it can be searched at `https://gracedb.ligo.org/search/`. The VOEvent is the third (`3-Initial`) reported in the chain and it refers to two previous VOEvents with the same IVORN except the suffix is replaced with `2-Preliminary` and `1-Preliminary`. The false alarm rate (FAR) indicates that such a classification is expected to be a false positive once every $\sim 350,000$ yr. External resources are referenced via a link within the VOEvent (`https://gracedb.ligo.org/superevents/MS200605u/view/`). Unlike Figure 5–6, the "CHIME/FRB Visibility" table remains incomplete, though important future work will centre on a meaningful way to translate the complicated localization region into the CHIME/FRB context. For example, it could be useful to compute the fraction of the GW localization region that is covered by the CHIME primary beam as a function of unknown DM.

observatories that publish sub-streams of VOEvents through the GCN VOEvent broker is not to be understated. Table 5–3 is expected to be a useful resource to see their basic observational capabilities all at once. Together with the formative efforts to build a suite of event handlers to bring the observations reported through GCN VOEvents into the CHIME/FRB experiment context, it is ultimately the author's aspiration that future CHIME/FRB Collaboration members can build a more complete service from the pillars that are laid out. The following is a discussion of remaining tasks and foreseeable projects that can be completed with this foundation.

To begin with, the `GRBReceiver` and `LVCReceiver` handlers should be integrated with the VOEvent broker that is designated for the CHIME/FRB VOEvent Service. As per §4.3.3, the CHIME/FRB VOEvent broker runs inside a Docker[12] container called the FRB VOE module, a framework that provides a virtual and self-contained development environment very amenable to continuous integration and micro-service infrastructures. Inside the container is a stable version of Comet cloned from the latest GitHub release[13] . To integrate the event handlers, one needs to install them as per §5.2.1; this has not been done yet with the current release of the FRB VOE module that is maintained in the CHIME/FRB GitHub repository `frb-voe`[14] .

In the author's current local (uncommitted) versions of the event handlers, their outputted Slack messages (Figures 5–6 & 5–7) are adequate for

[12] `https://github.com/docker`.

[13] `https://github.com/jdswinbank/Comet`.

[14] CHIME/FRB maintains a private GitHub repository accessible to CHIME/FRB Collaboration members.

CHIME/FRB Collaboration members to track reports of transient activity reported by the GCN VOEvent broker, but several improvements are desirable. In particular, the message content and structure can be made more accessible, readable, and linked with additional online information, especially in connection with other resources available through the CHIME internal Wiki page. In addition, the current filtering criteria (§5.2.2) are basic regarding transient activity from high-volume known sources that are likely irrelevant for the pursuit of contemporaneous multi-wavelength associations with CHIME/FRB. This mostly concerns packet type `140` and `141` representing observations of bursts with *Swift*-BAT from possibly known sources named according to the *Swift*-BAT source catalogue[15] . Conceivably, good future work involves a careful study of the sources in that catalogue, their relevance for CHIME/FRB, and what can be done with the event handlers. Besides these improvements to the event handlers, it is desirable that a more robust and precise scientific workflow be implemented for making good use of them in tandem with normal CHIME/FRB observations. Currently a handful of CHIME/FRB Collaboration members follow the GCN Circulars closely, but processing GCN VOEvents automatically in real-time through the event handlers promises to remove human latency and decision making. Overall, such an automated scientific workflow better contributes to the idealism perpetuated by the IVOA for a single, global, virtual observatory.

To fully automate the handling of GCN VOEvents, it is important for the event handlers to do something internally, besides alert human agents. One option is to transform the sky and temporal coordinates published in received

[15] `https://github.com/lanl/swiftbat_python/blob/master/swiftbat/catalog`

VOEvents into temporary known source objects within the CHIME/FRB Known Sources DataBase (KSDB)[16] (§2.3.4). This database is currently updated at a ~ 1 hr cadence through an offline management routine requiring human intervention at the L3 level of the real-time pipeline. One can imagine an automatic integration whereby the coordinates in a GCN VOEvent, published about an interesting burst from an unknown source, are added in real-time to the KSDB, along with some reasonable range of unknown DM over which to allow the L3 Known Source Association (KSA)[17] algorithm to search. Briefly, the KSA algorithm computes the `known_source_rating` and assigns the `known_source_name` appearing the L4 header (see 4–1), by assessing the proximity of entries in the KSDB relative to a new FRB candidate from the real-time pipeline in $(\alpha, \delta, \mathrm{DM})$-space where α is right ascension and δ is declination. For bursts published in GCN VOEvents this is complicated by poor localizations available from some observatories e.g. *Fermi*-GBM (although *Swift*-BAT is much less an issue here). Still more complicating is the factor of unknown DM. If the search DM range inputted to the KSA algorithm is too large, then such an automated GCN VOEvent-KSDB integration would yield many false positive associations with CHIME/FRB real-time detections. One option is to test multi-wavelength FRB models (§1.5) by their expected DM in combination with whatever salient source characteristics can be inferred from the energetics or timescales in published in the GCN VOEvent. This undertaking could be a good future project, albeit with many challenges: understanding multi-wavelength FRB models, understanding the limitations

[16] Author's abbreviation.

[17] Author's abbreviation.

of the GCN observatories, the CHIME/FRB L3 algorithms, and statistical efforts for ruling out false associations.

The integration of GCN VOEvents with the CHIME/FRB KSDB can be framed as a vital undertaking for the reason that bright FRB candidates can be detected relatively far away from the CHIME meridian. If an X-ray or gamma-ray burst is detected and published through the GCN VOEvent broker, it might happen that its coordinates are far from the CHIME meridian. If the source coordinates were integrated in real-time with the KSDB then an automatic comparison can be made with the FRB candidate via the KSA algorithm that will much better serve those who are monitoring the real-time pipeline when it comes to the human verification stage.

To complete the loop, one can imagine an expansion to the CHIME/FRB detection-type and update-type VOEvent (§4.3.4) that identifies an FRB candidate from the real-time pipeline and human verification (respectively) as a counterpart (to some estimated confidence or probability) to a burst published recently in a GCN VOEvent. This would require fulfilling the previous recommendations of improving the event handling in terms of filter criteria and KSDB integration first, an additionally saving the IVORN of the GCN VOEvent and citing it in the CHIME/FRB VOEvent (§3.2.7). With this in mind, it suggests that a minimal and logical integration with the KSDB is to simply use the IVORN as the name of the temporary source that is saved in the KSDB.

The last discussion item is how to better handle GCN VOEvents published by aLIGO/Virgo about GW candidates. The poorly localized GW candidates are of little real-time use to CHIME/FRB besides their timestamp. However, some candidates have in the past been very well localized to a region that could be significantly covered by the CHIME primary beam. It could be worth developing an algorithm to robustly convert such a localization region to a collection of temporary entries in the KSDB as described above. Furthermore, a distance estimate to the GW candidate can be obtained from the `.fits.gz` file in the `<Param>` called `"skymap_fits"` (§5.2.4) which could be useful for estimating a DM range to assign to the temporary entries in the KSDB. This could be its own project in which one creates many temporary KSDB entries and estimates DM ranges using the maximum Galactic DM contributions ([14], [57]) and the IGM contributions ([18], [17]), together with the aLIGO/Virgo GW candidate distance estimate.

CHAPTER 6
Conclusions and Future Work

6.1 Conclusion

The engines that exhibit the fast radio burst phenomenon (Chapter 1) continue to elude a precise description that is at once consistent with all observations to date. The CHIME/FRB experiment has played an important role in this field (Chapter 2) since its commissioning in September 2018, promising and delivering on detecting 2 to 3 FRBs each day, introducing the world to a host of repeating sources, and will soon publish many hundreds of FRBs not yet known to the world. Still, a family of classes of FRB progenitors remains possible (§1.5). The evidence that the Galactic magnetar SGR 1935+2154 has produced bright millisecond radio bursts with counterpart X-ray activity may connect the cosmological FRB population to a Galactic FRB population but it does not necessarily rule out that other astrophysical phenomena could produce FRBs [49]. However, additional detections of counterparts to other FRBs could rule out many of the models that remain plausible, especially if the observations could be made with very low-latency relative to the detection of either an initial FRB or an initial e.g. X-ray burst.

This MSc thesis was written with this scientific motivation in mind, together the wild vision of a "single observatory" that can observe transient astrophysical phenomenon with total coverage of the electromagnetic spectrum and even detect cosmogenic particles and gravitational waves. While a single physical facility that can achieve this sounds like science fiction, this thesis has shown that the VOEvent Network (Chapter 3) has the potential to connect separate facilities both around the Earth and the Solar System in a similar way.

The GCN/TAN (Chapter 5) is already using the VOEvent Network to produce machine-readable messages that can be received with low-latency through the Internet and act as triggers for robotic telescopes everywhere, a further source of inspiration for the creation of a VOEvent Service for the CHIME/FRB experiment (Chapter 4). The VOEvent medium has gained momentum in the FRB community and the CHIME/FRB VOEvent standard leans heavily on pre-existing recommendations [37].

In the near future, the CHIME/FRB VOEvent Service will publish VOEvents regarding new FRB detections from the real-time pipeline that will be available to the entire VOEvent Network following an initial testing phase with external collaborators that have signed a memorandum of understanding (MoU) with the CHIME/FRB Collaboration. If this Service proves useful, it will hopefully inspire researchers around the world to publish their own VOEvents in connection with multi-wavelength FRB follow-up campaigns. It could even serve as a role model for similar services in other areas of transient astronomy where latency is a contributing factor in writing campaign proposals.

6.2 Future Work and Extensions

6.2.1 A Task List for Outgoing VOEvents

CHIME/FRB is positioned to catalyze the process of multi-wavelength follow-up of FRB sources as the CHIME/FRB VOEvent Service (Chapter 4) comes fully online to the public. In order to make the CHIME/FRB VOEvent Service something that others in the astrophysical community can make good use of, and model their own services after, some upgrades are needed as specified in the following task list (see also §4.5).

1. The Service needs to be trialed internally to monitor the rate of outgoing VOEvents relative to the rate of events that pass through the internal CHIME/FRB candidate verification process.
2. After internal monitoring, the outgoing VOEvents will be made available to certain external collaborators with which a memorandum of understanding has been arranged, to trial the process of triggering external observatories through the VOEvent Network.
3. The subscription process for the Service needs to be made seamless, transparent, and user-friendly. Logically this can be handled through a simple sign-up form that can be hosted on the public-facing CHIME/FRB web page[1] .
4. The latency from the arrival of the radio light at the CHIME telescope at 400 MHz to the publication of the CHIME/FRB VOEvents (detection/subsequent, and various update types) needs to be measured. This will provide a concrete figure when collaborators are writing observing proposals for usage of other telescopes in connection with what FRB progenitor model they might be. testing.[2]
5. To provide quality assurance for follow-up campaigners, a full suite of monitoring tools and metrics is needed to regularly evaluate the performance and health of the Service.

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[1] `https://www.chime-frb.ca/`

[2] When testing multi-wavelength FRB models for which prompt (as opposed to afterglow) emission is predicted *contemporaneously* with the radio emission, observers will be looking for detections with their instrument that occurred in the past. That is, the radio waves will always lag behind other prompt emission according to the propagation physics (§1.1).

6. The health of the Service should be made available in real-time to the primary maintainer(s) and with some appropriate cadence to follow-up campaigners, as they will be resting their scientific efforts on it.
7. Test versions of all CHIME/FRB VOEvents should be made available in real-time on a defined cadence through the VOEvent Network, just as the GCN does with its test packets (Tables 5–1 & 5–2).
8. Priorities for the content of update-type VOEvents include especially formatting the improved localization from the offline intensity and baseband analysis pipelines. However, chronologically these may take longer to be ready to share with the public, where a workflow involving human verification is in need of specification. Before these results are ready for VOEvents, other offline analysis can be released in low-latency update alerts. One example of a low-latency quick analysis update-type VOEvent would contain estimates of the maximum redshift as calculated from the maximum excess DM that accounts for both ISM and IGM contributions. Another example is to publish lists of *plausible*[3] host galaxies in the best available CHIME/FRB localization region in an update-type VOEvent, an analysis effort that is currently in development and useful especially for low-DM FRB FRB sources, both repeating sources and new singleton bursts.
9. An additional service can be pursued to provide a special CHIME/FRB VOEvent type that indicates when a known FRB source (especially a repeating source) is about to enter or leave the CHIME horizon. This

[3] The plausibility of each galaxy being the host of an FRB within a given localization region, considering only CHIME/FRB data and certain appropriate available public sky surveys in optical and other bands, is currently in development in CHIME/FRB, primarily by Mohit Bhardwaj.

allows follow-up observatories to operate in tandem with CHIME/FRB for specific sources; a similar recommendation was made in [37] with the "Search" and "Targeted" type VOEvents.

6.2.2 A Task List for Incoming VOEvents

The event handlers for incoming GCN VOEvents (Chapter 5) are ready to be plugged into the CHIME/FRB VOEvent broker that will run perpetually in the FRB VOE module (§4.3.3). To make their output useful to the CHIME/FRB Collaboration, the following task list has been prepared to summarize what remains to be done and what can be done as part of a larger future project.

1. The event handlers (§5.2.1) must be installed in the local Comet framework that exists in the Docker container within the FRB VOE module (§4.3.3).
2. The event handlers should be integrated with the Known Sources DataBase (KSDB) to create *temporary* known sources using the IVORN of the received GCN VOEvent as a source name. The first step is to carefully circumscribe the filtering criteria for GCN VOEvents to know which of the packet types (Tables 5–1 & 5–2) are identifying new targets and in what capacity.
3. Further work with the KSDB requires specifying an expiration time for the temporary known sources. A basic approach could be to set the expiration time to be when the source exits the CHIME horizon. Complicating factors include the localization of the source from the GCN VOEvent.
4. Additionally, a reasonable range of DM values to attribute to the temporary known source must be calculated using available energetics and

timescales from the GCN VOEvent, in combination with distance estimates and line-of-sight Galactic electron density estimates.

Evidently, a great deal of work is needed to specify the workflow of integrating GCN VOEvents automatically with CHIME/FRB. In the long run it completes the loop and makes CHIME/FRB a *listener* in the VOEvent Network, in addition to being a *speaker*. A full solution to this would be an impressive accomplishment and would conceivably represent a significant contribution to the field of FRBs.

Improving the handling of gravitational wave (GW) transients reported by the aLIGO/Virgo Collaboration through GCN represents urgent and very interesting work. Many compact binary merger models exist for FRB progenitors (§1.5) and testing the low-latency regime for FRBs that are produced following an initial GW transient could corroborate or rule out these scenarios. The largest difficulty here is how to handle the often very complicated localization region, on top of all of the inferences that need to be made from the meta data provided in the aLIGO/Virgo VOEvent to understand the observation in the CHIME/FRB context. If the GW transient is not well-localized, even the most sophisticated handling techniques are not fruitful for CHIME/FRB because of a high probability of chance coincidence that an FRB is detected reasonably *contemporaneously* with the GW. Still, being able to make those claims precisely is a great future project.

Appendix A

To avoid interruptions to the flow of the main text, several figures have been collected here. These include examples of CHIME/FRB VOEvent XML content from Chapter 4, and the output of the GCN VOEvent handling code in Chapter 5.

```
"id": 1,
"record": [
  {
    "alert_type": "detection",
    "information_source_type": "HEADER",
    "message_ivorn": "ivo://ca.chimenet.frb/FRB-DETECTION
    -#2021-05-03-03:51:23.845903UTC+0000_e891f6f6bc63",
    "timestamp_utc": "2021-05-03 03:51:25.043601",
  },
  {
    "alert_type": "update",
    "information_source_type": "INTENSITY",
    "message_ivorn": "ivo://ca.chimenet.frb/FRB-UPDATE
    -#2021-05-03-05:12:54.647190UTC+0000_4ef1f5c645ca",
    "timestamp_utc": 2021-05-03-05:30:46.256900",
  },
]
```

Figure A–1: An example of the evolving transmission record for CHIME/FRB VOEvents published in connection with a single (hypothetical) CHIME/FRB event. Overall these records indicate that an initial VOEvent was published for the *detection* of an FRB as identified by the real-time pipeline, and this was followed some hours later by the publication of a second *update* VOEvent containing improvements and additions to initial measurements. The `"id"` indexes the entry in the database and is equal to the CHIME/FRB event number. The `"record"` is a list of dictionaries, each representing a unique CHIME/FRB VOEvent that was published about the event. The `"alert_type"` can take one of four values (§4.3.4). The `"information_source_type"` identifies the origin of the meta data in the VOEvent, with `"HEADER"` meaning the L4 header and `"INTENSITY"` meaning the offline intensity analysis pipeline (`"BASEBAND"` is the other possible option). The IVORN of the VOEvent is saved in `"message_ivorn"`, while the UTC time at which the VOEvent was published to the Network is saved in `"timestamp_UTC"`.

```
"id": 2,
"record": [
  {
    "alert_type": "subsequent",
    "information_source_type": "HEADER",
    "message_ivorn": "ivo://ca.chimenet.frb/FRB-SUBSEQUENT
    -#2021-05-04-02:55:43.473981UTC+0000_f561f5b6cc21",
    "timestamp_utc": "2021-05-04-02:57:11.000457",
  },
  {
    "alert_type": "retraction",
    "information_source_type": "HUMAN",
    "message_ivorn": "ivo://ca.chimenet.frb/OBS-RETRACTION
    -2021-05-04-03:03:55:38.567254UTC+0000_4311eef6bd19",
    "timestamp_utc": "2021-05-04-03:05:34.333943",
  }
]
```

Figure A–2: A second example of a transmission record for VOEvents published regarding a single (hypothetical) CHIME/FRB event. The structure is the same as in Figure A–1. Overall these records indicate that an initial VOEvent was published for the detection of a *subsequent* burst from a previously identified FRB source (possibly known only internally to CHIME/FRB, or otherwise a known source in an existing catalogue) that was identified with the real-time pipeline. However, the second VOEvent is a *retraction* issued by a human, illustrating a case in which the real-time pipeline falsely associated the detection represented in the subsequent-type alert with a known source. This hypothetical scenario is presented to demonstrate the necessity for issuing retractions through VOEvents for real-time detections. The real-time clustering algorithm that associates new FRBs - based solely on their sky-position and DM - from the real-time pipeline with catalogued known sources occasionally yields false associations, but this does not mean that the FRB is a false positive itself.

```
"id": 19950503,
"details": {
  "name": "JANE DOE",
  "association": "RANDOM TELESCOPE",
  "contact": "jdoe@physics.umisc.edu",
  "joined": "2018-09-01 08:00:00.000000+00:00",
  "expires": "2020-09-01 08:00:00.000000+00:00",
  "xmls": True,
  "emails": True,
  "ip_address": "192.168.2.10",
}
```


Figure A–3: An example of a subscription record that allows the user identified by `"name"` and scientific `"association"` to receive CHIME/FRB VOEvents both as XML documents through the VOEvent Network, and through email. This user can connect to the CHIME/FRB VOEvent broker with the listed `"ip_address"`. Regular pruning of the subscription Service will delete this record when `"expires"` exceeds the current UTC time, after which this user will no longer receive emails or be able to subscribe to the CHIME/FRB VOEvent broker. Because IP addresses are dynamic, changing based on one's local Internet connection, this subscription Service is designed to support subscribing VOEvent brokers that are run from a dedicated machine on a fixed network. That is, a user connecting a laptop to arbitrary networks and obtaining new IP addresses frequently will not be permitted under the current manual maintenance of the database.


```
<VOEvent xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
  xsi:schemaLocation="http://www.ivoa.net/xml/VOEvent/v2.0
  http://www.ivoa.net/xml/VOEvent/VOEvent-v2.0.xsd"
  version="2.0" role="observation"
  ivorn="ivo://ca.chimenet.frb/FRB-DETECTION-
  #2019-12-02-17:00:00.000000UTC+0000_107d691896f6">
```


Figure A–4: The `<VOEvent>` header for the four different CHIME/FRB VOEvent types has the same format. The `"role"` is set to `"observation"` and the latest VOEvent version is used (`"version"="2.0"`). Note this is not connected with a real CHIME/FRB detection, it is only a sample.

```xml
<Who>
  <Description>CHIME/FRB VOEvent Service</Description>
  <AuthorIVORN>ivo://ca.chimenet.frb/contact</AuthorIVORN>
  <Date>2019-12-02T17:00:00+00:00</Date>
  <Author>
    <contactEmail>andrew.zwaniga@mcgill.ca</contactEmail>
    <contactName>Andrew Zwaniga</contactName>
    <shortName>CHIME/FRB VOEvent Service</shortName>
  </Author>
</Who>
```

Figure A–5: The `<Who>` header for the four different CHIME/FRB VOEvent types has the same format. The `<Date>` is set to the same that appears in the IVORN, which varies between the VOEvent types (see Item 4.1). Note this is not connected with a real CHIME/FRB detection, it is only a sample.

```xml
<Group name="observatory parameters">
  <Param name="sampling_time" ucd="time.resolution"
    unit="ms" value="0.983">
    <Description>FRB search time resolution</Description>
  </Param>
  <Param name="bandwidth" ucd="instr.bandwidth"
    unit="MHz" value="400">
    <Description>CHIME telescope bandwidth</Description>
  </Param>
  <Param name="centre_frequency" ucd="em.freq;instr"
    unit="MHz" value="600">
    <Description>CHIME telescope central frequency
    </Description>
  </Param>
  <Param name="nchan" ucd="meta.number;em.freq;em.bin"
    unit="" value="16384">
    <Description>CHIME/FRB frequency channel count
    (up-channelized)</Description>
  </Param>
  <Param name="npol" ucd="" unit="" value="2">
    <Description>The CHIME telescope has dual-polarization
    feeds</Description>
  </Param>
  <Param name="bits_per_sample" ucd="" unit="" value="8">
    <Description>CHIME/FRB samples 16384 frequency channels
    at 0.983 ms cadence as 8-bit integers</Description>
  </Param>
  <Param name="gain" ucd="" unit="" value="">
    <Description>CHIME telescope gain</Description>
  </Param>
  <Param name="tsys" ucd="phot.antennaTemp" unit="K/Jy"
    value="">
    <Description>CHIME receiver noise temperature</Description>
  </Param>
  <Param name="backend" ucd="" unit="" value="">
    <Description>CHIME/FRB</Description>
  </Param>
</Group>
```


Figure A–6: The meta-data provided in the `observatory` grouping under the `<What>` header are fixed from one VOEvent XML to the next, since they originate from design specifications of the CHIME telescope and the CHIME/FRB instrument [10], with the exception of the `gain` that is determined once per day on the basis of calibrations performed on steady sources e.g. Cassiopeia A [10].

```
<Group name="event parameters">
  <Param name="event_no" ucd="" unit="" value="1">
    <Description>CHIME/FRB event number</Description>
  </Param>
  <Param name="known_source_name" ucd="" unit="" value="">
    <Description>CHIME/FRB internal known source name</Description>
  </Param>
   <Param name="beams" ucd="" unit="" value="[]">
    <Description>CHIME/FRB detection beam number(s)"</Description>
  </Param>
  <Param name="event_type" ucd="" unit="" value="EXTRAGALACTIC">
    <Description>Unknown event type</Description>
  </Param>
  <Param name="dm" ucd="phys.dispMeasure" unit="pc/cm^3"
    value="0">
    <Description>Dispersion measure from real-time pipeline</Description>
  </Param>
  <Param name="dm_error" ucd="stat.error;phys.dispMeasure"
    unit="pc/cm^3" value="0">
    <Description>Error in dispersion measure from real-time
    pipeline</Description>
  </Param>
  <Param name="flux" ucd="phot.flux" unit="mJy" value="0">
    <Description>Flux from real-time pipeline</Description>
  </Param>
  <Param name="flux_mjy_max_95" ucd="phot.flux" unit="mJy"
    value="0">
    <Description>Maximum flux to 95 percent C.L. from real-time
    pipeline</Description>
  </Param>
  <Param name="flux_mjy_min_95" ucd="phot.flux" unit="mJy"
    value="0">
    <Description>Minimum flux to 95 percent C.L. from real-time
    pipeline</Description>
  </Param>
  <Param name="dispersion_smearing" ucd="" unit=""
    value="0">
    <Description>Dispersion smearing from real-time
    pipeline</Description>
  </Param>
  <Param name="dispersion_smearing_error" ucd="" unit=""
    value="0">
    <Description>Error in dispersion smearing from real-time
    pipeline</Description>
  </Param>
</Group>
```

Figure A–7: The meta data provided in the event grouping under the <What> header for the detection-type VOEvent (placeholder values only). The planned low-latency update-type will also include the TNS name and Galactic coordinates here.

```xml
<Group name="advanced parameters">
  <Param name="dm_gal_ne_2001_max" ucd="" unit="pc/cm^3" value="0">
    <Description>Max Milky Way DM contribution (NE 2001 model) from
    real-time pipeline</Description>
  </Param>
  <Param name="dm_gal_ymw_2016_max" ucd="" unit="pc/cm^3" value="0">
    <Description>Max Milky Way DM contribution (YMW 2016 model) from
    real-time pipeline</Description>
  </Param>
</Group>
```

Figure A–8: The meta data provided in the advanced grouping under the <What> header shown here are particular to the detection-type VOEvent. Additional measurements obtained from the low-latency update will include inferred redshift limits here. Furthermore, offline intensity and baseband analysis will report the values and their errors that are listed in Table 4–2 here also. Note that these are placeholder values only.

```xml
<Why importance="1.0">
  <Inference probability="0.95" relation="Bayes factor as
  probability">
    <Name>FRB YYYYMMDDx</Name>
    <Concept>Known source association probability</Concept>
  </Inference>
  <Description>CHIME/FRB VOEvent Service subsequent-type alert
  astrophysical probability</Description>
  <Name>RFI classification score</Name>
  <Concept>Astrophysical probability</Concept>
</Why>
```

Figure A–9: Placeholder values for a sample <Why> header in a subsequent-type VOEvent. The importance value is optimal at 1.0 indicating the real-time pipeline classified the CHIME/FRB event as astrophysical with probability 1. The probability is 1.0 indicating that the meta data in the VOEvent was associated with the source FRB YYYYMMDDx with probability 0.95 from the real-time pipeline.

References

[1] R. Abbott, LIGO Scientific Collaboration, and Virgo Collaboration. GW190814: Gravitational Waves from the Coalescence of a 23 Solar Mass Black Hole with a 2.6 Solar Mass Compact Object. *The Astrophysical Journal Letters*, 896(2):L44, June 2020.

[2] National Aeronautics and Space Administration (NASA) web page. About the Swift Gamma-Ray Burst Mission https://swift.gsfc.nasa.gov/about$_{s}wift/.July$2020.

[3] National Aeronautics and Space Administration (NASA) web page. Fermi Gamma-ray Burst Monitor (GBM) https://fermi.gsfc.nasa.gov/science/instruments/gbm.html. July 2020.

[4] National Aeronautics and Space Administration (NASA) web page. InterPlanetary gamma-ray burst timing Network (IPN) https://heasarc.gsfc.nasa.gov/docs/heasarc/missions/ipn.html. July 2020.

[5] National Aeronautics and Space Administration (NASA) web page. Monitor of All-Sky X-ray Image (MAXI) https://heasarc.gsfc.nasa.gov/docs/maxi/. July 2020.

[6] M. Ajello, A. Allafort, M. Axelsson, L. Baldini, G. Barbiellini, M. G. Baring, D. Bastieri, R. Bellazzini, B. Berenji, E. Bissaldi, R. D. Bland ford, E. D. Bloom, R. Bonino, E. Bottacini, T. J. Brandt, J. Bregeon, P. Bruel, R. Buehler, T. H. Burnett, S. Buson, R. A. Cameron, R. Caputo, P. A. Caraveo, J. M. Casandjian, E. Cavazzuti, A. Chekhtman, C. C. Cheung, J. Chiang, G. Chiaro, S. Ciprini, J. Cohen-Tanugi, L. R. Cominsky, D. Costantin, A. Cuoco, S. Cutini, F. D'Ammando, F. de Palma, N. Di Lalla, M. Di Mauro, L. Di Venere, R. Dubois, D. Dumora, C. Favuzzi, E. C. Ferrara, A. Franckowiak, Y. Fukazawa, S. Funk, P. Fusco, F. Gargano, D. Gasparrini, N. Giglietto, R. Gill, F. Giordano, M. Giroletti, T. Glanzman, J. Granot, D. Green, I. A. Grenier, M. H. Grondin, L. Guillemot, S. Guiriec, A. K. Harding, E. Hays, D. Horan, F. Imazato, G. Jóhannesson, T. Kamae, S. Kensei, D. Kocevski, M. Kuss, G. La Mura, S. Larsson, L. Latronico, J. Li, F. Longo, F. Loparco, M. N. Lovellette, P. Lubrano, J. D. Magill, S. Maldera, A. Manfreda, M. N. Mazziotta, P. F. Michelson, T. Mizuno, A. A. Moiseev, M. E. Monzani, E. Moretti, A. Morselli, I. V. Moskalenko, M. Negro, E. Nuss, R. Ojha, N. Omodei, E. Orlando, J. F. Ormes, M. Palatiello, V. S. Paliya,

D. Paneque, M. Persic, M. Pesce-Rollins, V. Petrosian, F. Piron, T. A. Porter, G. Principe, J. L. Racusin, S. Rainò, R. Rando, M. Razzano, S. Razzaque, A. Reimer, O. Reimer, S. Ritz, L. S. Rochester, F. Ryde, P. M. Saz Parkinson, C. Sgrò, E. J. Siskind, F. Spada, G. Spandre, P. Spinelli, D. J. Suson, H. Tajima, M. Takahashi, D. Tak, J. G. Thayer, J. B. Thayer, D. F. Torres, E. Torresi, G. Tosti, E. Troja, J. Valverde, T. M. Venters, G. Vianello, K. Wood, C. Yang, and G. Zaharijas. Fermi-LAT Observations of LIGO/Virgo Event GW170817. *The Astrophysical Journal*, 861(2):85, July 2018.

[7] Hugo A. Ayala Solares, Stephane Coutu, D. F. Cowen, James J. DeLaunay, Derek B. Fox, Azadeh Keivani, Miguel Mostafá, Kohta Murase, Foteini Oikonomou, Monica Seglar-Arroyo, Gordana Tešić, and Colin F. Turley. The Astrophysical Multimessenger Observatory Network (AMON): Performance and science program. *Astroparticle Physics*, 114:68–76, January 2020.

[8] Kevin Bandura, Graeme E. Addison, Mandana Amiri, J. Richard Bond, Duncan Campbell-Wilson, Liam Connor, Jean-François Cliche, Greg Davis, Meiling Deng, Nolan Denman, Matt Dobbs, Mateus Fandino, Kenneth Gibbs, Adam Gilbert, Mark Halpern, David Hanna, Adam D. Hincks, Gary Hinshaw, Carolin Höfer, Peter Klages, Tom L. Landecker, Kiyoshi Masui, Juan Mena Parra, Laura B. Newburgh, Ue-li Pen, Jeffrey B. Peterson, Andre Recnik, J. Richard Shaw, Kris Sigurdson, Mike Sitwell, Graeme Smecher, Rick Smegal, Keith Vanderlinde, and Don Wiebe. Canadian Hydrogen Intensity Mapping Experiment (CHIME) pathfinder. In *Ground-based and Airborne Telescopes V*, volume 9145 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, page 914522, July 2014.

[9] P. Chawla, V. M. Kaspi, A. Josephy, K. M. Rajwade, D. R. Lorimer, A. M. Archibald, M. E. DeCesar, J. W. T. Hessels, D. L. Kaplan, C. Karako-Argaman, V. I. Kondratiev, L. Levin, R. S. Lynch, M. A. McLaughlin, S. M. Ransom, M. S. E. Roberts, I. H. Stairs, K. Stovall, J. K. Swiggum, and J. van Leeuwen. A Search for Fast Radio Bursts with the GBNCC Pulsar Survey. *The Astrophysical Journal*, 844(2):140, August 2017.

[10] CHIME/FRB Collaboration, M. Amiri, K. Bandura, P. Berger, M. Bhardwaj, 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. Höfer, A. Josephy, V. M. Kaspi, T. L. Landecker, D. Lang, H. Liao, K. W. Masui, 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. Ransom, 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.

[11] CHIME/FRB Collaboration, M. Amiri, K. Bandura, M. Bhardwaj, P. Boubel, M. M. Boyce, P. J Boyle, C. . Brar, M. Burhanpurkar, T. Cassanelli, P. Chawla, J. F. Cliche, D. Cubranic, M. Deng, N. Denman, M. Dobbs, M. Fandino, E. Fonseca, B. M. Gaensler, A. J. Gilbert, A. Gill, U. Giri, D. C. Good, M. Halpern, D. S. Hanna, A. S. Hill, G. Hinshaw, C. Höfer, A. Josephy, V. M. Kaspi, T. L. Landecker, D. A. Lang, H. H. Lin, K. W. Masui, R. Mckinven, J. Mena-Parra, M. Merryfield, D. Michilli, N. Milutinovic, C. Moatti, 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, J. R. Shaw, S. R. Siegel, K. M. Smith, I. H. Stairs, S. P. Tendulkar, I. Tretyakov, K. Vanderlinde, and P. Yadav. A second source of repeating fast radio bursts. *Nature*, 566(7743):235–238, January 2019.

[12] CHIME/FRB Collaboration, M. Amiri, K. Bandura, M. Bhardwaj, P. Boubel, M. M. Boyce, P. J. Boyle, C. Brar, M. Burhanpurkar, P. Chawla, J. F. Cliche, D. Cubranic, M. Deng, N. Denman, M. Dobbs, M. Fand ino, E. Fonseca, B. M. Gaensler, A. J. Gilbert, U. Giri, D. C. Good, M. Halpern, D Hanna, A. S. Hill, G. Hinshaw, C. Höfer, A. Josephy, V. M. Kaspi, T. L. Landecker, D. A. Lang, K. W. Masui, R. Mckinven, J. Mena-Parra, M. Merryfield, N. Milutinovic, C. Moatti, A. Naidu, L. B. Newburgh, C. Ng, C. Patel, U. Pen, T. Pinsonneault-Marotte, Z. Pleunis, M. Rafiei-Ravandi, S. M. Ransom, A. Renard, P. Scholz, J. R. Shaw, S. R. Siegel, K. M. Smith, I. H. Stairs, S. P. Tendulkar, I. Tretyakov, K. Vand erlinde, and P. Yadav. Observations of fast radio bursts at frequencies down to 400 megahertz. *Nature*, 566(7743):230–234, January 2019.

[13] CHIME/FRB Collaboration, B. C. Andersen, K. Bandura, M. Bhardwaj, 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. Höfer, 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.

[14] J. M. Cordes and T. J. W. Lazio. NE2001.I. A New Model for the Galactic Distribution of Free Electrons and its Fluctuations. *arXiv e-prints*, pages astro–ph/0207156, July 2002.

[15] Bruce T. Draine. *Physics of the Interstellar and Intergalactic Medium.* 2011.

[16] E. Fonseca, B. C. Andersen, M. Bhardwaj, P. Chawla, D. C. Good, A. Josephy, V. M. Kaspi, K. W. Masui, R. Mckinven, D. Michilli, Z. Pleunis, K. Shin, S. P. Tendulkar, K. M. Bandura, P. J. Boyle, C. Brar, T. Cassanelli, D. Cubranic, M. Dobbs, F. Q. Dong, B. M. Gaensler, G. Hinshaw, T. L. Land ecker, C. Leung, D. Z. Li, H. H. Lin, J. Mena-Parra, M. Merryfield, A. Naidu, C. Ng, C. Patel, U. Pen, M. Rafiei-Ravandi, M. Rahman, S. M. Ransom, P. Scholz, K. M. Smith, I. H. Stairs, K. Vanderlinde, P. Yadav, and A. V. Zwaniga. Nine New Repeating Fast Radio Burst Sources from CHIME/FRB. *The Astrophysical Journal Letters*, 891(1):L6, March 2020.

[17] Susumu Inoue. Probing the cosmic reionization history and local environment of gamma-ray bursts through radio dispersion. *Monthly Notices of the Royal Astronomical Society*, 348(3):999–1008, March 2004.

[18] Kunihito Ioka. The Cosmic Dispersion Measure from Gamma-Ray Burst Afterglows: Probing the Reionization History and the Burst Environment. *The Astrophysical Journal*, 598(2):L79–L82, December 2003.

[19] A. Josephy, P. Chawla, E. Fonseca, C. Ng, C. Patel, Z. Pleunis, P. Scholz, B. C. Andersen, K. Bandura, M. Bhardwaj, M. M. Boyce, P. J. Boyle, C. Brar, D. Cubranic, M. Dobbs, B. M. Gaensler, A. Gill, U. Giri, D. C. Good, M. Halpern, G. Hinshaw, V. M. Kaspi, T. L. Landecker, D. A. Lang, H. H. Lin, K. W. Masui, R. Mckinven, J. Mena-Parra, M. Merryfield, D. Michilli, N. Milutinovic, A. Naidu, U. Pen, M. Rafiei-Ravand i, M. Rahman, S. M. Ransom, A. Renard, S. R. Siegel, K. M. Smith, I. H. Stairs, S. P. Tendulkar, K. Vanderlinde, P. Yadav, and A. V. Zwaniga. CHIME/FRB Detection of the Original Repeating Fast Radio Burst Source FRB 121102. *The Astrophysical Journal Letters*, 882(2):L18, September 2019.

[20] A. Karastergiou, J. Chennamangalam, W. Armour, C. Williams, B. Mort, F. Dulwich, S. Salvini, A. Magro, S. Roberts, M. Serylak, A. Doo, A. V. Bilous, R. P. Breton, H. Falcke, J. M. Grießmeier, J. W. T. Hessels, E. F. Keane, V. I. Kondratiev, M. Kramer, J. van Leeuwen, A. Noutsos, S. Osłowski, C. Sobey, B. W. Stappers, and P. Weltevrede. Limits on fast radio bursts at 145 MHz with ARTEMIS, a real-time software backend. *Monthly Notices of the Royal Astronomical Society*, 452(2):1254–1262, September 2015.

[21] J. I. Katz. Fast radio bursts — A brief review: Some questions, fewer answers. *Modern Physics Letters A*, 31(14):1630013, April 2016.

[22] S. R. Kulkarni, E. O. Ofek, J. D. Neill, Z. Zheng, and M. Juric. Giant Sparks at Cosmological Distances? *The Astrophysical Journal*, 797(1):70, December 2014.

[23] Earl Lawrence, Scott Vander Wiel, Casey Law, Sarah Burke Spolaor, and Geoffrey C. Bower. The Nonhomogeneous Poisson Process for Fast Radio Burst Rates. *The Astronomical Journal*, 154(3):117, September 2017.

[24] D. R. Lorimer, M. Bailes, M. A. McLaughlin, D. J. Narkevic, and F. Crawford. A Bright Millisecond Radio Burst of Extragalactic Origin. *Science*, 318(5851):777, November 2007.

[25] D. R. Lorimer and M. Kramer. *Handbook of Pulsar Astronomy*, volume 4. 2004.

[26] B. Marcote, K. Nimmo, J. W. T. Hessels, S. P. Tendulkar, C. G. Bassa, Z. Paragi, A. Keimpema, M. Bhardwaj, R. Karuppusamy, V. M. Kaspi, C. J. Law, D. Michilli, K. Aggarwal, B. Andersen, A. M. Archibald, K. Bandura, G. C. Bower, P. J. Boyle, C. Brar, S. Burke-Spolaor, B. J. Butler, T. Cassanelli, P. Chawla, P. Demorest, M. Dobbs, E. Fonseca, U. Giri, D. C. Good, K. Gourdji, A. Josephy, A. Yu. Kirichenko, F. Kirsten, T. L. Landecker, D. Lang, T. J. W. Lazio, D. Z. Li, H. H. Lin, J. D. Linford, K. Masui, J. Mena-Parra, A. Naidu, C. Ng, C. Patel, U. L. Pen, Z. Pleunis, M. Rafiei-Ravandi, M. Rahman, A. Renard, P. Scholz, S. R. Siegel, K. M. Smith, I. H. Stairs, K. Vanderlinde, and A. V. Zwaniga. A repeating fast radio burst source localized to a nearby spiral galaxy. *Nature*, 577(7789):190–194, January 2020.

[27] B. Marcote, Z. Paragi, J. W. T. Hessels, A. Keimpema, H. J. van Langevelde, Y. Huang, C. G. Bassa, S. Bogdanov, G. C. Bower, S. Burke-Spolaor, B. J. Butler, R. M. Campbell, S. Chatterjee, J. M. Cordes, P. Demorest, M. A. Garrett, T. Ghosh, V. M. Kaspi, C. J. Law, T. J. W. Lazio, M. A. McLaughlin, S. M. Ransom, C. J. Salter, P. Scholz, A. Seymour, A. Siemion, L. G. Spitler, S. P. Tendulkar, and R. S. Wharton. The Repeating Fast Radio Burst FRB 121102 as Seen on Milliarcsecond Angular Scales. *The Astrophysical Journal Letters*, 834(2):L8, January 2017.

[28] Ben Margalit, Edo Berger, and Brian D. Metzger. Fast Radio Bursts from Magnetars Born in Binary Neutron Star Mergers and Accretion Induced Collapse. *The Astrophysical Journal*, 886(2):110, December 2019.

[29] D. V. et al. Martynov. Sensitivity of the Advanced LIGO detectors at the beginning of gravitational wave astronomy. *Physical Review D*.

[30] S. et al. Mereghetti. INTEGRAL IBIS and SPI-ACS detection of a hard X-ray counterpart of the radio burst from SGR 1935+2154. *The Astronomer's Telegram*, 13685(1), 2020.

[31] Chiara M. F. Mingarelli, Janna Levin, and T. Joseph W. Lazio. Fast Radio Bursts and Radio Transients from Black Hole Batteries. *The Astrophysical Journal Letters*, 814(2):L20, December 2015.

[32] Laura B. Newburgh, Graeme E. Addison, Mandana Amiri, Kevin Bandura, J. Richard Bond, Liam Connor, Jean-François Cliche, Greg Davis, Meiling Deng, Nolan Denman, Matt Dobbs, Mateus Fandino, Heather Fong, Kenneth Gibbs, Adam Gilbert, Elizabeth Griffin, Mark Halpern, David Hanna, Adam D. Hincks, Gary Hinshaw, Carolin Höfer, Peter Klages, Tom Landecker, Kiyoshi Masui, Juan Mena Parra, Ue-Li Pen, Jeff Peterson, Andre Recnik, J. Richard Shaw, Kris Sigurdson, Micheal Sitwell, Graeme Smecher, Rick Smegal, Keith Vand erlinde, and Don Wiebe. Calibrating CHIME: a new radio interferometer to probe dark energy. In *Proceedings of the SPIE*, volume 9145 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, page 91454V, July 2014.

[33] C. Ng, K. Vanderlinde, A. Paradise, P. Klages, K. Masui, K. Smith, K. Bandura, P. J. Boyle, M. Dobbs, V. Kaspi, A. Renard, J. R. Shaw, I. Stairs, and I. Tretyakov. CHIME FRB: An application of FFT beamforming for a radio telescope. *arXiv e-prints*, page arXiv:1702.04728, February 2017.

[34] D.M. Palmer and Swift/BAT Team. A Forest of Bursts from SGR 1935+2154. *The Astronomer's Telegram*, 13675(1), 2020.

[35] E. Petroff, J. W. T. Hessels, and D. R. Lorimer. Fast radio bursts. *The Astronomy and Astrophysics Review*, 27(1), May 2019.

[36] E. Petroff, E. F. Keane, E. D. Barr, J. E. Reynolds, J. Sarkissian, P. G. Edwards, J. Stevens, C. Brem, A. Jameson, S. Burke-Spolaor, S. Johnston, N. D. R. Bhat, P. Chandra S. Kudale, and S. Bhand ari. Identifying the source of perytons at the Parkes radio telescope. *Monthly Notices of the Royal Astronomical Society*, 451(4):3933–3940, August 2015.

[37] Emily Petroff, Leon Houben, Keith Bannister, Sarah Burke-Spolaor, Jim Cordes, Heino Falcke, Ronald van Haren, Aris Karastergiou, Michael Kramer, Casey Law, Joeri van Leeuwen, Duncan Lorimer, Oscar Martinez-Rubi, Jörg Rachen, Laura Spitler, and Amanda Weltman. VOEvent Standard for Fast Radio Bursts. *arXiv e-prints*, page arXiv:1710.08155, October 2017.

[38] Sergey B. Popov and K. A. Postnov. Hyperflares of SGRs as an engine for millisecond extragalactic radio bursts. In H. A. Harutyunian, A. M. Mickaelian, and Y. Terzian, editors, *Evolution of Cosmic Objects through their Physical Activity*, pages 129–132, November 2010.

[39] Akshaya Rane and Duncan Lorimer. Fast Radio Bursts. *Journal of Astrophysics and Astronomy*, 38(3):55, September 2017.

[40] A. et al. Ridnaia. Konus-Wind observation of hard X-ray counterpart of the radio burst from SGR 1935+2154. *The Astronomer's Telegram*, 13688(1), 2020.

[41] A. Rowlinson, M. E. Bell, T. Murphy, C. M. Trott, N. Hurley-Walker, S. Johnston, S. J. Tingay, D. L. Kaplan, D. Carbone, P. J. Hancock, L. Feng, A. R. Offringa, G. Bernardi, J. D. Bowman, F. Briggs, R. J. Cappallo, A. A. Deshpande, B. M. Gaensler, L. J. Greenhill, B. J. Hazelton, M. Johnston-Hollitt, C. J. Lonsdale, S. R. McWhirter, D. A. Mitchell, M. F. Morales, E. Morgan, D. Oberoi, S. M. Ord, T. Prabu, N. Udaya Shankar, K. S. Srivani, R. Subrahmanyan, R. B. Wayth, R. L. Webster, A. Williams, and C. L. Williams. Limits on Fast Radio Bursts and other transient sources at 182 MHz using the Murchison Widefield Array. *Monthly Notices of the Royal Astronomical Society*, 458(4):3506–3522, June 2016.

[42] P. Scholz, L. G. Spitler, J. W. T. Hessels, S. Chatterjee, J. M. Cordes, V. M. Kaspi, R. S. Wharton, C. G. Bassa, S. Bogdanov, F. Camilo, F. Crawford, J. Deneva, J. van Leeuwen, R. Lynch, E. C. Madsen, M. A. McLaughlin, M. Mickaliger, E. Parent, C. Patel, S. M. Ransom, A. Seymour, I. H. Stairs, B. W. Stappers, and S. P. Tendulkar. The Repeating Fast Radio Burst FRB 121102: Multi-wavelength Observations and Additional Bursts. *The Astrophysical Journal*, 833(2):177, December 2016.

[43] Paul Scholz, Laura Spitler, Jason Hessels, Slavko Bogdanov, Adam Brazier, Fernando Camilo, Shami Chatterjee, James M. Cordes, Fronefield Crawford, Julia S. Deneva, Robert Ferdman, Paulo Freire, Victoria M. Kaspi, Patrick Lazarus, Ryan Lynch, Erik Madsen, Maura McLaughlin, Chitrang Patel, Scott M. Ransom, Andrew Seymour, Ingrid H. Stairs, Benjamin Stappers, Joeri van Leeuwen, and Weiwei Zhu. A Repeating Fast Radio Burst: Radio and X-ray Follow-up Observations of FRB 121102. In *AAS/High Energy Astrophysics Division #15*, AAS/High Energy Astrophysics Division, page 105.03, April 2016.

[44] Rob Seaman, Roy Williams, Alasdair Allan, Scott Barthelmy, Joshua Bloom, John Brewer, Robert Denny, Mike Fitzpatrick, Matthew Graham, Norman Gray, Frederic Hessman, Szabolcs Marka, Arnold Rots, Tom Vestrand, and Przemyslaw Wozniak. Sky Event Reporting Metadata Version 2.0. IVOA Recommendation 11 July 2011, July 2011.

[45] Zachary Shand, Amir Ouyed, Nico Koning, and Rachid Ouyed. Quark nova model for fast radio bursts. *Research in Astronomy and Astrophysics*, 16(5):80, May 2016.

[46] L. G. Spitler, J. M. Cordes, J. W. T. Hessels, D. R. Lorimer, M. A. McLaughlin, S. Chatterjee, F. Crawford, J. S. Deneva, V. M. Kaspi, R. S. Wharton, B. Allen, S. Bogdanov, A. Brazier, F. Camilo, P. C. C. Freire, F. A. Jenet, C. Karako-Argaman, B. Knispel, P. Lazarus, K. J. Lee, J. van Leeuwen, R. Lynch, S. M. Ransom, P. Scholz, X. Siemens, I. H. Stairs, K. Stovall, J. K. Swiggum, A. Venkataraman, W. W. Zhu, C. Aulbert, and H. Fehrmann. Fast Radio Burst Discovered in the Arecibo Pulsar ALFA Survey. *The Astrophysical Journal*, 790(2):101, August 2014.

[47] Tim D. Staley. voevent-parse: Parse, manipulate, and generate VOEvent XML packets, November 2014.

[48] J. Swinbank. Comet: A VOEvent broker. *Astronomy and Computing*, 7:12–26, November 2014.

[49] The CHIME/FRB Collaboration, :, B. C. Andersen, K. M. Band ura, M. Bhardwaj, A. Bij, M. M. Boyce, P. J. Boyle, C. Brar, T. Cassanelli, P. Chawla, T. Chen, J. F. Cliche, A. Cook, D. Cubranic, A. P. Curtin, N. T. Denman, M. Dobbs, F. Q. Dong, M. Fandino, E. Fonseca, B. M. Gaensler, U. Giri, D. C. Good, M. Halpern, A. S. Hill, G. F. Hinshaw, C. Höfer, A. Josephy, J. W. Kania, V. M. Kaspi, T. L. Landecker, C. Leung, D. Z. Li, H. H. Lin, K. W. Masui, R. Mckinven, J. Mena-Parra, M. Merryfield, B. W. Meyers, D. Michilli, N. Milutinovic, A. Mirhosseini, M. Münchmeyer, A. Naidu, L. B. Newburgh, C. Ng, C. Patel, U. L. Pen, T. Pinsonneault-Marotte, Z. Pleunis, B. M. Quine, M. Rafiei-Ravandi, M. Rahman, S. M. Ransom, A. Renard, P. Sanghavi, P. Scholz, J. R. Shaw, K. Shin, S. R. Siegel, S. Singh, R. J. Smegal, K. M. Smith, I. H. Stairs, C. M. Tan, S. P. Tendulkar, I. Tretyakov, K. Vanderlinde, H. Wang, D. Wulf, and A. V. Zwaniga. A bright millisecond-duration radio burst from a Galactic magnetar. *arXiv e-prints*, page arXiv:2005.10324, May 2020.

[50] The CHIME/FRB Collaboration, M. Amiri, B. C. Andersen, K. M. Bandura, M. Bhardwaj, P. J. Boyle, C. Brar, P. Chawla, T. Chen, J. F. Cliche, D. Cubranic, M. Deng, N. T. Denman, M. Dobbs, F. Q. Dong, M. Fand ino, E. Fonseca, B. M. Gaensler, U. Giri, D. C. Good, M. Halpern, J. W. T. Hessels, A. S. Hill, C. Höfer, A. Josephy, J. W. Kania, R. Karuppusamy, V. M. Kaspi, A. Keimpema, F. Kirsten, T. L. Landecker, D. A. Lang, C. Leung, D. Z. Li, H. H. Lin, B. Marcote, K. W. Masui, R. Mckinven, J. Mena-Parra, M. Merryfield, D. Michilli, N. Milutinovic, A. Mirhosseini, A. Naidu, L. B. Newburgh, C. Ng, K. Nimmo, Z. Paragi, C. Patel, U. L. Pen, T. Pinsonneault-Marotte, Z. Pleunis, M. Rafiei-Ravandi,

M. Rahman, S. M. Ransom, A. Renard, P. Sanghavi, P. Scholz, J. R. Shaw, K. Shin, S. R. Siegel, S. Singh, R. J. Smegal, K. M. Smith, I. H. Stairs, S. P. Tendulkar, I. Tretyakov, K. Vanderlinde, H. Wang, X. Wang, D. Wulf, P. Yadav, and A. V. Zwaniga. Periodic activity from a fast radio burst source. *arXiv e-prints*, page arXiv:2001.10275, January 2020.

[51] D. Thornton, B. Stappers, M. Bailes, B. Barsdell, S. Bates, N. D. R. Bhat, M. Burgay, S. Burke-Spolaor, D. J. Champion, P. Coster, N. D'Amico, A. Jameson, S. Johnston, M. Keith, M. Kramer, L. Levin, S. Milia, C. Ng, A. Possenti, and W. van Straten. A Population of Fast Radio Bursts at Cosmological Distances. *Science*, 341(6141):53–56, July 2013.

[52] A. Tsvetkova, D. Frederiks, S. Golenetskii, A. Lysenko, P. Oleynik, V. Pal'shin, D. Svinkin, M. Ulanov, T. Cline, K. Hurley, and R. Aptekar. The Konus-Wind Catalog of Gamma-Ray Bursts with Known Redshifts. I. Bursts Detected in the Triggered Mode. *The Astrophysical Journal*, 850(2):161, December 2017.

[53] Jie-Shuang Wang, Yuan-Pei Yang, Xue-Feng Wu, Zi-Gao Dai, and Fa-Yin Wang. Fast Radio Bursts from the Inspiral of Double Neutron Stars. *The Astrophysical Journal Letters*, 822(1):L7, May 2016.

[54] European Space Agency (ESA) web page. INTEGRAL Overview https://sci.esa.int/web/integral/-/31175-instruments?section=overview. July 2020.

[55] Space Science Data Center (SSDC) web page. Astrorivelatore Gamma a Immagini Leggero (AGILE) Mission Overview http://agile.asdc.asi.it/overview.html. July 2020.

[56] K. Yamaoka and Calet Collaboration. CALET GBM Observations of Gamma-ray Bursts and Gravitational Wave Sources. In *35th International Cosmic Ray Conference (ICRC2017)*, volume 301 of *International Cosmic Ray Conference*, page 614, January 2017.

[57] J. M. Yao, R. N. Manchester, and N. Wang. A New Electron-density Model for Estimation of Pulsar and FRB Distances. *The Astrophysical Journal*, 835(1):29, January 2017.

[58] Bing Zhang. Mergers of Charged Black Holes: Gravitational-wave Events, Short Gamma-Ray Bursts, and Fast Radio Bursts. *The Astrophysical Journal Letters*, 827(2):L31, August 2016.

[59] S.N. et al. Zhang. Insight-HXMT X-ray and hard X-ray detection of the double peaks of the Fast Radio Burst from SGR 1935+2154. *The Astronomer's Telegram*, 13696(1), 2020.