Mock TAC Proposal

Observational Techniques of Modern Astrophysics — PHYS 641 — Fall 2018

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Fast Radio Burst VLBI Localization with CHIME

Abstract

Subarcsecond localization is crucial for exploring FRB origins. In this proposal we put forth a plan to localize FRBs using interferometric techniques to correlate signals at $\sim 800\,\mathrm{MHz}$ from compatible dishes at the Canadian Hydrogen Intensity Mapping Experiment (CHIME), Algonquin Radio Observatory (ARO), and the Green Bank Telescope (GBT). We ask for a short concurrent pulsar observation with these three instruments to serve as a proof-of-concept for future repeating FRB localizations and to aid in the design and development of CHIME VLBI outrigger dishes.

Scientific Justification

1 Fast Radio Burst Localization

Fast Radio Bursts (FRBs) are highly dispersed radio transients of millisecond duration and unknown extragalactic origin coming from seemingly random locations on the sky. Since their initial discovery eleven years ago in Parkes Radio Telescope archival data (Lorimer et al., 2007), more than 60 FRBs have been detected at multiple observatories around the world (e.g., Thornton et al., 2013; Spitler et al., 2014; Masui et al., 2015; Caleb et al., 2017; Farah et al., 2018; Shannon et al., 2018). These detections have manifested at radio frequencies ranging from 400 MHz to 8 GHz and peak flux densities ranging from 0.1 to 100 Jy.[1] Current estimated rates suggest that FRBs are prolific, occurring ~ 1000 times across the sky per day (Lawrence et al., 2017). Despite recent rapid advances, we are still just beginning to understand FRBs, and fundamental questions about FRB origins and population characteristics remain largely unanswered.

Our understanding of the underlying physical mechanism of these enigmatic bursts has been significantly limited by our inability to spatially associate them with their progenitors. Most FRBs that have been discovered to-date were detected using single-dish radio telescopes with ∼arcminute localization capability insufficient to identify a host galaxy, let alone a progenitor source within the galaxy. Only a single **repeating burst**, FRB 121102, has been successfully localized to a host galaxy with subarcsecond-level precision using interferometric observations from the Very Large Array ($0.1''$; Chatterjee et al., 2017). This localization was a pivotal moment for FRB science, unambiguously confirming the extragalactic nature of FRBs and enabling multi-wavelength follow-up that illuminated the host environment. Optical observations from the Gemini North telescope identified the host as a low-metallicity, star-forming dwarf galaxy located at $z \sim 0.2$ (Tendulkar et al.,

[1]See http://www.frbcat.org

2017). Higher resolution follow-up from the European VLBI Network ($0.005''$; Marcote et al., 2017) further identified that the bursts were coincident with a persistent radio source offset from the galaxy center. Green Bank Telescope (GBT) observations revealed the high rotation measure of subsequent bursts, consistent with an extreme magneto-ionic environment around the progenitor (Michilli et al., 2018). The sum of these results has led to more informed speculation about the source of the bursts, with some theories pointing to a highly magnetized wind nebula or supernova remnant surrounding a young neutron star.

The abundance of science resulting from just this single localization of FRB 121102 is a testament to the importance of host identification and characterization. Further localizations of both repeating and non-repeating FRBs are crucial to developing a more generalized picture of FRB origins. However, it is important to note that **the localization of FRB121102 was uniquely enabled by its repeating nature**. Although interferometric instruments like the VLA and EVN have subarcsecond resolution, their fields of view are so small (typically $1.2\lambda/D \sim 30'$ at L-band), that it could take upwards of $\sim$ 1000 hours of blind searching to detect a non-repeating FRB (see Appendix for typical calculation). Although this can, in principle, be done (see efforts by the `realfast` team to produce a commensal FRB search at the VLA; Law et al., 2018), a repeating FRB lends itself to more efficient localization since interferometric searches can be focused on the $\sim$arcminute field of view suggested by the initial single-dish detection.

2 CHIME

The Canadian Hydrogen Intensity Mapping Experiment (CHIME) is a new 400 to 800 MHz transit radio telescope located at the Dominion Radio Astrophysical Observatory in British Columbia, Canada. CHIME consists of four 20 m by 100 m cylindrical reflectors oriented such that the field of view extends 100° in the North-South direction and 2° in the East-West direction (CHIME/FRB Collaboration et al., 2018). Significant effort has been expended to develop a robust CHIME/FRB backend software pipeline for mitigating RFI and detecting FRBs over the entire $\sim$ 200 square degree field of view in real-time. CHIME's large field of view and high sensitivity make it uniquely poised to detect FRBs, with current rate estimates indicating that CHIME could detect anywhere from 2 to 42 FRBs per day (Chawla et al., 2017). In fact, although CHIME/FRB is still in its precommissioning phase, it has already detected multiple FRBs (see ATel #11901). In addition, as a transit telescope, CHIME will be especially good at identifying repeating FRBs by observing their sky positions every day, achieving a better sampling than most other FRB surveys.

Although the deluge of detections expected from CHIME/FRB promises to revolutionize our understanding of FRB population statistics, CHIME's current design can only localize these detections to within $\sim$ 10 arcminutes, which is insufficient for host identification. However, **interferometric follow-up, especially of repeating FRBs detected by CHIME/FRB, is a promising avenue for localization.** Another longer-term option would be to combine the advantages of VLBI subarcsecond localization with the CHIME field of view by correlating CHIME/FRB baseband data with those obtained from an array of CHIME/FRB "outriggers" located across North America. **The first incremental step to developing these outriggers is to test CHIME VLBI with other existing compatible telescopes.** Such a test would necessitate the development of tools that could be used later in outrigger designs, such as a system for triggering baseband dumps at VLBI stations based on CHIME FRB detections as well as CHIME-tailored VLBI calibration and correlation software.

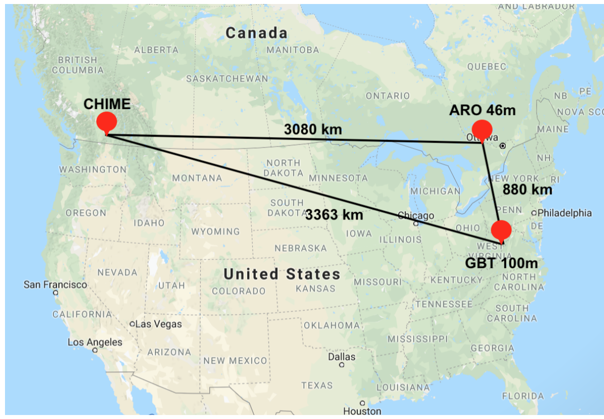

Figure 1: A map showing the location of each of the sites in our proposed VLBI network with baseline distances labeled (courtesy of Google Maps).

Technical Justification

3 VLBI Proposal

In this proposal we put forth a plan to localize FRBs using interferometric techniques to correlate signals received at CHIME, the Algonquin Radio Observatory (ARO) 46 m, and the GBT 100 m for a frequency range of 680 to 800 MHz (bandwidth 120 MHz). This particular set of telescopes has been chosen for a number of reasons:

1) Both the ARO 46 m and the GBT have receivers that allow observing in frequency ranges overlapping the CHIME band, a necessity for VLBI correlation. More specifically, the ARO 46 m has a UHF receiver and the GBT has the PF1 receiver ranging from 680 MHz to 920 MHz.

2) All of these telescopes have masers on-site with sufficient timing precision for VLBI correlation.

3) The layout of the baselines between each of these telescopes will allow us to achieve subarcsecond localization in two dimensions. For example, our longest baseline extends from from CHIME to the GBT, spanning an approximate distance of $b = 3363$ km (see Figure 1). This gives us a maximum resolution of $\theta_{\rm res} = 1.2\lambda/b \sim 0.030''$ in the middle of the band at 740 MHz. By similar calculations, the baselines from CHIME to ARO and ARO to the GBT yield resolutions of $\sim 0.033''$ and $\sim 0.11''$, respectively. Thus, although our localization capabilities will vary directionally, the suggested baselines should be sufficient for 2D subarcsecond localization (see Figure 2).

4) With CHIME, we can leverage the pre-existing FRB detection pipeline to trigger baseband dumps at the other stations in quasi-real-time as FRBs are detected in the VLBI field of view.

As an initial step in the commissioning of this system, we request a short concurrent baseband observation of a pulsar to test our astrometry. Using these observations, we will conduct an analysis similar to that presented in section 3.2 of Marcote et al. (2017). Given the duration of the bursts (∼milliseconds), our interferometric VLBI data for each burst can only contain a very limited amount of uv-coverage, resulting in strong sidelobes in the image plane (see Figure 2). We can use the pulsar pulses from our observation as an FRB analogue to test how these sidelobes affect our localization ability.

In short, this observation would allow us to test out VLBI with CHIME in preparation for repeater localization efforts in the short-term, and provide an initial proof-of-concept for future CHIME outrigger stations in the long-term.

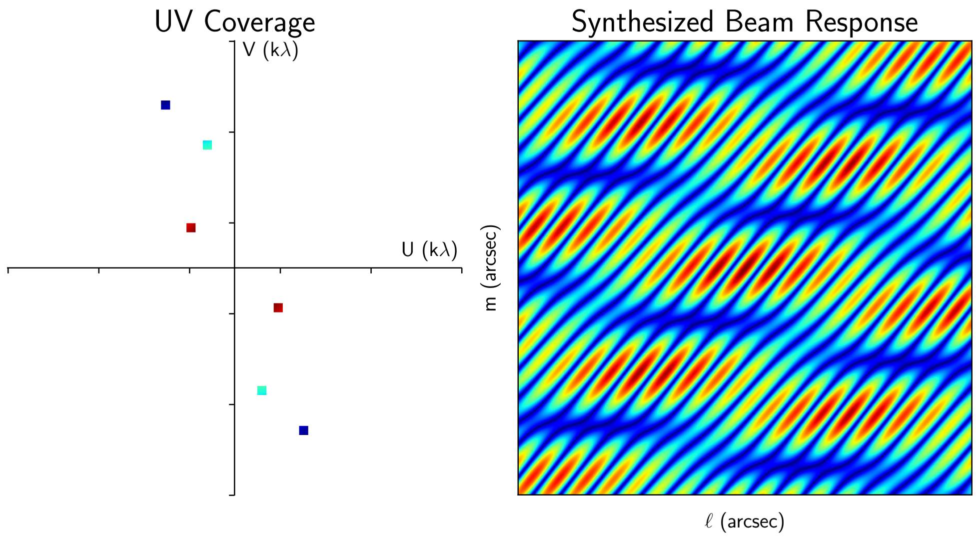

Figure 2: A qualitative monochromatic simulation of the general shape of the instantaneous uv-coverage for our proposed VLBI network (left) as well as the resulting synthesized beam response to a point source (right). Note the large sidelobes. Also, the beam shape is elongated in the diagonal direction and shortened in the horizontal direction due to the varying baseline lengths between each VLBI station. Regardless, based on our calculations in section 3, the beam shape should be small enough in each direction to achieve subarcsecond localization.

4 Observation Specifications

We request a concurrent baseband observation of the well-known pulsar PSR B0329+54 (α = 03:32:59.368, δ = +54:34:43.57) as it has already been detected by the CHIME/FRB backend. Since the period of B0329+54 is 0.7145 s (Manchester et al., 2005), observing for 10-minutes would give us approximately $\sim$ 840 pulses to localize, allowing us to create a distribution of positions. The ARO 46 m should observe with its UHF receiver and the GBT with the PF1 receiver. We also require a 3-minute observation of the phase calibrator J0347+555, which is 2.54° away from the pulsar.

Since CHIME/FRB cannot track, the observations must occur when B0329+54 and the phase calibrator are transiting the CHIME beam. Other than this restriction, the scheduling of the observation is flexible.

References

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Appendix

Note that this section is just for fun. I only calculated it for my own education and to use a bunch of the concepts that we learned in this course. It is not necessary for understanding my proposal.

In this appendix, we step through the calculation of the approximate number of hours that would be needed to detect an FRB in a blind search using the VLBI setup that we outline in section 3. Since we plan on saving baseband for each of the telescopes once an FRB is detected in CHIME, the number of hours will be constrained by the sensitivity of CHIME and the smallest field of view of all the dishes in our interferometer. First, we estimate the minimum detectable flux density S_0 for FRBs searched with CHIME using the modified radiometer equation for FRB searches (Cordes & McLaughlin, 2003; Chawla et al., 2017):

$$S_0 = \frac{(S/N)_b\,(T_{\rm rec} + T_{\rm sky})}{G W_i}\sqrt{\frac{W_b}{n_p \Delta\nu}} \tag{1}$$

where $(S/N)_b$ is the minimum detectable signal-to-noise ratio of the broadened burst, $T_{\rm rec}$ is the receiver temperature, $T_{\rm sky}$ is the sky temperature, W_i and W_b are the intrinsic and broadened burst widths, G is the telescope gain, n_p is the number of polarizations summed, and $\Delta\nu$ is the bandwidth. The broadened pulse width W_b accounts for both instrumental and propagation effects, and is calculated as:

$$W_b = \sqrt{W_i^2 + t_{\rm samp}^2 + t_{\rm chan}^2 + t_{\rm scatt}^2} \tag{2}$$

where $t_{\rm samp}$ is the telescope sampling time and $t_{\rm scatt}$ is the scattering time of the burst. The dispersive delay within each frequency channel is given by (Lorimer et al., 2005):

$$t_{\rm chan} = 8.3\mu s \left(\frac{\Delta\nu_{\rm chan}}{\rm MHz}\right)\left(\frac{\nu}{\rm GHz}\right)^{-3}\left(\frac{\rm DM}{\rm pc\,cm^{-3}}\right) \tag{3}$$

The sky temperature in equation 4 is approximated by extrapolating the $T_{\rm sky,0} = 34\,{\rm K}$ average sky temperature obtained from the 408 MHz Remazeilles et al. (2015) temperature map to the CHIME central observing frequency $\nu = 650\,{\rm MHz}$ using a simple power law with index -2.6. The resulting estimated sky temperature is $T_{\rm sky} \sim 10\,{\rm K}$. We also take the dispersion measure in equation 4 to be the average of known FRBs: ${\rm DM} = 756\,{\rm pc\,cm^{-3}}$. The channel bandwidth is given by $\Delta\nu_{\rm chan} = \Delta\nu/N_{\rm chan} = 25\,{\rm kHz}$, where $\Delta\nu = 400\,{\rm MHz}$ and $N_{\rm chan} = 16000$.

The rest of the necessary parameters are set by the system properties of CHIME (see CHIME/FRB Collaboration et al., 2018) and our desire to derive a *minimum* observing time: $n_p = 2$, $t_{\rm samp} = 0.983\,{\rm ms}$, $t_{\rm scatt} \sim 0\,{\rm ms}$, $(S/N)_b = 10$, $W_i \sim 5\,{\rm ms}$, $T_{\rm rec} = 50\,{\rm K}$, and $G = 1.38\,{\rm K/Jy}$. Plugging all of these into equation 4 yields a minimum detectable flux density of $\boxed{S_0 = 0.22\,{\rm Jy}.}$

Next, we start with the FRB rate estimated by Vander Wiel et al. (2016) for high galactic latitudes where CHIME primarily observes: $R_{\rm ref} = 2866\,{\rm sky^{-1}\,day^{-1}}$ at $\nu_{\rm ref} = 1.4\,{\rm GHz}$ above $S_{\rm ref} = 1\,{\rm Jy}$. Assuming power-law relations for the spectral index and flux distribution of

FRBs ($S_\nu \propto \nu^\alpha$ and $N(> S) \propto S^{-\gamma}$), we can then extrapolate this rate to the observing frequency and sensitivity of CHIME using the following equation:

$$R\left(> S_0\right) = R_{\mathrm{ref}} \left(\frac{S_0}{S_{\mathrm{ref}} \left(\frac{\nu_0}{\nu_{\mathrm{ref}}}\right)^{\alpha}} \right)^{-\gamma} = R_{\mathrm{ref}} \left(\frac{S_0}{S_{\mathrm{ref}}}\right)^{-\gamma} \left(\frac{\nu_0}{\nu_{\mathrm{ref}}}\right)^{\alpha\gamma} \tag{4}$$

where we set $\alpha = 0.3$ and $\gamma = 1.5$ (euclidean) based on the constraints given by (Chawla et al., 2017). Now of course this equation is inaccurate because it does not allow for a range of FRB spectral indices and scattering timescales. However, for the purposes of our estimation, it will do. We use this equation with $\nu_0 = 800\,\mathrm{MHz}$ to obtain a rate of $\boxed{R\left(> 0.22\,\mathrm{Jy}\right) = 20615\,\mathrm{sky}^{-1}\,\mathrm{day}^{-1}}$ at 800 MHz.

Next, we need to determine the smallest single-dish field of view of our VLBI setup that limits the amount of sky that we can probe at any given moment. In our case, the GBT gives the smallest field of view, the FWHM diameter of which we can calculate simply:

$$\theta_{\mathrm{FWHM}} = \frac{1.2\lambda}{D} = \frac{1.2\left(\frac{3\cdot 10^8\,\mathrm{m/s}}{800\cdot 10^6\,\mathrm{Hz}}\right)}{100\,\mathrm{m}} \sim 15.5' \tag{5}$$

Then approximating the GBT beam as a 2D Gaussian, the solid angle covered by the beam is given by:

$$\Omega = \left(\frac{\pi}{4\ln(2)}\right) \cdot \theta_{\mathrm{FWHM}}^2 = \boxed{0.075\,\mathrm{deg}^2} \tag{6}$$

Next, assuming that FRBs that FRBs follow Poisson statistics, the probability of detecting N FRBs is given by:

$$P(N) = \frac{(RT\Omega)^N\, e^{-(RT\Omega)}}{N!} \tag{7}$$

where R is the predicted rate, T is the amount of time observed, and Ω is the solid angle of the limiting beam. Then we have that the probability of detecting at least one FRB in a time interval T is:

$$P(\geq 1) = 1 - P(0) = 1 - e^{-(RT\Omega)} \tag{8}$$

Solving this for the amount of observing time needed and plugging in our derived values for the rate and a probability of 95%:

$$T = -\frac{1}{R\Omega}\ln\left(1 - P(\geq 1)\right) = -\frac{\ln\left(1 - 0.95\right)}{\left(20615\,\mathrm{sky}^{-1}\,\mathrm{day}^{-1}\right)\left(0.075\,\mathrm{deg}^2\right)} = 1910\,\mathrm{hours} \tag{9}$$

Therefore, our calculations indicate that it would take at least ~ 2000 hours of blind searching to detect a burst with 95% confidence using our VLBI setup.