Using Continuum Sources For CHIME/FRB Outrigger Calibration

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Goal:

To blindly localise a pulsar to arcsecond precision using high declination traditional, continuum VLBI calibrators on a 200 kλ baseline between the CHIME telescope and KKO[1] outrigger from $400 - 800$ MHz. [2]

Scientific Context and Motivation:

Fast radio bursts are short, bright pulses of radio emission originating from cosmological distances. To infer their distance, the dispersion induced in the signal by the integrated column density of electrons along the line-of-sight is calculated and is quantified by the dispersion measure (DM). The majority of FRBs have DMs that greatly exceed the maximum contributions from the Milky Way and its halo (NE2001; Cordes & Lazio, 2002, YMW16; Yao et al. 2017) suggesting that most FRBs are of extragalactic origin. This has been confirmed by > 15 host galaxy associations that have been made to-date (see e.g. Chatterjee et al. 2017, Tendulkar et al. 2017, Marcote et al. 2020, and Macquart et al. 2020). However, the question of what causes these bursts remains, for the most part, unanswered. For example, although FRB-like emission was recently detected from a Galactic magnetar (CHIME/FRB Collaboration et al. 2020b, Bochenek et al. 2020), other localised FRBs have not been coincident with magnetars, suggesting the high likelihood of multiple progenitor models (Platts et al. 2019). Ultimately, the key to understanding FRBs lies in being able to localise them. By associating a host galaxy we immediately obtain distance estimates for FRBs. By studying their local environment, we can distinguish between various progenitor models. Additionally, robust measurements of line-of-sight DM contributions will enable FRBs to be used as cosmological tools.

Despite the total number of detected FRBs to-date having exceeded over 3,000 (CHIME/FRB Collaboration 2021a), the ability to localise an FRB well enough to associate it with a host galaxy (and thus infer their redshift) has been limited by the angular resolution of the observing telescopes. For example, the Canadian Hydrogen Intensity Mapping Experiment (CHIME) telescope, which observes from $400 - 800$ MHz and has a maximum diameter of approximately 100 m, can only achieve an angular resolution of *at best* 13 arcminutes at 800 MHz, most often insufficient to unambiguously identify a host galaxy [3]. Consequently, the majority of detected FRBs go unlocalised.

The CHIME/FRB Outriggers project is designed to localise FRBs to milliarcsecond precision using very-long-baseline-interferometry (VLBI). Three single CHIME-like cylinders (hereafter referred to as outriggers) are under construction at three separate locations across North America. Each outrigger is constructed such that they share nearly the same field-of-view (FOV) as the CHIME telescope. Forming baselines of 80, 1,000 and 3,000 km ($200\ \mathrm{k}\lambda,\ 2.7\ \mathrm{M}\lambda,$ and $8\ \mathrm{M}\lambda$) respectively with CHIME, the VLBI network aims to localise thousands of FRBs to their host galaxy upon detection. At present, the first of the three outriggers (hereafter referred to as KKO) is on sky and ready to localise FRBs.

To successfully localise an FRB, a bright, compact radio source is used as a calibrator to remove delay errors (see §Technical Justification). However, unlike traditional VLBI telescopes, CHIME and KKO are stationary phased arrays which rely on the rotation of the Earth to see different parts of the sky. Finding suitable VLBI calibrators thus becomes a challenge as the arrays are unable to continously track traditional VLBI calibrator sources long enough to calibrate before it exits the FOV. This challenge is compounded by the limited number of compact, unresolved calibrator sources at low frequencies as well as the storage required to save large sets of raw voltage data. Consequently, CHIME/FRB Outriggers has opted to use pulsars as its primary method of calibration given their large sky distribution and brightness in the $400 - 800$ MHz band (Cassanelli et al. 2021, Leung et al. 2021).

However, Figure 1 highlights that pulsars have a preferential distribution in the plane of the Galaxy and there are not enough bright pulsars to keep the outriggers constantly calibrated. Consequently, there are gaps in our sky coverage for localisable FRBs. For this reason, we are interested in investigating the feasibility of using bright, high-declination, traditional VLBI continuum sources to calibrate and localise FRBs. We opt to use high-declination steady sources because they are circumpolar and will nearly always be within the CHIME and Outriggers FOV. From the limited number of candidate sources available from completed low-frequency surveys (see e.g. Moldon et al. 2015 and Lenc et al. 2008), we believe that there exist sufficiently bright and unresolved sources on our

[1] The KK in KKO stands for k'niatn k'lstk'masqt, meaning "a device for listening to outer space", provided by the Similamix, part of the Sylix nation, where the telescope was built. The O stands for "outrigger".

[2] Of course, the CHIME telescope and KKO outrigger both fall under the CHIME/FRB Collaboration. However, for the sake of this practice proposal, I am pretending that I have access to KKO data and am requesting data from CHIME for the particular analysis that I am interested in.

[3] There are cases where host galaxies can be inferred by low DM FRBs. However, these represent a small fraction of the total number of detected FRBs.

baselines to calibrate our array. *With data obtained from the CHIME telescope, we will introduce a novel method of localising FRBs by utilising the large FOVs of both interferometers to calibrate the array using the voltage data that contains information about both the FRB as well as the calibrator. Using high declination calibrators will guarantee that CHIME/FRB Outriggers continuously has a calibrator within its primary beam, allowing any FRB detected by CHIME and KKO to be localised.*

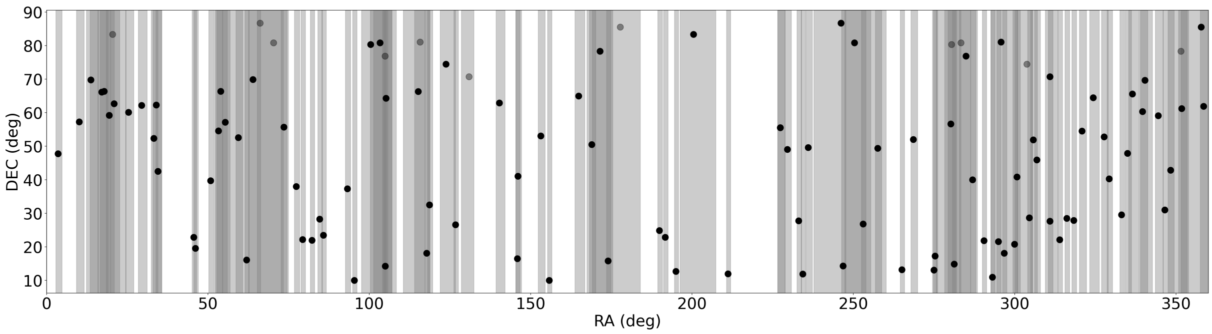

Figure 1: Cartesian projection of the 100 pulsars that the Outriggers will use as calibrators. The width of the grey shaded area indicates the range of hour angles that the pulsar is observable by CHIME. Non-shaded regions indicate when no pulsar is visible by CHIME (and hence no calibrator), motivating the use of high declination steady sources as calibrators. Image credit: Alice Curtin & Jane Kaczmarek.

IMMEDIATE OBJECTIVES:

1) Cross-correlate signals from continuum sources between CHIME and KKO

To use a steady source as a calibrator, the source must be detectable in cross correlation between the combined CHIME-KKO array. This is achievable if the source is sufficiently bright and compact on our maximum $\sim$ 200 kλ baseline. To achieve arcsecond localisation along the direction of the baseline with a 10% uncertainty on the measurement, a detection of the signal with signal-to-noise ratio (S/N) of $\gtrsim$ 15 is required after cross correlating the signals between CHIME and KKO (see §Technical Justification). We describe our candidate source in §Target Selection & Time Justification which we claim satisfies both of the aforementioned requirements.

2) Localise PSR B0329+54 to arcsecond precision using a steady source to calibrate delay errors.

We will blindly localise PSR B0329+54 to arcsecond precision with 10% localisation uncertainty ($0.1''$) along the direction of the baseline, calibrating the instrumental delays using the cross-correlated VLBI signal. Given that the position of PSR B0329+54 is already known to milliarcsecond uncertainty, we will be able to characterize the success of our analysis. To localise PSR B0329+54, we phase reference the pulsar to a calibrator and compute the maximum likelihood estimator to extract the optimal differential geometric delay corresponding to a sky position, a method which was proven successful by Cassanelli et al. (2021) and Leung et al. (2021). The only difference here is that we instead opt to use a steady continuum source to calibrate the instrumental delays instead of a pulsar.

3) Contribute to the catalog of VLBI calibrators at 40- and 70- cm.

As previously mentioned, few calibrators exist on very long baselines at low frequencies. Successfully calibrating on a $\sim$ 200 kλ baseline will immediately lead to a similar attempt on our maximum $\sim$ 8 Mλ baseline once the GBO outrigger is online. Repeating this experiment and analysis on all existing steady source calibrators within our FOV will immediately provide invaluable insight to the low-frequency VLBI community where the compactness of calibrators at large Mλ is scarcely tested.

TECHNICAL JUSTIFICATION:

Required VLBI signal-to-noise ratio – The combined CHIME–KKO array forms a baseline of length $b \sim 80$ km. By measuring the delay in arrival of the wavefront at one telescope versus the other, we can constrain the source's location on the sky along the direction of the baseline. Using Figure 2 as a visual reference, the source location, characterized by the baseline angle γ, can be computed as $\gamma = \arccos\left(\frac{c\tau}{b}\right)$. For the combined array that observes from $400 - 800$ MHz, the diffraction limited angular resolution along the 80 km baseline is approximately $1.3''$ at 600 MHz. In an ideal world, τ is purely the geometric delay: however, in reality, the contributions to the total delay are composed of the geometric ($\tau_{\rm geo}$), clock ($\tau_{\rm clock}$), ionospheric ($\tau_{\rm iono}$), instrumental ($\tau_{\rm inst}$) and noise delay (ζ), which are all known to varying degrees of uncertainty. For example, the calibrator source that we are interested in has a known position to sub-mas precision, corresponding to a geometric delay uncertainty contribution on the order of picoseconds. On the other hand, the ionosphere – the ionized part of the upper atmosphere of the Earth –

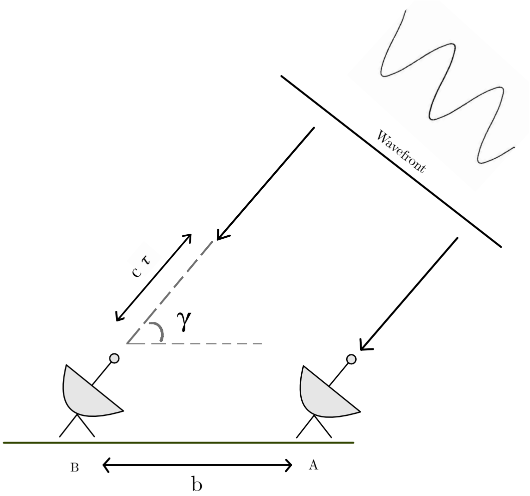

Figure 2: Visual representation of the geometric delay intrinsic to two telescopes detecting an incoming wavefront separated by a baseline distance b. Due to the natural geometry of the Earth, the wavefront will arrive at antenna B at a later time than antenna A, forming a baseline angle γ with the Earth. The delay in arrival is characterized by the geometric delay, $\tau_{\rm geo}$.

is poorly understood and can introduce nanosecond delay uncertainties (Cassanelli et al. 2021), corresponding to arcsecond positional uncertainties. However, one contribution to the uncertainty that we *do* have control over is the delay induced by the instrument, which can be calibrate by a sufficiently bright source.

Our goal is to eventually localise FRBs with a positional uncertainty of $0.1''$. This corresponds to a maximum delay error budget of 0.13 ns and we estimate that 70% of our error budget is required to compensate for the ionospheric, clock, noise and geometric delays. That leaves 30% of our error budget to calibrate instrumental errors, corresponding to a delay uncertainty of 0.0387 ns. The required signal-to-noise ratio of a detected continuum calibrator source to achieve this instrumental delay uncertainty is $(\mathrm{S/N})_{\rm VLBI} \gtrsim 15$ in cross-correlation between CHIME and KKO (Rogers 1970, Mena-Parra et al. 2022). Note that in order to compensate for radio frequency interference (RFI) flagging at both CHIME and KKO, we assume throughout our analysis that our effective bandwidth is 70% of the maximum bandwidth of 400 MHz, e.g. $\Delta\nu = 260$ MHz.

Required integration time – The KKO telescope (effective area $A_{\rm KKO}$) is a small version of the CHIME telescope (effective area $A_{\rm CHIME}$) such that $A_{\rm KKO}/A_{\rm CHIME} = 1/16$. The individual receivers of both telescopes are nearly identical such that $50\ \mathrm{K} \lesssim T_{\rm sys,\,KKO} = T_{\rm sys,\,CHIME} \equiv T_{\rm sys} \lesssim 100$ K. Additionally, the response of each *individual* antenna at CHIME and KKO to an observed source is $T_{\rm src}$. We utilize the fact that KKO is identical to CHIME in all aspects except its collecting area to estimate that the minimum required integration time, Δt, to obtain $(\mathrm{S/N})_{\rm VLBI} \gtrsim 15$ scales as a function of the average flux density, $\langle S\rangle$, of the source in our band:

$$\Delta t \approx 64\ \mathrm{ms}\left(\frac{1\ \mathrm{Jy}}{\langle S\rangle}\right)^2\Bigg|_{(\mathrm{S/N})_{\rm VLBI}\gtrsim 15}. \tag{1}$$

To obtain this result, we consider the radiometer equation for an N element interferometer and estimate that $50\ \mathrm{Jy} \lesssim \mathrm{SEFD}_{\rm CHIME} \lesssim 100$ Jy is the system equivalent flux density density of the entire CHIME array (CHIME Collaboration, 2022). Note that CHIME has 1024 dual-polarization feeds, while KKO has 64. In §Target Selection & Time Justification, once a target has been selected, we compute the required integration time using eq. 1.

Confusion Limit for Combined CHIME–KKO Array – CHIME Collaboration (2022) estimates that the CHIME telescope, with an effective beam solid angle of approximately 230 square degrees, has a confusion limit of $\sigma_{c,\rm CHIME} \approx$ 100 mJy / beam. For the combined CHIME-KKO telescope, with an effective beam solid angle of approximately 0.06 square degrees, we conservatively estimate that $\sigma_{c,\rm CHIME\text{-}KKO} \approx 5$ mJy / beam. Note that the beam solid angle of the very-long-baseline interferometer is significantly smaller than the CHIME telescope by itself, a consequence of the large separation of the two telescopes in the EW direction. We have also taken into consideration the effects of sidelobes, increasing our effective beam solid angle by 30% to compensate for their contributions. Notably, the CHIME-KKO array becomes confusion limited after an integration duration of $\Delta t_c \approx 300$ ms. Since triggered baseband dumps between CHIME and KKO are limited to 127 ms, we do not expect to ever be confusion limited.

TARGET SELECTION AND TIME JUSTIFICATION:

Our target selection is separated into two groups: calibrators and pulsars, the former being used to localise the latter.

The calibrator source must be at a sufficiently high declination such that it is almost always within both CHIME and KKO's FOV. Given that both telescopes are located at a latitude of 49°, their large FOVs enable them to see the sky at a declination of $\delta > -11°$ all the way to the North Celestial Pole (NCP; $\delta = 90°$). *A near circumpolar calibrator will guarantee that a calibrator will be available when a baseband dump is triggered upon the detection*

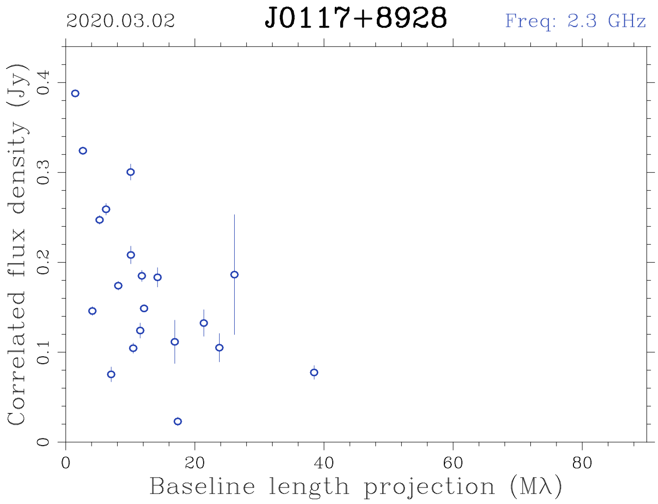

Figure 3: *Left:* Correlated flux density (Jy) as a function of project baseline length (Mλ) for NVSS J011732+892848, a bright quasar located approximately 30′ from the North Celestial Pole (Condon et al. 1998). The source is likely sufficiently compact on our $\sim$ 0.2 Mλ baseline to be used as a calibrator (Moldón et al. 2015). Image retrieved from astrogeo.org.

of a pulsar or FRB. The source must also be sufficiently bright such that the required integration time to achieve $(S/N)_{VLBI} \gtrsim 15$ does not exceed the maximum duration of the baseband dump of 127 ms. Finally, the source must be unresolved on our 200 kλ baseline. When choosing the pulsar to blindly localise, the only requirement is that it is bright enough from 400 – 800 MHz with sufficiently large S/N to be detectable by CHIME and KKO in cross correlation.

Calibrator Candidate: NVSS J011732+892848 – The candidate calibrator source that we have chosen to observe for this analysis is NVSS J011732+892848 (J200.0: RA = 01hr 17′16.4038″, DEC = +89°28′47.976″), a central bright quasar located approximately 30′ from the NCP (Condon et al. 1998). It has most recently been determined to be compact by LOFAR on their $\sim$ 43.5 kλ baseline (Yatawatta et al. 2013). The correlated flux density as a function of baseline length projection at 2.3 GHz for J0117+8928 is provided in Figure 3. While likely not suitable as a VLBI calibrator on our upcoming 8 Mλ baseline with the GBO outrigger, it is likely still unresolved on our much smaller $\sim$ 200kλ = 0.2 Mλ baseline for CHIME-KKO. Additionally, in our observing band, the calibrator is expected to have an average flux density ranging between 2 and 5 Jy: we assume the minimum value to get a conservative estimate on the required integration time. *To obtain a cross-correlated signal with detection significance* $(S/N)_{VLBI} \gtrsim 15$ *for our chosen 2 Jy source, a required integration time of 16 ms is required, falling far below the 127 ms dump duration limit.*

Pulsar Candidate: PSR B0329+54 – The pulsar we will attempt to blindly localise is PSR B0329+54 (J2000: RA = 03hr 32′59.368″, DEC = +54°34′43.57″; ATNF Catalog[4], Manchester et al. 2005). PSR B0329+54 has a spin period of $\sim$ 700 ms and pulse width of 7 ms, with bursts detected at CHIME with S/N ranging from 12 – 50 during an average transit. It is one of the brightest, most consistently detected pulsars by the CHIME telescope, hence our decision to use the pulsar as a candidate "fake FRB".

Observation Specifications:

We seek a single triggered baseband dump, containing 127 ms of raw voltage data from the CHIME telescope, centred upon the detection of a PSR B0329+54 pulse with $(S/N)_{CHIME} \geq 45$. *The 127 ms of baseband data will be sufficient to guarantee the capture of B0329+54 and only a fraction will be used to detect the NVSS J011732+892848 calibrator in the same raw voltage dataset*. This dataset, combined with a triggered dataset at KKO, will enable the blind localisation of PSR B0329+54. The only time requirement for this observation is that it is done while PSR B0329+54 is within 0.5 degrees from the centre of CHIME's primary beam to guarantee that the pulse does not fall into either of the telescopes' sidelobes. This one time observation could be done whenever is convenient for the CHIME collaboration.

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