A Synoptic VLBI Technique for Localizing Nonrepeating Fast Radio Bursts with CHIME/FRB

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Received 2020 August 25; revised 2020 December 2; accepted 2020 December 5; published 2021 January 22

Abstract

We demonstrate the blind interferometric detection and localization of two fast radio bursts (FRBs) with subarcminute precision on the 400 m baseline between the Canadian Hydrogen Intensity Mapping Experiment (CHIME) and the CHIME Pathfinder. In the same spirit as Very Long Baseline Interferometry (VLBI), the telescopes were synchronized to separate clocks, and the channelized voltage (herein referred to as baseband) data were saved to a disk with correlation performed offline. The simultaneous wide field of view and high sensitivity required for blind FRB searches implies a high data rate—6.5 terabits per second (Tb/s) for CHIME and 0.8 Tb s−1 for the Pathfinder. Since such high data rates cannot be continuously saved, we buffer data from both telescopes locally in memory for ≈40 s, and write to the disk upon receipt of a low-latency trigger from the CHIME Fast Radio Burst Instrument (CHIME/FRB). The ≈200 deg2 field of view of the two telescopes allows us to use in-field calibrators to synchronize the two telescopes without needing either separate calibrator observations or an atomic timing standard. In addition to our FRB observations, we analyze bright single pulses from the pulsars B0329+54 and B0355+54 to characterize systematic localization errors. Our results demonstrate the successful implementation of key software, triggering, and calibration challenges for CHIME/FRB Outriggers: cylindrical VLBI outrigger telescopes which, along with the CHIME telescope, will localize thousands of single FRB events with sufficient precision to unambiguously associate a host galaxy with each burst.

Unified Astronomy Thesaurus concepts: Very long baseline interferometry (1769); Radio astrometry (1337); Radio transient sources (2008); Radio pulsars (1353)

1. Introduction

Fast radio bursts (FRBs; Lorimer et al. 2007; Thornton et al. 2013) are brief (~millisecond), usually nonrepeating radio transient events. One of the most salient characteristics of FRBs is the amount of dispersive temporal smearing of the burst caused by the presence of a cold plasma along the line of sight. The amount of smearing in FRBs, quantified by the dispersion measure (DM), can significantly exceed the amount predicted by the electron content of the Milky Way. Currently, their progenitors and production mechanism are unknown but their high luminosity and impulsive nature have generated significant interest in the astrophysics community (Platts et al. 2019). In addition, due to their cosmological distances (Thornton et al. 2013), FRB pulses are strongly dispersed by the ionized intergalactic medium and have the potential to probe the large-scale structure of the universe (McQuinn 2014; Masui & Sigurdson 2015; Macquart et al. 2020).

The vast majority of FRBs are not observed to emit multiple bursts (Petroff et al. 2016),12 and the handful of known repeaters are observed to do so stochastically with the notable exceptions of FRB 180916.J0158+65 (CHIME/FRB Collaboration et al. 2020a) and possibly FRB 121102 (Zhang et al. 2018; Rajwade et al. 2020). This unpredictability makes localization and follow-up studies extremely challenging. Since the serendipitous detection of the first FRB in 2007 (Lorimer et al. 2007), two repeating FRBs have been studied with Very Long Baseline Interferometry (VLBI): FRB 121102 (Chatterjee et al. 2017; Marcote et al. 2017), with optical follow up performed by Tendulkar et al. (2017), and FRB 180906.J0158+65 (Marcote et al. 2020). The localization of seven others with sufficient precision to identify their respective host

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12 See http://frbcat.org/ for the latest statistics on repeat bursts from known FRB sources.
galaxies at redshifts between $z = 0.1$–$0.6$ (Bannister et al. 2019; Prochaska et al. 2019; Ravi et al. 2019; Macquart et al. 2020) demonstrated a modern-universe measurement of $\Omega_b$ using FRBs, including the so-called missing baryons. This measurement is consistent with that of Planck Collaboration et al. (2020), experimentally evaluating the possibility of using localized FRBs as cosmological probes (Macquart et al. 2020).

Having detected over 700 FRBs in its first year of operation (Fonseca et al. 2020), the Canadian Hydrogen Intensity Mapping Experiment (CHIME)/FRB Project (CHIME/FRB Collaboration et al. 2018) has opened up a window for population-level studies of the properties of FRBs (Josephy et al. 2019; CHIME/FRB Collaboration et al. 2019b, 2019a; Fonseca et al. 2020; CHIME/FRB Collaboration et al. 2020a, 2020b). However, the real-time localization pipeline of CHIME/FRB, which has a precision of arcminutes, does not yet always allow for unambiguous identification of an FRB’s host galaxy. For very bright FRBs with very low DM excess, it has been shown that identifying a host is possible by imposing a prior on the host galaxy’s maximum redshift (Michilli et al. 2020; M. Bhardwaj et al. 2021, in preparation).

To routinely pinpoint the host galaxy of FRBs detected by CHIME/FRB, the CHIME/FRB collaboration is developing CHIME/FRB Outriggers, a set of cylindrical telescopes at distances of one hundred to several thousand kilometers from the CHIME telescope. The outriggers will take real-time detection triggers from CHIME to dump voltage data to a disk. This capability will enable a blind, wide-field VLBI survey to localize thousands of FRBs with astrometric precision matching that of leading optical telescopes. To our knowledge, there has only been one previous attempt to blindly localize FRBs with VLBI. V-FASTR was a campaign to search for FRBs in real-time data taken by the Very Long Baseline Array (Wayth et al. 2011; Burke-Spolaor et al. 2016; Wagstaff et al. 2016). During this campaign, no FRBs were found, highlighting the difficulty of detecting FRBs with traditional radio telescopes. In contrast, the CHIME/FRB Outriggers program will combine CHIME/FRB’s high discovery rate with the localization precision afforded by continental baselines, allowing astronomers to conduct detailed population-level studies of FRB host environments.

We report here on the development of a voltage recording backend as a testbed for CHIME/FRB Outriggers that was deployed on the CHIME Pathfinder, itself a reduced-scale testbed for the CHIME telescope (Bandura et al. 2014). We demonstrate a synoptic VLBI calibration technique for CHIME/FRB outriggers, and demonstrate the performance of our technique on automatically triggered single-pulse detections of the bright pulsars B0329+54 and B0355+54. We also localize two FRBs detected during two observing campaigns using CHIME and the Pathfinder in 2019 October and December.

2. Instrumentation

CHIME (Bandura et al. 2014) is a beamforming (Ng et al. 2017) interferometer located at the Dominion Radio Astrophysical Observatory (DRAO) near Penticton, British Columbia, Canada. It consists of four stationary 20 m $\times$ 100 m parabolic cylindrical reflectors oriented north–south; each reflector focuses incoming radiation onto a focal line with 256 uniformly spaced, dual-polarization antennas for a total of 2048 correlator inputs. Operating as a phased array over the frequency range of 400–800 MHz, each reflector has a primary beam of 2$^\circ$.6–1$^\circ$.3 east–west, directable to any north–south direction from horizon to horizon, with north–south beamwidth increased by the cosecant of the zenith angle of the pointing direction.

The telescope backend is constructed with a two-stage FX correlator architecture. The first correlator stage, the F-engine, digitizes the analog voltage inputs and spectrally divides the incoming data into 1024 frequency channels over the 400–800 MHz frequency band using a polyphase filter bank (Bandura et al. 2016). It is synchronized to a GPS-disciplined ovenized crystal oscillator. The channelized voltage data, hereafter referred to as baseband data, are passed to the second stage of the correlator (the X-engine; Denman et al. 2015) at a 4 real + 4 imaginary bit depth, for all 1024 frequencies and 2048 correlator inputs every 2.56 $\mu$s for an overall rate of 6.5 Tb s$^{-1}$. In addition to performing real-time processing, the X-engine buffers the baseband data in memory in a 36 s ring buffer. When the real-time FRB search pipeline (CHIME/FRB Collaboration et al. 2018) detects an FRB candidate, it reports a time of arrival referenced to 400 MHz and a coarse estimate of the FRB’s DM with uncertainties. In real time, the time of the burst’s arrival as a function of frequency is calculated for all 1024 observing frequencies, and a different $\approx$100 ms segment of data is dumped to a disk. The exact duration of the dumped segment is determined by the uncertainty in the DM estimated by the real-time search pipeline.

The CHIME Pathfinder was constructed prior to CHIME and is used for ongoing technology development for projects such as CHIME/FRB Outriggers. It has approximately one-eighth of the collecting area of CHIME and operates on an independent clock. The effective baseline of Pathinder is 385.4 m due east, 50.4 m due south, and 5.2 m lower in altitude than that of CHIME. It consists of two 20 m $\times$ 40 m cylinders which have the same field of view as CHIME, and have 64 dual-polarization antennas per cylinder for a total of 256 correlator inputs. The Pathinder has the same F-engine architecture as CHIME, and runs on an independent GPS-disciplined crystal oscillator from that of CHIME. However, in contrast to a full FX correlator, the Pathinder F-engine feeds baseband data to a baseband recorder backend. This backend, shown in Figure 1, was constructed to demonstrate the technique of triggered VLBI observations for CHIME/FRB Outriggers. Using four server-grade network cards which each provide 80 Gb s$^{-1}$ of bandwidth, the recorder stores baseband data in RAM for a quarter of CHIME/FRB’s 1024 frequency channels, spaced approximately evenly across the band, at an input data rate of 204.8 gigabits per second (Gb/s; for details, see the Appendix). Our ring buffer architecture is implemented in kotekan,13 a flexible and efficient software framework written in C++ for real-time data processing for digital radio astronomy (Recnik et al. 2015).

3. Interferometric Localization

3.1. Detection at CHIME

CHIME/FRB features a real-time processing pipeline that coarsely estimates the DM, time of arrival, and signal-to-noise ratio (S/N) of dispersed radio transients (CHIME/FRB Collaboration et al. 2018). Upon detecting a sufficiently bright transient, a classification algorithm filters out false positives

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13 https://github.com/kotekan/kotekan
from radio frequency interference and known pulsars. Successful classification of a dispersed radio transient as an FRB triggers the dump of $\approx 100$ ms of baseband data to a disk at both telescopes with subsecond latency.

After the data is dumped to the disk, but prior to the data transfer and cross-correlation, the baseband data from only the CHIME/FRB instrument are processed to estimate the FRB’s dispersion measure and sky position. This is done by beamforming baseband data from CHIME/FRB’s 2048 correlator inputs toward a regular grid of $3 \times 10$ sky positions spaced by $0.1$ degrees around the real-time detection position (Michilli et al. 2020). We choose the optimal sky position by calculating the $S/N$ of the burst detection for each grid location, and then fitting a 2D Gaussian model to the resulting intensity map of the signal. Finally, we perform coherent de-dispersion to the optimal DM maximizing the burst $S/N$ and form tied-array beams for both linear polarizations (north–south and east–west, hereafter NS and EW) to the refined coordinates provided by the baseband pipeline. Similarly, we produce tied-array beams for both polarizations on calibrator sources that are in the field of view of both telescopes (which we discuss in Section 3.3).

We denote the beamformed baseband data from CHIME as $F_{\nu \theta \nu \nu}^C$. Here, $C$ stands for CHIME while $\nu$ represents the frequency channel ($N_\nu = 1024$) ranging from 400 to 800 MHz. The integer $b$ indexes whether the beam is formed toward the FRB position or a calibrator position, as well as the antenna polarization (NS or EW). Finally, $t$ is the time index, measured in units of 2.56 $\mu$s. We calculate the flux as a function of the frequency channel, polarization, and time block, albeit at a lower time resolution, indexed by $T$:

$$ S_{\nu \theta \nu \nu}^C = \sum_{t \equiv T} F_{\nu \theta \nu \nu}^C t. $$

(1)

Setting the integration time as $t_{\text{int}} = 40.96$ $\mu$s yields the plots in Figure 2.

3.2. FRB Cross-correlation Pipeline

Our cross-correlation pipeline picks up where the baseband pipeline leaves off. Due to the reduced sensitivity of the Pathfinder, we only cross-correlate the baseband data from bright FRBs. The GPS timestamps of each triggered baseband dump are recorded as a function of frequency; this allows us to align the baseband data from both telescopes. On our short baseline, the geometric delays expected are not larger than 2.56 $\mu$s. This eliminates the need for additional alignment of the data streams due to geometric delays, though it is in principle possible.

We calculate beamformed baseband data at both telescopes ($F_{b\theta}^C$ for CHIME and $F_{b\theta}^P$ for the Pathfinder) and correlate the baseband data channel by channel in segments of $40.96$ $\mu$s. For each segment we calculate the complex temperature-normalized visibility $V_{b\theta}^{CP}$ as a function of frequency, polarization/beam, and time block $T$ as we did previously for the flux. Here, we use the bar to denote complex conjugation:

$$ V_{b\theta}^{CP} = \frac{\sum_{i=1}^{T+\int_{t_{\text{int}}}} F_{i \theta \nu \nu}^C F_{i \theta \theta \nu}^{P}}{\sqrt{\sum_{i=1}^{T+\int_{t_{\text{int}}}} |F_{i \theta \nu \nu}^C|^2 \sum_{i=1}^{T+\int_{t_{\text{int}}}} |F_{i \theta \theta \nu}^{P}|^2}}. $$

(2)

The visibility, $V_{b\theta}^{CP}$, which encapsulates the cross-correlation information between the two sites, is complex-valued much like the baseband data. For geometric delays shorter than 2.56 $\mu$s the information about the geometric delay is completely encoded in the phase of the numerator of $V_{b\theta}^{CP}$. The denominator ensures that changing the system gain (i.e., scaling any of the $F_{b\theta}$ by a constant factor) does not affect $|V_{b\theta}^{CP}|$. Hence, $|V_{b\theta}^{CP}|$ as plotted in Figure 3, measures the strength of the cross-correlation independently of the system temperature. The morphological similarity of $|V_{b\theta}^{CP}|$ in Figure 3 and $S_{b\theta}$ in Figure 2 allows us to unambiguously interpret
our cross-correlated baseband data as a genuine FRB detection. The FRB signal is fainter at high frequencies in cross-correlation. However, slight morphological differences between the dynamic spectrum of the CHIME autocorrelation and the CHIME Pathfinder cross-correlation are expected since the analog frequency responses of the two telescopes are different. The overall response of the Pathfinder analog receiving system has lower gain and higher noise at higher frequencies. The CHIME analog receiving system is an evolution of the Pathfinder system and includes a gain shaping network that flattens the overall frequency response. We cross-correlate the NS polarizations and EW polarizations at both telescopes separately; since the two telescopes’ polarization axes differ by only ≈2 degrees, this approach is close to optimal.

While the above visibilities are sufficient for assessing a detection, for astrometric precision it is necessary to minimize the uncertainty on the phase of the visibility. To do this, we formed a set of visibilities in which we integrated over the entire ≈100 ms baseband dump to reduce statistical uncertainty of the visibility phase. In addition, for the beams with pulsed emission we perform the integration with the help of a real-valued time-domain matched filter, \( h_\nu \), constructed from the pulse’s intensity profile as detected in CHIME autocorrelation (i.e., the curves shown in the top panel of Figure 2).

\[
V_{\nu b}^{CP} = \frac{\sum_i P_{\nu b}^i h_\nu F_{\nu b}^i}{\sqrt{\sum_i |F_{\nu b}^i|^2}}
\]

The filter is normalized to have \( \langle h_\nu \rangle = 0 \) and \( \langle h_\nu^2 \rangle = 1 \). The former constraint enables optimal rejection of steady sources of correlated voltage signals other than the pulse of interest, and the latter constraint ensures that the noise variance of the data is preserved.

### 3.3. Synoptic Calibration Technique

Our calibration technique fundamentally relies on in-field steady sources to keep the two telescope backends synchronized over the ~10 s duration of the dispersed burst. It is very similar to the in-field calibration technique used in Bannister et al. (2019), the primary difference being the calibration being done in visibility space rather than by creating a map of the field. Each array only needs to be individually synchronized once per day during the transit of a bright radio calibrator, to recompense for the slow thermal expansion of cables between the antennas and the correlator. However, since CHIME and the Pathfinder are each synchronized to independent ovenized crystal oscillator clocks, the time difference between the two arrays jitters on timescales of minutes. Clock jitter and differences in the telescopes’ analog chains introduce an unknown instrumental phase between the two telescopes which must be calibrated near or during the time of observation. By referencing a passive hydrogen maser we have measured the jitter of one of our ovenized crystal oscillator clocks to be on the order of 30–50 ps rms jitter on minute-long timescales, which corresponds to an Allan deviation of \( \sim 10^{-12} \).

To solve for the instrumental phase, we used the fact that the primary beams of CHIME and Pathfinder completely overlap and that their large size virtually guarantees that there will be ~5–10 bright calibrators from the NRAO VLA Sky Survey (NVSS) Catalog (Condon et al. 1998) calibrators \( S_\nu > 1.5 \) Jy detectable with a high S/N in 100 ms of integration time. After dumping the data to the disk, seven of the brightest NVSS calibrators within the field of view are selected based on their proximity to the local meridian. As described earlier in Section 3.1, we form a total of 16 beams from each triggered baseband dump: one per polarization (NS and EW) per source (one transient and seven steady-source calibrators) toward cataloged positions of the calibrators as well as our initial estimate of the transient’s position from the CHIME/FRB baseband pipeline. We calculated the visibility between the two telescopes as a function of beam and frequency as described in Equation (3) and we fit a delay model.

### 3.4. Delay Model

For each formed beam (indexed by \( b \)) and each frequency channel (indexed by \( \nu \)), our general delay model (more generally, a phase model) can be written as

\[
\Phi_{\nu b} = \phi_{\nu b}^i + \ddot{u}(\nu) + \frac{K \Delta DM(\hat{n}_b)}{\nu},
\]

where \( \phi_{\nu b}^i \) is a free function representing the instrumental phase for the \( b \)th telescope, \( \ddot{u}(\nu) \) is the (time dependent) position of the \( b \)th beam, and where the dispersive delay due to the ionosphere is a free function \( \Delta DM(\hat{n}_b, \ddot{u}(\nu)) \) and where the DM constant is taken to be \( K = 1/(2.41 \times 10^{-4}) \) s MHz\(^{-2}\) cm\(^{-3}\). This simple model takes into account the time-variable geometric delay and ionospheric delays; for simplicity we neglect small corrections such as tidal deformation that become necessary over long baselines. From here on, we suppress the time dependence of the telescope positions \( \ddot{u}(\nu) \). For the purpose of this investigation, we choose to neglect the ionospheric term since CHIME and Pathfinder are approximately colocated. However, for long baselines, ionospheric delays are likely to be the
dominant systematic effect affecting the precision of our final localization.

While Equation (4) could in principle be fitted directly to the visibilities with a least-squares algorithm, in practice, we have not yet compensated for geometric delays. We set the visibility delay center to the nominal source location using fiducial estimates for $\tilde{u}$ and $\tilde{v}$, which are denoted with an additional subscript zero.

This delay compensation improves the robustness and convergence of the fit especially in the presence of noise. First, we remove the geometric delay due to the nominal baseline $(\tilde{u}_0 - \tilde{v}_0)$, an estimate which is accurate to within a meter. We calculated the (uncalibrated) visibilities $V_{\nu,0}$, reducing our data set to a set of $\approx 10^6$ complex numbers, one per frequency channel per formed beam. The phase of the uncalibrated visibilities after delay compensation can be modeled as

$$\phi_{\nu,0} = \phi_{\nu} - (\tilde{u}_0 - \tilde{v}_0) \cdot \tilde{b}_0,$$  

(5)

where $\phi_{\nu}$ represents the differential instrumental phase between CHIME and Pathfinder, $(\tilde{u} - \tilde{v})$ is the true baseline, $\tilde{b}_0$ are the true positions, and the last term encodes our delay compensation using nominal estimates of the sky positions and baseline. Note that for reasons stated previously the ionosphere localization.

In essence, the brightness of the calibrators used respectively. In essence, the brightness of the calibrators used where $\mathcal{b}_0$ and $\mathcal{b}_0$ are the uncertain field delay model is

$$\phi_{\nu,0} = \phi_{\nu} - (\tilde{u}_0 - \tilde{v}_0) \cdot \tilde{b}_0.\$$

3.5. Fringe Fitting

After applying this calibration procedure, the phase of the delay-compensated and calibrated visibilities which we fit to our delay model is

$$\phi_{\nu,0} = (\tilde{u} - \tilde{v}) \cdot (\tilde{b} - \tilde{b}_0) - (\tilde{u}_0 - \tilde{v}_0) \cdot (\tilde{b}_0 - \tilde{b}_0).$$

(6)

With a good guess of the baseline offset, Equation (6) varies slowly as a function of frequency and can be fitted to extract sky localizations and baseline information, as shown in Figure 4. First, using $\approx 10$ auxiliary 100 ms snapshots similar to those shown in Figure 5, each targeting $\approx 7$ sufficiently bright NVSS calibrators (for which $\mathcal{b}_0 = \mathcal{b}_0$) at a wide range of sky positions, we determine the remaining baseline offset $\delta \mathcal{b} = (\mathcal{u} - \tilde{u}) - (\tilde{u}_0 - \tilde{u}_0)$. Next, fixing $\delta \mathcal{u}$, we can determine the unknown sources’ offsets from their nominal positions, denoted by $\delta \mathcal{b}_0 = \mathcal{b}_0 - \mathcal{b}_0$. Note that our approximately EW baseline make us insensitive to the decl. of sources in the sky, and that the sky positions we are observing (all close to the local meridian) make our data insensitive to EW baseline errors.

The parameters $\delta \mathcal{u}$ and $\delta \mathcal{b}$ are estimated by maximizing the likelihood $\mathcal{L}$ using an expression that does not depend on the intrinsic emission spectra of any of the sources. Since only the phase of the visibility is sensitive to astrometric quantities, we can analytically marginalize over the amplitude $A_{\nu}$ of the calibrated visibilities without losing phase information. We suppress the superscript in Equation (6), treating it as a free function $\phi_{\nu}$ of sky positions and baseline parameters which we collectively refer to as $\lambda$. Assuming a uniform prior and applying Bayes’s theorem we can write the posterior distribution of $\lambda$ with a $\chi^2$ maximum-likelihood estimator. Integrating over the amplitude of the visibility $A_{\nu}$ simplifies our full $\chi^2$ likelihood to its form in Equation (7):

$$\chi^2 = \sum_{\nu} \frac{(V_{\nu} - \mathcal{V}_{\nu})^2}{\sigma_{\nu}^2},$$

Figure 4. Top: successful fringe fit for FRB 20191021A. We plot the slowly varying phase $\phi_{\nu}$ of the CHIME—Pathfinder visibility as a function of frequency in the NS and EW polarizations. To guide the eye, we bin over frequency channels with a resolution of 16 MHz, and overlay the corresponding best-fit delay model (solid line). Bottom: maximum-likelihood $\chi^2$ statistic as a function of R.A. The log-likelihood function (negative of Equation (7)) shows a clear minimum at the best-fit position of the FRB. Though we are fitting $N \approx 512$ visibilities, systematic effects such as a differential beam phase and confused calibrators prevent the $\chi^2$ statistic from reaching its expected value of $\approx 512$ at its minimum in parameter space. In addition, we slightly underestimate the thermal noise on the visibility, not taking into account the increased system temperature when the transient is on.

Figure 5. Sky maps of the four fields we observed, with a “+” denoting the approximate position of the pulsar/FRB, and bright NVSS calibrators with $S_{1.4\text{GHz}} > 1.5$ Jy indicated with black dots. The thick black lines denote the calibrator used to phase-reference each pulsar/FRB. Contours denote the FWHM of the primary beam of both telescopes (Newburgh et al. 2014) in the NS and EW polarizations at 600 MHz. The vertical black bars denote the meridian at the time of observation.
We report the DM, nominal sky position, and observing epoch during which we collected baseband data on each source. For pulsars, the nominal R.A. and decl. at which the FRB was detected by CHIME/FRB’s real-time pipeline. We report the measured R.A. from our localization pipeline with statistical uncertainties and systematic offset of each source from its true position. For the pulsars, the systematic offset is known, and for the FRBs, the systematic offsets are extrapolated from those of pulsars (see the text and Figure 6). We are unable to unambiguously identify a single host galaxy with our current localization precision.

\[
P(\lambda | \nu_{\text{obs}}) \propto P(\nu_{\text{obs}}|\lambda) \\
\propto \exp \left( -\frac{1}{2} \sum_{i,b} \frac{[\nu_{\text{obs},i} - A_{\nu,i} \exp(i\nu_{\text{obs},i}(\lambda))]^2}{\sigma_{\nu,i}^2} \right) \\
\propto \exp \left( -\frac{1}{2} \sum_{i,b} \text{Im}[\nu_{\text{obs},i}\exp(-i\nu_{\text{obs},i}(\lambda))/\sigma_{\nu,i}]^2 \right). \\
\log \mathcal{L} \propto -\frac{1}{2} \sum_{i,b} \text{Im}[\nu_{\text{obs},i}\exp(-i\nu_{\text{obs},i}(\lambda))/\sigma_{\nu,i}]^2. 
\]

Intuitively, this can be understood as follows. If the delay model allows us to perfectly derotate the \( \nu_{\text{obs}} \) to the real axis of the complex plane, the imaginary part of \( \nu_{\text{obs}} \), normalized by its standard deviation, will be minimized and will be a zero-mean, unit-variance Gaussian random variable. Hence, the sum of local radio-frequency interference (RFI) will be minimized and will be a zero-mean, unit-variance Gaussian random variable. Therefore, the sum of local radio-frequency interference (RFI) will be minimized and will be a zero-mean, unit-variance Gaussian random variable. Hence, the sum of local radio-frequency interference (RFI), which would show up as an angular distance from the transient of interest. The more serious impact of astrometric discrepancies is on baseline determination. Equation (6) implies that an inaccurate determination of the baseline translates to a systematic localization offset proportional to the on-sky distance between the target of interest (\( \hat{n}_b \)) and the delay center (\( \hat{n}_b \)).

To quantify the systematic offsets in our R.A. measurements, we conducted triggered observations of pulsars, which are also summarized in Table 1. We added rules to the event classifier in the real-time FRB detection pipeline to allow bright pulses from known pulsars to trigger a baseband dump, in the same way that an FRB would. In this way, we collected baseband data for three bright single pulses from PSR B0329+54 and one from PSR B0355+54, and localized the pulsars as if they were FRBs. We estimated the systematic errors in our localization analysis using the discrepancy between our results and the pulsars’ known position, corrected for their proper motion.

We phase-reference the pulsar position to the seven in-beam NVSS calibrators, whose sky positions are as far as 60° away from the pulsar. We plot the astrometric localization error against the angular distance between the pulsar and the delay center in Figure 6. We find that the astrometric discrepancy is roughly linearly proportional to the on-sky distance to the calendar, and that using the nearest on-sky calendar minimizes discrepancies from the cataloged positions of pulsars even with truly simultaneous phased-array observations through similar ionospheric screens. We attribute this discrepancy chiefly to a static baseline determination error corresponding to time delays of less than a nanosecond. To estimate the magnitude of systematic uncertainty in our FRB localizations, we find the intersection of the upper edge of the shaded area in Figure 6 with the on-sky distance to the nearest calendar to each FRB.

In addition to an unknown static baseline error, the effective centroid of a beamforming telescope drifts slightly every day. The effective centroid is given by the sensitivity-weighted average of the active antenna positions, causing it to drift from day to day on the order of \( \sim \text{cm} \) because a slightly different set of antennas are flagged (i.e., nulled) every day due to factors like rainfall. We take this effect into account during tied-array beamforming, but the current baseline positions are not yet constrained at a level to measure this day-to-day drift in astronomical data. Using a larger

### Table 1: Localization of Known Pulsars and Fast Radio Bursts Detected by CHIME/FRB

| Source         | DM          | R.A. (nominal) | Decl. (nominal) | Epoch (MJD) | R.A. (measured) ± Stat Offset (deg) |
|----------------|-------------|---------------|----------------|-------------|-------------------------------------|
| PSR B0329+54   | 26.776      | 53.24770      | 54.57860       | 58772.412   | 53.24538 ± 0.00017 −0.00232         |
| PSR B0329+54   | 59032.701   | 53.25361 ± 0.00591 | 59033.713   | 59.72725 ± 0.00101 0.00334         |
| PSR B0355+54   | 57.142      | 59.72391      | 54.2205       | 59034.696   | 59.72391 ± 0.00021 0.00568         |
| FRB 20191021A  | 388.659     | 124.92        | 54033.713     | 58777.595   | 124.92521 ± 0.00044 ±0.0025         |
| FRB 20191219F  | 464.560     | 225.92        | 54034.696     | 58836.702   | 226.56408 ± 0.00694 ±0.0055         |

Note. We report the DM, nominal sky position, and observing epoch during which we collected baseband data on each source. For pulsars, the nominal R.A. and decl. (in degrees) are taken from the Australia Telescope National Facility (ATNF) Pulsar Catalog (Manchester et al. 2005). For FRBs, we instead report the nominal R.A. and decl. at which the FRB was detected by CHIME/FRB’s real-time pipeline. We report the measured R.A. from our localization pipeline with statistical uncertainties and systematic offset of each source from its true position. For the pulsars, the systematic offset is known, and for the FRBs, the systematic offsets are extrapolated from those of pulsars (see the text and Figure 6).
sample of pulsars at a wide range of declinations for baseline determination, not just validation, will reduce our systematic error floor and improve our ability to phase-reference our observations to calibrators far away on the sky.

4. Discussion and Conclusion

The systematic errors on the FRB localizations obtained in this work are currently dominated by errors in baseline determination using NVSS calibrators and will improve by observing more NVSS calibrators. The ionosphere will introduce an additional systematic uncertainty due to fluctuations in electron column density on the order of ~100 TECU (where 1 TECU ≈ 3.24 × 10^18 cm^-3). This causes stochastic spatially and temporally varying time delays of ~600 ns at subgigahertz frequencies. Removing this delay to achieve high astrometric precision will require observations of suitable calibrators close to the FRB both spatially and temporally, a feat achieved for steady sources by Rioja et al. (2017). The relatively uncharted territory of low-frequency VLBI calibrators poses a major uncertainty for ongoing efforts to CHIME/FRB VLBI observations to continental baselines. Following pioneering low-frequency VLBI surveys by Garrett et al. (2005) and Lenc et al. (2008), the advent of the International Low Frequency Array (LOFAR) Telescope has made systematic surveys of the low-frequency sky possible. The LOFAR Snapshot Calibrator Survey (Moldón et al. 2015) has demonstrated that high-quality, compact VLBI calibrators at low frequencies tend to be bright at 328 MHz (S = 0.1 – 1 Jy) and have a flat low-frequency spectrum on short baselines. Recent results from the ongoing LOFAR Long-Baseline Calibrator Survey (LBCS; Jackson et al. 2016) project the density of high-quality VLBI calibrators over long baselines at subgigahertz frequencies to be ~1 deg^-2.

To mitigate this uncertainty, multiple different strategies to calibrate out the ionosphere are under study within the CHIME/FRB collaboration (Cassanelli 2020) and will be addressed separately in future work. These include efforts to use high Galactic latitude pulsars as a network of compact, well-understood low-frequency calibrators, performing joint fringe fits on a combination of short- and long-baseline data, and efforts to use GPS satellites for independent total electron content (TEC) measurements. The goal of this overall calibration program is to allow CHIME/FRB Outriggers to localize thousands of FRBs to a target precision of ~50 milliarcseconds. This will allow leading optical telescopes to perform follow-up studies of FRB host environments.

In conclusion, we have developed baseband recording hardware and software capable of handling the high data rate of wideband, multi-element radio interferometers such as CHIME for VLBI observations (Section 2). We have demonstrated a calibration technique that exploits CHIME’s wide field of view to localize several radio transients detected by CHIME/FRB and the CHIME Pathfinder in the same spirit as VLBI (Section 3). In an automatically triggered ~100 ms dump of baseline data at CHIME and Pathfinder, we can simultaneously detect a single FRB in cross-correlation between CHIME and Pathfinder, as well as multiple calibrators for phase referencing our telescopes.

We have developed efficient maximum-likelihood estimators to perform fringe fitting in the absence of knowledge about the FRB spectrum (Section 3.5), and have localized FRB 20191021A and FRB 20191219F with statistical uncertainties of 1°6 and 25°, respectively, along one direction in the sky (Table 1). Using single pulses from bright pulsars we have characterized the systematic errors on the FRB localized here (18° and 3° respectively) which are dominated by errors in baseline determination using NVSS calibrators (Section 3.6). The instrumentation and analysis formalism developed in this paper show that wideband, multi-element radio interferometers can be used together to detect and localize FRBs. Extending this to longer baselines using CHIME/FRB Outriggers will pave the way for transformative studies of FRB host environments and of the intergalactic medium.

We thank the CHIME Collaboration for use of the Pathfinder, and the staff at the Dominion Radio Astrophysical Observatory and Ev Sheehan for their hospitality and efforts to ensure the smooth deployment of our instrumentation. C.L. was supported by the U.S. Department of Defense (DoD) through the National Defense Science & Engineering Graduate (NDSEG) Fellowship. M.B. is supported by an FRQNT Doctoral Research Award. D.M. was supported by the Banting Postdoctoral Fellowships Program.

This research is funded in part by the Gordon and Betty Moore Foundation and the NEC Corporation Fund for Research in Computers and Communication. FRB research at UBC is supported by an NSERC Discovery Grant and by the Canadian Institute for Advanced Research. V.M.K. holds a Distinguished James McGill Chair and the Lorne Trottier Chair in Astrophysics & Cosmology and receives support from an NSERC Discovery Grant and Herzberg Award, from an R. Howard Webster Foundation Fellowship from the Canadian Institute for Advanced Research (CIFAR), and from the FRQNT Centre de Recherche en Astrophysique du Québec. P.S. is a Dunlap Fellow and an NSERC Postdoctoral Fellow. The Dunlap Institute is funded through an endowment established by the David Dunlap family and the University of Toronto. The CHIME/FRB baseband recording system was funded in part by a CFI John R. Evans Leaders Fund award to I.H.S.

Software: numpy (Oliphant 2006), scipy (Virtanen et al. 2020), matplotlib (Hunter 2007).
The total cost of the recorder was less than $20 k USD in 2019 Spring and was dominated by the cost of the high-density RAM.

Appendix

Baseband Recorder Parts List

Our recorder uses 1 terabyte of RAM to buffer approximately 40 s of baseband data corresponding to DMs of up to \( \approx 2000 \) pc cm\(^{-3} \) upon receiving a trigger from CHIME/FRB’s real-time detection pipeline. A photograph of the inside of the node is shown in Figure 1, and a full parts list is given in Table 2. Future recorders may feature an auxiliary buffer or GPUs for real-time beamforming capabilities (Ng et al. 2017), which will facilitate longer integration times on fainter calibrators, though this technical capability is not necessary for our bright calibrators.

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**Table 2**

Components Used in the Prototype Baseband Recorder for CHIME/FRB Outiggers

| Parts       | Part Number | Specifications (each) |
|-------------|-------------|-----------------------|
| Motherboard | 1 × TYAN Tempest EX S7100-EX | 4 × PCIeX16, 3 × PCIeX8, 2 sockets |
| CPU         | 2 × Intel Xeon Silver 4116 | 12 cores (hyperthreaded) × 2.10 GHz |
| RAM         | 8 × Hynix HMAA8GR7A2R4N-VN | 128 GB |
| Network     | 4 × Silicon PI 31640Q2QF1/QX4 | 2 × 4 × 10Gbe |

**Note.** The total cost of the recorder was less than $20 k USD in 2019 Spring and was dominated by the cost of the high-density RAM.