Search for persistent radio emission towards selected localised Fast Radio Burst positions using the MeerKAT Telescope

Thulo Letsele[1], Lebogang Mfulwane[1], Christo Venter[1,2], James O. Chibueze [3,4], and Mechiel Christiaan Bezuidenhout[5,1]

[1]Centre for Space Research, North-West University, Private Bag X6001, Potchefstroom 2520, South Africa
[2]National Institute for Theoretical and Computational Sciences (NITheCS), Potchefstroom, 2520, South Africa
[3]Department of Mathematical Sciences, University of South Africa, Cnr Christian de Wet Rd and Pioneer Avenue, Florida Park, 1709, Roodepoort, South Africa
[4]Department of Physics and Astronomy, Faculty of Physical Sciences, University of Nigeria, Carver Building, 1 University Road, Nsukka 410001, Nigeria
[5]SKA Observatory, 2 Fir Street, Observatory 7925, Cape Town, South Africa

E-mail: `thuloletsele1999@gmail.com`

Abstract. Fast Radio Bursts (FRBs) are millisecond-duration radio pulses originating from cosmological distances, as indicated by their large dispersion measures. While numerous FRBs have now been localised to their host galaxies, a distinct class of compact electromagnetic counterpart, a Persistent Radio Source (PRS), has also been identified in some cases. Currently, only four repeating FRBs (FRB20121102A, FRB20190520B, FRB20201124A, and FRB20240114A) have confirmed associations with a PRS. Insight into progenitors, local environments, and the evolution of FRBs can be clarified by characterising these PRSs. In this work, we present 2 detected candidate PRSs using MeerKAT radio telescope data and one non-detection (as part of a larger study involving 25 FRB positions). Both FRB20221106 and FRB20181112 were found to have a host galaxy, and whether the detected radio continuum emission comes from the host galaxy or PRS is still an open question. High-resolution observations from a telescope such as e-MERLIN are required to resolve this question. If a compact PRS is detected, this telescope will provide the size, and investigate the flux variability and spectral shape of this compact PRS. Lastly, in the case of FRB220190102, which was observed over two epochs, no radio continuum was detected. However, a flux upper limit is provided for both epochs.

1 Introduction

Radio transients with signals lasting in the range of micro to milliseconds, and characterised by luminosities that make them visible from extragalactic distances [1, 2], are known as Fast Radio Bursts (FRBs). They were first discovered in 2007 when Duncan Lorimer and his student were analysing archival data of Manchester et al. [3], searching for a sub-population of pulsars known as rotating radio transients. FRBs were believed to be one-off events until the discovery of the first repeating FRB [4], which was localised by the Karl G. Jansky Very Large Array (VLA) to a dwarf star-forming galaxy of redshift of $z = 0.19$ following its discovery [5, 6]. The mechanism behind the radiation and the origin of FRBs remains a mystery.

Many researchers have proposed different possible progenitors for FRBs. These include the merging of a white dwarf and a black hole [7], the merger of binary white dwarf stars [8], the collision of two neutron stars [9], and the interaction of neutron stars with active galactic nuclei [10]. The magnetar model became an interesting model because [11] suggested that magnetar flares can produce FRBs. In addition, the association of the Galactic magnetar SGR J1935+2154 with FRB20200428 provided strong support for the magnetar model [12, 13].

The environment in which FRBs occur is also a subject of interest to researchers. A Persistent Radio Source (PRS) observed in the vicinity of the FRB environment may provide important constraints on this environment. Currently, there are four actively repeating FRBs associated with PRSs [14, 15, 5, 16]. Most of these PRSs show high Faraday rotating measures (RMs), which suggests that the environment contains a compact nebula that is highly magnetised. Bruni et al. [14] suggested that low RMs cannot be detected, and this can explain the low number of FRBs with PRSs. The nature of the PRS also remains a mystery, and scenarios proposed to explain this include a connection between supernova remnants and FRBs [17] and binary systems [18].

Three FRBs, namely FRB20181112, FRB20190102, and FRB20221106, form part of this work. FRB20181112 and FRB20190102 show dispersion measures (DMs) of 589.27 pc cm^{-3} and 363.6 pc cm^{-3}, with corresponding redshifts of $z = 0.4755$ and $z = 0.291$, respectively [19]. Both FRB20181112 and FRB20190102 are non-repeating FRBs that have significantly contributed to the Macquart relation and cosmological constraints [20]. Lastly, we have FRB20221106, which remains one of the least studied FRBs; not much information about this FRB is available.

The goal of this work is to expand this list of FRBs with identified PRSs. This will be done by searching for persistent radio emissions at FRB positions that have been well localised by the Australian Square Kilometre Array Pathfinder (ASKAP) telescope. If a radio source is detected, multiwavelength follow-up observations have to be conducted to confirm the existence of a PRS. However, if a radio source is not detected, this work will provide the upper flux limit. This work is part of a larger project involving follow-up of 25 well-localised FRB positions [21, 22, 23].
The paper is divided as follows: in Section 2, we present MeerKAT data reduction and describe how the images are produced. In Section 3, we provide our results, a subset of those presented elsewhere [23]. We conclude in Section 4.

2 Observations and Imaging

The MeerKAT radio telescope conducted the observational campaigns for open time proposals in 2021, 2022, and 2023 (SCI-20210212-CV-01, SCI-20220822-CV-01, SCI-20230907-CV-01, respectively). The observations were done using the L-band (856-1712 MHz) receiver, and the FRB positions were observed for 120 minutes on source for each epoch, with a phase calibrator observed for 2 minutes, every 15 minutes. Tables 1 and 2 contain important observation details, including observation date, Right Ascension (RA), Declination (Dec), and synthesised beam of the observed FRBs.

2.1 Calibration and Imaging

MeerKAT data are obtained in visibility format, and they are converted into a Measurement Set (MS) format using the KAT Data Access Library[1]. The OXKAT3[24] analysis pipeline flags the low-gain bandpass edges on all baselines. In addition, radio frequency interferences are also flagged, and in cases where they might affect data, the `CASA` task such as `RFLAG` is used. The `TRICOLOR` and `TFCROP` packages are used for the target field and calibrators, respectively [25].

The OXKAT3 pipeline uses tasks from `CASA` to obtain the flux scale and corrections for residual delay calibrators, time-varying gain, and bandpass in the case of cross-calibration [25]. The corrections obtained are applied to the target field, and calibrated visibilities of the target field are extracted to obtain the science target. `WSClean` imager is then used to deconvolve and image the target data. In addition, deconvolution is applied to each subband image(obtained by dividing full bandwidth into 10 subbands with a bandwidth of 82 MHz each).

A Multi-Frequency Synthesis (MFS) map is generated by `WSClean` [26]. This map consists of the full bandwidth, which has a central frequency of 1283 MHz in joined deconvolution mode. Auto-masking from `WSClean` deconvolves each of the 10 subbands with an initial mask of $20\sigma_{\rm rms}$, i.e., 20 times the level of the root-mean-square (RMS) of the image. An artefact-free model of the target is created after the deconvolution process, and it is used

[1] `www.github.com/ska-sa/katdal`

Table 1: Detected persistent continuum emission from FRB20221106 and FRB20181112.

Source name	Observation date	R.A.(J2000)	Dec.(J2000)	Synthesised beam	rms (mJy beam^{-1})	Peak Flux (mJy beam^{-1})	Maj×Min axis	Pos. Angle	Int. Flux (mJy)
FRB20221106	21-Nov-2023	03:46:49.15	-25:34:11.3	5".649×5".649	0.0048	0.0656± 0.0055	20".35×16".38	69°	0.5032
FRB20221106	05-Dec-2023	03:46:49.15	-25:34:11.3	6".264×6".264	0.0054	0.0807±0.0046	34".84×17".61	76°	0.5391
FRB20221106	20-Jan-2024	03:46:49.15	-25:34:11.3	5".452×5".452	0.0053	0.0579±0.0051	38".82×35".64	76°	0.4768
FRB20181112	19-Apr-2021	21:49:23.63	-52:58:15.4	7".304×7".304	0.0047	0.0484±0.0055	10".17×7".18	44°	0.0663
FRB20181112	03-Sep-2021	21:49:23.63	-52:58:15.4	5".940×5".940	0.0054	0.0291±0.0069	7".58×3".81	38°	0.0238

for the self-calibration process. For this self-calibration process, tasks from `Cubical software` are used [27]. Lastly, the final image has a reduced $3\sigma_{\rm rms}$ threshold.

3 Results

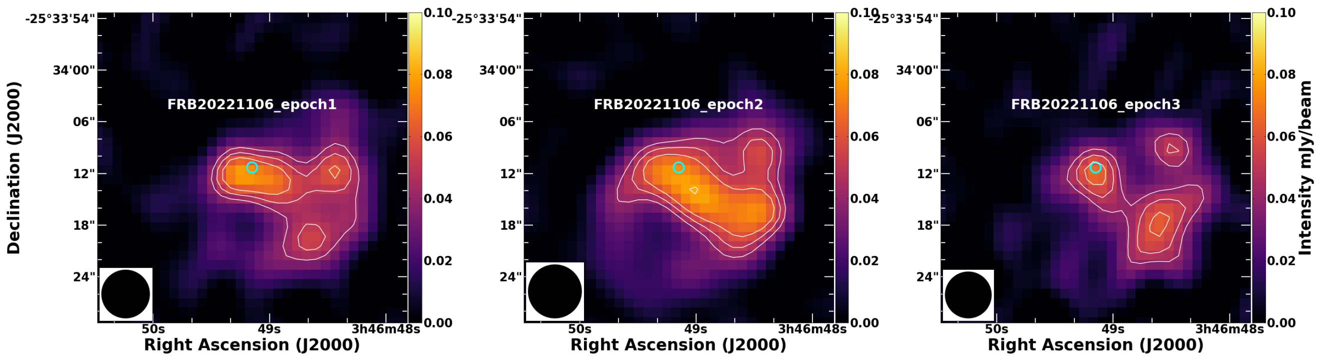

Figure 1: MeerKAT image of the FRB20221106 position as indicated by the green circle, observed during three different epochs. The black eclipse in the bottom left corner represents the beam size of MeerKAT. The white contours indicate continuum radio emission that coincides with the FRB position, represented at 3, 9, and 12 times the image's RMS.

The position of FRB20221106 was observed over three epochs. During these observations, there is consistent detection of radio emissions, and Figure 1 reveals that FRB20221106 showed three different morphologies, and it also showed three different peak fluxes as indicated in Table 1. The small change in peak flux is in the range of $2-3\sigma$, which is not statistically significant. In addition, the change in integrated flux suggests that the source is not static, and shows a possible slow or variable evolution, which can be explained by an afterflow-like scenario. The source also expands as observed in the Maj×Min axis, suggesting structural development. The consistent coincidence of the source with the FRB position, along with the observed flux evolution, suggests that the radio source is associated with the FRB. This was not the first time flux variability was observed; a similar occurrence was seen in the case of FRB20190520B: A multi-wavelength study of FRB20190520B showed a $\approx 20\%$ decrease in flux at 3 GHz over 2 years [28]. It was concluded that the variability of FRB20190520B is unlikely due to scintillation, but rather suggests an evolving PRS on yearly timescales.

Another interesting position is that of FRB20181112, which was observed over two epochs (see Figure 2). While previous studies did not reveal any PRS associated with this FRB [29], our observations revealed radio emission in the direction of this FRB. This may indicate that there was low-level persistent emission or maybe afterglow-like activity, which was not detected previously due to sensitivity limits. The measured flux of this FRB appears to decline between the two epochs as shown in Table 1, but the change is within 2σ, which means it is not statistically significant. Additionally and importantly, a massive halo of gas surrounds the host galaxy of this FRB [29]. It was found that the contributions of this galaxy to DM and scattering are minimal, suggesting weakly magnetised halo gas. If the persistent radio emission is detected during follow-up observations by the e-MERLIN telescope, it is unlikely to be associated with the halo itself and may instead come from the host galaxy or the PRS.

Lastly, we did not detect any radio emission from FRB20190102 over two epochs as shown in Figure 3. Table 2 shows our derived flux upper limits.

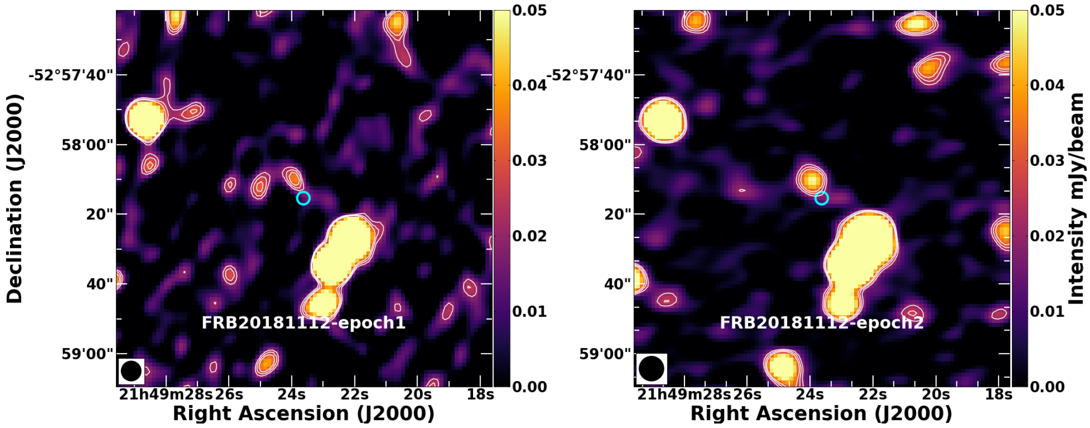

Figure 2: Same as in Figure 1, but for FRB20181112, observed during two different epochs.

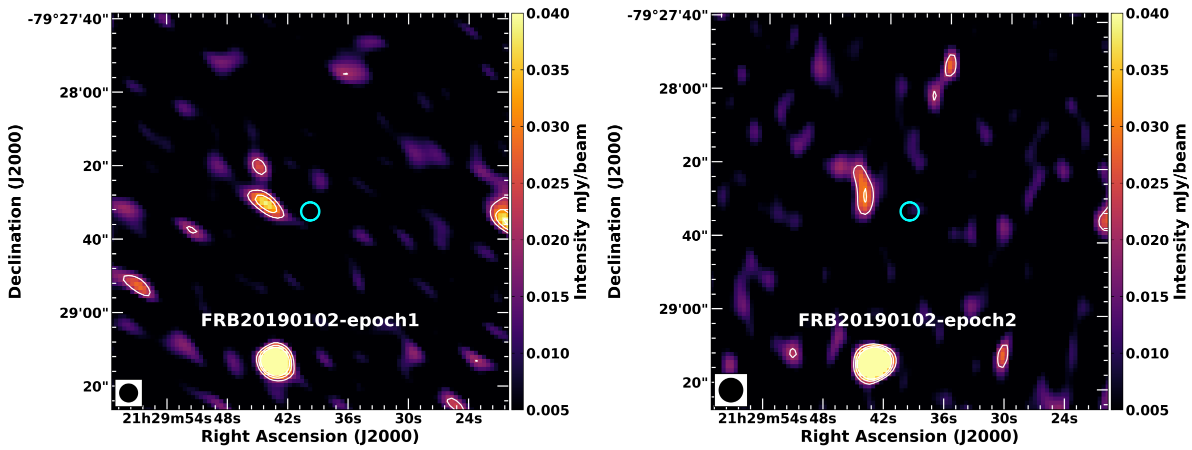

Figure 3: Same as Figure 2, but for FRB20190102.

Table 2: Observational information of FRB20190102.

Source name	Observation date	R.A.(J2000)	Dec.(J2000)	Synthesised beam	rms mJy beam^{-1}	Upper limit mJy beam^{-1}
FRB20190102	10-Apr-2021	21:29:39.76	-79:28:32.5	5".709× 5".709	0.0054	<0.0162
FRB20190102	05-Sep-2021	21:29:39.76	-79:28:32.5	6".723× 6".723	0.0055	<0.0164

4 Conclusion

As part of an ongoing study targeting 25 FRB positions, we presented results for 3 of them here. Out of the three FRB positions, we have two detections and one non-detection. For FRB20221106, we have positive detections for observations during three epochs. The position of the FRB20221106 coincides with a galaxy; whether the detected radio source originates from the PRS or the galaxy will remain to be seen. To answer this question, a telescope with high angular resolution, such as e-MERLIN, is required. Such a telescope will help us to identify compact PRSs from the observed radio sources. In addition, it will provide the size of the compact PRS if detected, and constrain its spectral shape and variability. In the case of FRB20181112, a telescope with high angular resolution is also needed to elucidate whether the host galaxy is the one providing the radio emissions, or if the emissions come from the PRS. Lastly, for FRB20190102, a flux upper limit was provided.

To resolve the detected radio sources, a proposal for a telescope with high angular resolution will be written, which will help to determine if we have detected PRSs with MeerKAT.

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