The Northern Cross Fast Radio Burst project - II. Monitoring of repeating FRB 20180916B, 20181030A, 20200120E and 20201124A

M. Trudu1,2*, M. Pilia2, G. Bernardi3,4,5, A. Addis6, G. Bianchi3, A. Magro7, G. Naldi3, D. Pelliciari3,8, G. Pupillo3, G. Setti3,8, C. Bortolotti3, C. Casentini9,10, D. Dallacasa3,8, V. Gajjar11, N. Locatelli12, R. Lulli3, G. Maccaferrì3, A. Mattana3, D. Michilli13,14, F. Perini3, A. Possenti1,2, M. Roma3, M. Schiaffino3, M. Tavani9,15 and F. Verrecchia16,17

1 Università degli Studi di Cagliari, Dipartimento di Fisica, SP Monserrato-Sestu km 0,7, I-09042 Monserrato (CA), Italy
2 INAF-Osservatorio Astronomico di Cagliari, via della Scienza 5, I-09047, Selargius (CA), Italy
3 INAF-Istituto di Radio Astronomia, via Gobetti 101, 40129 Bologna, Italy
4 South African Radio Astronomy Observatory, Black River Park, 2 Fir Street, Observatory, Cape Town, 7925, South Africa
5 Department of Physics and Electronics, Rhodes University, PO Box 94, Makhanda, 6140, South Africa
6 INAF-Osservatorio di Astrofisica e Scienza dello Spazio di Bologna, Via Piero Gobetti, 93/3, 40129, Bologna, Italy
7 Dipartimento di Spazio e Scienze dello Spazio, Università di Bologna, Via Gobetti 93/2, 40129, Bologna, Italy
8 Institute of Space Sciences and Astronomy (ISSA), University of Malta, Msida MSD 2080, Malta
9 INAF-IAPS, via del Fosso del Cavaliere 100, I-00133 Roma (RM), Italy
10 INAF/IASF, via del Fosso del Cavaliere 100, I-00133 Roma (RM), Italy
11 Department of Astronomy, University of California Berkeley, Berkeley CA 94720
12 Max-Planck-Institut für Extraterrestrische Physik (MPE), Giessenbachstrasse 1, 85748 Garching bei München, Germany
13 MIT Kavli Institute for Astrophysics and Space Research, Massachusetts Institute of Technology, 77 Massachusetts Ave, Cambridge, MA 02139, USA
14 Department of Physics, Massachusetts Institute of Technology, 77 Massachusetts Ave, Cambridge, MA 02139, USA
15 Università degli Studi di Roma "Tor Vergata", via della Ricerca Scientifica 1, I-00133 Roma (RM), Italy
16 SSDL/ASI, via del Politecnico snc, I-00133 Roma (RM), Italy
17 INAF-Osservatorio Astronomico di Roma, via Frascati 33, 00078 Monte Porzio Catone (RM), Italy

Accepted XXX. Received YYY; in original form ZZZ.

ABSTRACT

In this work we report the results of a nineteen-month Fast Radio Burst observational campaign carried out with the North-South arm of the Medicina Northern Cross radio telescope at 408 MHz in which we monitored four repeating sources: FRB20180916B, FRB20181030A, FRB20200120E and FRB20201124A. We present the current state of the instrument and the detection and characterisation of three bursts from FRB20180916B. Given our observing time, our detections are consistent with the event FRB20181030A, FRB20200120E and FRB20201124A. We present the current state of the instrument and the detection and characterisation of three bursts from FRB20180916B. Given our observing time, our detections are consistent with the event FRB20181030A, FRB20200120E and FRB20201124A.

Key words: methods: observational – radio continuum: transients – transients: fast radio bursts

1 INTRODUCTION

Fast Radio Bursts (FRBs) are millisecond-duration radio transients with high fluxes (~ 1–100 Jy ms) and (mostly) extragalactic origin (Petroff et al. 2019; Cordes & Chatterjee 2019; Petroff et al. 2021). The discovery of repeating FRBs (or repeaters, Spitler et al. 2016; CHIME/FRB Collaboration et al. 2019c,a) has opened the window to in-depth studies of some of these sources, which have provided the most stringent constraints to FRB models so far. Not all repeaters seem to behave similarly and possess the same kind of progenitor.

The first known repeater, FRB20121102A (Spitler et al. 2014, 2016) appears to be a very active and, possibly, very young source, located in the star forming region of a dwarf galaxy at z = 0.193 (Chatterjee et al. 2017; Tendulkar et al. 2017; Marcote et al. 2017), corresponding to a luminosity distance of ~ 1 Gpc. The presence of a persistent radio source co-located with the FRB emission (Marcote et al. 2017), the observation of significant variations in dispersion measure (DM) and rotation measure (Michilli et al. 2018), and the high number of detections at high frequencies (up to 8 GHz, Gajjar et al. 2020; CHIME/FRB Collaboration et al. 2019d) compared to

* E-mail: matteo.trudu@inaf.it

© 2021 The Authors
a low number (only one) of detections at low frequencies (below 1 GHz, Josephy et al. 2019), all concurred to interpret this source as a very young compact object surrounded by a dense medium. In particular, many of the models relied on an active magnetar, as the progenitor of FRB20121102A, possibly residing in its wind nebula. (see Zhang 2020).

The third discovered repeater, FRB20180916B (CHIME/FRB Collaboration et al. 2019a), was also soon found to be a very active source, which was localised to the outskirts of a star forming region in a nearby massive spiral galaxy (z = 0.0337, Marcote et al. 2020; Tendulkar et al. 2021). A high activity rate is the main common feature between the two sources. FRB20180916B is not coincident with a persistent source, with an upper-limit on the luminosity that is forty times lower than the persistent source associated with FRB20121102A; no significant DM or RM variations have been observed in time and its emission seems prominent at low frequencies (below 1 GHz, see, e.g., Marcote et al. 2020; Pilia et al. 2020; Chawla et al. 2020; Pleunis et al. 2021; Pastor-Marazuela et al. 2020) while it has never been observed above 2 GHz (Pearlman et al. 2020). FRB20180916B was also the first repeater for which a periodicity was established (CHIME/FRB Collaboration et al. 2020), which afterwards led to a similar finding for FRB20121102A (Rajwade et al. 2020). FRB20180916B has a period of 161 days (refined by Pleunis et al. 2021) with an active window of ±2.6 days around its peak phase. FRB20121102A, on the other hand, has a period of 161 days (refined by Cruces et al. 2021) with a 54% duty cycle. The discovery of periodicity, in particular in the case of the nearby and frequently active FRB20180916B has made extensive sensitive follow-up possible and rewarding, allowing for an unprecedented availability of radio data on this source.

The study of FRBs has received significant momentum from the advent of the CHIME telescope (CHIME/FRB Collaboration et al. 2018) operating as a transit instrument and being able to monitor the transient sky virtually full time and with real time capability to analyse the data and trigger alerts. The success of the CHIME/FRB experiment, which led in one year to the discovery of ~500 FRBs, about 20 of which being repeating sources (The CHIME/FRB Collaboration et al. 2021), demonstrated that field of view and time on sky are two strong requirements to carry out extensive FRB searches. The experience that has built up on that, and on the continuous study of repeaters in particular, has further highlighted the need of an immediate reaction on possible burst alerts in order to both understand multi-frequency or chromatic properties of the radio emission and try to catch the elusive multi-wavelength counterpart of this emission.

The Northern Cross (NC) radio telescope, located in Medicina near Bologna (Italy), is a transit telescope which operates at 408 MHz (P-band) with an observational bandwidth of 16 MHz. It is a T-shaped interferometer with two arms aligned along the North-South and East-West directions. The North-South arm has been going through a software and hardware upgrade which made it suitable for FRB observations, whereas the East-West arm is not currently in use. The system and its survey capabilities are described in Locatelli et al. (2020), hereafter Paper I.

In this paper we present the results of an observational campaign, spread over about nineteen months, which monitored four repeaters, mainly performed during known or presumed active phases in the NC observing band. The selected targets are FRB20180916B, FRB20181030A, FRB20200120E and FRB20201124A. The paper is organised as follows: in § 2 we report the current state of system deployed at the NC for the FRB data acquisition and the FRB detection pipeline; in § 3 we describe the targets selected in this observational campaign; in § 4 we report the results obtained from this monitoring and in § 5 we provide a short summary.

2 SYSTEM DESCRIPTION

2.1 Data Acquisition System

In this section we provide a brief overview of the NC system as presented in Paper I and describe the most recent updates. The North-South arm of the NC used in our observations includes sixty four parabolic cylinders. Each cylinder illuminates four groups of sixteen dipoles each, for a total of sixty four dipoles. Signals from each of the sixteen dipoles are combined together analogically and fed to a single receiver. Until March 21st 2021, six cylinders were used, for a total of twenty four receivers, whereas afterwards eight cylinders were equipped and used, for a total of thirty two receivers. Signals from the receivers were digitised, channelised, combined into a single beam and then written to disk. Unlike the system used in Paper I, we have routinely implemented a second channelisation stage with a windowed FFT that effectively leads to a power stream with a 138.24 µs time resolution and a 14.468 kHz frequency resolution, in order to reduce the intra-channel smearing for high DM events. The oversampling polyphase filterbank architecture of the first stage channeliser used in Paper I (see Comoretto et al. 2017, for details) causes an overlap between adjacent coarse channels by a factor of 5/32 (oversampling of 32/27). The overlapping portions of each pair of adjacent channels, that coincide with the filter transition region in the channel edges, are discarded and the resulting bandpass, consisting of 1024 fine spectral channels, is seamless and flat. The 32 bit time series of each frequency channel are then equalised and rescaled, over discrete time intervals of 10 s, in order to correctly represent 6σ samples with 16 bit data, using digi1.f11 from the DSPSR toolkit (van Straten & Bailes 2011). Output data are saved to disk using the SIGPROC Filterbank file format (Lorimer 2011).

During the observing campaign we used the eight-cylinder system to observe the transit of two bright sources, Taurus A and Virgo A, for 2 hours each, in order to further characterise the System Equivalent Flux Density (SEFD), following up on the estimates derived in Paper I from observations of the PSR B0329+54 pulsar. Figure 1 shows the corresponding transit observations, where the telescope was steered towards the corresponding declination of each source. We perform
Table 1. Astronomical sources used as calibrators. SEFDs are estimated for groups of 16 dipoles (i.e. one receiver). The SEFD for six and eight cylinders can be obtained by multiplying for the corresponding number of receivers, 24 and 32 respectively.

| Source        | Sky Position (RA 12000, DEC 12000) | Starting Time UT | SEFD (Jy) |
|---------------|-----------------------------------|------------------|-----------|
| Taurus A      | 05°34′31.940″, +22°00′52.20″       | 2021/04/13 14:21:03 | 9000 ± 400 |
| Virgo A       | 12°30′49.423″, +12°23′28.05″       | 2021/04/01 22:03:02 | 7800 ± 180 |

a standard on-off observation, where we estimate the background contribution as the average of the power away from source, i.e. for hour angles > [6°], and subtract it from the observed power when the source is within the main beam. We then fit a Gaussian model to the profile full width at half maximum (FWHM) for 21 frequency channels equally spaced across the 16 MHz bandwidth. Taurus A and Virgo A are assumed to be 1080 Jy and 569 Jy at 408 MHz respectively (Perley & Butler 2017), and the best fit to the curve peak provides the conversion from counts to Jy for each channel. The SEFD is derived from the rms of the calibrated power away from sources, i.e. for hour angle > [6°]. The SEFD is found to vary up to 20% across the bandwidth, a negligible variation for the purpose of the current analysis. We eventually average the SEFD estimates to obtain a band-averaged value (Tab. 1).

We note a slight dependence of the SEFD with the Galactic latitude, varying by ~ 14% from the Galactic plane (Taurus A is at a ~ ~5° Galactic latitude) to high Galactic latitudes (Virgo A is at a ~ ~74° Galactic latitude). This dependence is qualitatively expected as the sky temperature contribution to the SEFD increases towards the plane. At the same time, our results indicate that the sky temperature contribution to the SEFD is minor. For the purpose of this work we will adopt the same SEFD estimate for all FRB source, obtained by averaging the Taurus A and Virgo A values:

\[
\text{SEFD} = 8400 \pm 420 \text{ Jy}.
\]

2.2 Single Pulse Search Pipeline

The search for FRB candidates is currently performed through an adaptation of the SPANDAK pipeline (Gajjar et al. 2020). The pipeline uses {	extit{rpfend}} from PRESTO (Ransom et al. 2002) to prepare the radio frequency interference (RFI) mask, which is then used by {	extit{Heimdall}} (Barsdell et al. 2012) in order to flag out the noisiest frequency channels. The data are then searched by SPANDAK through {	extit{Heimdall}} across a DM range from 0 to 1000 pc cm^{-3} with a signal-to-noise ratio (S/N) loss tolerance in each DM trial of 10% and the width of the burst \(\Delta t\), the maximum number \(N_w\) of allowed candidates found within a time window \(w\) centred at the time of the candidate and the number \(N_m\) of distinct boxcar/DM trials (members) clustered into a candidate. Candidates found by SPANDAK are then further selected according to the S/N, the DM, the width of the burst \(\Delta t\), the maximum number \(N_w\) of allowed candidates found within a time window \(w\) centred at the time of the candidate and the minimum number \(N_m\) of distinct boxcar/DM trials (members) clustered into a candidate. Candidates which agree with the following criteria are classified as plausible FRB candidates:

\[
\begin{align*}
\text{S/N} & \geq 10; \\
\text{DM} & \geq 10 \text{ pc cm}^{-3}; \\
\Delta t & \leq 141.6 \text{ ms}; \\
N_w &= 4 \times 10^4; \\
N_m &\geq 2.
\end{align*}
\]

Filtered candidates are then validated by the artificial neural network classifier FETCH (Agarwal et al. 2020) and, eventually, manually inspected.

3 SELECTED TARGETS

We report the results of the observational campaign conducted between the 16th of January 2020 and the 29th of August 2021 for the following four repeating FRB sources: FRB20180916B, FRB20181030A, FRB20200120E, FRB20201124A. Sources were selected for their proximity (as initially suggested by their low DM values and later confirmed by their localisation) and therefore as favourable targets both for our new system and for the multi-wavelength campaign that included the NC (see, e.g. Pilia et al. 2020; Tavani et al. 2020a, b).

The whole NC campaign is summarised in Fig. 2, including all the observations performed for the monitored sources at the various epochs. We highlight the time when the transition between the six-cylinders system and the eight-cylinders system occurred. In the following sections we will describe the targets in more detail.

3.1 FRB20180916B

FRB20180916B is our main target and was observed for a total of ~180 hours throughout the campaign. Starting in January 2020, when its periodic activity was announced (CHIME/FRB Collaboration et al. 2020), the NC observed FRB20180916B regularly during its active cycles. FRB20180916B has a periodic activity of ~16 days with an active window of 5.2 days and we observed the source for about seven days each cycle, beginning one day before the period (predicted in the CHIME/FRB bandwidth) in order to match the multi-wavelength campaign from the Swift and AGILE satellites, trying to catch earlier emission (Casentini et al. 2020; Tavani et al. 2020a; Verrecchia et al. 2021). The primary aim of these observations was indeed to find theoretically predicted multi-wavelength counterparts (Lyubarsky 2014; Beloborodov 2017; Kumar et al. 2017; Ghisellini & Locatelli 2018; Metzger et al. 2019; Lu et al. 2020; Lyutikov & Popov 2020), looking for time coincidences with other instruments (see Nicastro et al. 2021, for an updated review).

3.2 FRB20181030A

FRB20181030A is the fourth known repeater, with two bursts detected by CHIME/FRB in October 2018 (CHIME/FRB Collaboration et al. 2019b) and seven new bursts detected in January 2020. It has a DM ~ 103 pc cm^{-3} and a maximum estimated redshift of \(z = 0.05\). The star-forming spiral galaxy NGC 3252 (\(z \sim 0.004\)) has been identified as its most auspicious host among seven plausible galaxies within the 90% confidence localisation region (Bhardwaj et al. 2021b).

Due to its small DM value, with an associated distance of ~20 Mpc, FRB20181030A has been monitored, on an approximately
3.3 FRB20200120E

FRB20200120E is a repeater with DM ~ 88 pc cm\(^{-3}\) (Bhardwaj et al. 2021a), initially localised in the outskirts of M81, a spiral galaxy with a distance of ~ 3.6 Mpc (Freedman et al. 1994) and afterwards precisely localised in a globular cluster within M81 with the detection of five bursts from the source at 1.4 GHz (L-band) by the European VLBI Network (EVN) (Kirsten et al. 2021). Thanks to the relative proximity of the source and also thanks to its high Galactic latitude (~ 41.2°), which makes the scattering broadening due to the Milky Way interstellar medium negligible, an ultra-high-time resolution analysis of the five bursts detected by Kirsten et al. (2021) has been performed, showing that this source can produce nanosecond duration isolated bursts with 1.0\(^{11}\) K brightness temperature (Nimmo et al. 2021a), similar to the Crab pulsars (Hankins et al. 2003). This unprecedented finding marked a bridge between young Galactic pulsars and magnetars and the more distant FRBs in terms of burst durations and luminosities (see in particular Fig. 3 from Nimmo et al. 2021a).

This target was included in the selection being the closest known repeater so far. Analogously to FRB201801030A we monitored this source about once a day from March 2021 to the last day of the campaign reported in this paper, for a total observing time of ~ 109 hours.

3.4 FRB20201124A

FRB20201124A is a repeater with DM ~ 410 pc cm\(^{-3}\), discovered by CHIME/FRB in November 2020. It had a very active phase between March and May 2021 (CHIME/FRB Collaboration 2021; Lanman et al. 2021), with a plethora of follow-up detections by other radio telescopes (Kumar et al. 2021; Marcote et al. 2021; Xu et al. 2021; Law et al. 2021; Wharton et al. 2021) at both P and L bands, with an initial localisation of the source by ASKAP (Day et al. 2021), FAST (Xu et al. 2021), uGMRT (Wharton et al. 2021) and VLA (Law et al. 2021) and further refined, with a milliarcsecond precision, by the EVN (Nimmo et al. 2021b). It was localised in a nearby (z ~ 0.098) (Fong et al. 2021) galaxy with a high star formation rate which suggests a new-born magnetar as the most likely progenitor (Piro et al. 2021). We monitored this source daily from April 2021 to June 2021 for a total observing time of 68 hours.

4 BURSTS DETECTED

We report the detection of three bursts from FRB20180916B: B1, B2 and B3, from now onward. These bursts happened on March 3\(^{rd}\) 2021, April 3\(^{rd}\) 2021 and July 13\(^{th}\) 2021, respectively. Tab. 2 contains the observed properties of the detected bursts. Fig. 3 shows the dedispersed waterfall plots of B1, B2 and B3, obtained with the fit-optimised DM reported in Tab. 2.

4.1 Burst Characterisation

The properties of the detected bursts, that is their time of arrival (TOA), the width \(\Delta\), the best DM and the scattering time \(\tau\) have been computed by making a fit of the spectro-temporal data array. We use, as a template for the burst in the time domain, a Gaussian function convolved with an exponential decay function (McKinnon 2014) and a Gaussian function for the burst in the frequency domain. The fit procedure has been performed using the software package BURSTFIT, a detailed description of this package can be found in Aggarwal et al. (2021).

The flux density \(S\) of the incoming radiation from the source is then computed by using a modified version of the standard radiometer equation for single pulses (Lorimer & Kramer 2005):

\[
S = \frac{S/N \SEFD \zeta}{A \sqrt{N_P N_c (1 - \xi) \Delta \nu \Delta t}} ~ (\text{TOA})
\]

Here \(S/N\) is the integrated signal-to-noise ratio of the frequency averaged time series, \(A = 24\) or 32 is a geometric factor which takes into account the ratio between the collecting area of the six or eight cylinders system and one receiver (see Paper I for further details),

\[
\SEFD = \frac{\zeta}{\Delta \nu \Delta t}
\]
$N_p = 1$ is the number of polarisations, $N_c = 1024$ is the number of spectral channels of the observation, $\xi$ is the fraction of channels excised as RFI and $\Delta v_{ch}$ is the channel width. The multiplicative factor $\zeta$ (TOA) takes into account the primary beam attenuation at the burst TOA.

The estimated fluxes $F$ of the bursts were calculated as the product between the flux density $S$ and the duration of the burst $\Delta t$.

### 4.2 Bursts Properties

The top panels of Fig. 3 show the frequency averaged time series of B1, B2 and B3. We obtain a significant measurement for the scattering time only for B2, with a value of 3.6 ms at 408 MHz. This would correspond to ~0.8 ms at 600 MHz, consistent with previous scattering time measurements reported for this source (CHIME/FRB Collaboration et al. 2019b). However, we consider this value as an upper limit as Marcote et al. (2020) and Pastor-Marazuela et al. (2020) placed a tighter constraint on the scattering time scale of the order of 3 $\mu$s at 1.7 GHz, similar to the NE2001 (Cordes & Lazio 2002) prediction of 2 $\mu$s. Our estimate would correspond to 10 $\mu$s at 1.7 GHz. Hence, we conclude that this apparent scattering tail, as showed in the model for B2 in Fig. 3, could be originated by the presence of not resolvable sub-bursts (CHIME/FRB Collaboration et al. 2019b).

None of the three detected burst show peculiar spectro-temporal features (bottom panels of Fig. 3), that is the typical downward drift of the signal in the time-frequency plane (oftentimes called "sad trombone effect") as often reported for repeater sources (CHIME/FRB Collaboration et al. 2019c; Hessels et al. 2019; Pleunis et al. 2021), as can be seen from the dynamic spectra in Fig. 3.

Figure 4 shows the span of our observations and the occurrence of B1, B2 and B3 as a function of the relative phase $\phi$, during the activity cycles of FRB20180916B. The phases are obtained folding the data at the nominal period of 16.33 days taking a starting phase $\phi_0 = 58369.40$ MJD (corresponding to Cycle 1), such that $\phi = 0.5$ corresponds to the peak of the activity of the source (see Pleunis et al. 2021, for further details).

The obtained phases for B1, B2 and B3 are reported in Tab. 2. From Fig. 4 we see that the three bursts are consistently located within the predicted activity window of 5.2 days from CHIME/FRB, since our observational bandwidth overlaps with theirs (see again Pleunis et al. 2021, Fig. 9). We do not report any detection from outside its window of activity (Fig. 4), consistently with the observed chromatic activity, as burst were detected at $\phi \sim 0.7$ at lower frequencies (Pastor-Marazuela et al. 2020; Pleunis et al. 2021).

### 4.3 Rate Estimation and Comparison with CHIME/FRB

We estimate the number of expected bursts at our facility for the monitored sources, making a comparison with the detection rates reported by CHIME/FRB, due to the partially overlapping observational bandwidths. Let us assume that the differential number of bursts $dN$, for a facility $x$ which operates at the central frequency $v_x^c$, with fluence (or equivalently flux density for a 1 ms burst), within the interval $(F, F + dF)$ follows a power law of the kind:

$$
\frac{dN}{dF} = K \left( \frac{v_x^c}{v_{ref}} \right)^{-\alpha} \left( \frac{F}{F_{ref}} \right)^{-\beta},
$$

where $F_{ref}$, $v_{ref}$ are respectively a reference fluence and a reference frequency, $K$ corresponds to $dN^x/df$ at $v = v_{ref}$ and $F = F_{ref}$, $\beta = 1.6\pm0.3$ (Macquart et al. 2019) is the spectral index, and lastly $\alpha$ is the slope of the differential fluence distribution (see The CHIME/FRB Collaboration et al. 2021, §6.2). The value of $\alpha$ appears to be different for each source, with a value for instance of $\alpha = 2.3 \pm 0.8$.
Table 2. Properties of the detected bursts of FRB20180916B from the NC campaign. The second column reports the percentage of channels excised as RFI; the third, the fourth and the fifth columns report the barycentric (MHz) time of arrival of the bursts as MJD, UT and phase of the activity period of FRB20180916B (see § 4.2); the sixth column reports the fit-optimised DM; the seventh column the S/N; the eighth column reports the FWHM burst duration in ms; the ninth column reports the scattering time computed with respect to the reference frequency of 408 MHz; the tenth and eleventh columns report respectively the flux densities and the fluences of the bursts.

| B1  | 2      | 59276.5954859605(4) | 2021-03-03 14:17:29.987(1) | 0.554±0.008 | 349.28±0.25 | 14.5 | 4.76±0.57 | 20±2 | 96±14 |
|-----|--------|---------------------|-----------------------------|-------------|-------------|------|----------|------|-------|
| B2  | 12     | 59307.5148011862(7) | 2021-04-03 12:21:18.822(4) | 0.447±0.007 | 349.57±0.36 | 21.7 | 5.95±0.75 | <3.6 | 22±3 | 135±19 |
| B3  | 8      | 59408.2528584486(4) | 2021-07-13 06:04:06.970(6) | 0.616±0.009 | 349.64±0.35 | 12.5 | 4.33±0.45 | /    | 16±1 | 71±8  |

Henceforth the expected detection rate of bursts with fluence exceeding a given threshold \( F_1 \) is:

\[
R^x (F > F_1) = R^x = \frac{K}{\delta F_{\text{obs}}} \left( \frac{v_{\text{c}}}{v_{\text{ref}}} \right)^{-\beta} \int_0^{\infty} \left( \frac{F}{F_{\text{ref}}} \right)^{-\alpha} dF .
\]  

(6)

Taking \( \alpha > 1 \), we can ensure the convergence of the integral in Eq. 6 and we obtain the following expression:

\[
R^x = \frac{K}{\delta F_{\text{obs}}} \left( \frac{v_{\text{c}}}{v_{\text{ref}}} \right)^{-\beta} \left( \frac{F}{F_{\text{ref}}} \right)^{-\alpha+1} .
\]  

(7)

Considering now Eq. 7 for both the NC and CHIME/FRB (CF) and calculating the ratios between the two equations, we can evaluate the rate of bursts expected at the NC with respect to the rate of bursts expected by CHIME/FRB as:

\[
R^{NC} = R^{CF} \left( \frac{\delta F_{\text{obs}}}{\delta F_{\text{obs}}} \right)^{-1} \left( \frac{v_{\text{c}}}{v_{\text{ref}}} \right)^{-\beta} \left( \frac{F_{\text{NC}}}{F_{\text{CF}}} \right)^{-\alpha+1} .
\]  

(8)

Lastly, the average number of bursts \( N^{NC} \) that we expect at the NC, with fluence greater than \( F_1^{NC} \), throughout a campaign of total duration \( \Delta T_{c} \) will be:

\[
N^{NC} = R^{NC} \Delta T_{c} .
\]  

(9)

4.3.1 Instrument Fluence Detection Threshold

In order to evaluate the number of bursts throughout the campaign we need to estimate the minimum fluence detectable, given a certain threshold, we can achieve with the NC. In general this fluence will depend on the physics which impact the arrived signal (e.g. the scattering) and also on the instrumental performances (e.g. the sampling time). From the radiometer equation we can compute the minimum flux density \( S'_l \), considering a minimum S/N of 10, we are able to detect with the NC (Burke-Spolaor et al. 2011):

\[
S'_l = S'_l \frac{\Delta m}{\Delta t} ,
\]  

(10)

\[
S'_l = 10 \times \frac{\text{SEFD}^*}{A \sqrt{N_p N_c \Delta v_{ch} \Delta t}} \xi \left( \text{TOA} \right) ,
\]  

(11)

where

\[
\Delta m = \sqrt{\Delta t^2 + t_{DM}^2 + \tau^2 + t_s^2}
\]  

(12)

consists in the measured width of the burst, which will be generally broadened by the scattering time \( \tau \), the sampling time \( t_s \) of the receiver and the intra-channel smearing:

\[
t_{DM} = 8.3 \times 10^{-3} \left( \frac{\text{DM}}{\text{pc cm}^{-3}} \right) \left( \frac{\Delta v_{ch}}{\text{MHz}} \right) \left( \frac{v_{\text{c}}}{\text{GHz}} \right)^{-3} \text{ ms} .
\]  

(13)
The quantity \( S_l^f \) in Eq. 11 corresponds so to the minimum flux density detectable in the case of negligible intra-channel smearing, scattering and sampling time. Considering now a nominal width of a burst of \( \Delta t = 1 \) ms and assuming \( \zeta = 1.5 \) throughout the whole transit of the source\(^3\), substituting all the numbers in Eq. 10 we can express the minimum detectable fluence (at 10\(\tau\)) \( F_{l}^{\text{NC}} \) of the instrument as:

\[
F_{l}^{\text{NC}} = S_l^f (\Delta t = 1 \text{ ms}) \times 1 \text{ ms} = \frac{690.12 \sqrt{1.02 + \frac{t_{\text{DM}}^2 + \tau^2}{1 \text{ ms}}}}{A} \text{ Jy ms}. \tag{14}
\]

Figure 5 displays the fluence detection threshold of the NC, computed via Eq. 14, as a function of DM. In addition to the previously considered values of 24 and 32 for the six and eight-cylinders systems, we consider \( A = 64, 128, 256 \) for the futures sixteen, thirty-two and sixty-four cylinders systems, respectively.

The scattering time is more uncertain to estimate, and we consider two cases: the case in which we neglect it and the case of a scattering time of 1 ms. From Fig. 5 we see the detection threshold increase as the DM increases, consistently with the fact the DM smearing dominates at higher DM. Regarding the scattering time, from the top panel of Fig. 5 we see that it is quite relevant at low DM, whereas for DMs higher than 1000 pc cm\(^{-3}\) the relative variation between the two defined regimes is below the 10%.

We estimate the minimum fluence that can be detected from the monitored sources using Eq. 14 and assuming \( \tau = 0 \). In the case of FRB20180916B, we can detect bursts with fluences greater than 51 and 38 Jy ms for the six and eight cylinders system respectively. FRB20181030A has been monitored only when the six-cylinders system were in place and we estimate a fluence detection threshold of 44 Jy ms. FRB20200120E and FRB20201124A were both monitored with the eight-cylinders system and we place for them, respectively, a fluence detection threshold of 33 and 42 Jy ms.

With current upgrades in progress, when the full North-South arm will be in use, we expect to find bursts, for instance from FRB20180916B, with 5 Jy ms fluence at S/N = 10.

### 4.3.2 FRB20180916B

Table 2 reports the flux densities and the fluences of the three bursts detected, computed from Eq. 3. We compute the expected number of bursts from FRB20180916B above our detection threshold by using Eqs. 9 and 8. In order to do so, we make the following assumptions. The observing time of CHIME/FRB requires the knowledge of the time when the source was within the FWHM of their beam at 600 MHz: as observing time for CHIME/FRB we assume 70% of the expected number of bursts for the total monitoring period. We assume the burst rate to be \( 0.9 \pm 0.5 \) hours\(^-1\) above a fluence limit of 5.2 Jy ms within its activity window of 5.2 days (CHIME/FRB Collaboration et al. 2020).

Tab. 3 we report the expected number of bursts for \(~ 102\) hours (six-cylinders) and \(~ 70\) hours (eight-cylinders). We expect \(~ 4.3\) bursts respectively, and a total of \(~ 2.7 \pm 1.9\) bursts for the total monitoring of \(~ 180\) hours, consistent with our three detections. When the full North-South arm will be operational, we can expect \(~ 36\) bursts from this source for a campaign of the same duration as the one performed.

### 4.3.3 FRB20181030A, FRB20200120E and FRB20201124A

No detections were obtained for FRB20181030A, FRB20200120E and FRB20201124A after an observing campaign of 93, 109 and 68 hours, respectively. We used our observations to constrain \( \alpha \), the source transit time can be computed thanks to the CHIME/FRB Online Calculator: https://www.chime-frb.ca/astronomytools

---

\(^3\) \( \zeta \) can actually vary between one and two throughout our observations, following the primary beam variations in a transit observation.

---

**Table 3.** Results for the NC observational campaign. For each source we report the observational system deployed (see § 2) in the second column, the fluence detection threshold in the third column and the total observing time in the fourth column. For FRB20180916B and FRB20201124A we report in the fifth column the expected number of bursts \( N_{\text{NC}} \), whereas for the other two sources we report the 95% confidence level lower limits of the slope of the differential fluence distribution \( \alpha \).

| Source          | System | \( F_{l}^{\text{NC}} \) (Jy ms) | \( \Delta T_c \) (hours) | \( N_{\text{NC}} \) |
|-----------------|--------|-------------------------------|--------------------------|----------------------|
| FRB20180916B    | Six    | 51                            | 1.4 ± 1.5                |                      |
|                 | Eight  | 38                            | 1.3 ± 1.2                |                      |
| FRB20201124A    | Eight  | 44                            | 1.0 ± 1.1                |                      |

---

\( \zeta \) can actually vary between one and two throughout our observations, following the primary beam variations in a transit observation.
slope of the fluence distribution for each source (see Eq. 4). Following Amiri et al. (2017) and Paper I, if we assume that the occurrence of a burst is a Poissonian process, we can compute the likelihood of detecting $M$ bursts with expectation number $N(\alpha)$ (computing this with Eq. 8 and Eq. 9) as:

$$p\{M; N(\alpha)\} = \frac{N(\alpha)^M e^{-N(\alpha)}}{M!}.$$  \hspace{1cm} (16)

The cumulative distribution function (CDF) of seeing $X$ events lower than $M$, with $N(\alpha)$ expected, results then as the following expression:

$$P\{X < M|N(\alpha)\} = \sum_{k=0}^{M-1} p\{k; N(\alpha)\}.$$  \hspace{1cm} (17)

Hence in the case of less than $M = 1$ events (non-detection case):

$$P\{X < M = 1|N(\alpha)\} = e^{-N(\alpha)}.$$  \hspace{1cm} (18)

In order to estimate $N(\alpha)$ we make some assumptions for the three sources. We separate the case of FRB20181030A and FRB20200120E from that of FRB20201124A for reasons that we report below.

Figure 6 shows the CDF for the detection of zero events as a function of the slope $\alpha$, for FRB20181030A and FRB20200120E, considering their respective total observing time (Tab. 3). In the cases of FRB20181030A and FRB20200120E, we assume a measured rate for CHIME/FRB equivalent to the predicted rate of the facility: ~820 sky$^{-1}$ day$^{-1}$ above a threshold of 5 Jy ms at 600 MHz (The CHIME/FRB Collaboration et al. 2021). Under the same hypotheses as for FRB20180916B, we set 13 min as the average observing time at CHIME/FRB for FRB20181030A and 10 minutes for FRB20200120E. The average observing times at the NC for the two sources were 90 and 72 minutes respectively.

Setting a confidence level of 95%, from Fig. 6 we can rule out the values of $\alpha$ for which the probability computed by Eq. 18 is less than 0.05. The lower limits obtained for the values of $\alpha$ for both sources are reported in Tab. 3. These limits are consistent with the estimated values of $\alpha$ for a low-DM population as showed by The CHIME/FRB Collaboration et al. (2021). In their work they searched for correlations between fluences and DMs among the current population of detected FRBs and found that the distributions of fluence versus $\alpha$ peak at two different values: $\alpha \sim 2$ for FRBs with DM between 100-500 pc cm$^{-3}$ and $\alpha \sim 2.8$ for FRBs with DM > 500 pc cm$^{-3}$ (this retains the value of $\alpha = 2.5$, considering the whole sample of bursts, compatible with an Euclidean Universe).

In the case of FRB20201124A, Lanman et al. (2021) report a significant increase of the burst rate from the source in the period March-May 2021 with respect to the period between its discovery in November 2020 and March 2021, implying a non-Poissonian distribution of the events.

Due to this non-Poissonianity we only conservatively estimate the expected number of bursts above the estimated threshold for our facility for this source, in order to assess the compatibility with a non-detection. Following Lanman et al. (2021), we consider 4 minutes as the average observing time and a value of $\alpha = 4.5 \pm 2.2$ for CHIME/FRB. For CHIME/FRB we assume a rate of 5.4 hour$^{-1}$ (see Fig. 3 of the aforementioned paper) above a fluence limit of 17 Jy ms. We observed this source with NC for 120 minutes on average. The expected number of bursts from FRB20201124A for the NC was calculated as $1.0 \pm 1.1$, consistent with a non-detection.

5 CONCLUSIONS

This work presents the first FRB detections from the Medicina Northern Cross radio telescope, whose North-South arm is currently equipped to carry out FRB observations at 408 MHz with an observational bandwidth of 16 MHz. We performed a nineteen months observational campaign in which we targeted FRB20180916B, FRB20181030A, FRB20200120E and FRB20201124A.

We describe the facility upgrade from the six-cylinder system to the eight-cylinder system. Before the upgrade we report the detection of a single burst from FRB20180916B above a 10$\sigma$ fluence threshold of 51 Jy ms (which also accounts for the intra-channel smearing for our current frequency resolution of 14.468 kHz). After the upgrade we report the detection of two bursts from the same source above a fluence threshold of 38 Jy ms. All bursts were found within the 5.2 day activity window of the source, confirming the source periodicity. Assuming the CHIME/FRB source rate, we expected to detect $2.7 \pm 1.9$ bursts in our campaign, above the aforementioned fluence detection thresholds, consistent with our results.

We report no detections for the other three sources. In the cases of FRB20181030A and FRB20200120E, we constrain the slope of the differential fluence distribution $\alpha$ to be $\alpha > 2.1$ and $\alpha > 2.2$ at the 95% confidence level, respectively. In the case of FRB20201124A we estimate $1.0 \pm 1.1$ bursts to be observed above a fluence detection threshold of 42 Jy ms, consistent with our non-detection.

ACKNOWLEDGEMENTS

The authors thanks the anonymous referee for the useful comments which significantly improved the quality of this work. The Northern Cross radio telescope is a facility of the University of Bologna operated under agreement by the Institute of Radio Astronomy of Bologna (Istituto Nazionale di Astrofisica, INAF). MT gratefully acknowledges INAF for the financial support for his PhD program.
acknowledges financial support from the European Research Council (ERC) under the European Union’s Horizon 2020 research and innovation program Hot-Milk (grant agreement No. [865637]).

DATA AVAILABILITY
The data presented in this paper and the software used can be shared upon reasonable request to the corresponding author.

SOFTWARE PACKAGES

Python Packages

**burstfit** (Aggarwal et al. 2021); **Matplotlib** (Hunter 2007); **NumPy** (Harris et al. 2020); **Scipy** (Virtanen et al. 2020); **YOUR** (Aggarwal et al. 2020).

FRB/Pulsar Softwares

**DPSPR** (van Straten & Bailes 2011); **FETCH** (Aggarwal et al. 2020); **HEIMDALL** (Barsdell et al. 2012); **PRESTO** (Ransom et al. 2002); **SIGPROC** (Lorimer 2011); **SPANDAK** (Gajjar et al. 2020).

REFERENCES

Aggarwal D., Aggarwal K., Burke-Spolaor S., Lorimer D. R., Garver-Daniels N., 2020, Monthly Notices of the Royal Astronomical Society, 497, 1661
Aggarwal K., et al., 2020, Journal of Open Source Software, 5, 2750
Aggarwal K., Aggarwal D., Lewis E. F., Anna-Thomas R., Cardinal Tremblay J., Burke-Spolaor S., McLaughlin M. A., Lorimer D. R., 2021, arXiv e-prints, p. arXiv:2107.05658
Amiri M., et al., 2017, ApJ, 844, 161
Barsdell B. R., Bailes M., Barnes D. G., Fluke C. J., 2012, MNRAS, 422, 379
Beloborodov A. M., 2017, ApJ, 843, L26
Bhardwaj M., et al., 2021a, ApJ, 910, L18
Bhardwaj M. et al., 2021b, ApJ, 919, L24
Burke-Spolaor S., et al., 2011, Monthly Notices of the Royal Astronomical Society, 416, 2465
CHIME/FRB Collaboration 2021, The Astronomer’s Telegram, 14497, 1
CHIME/FRB Collaboration et al., 2018, ApJ, 863, 48
CHIME/FRB Collaboration et al., 2019a, arXiv e-prints, p. arXiv:1908.03507
CHIME/FRB Collaboration et al., 2019b, arXiv e-prints, p. arXiv:1908.03507
CHIME/FRB Collaboration et al., 2019c, Nature, 566, 235
CHIME/FRB Collaboration et al., 2020a, Nature, 579, 448
CHIME/FRB Collaboration et al., 2020b, arXiv e-prints, p. arXiv:2001.10275
Casentini C., et al., 2020, ApJ, 890, L32
Chatterjee S., et al., 2017, Nature, 541, 58
Chawla P., et al., 2020, ApJ, 896, L41
Comoretto G., et al., 2017, JAA, 106
Cordes J. M., Chatterjee S., 2019, ARA&A, 57, 417
Cordes J. M., Lazio T. J. W., 2002, arXiv e-prints, pp astro-ph/0207156

5 https://github.com/thepetabyteproject/burstfit
6 https://github.com/thepetabyteproject/your
7 http://dpsr.sourceforge.net/
8 https://github.com/devanshvk/fetch
9 https://sourceforge.net/projects/heimdall-astro/
10 https://github.com/scottransom/PRESTO
11 http://sigproc.sourceforge.net/
12 https://github.com/gajjarv/PulsarSearch

Cruces M., et al., 2021, MNRAS, 500, 448
Day C. K., Bhandari S., Deller A. T., Shannon R. M., Moss V. A., 2021, The Astronomer’s Telegram, 14515, 1
Fong W.-f., et al., 2021, ApJ, 919, L23
Freedman W. L., et al., 1994, ApJ, 427, 628
Gajjar V. et al., 2020, arXiv e-prints, p. arXiv:2003.10889
Ghisellini G., Locatelli N., 2018, A&A, 613, A61
Hankins T. H., Kern J. S., Weatherall J. C., Eilek J. A., 2003, Nature, 422, 141
Harris C. R., et al., 2020, Nature, 585, 357
Hessels J. W. T., et al., 2019, ApJ, 876, L23
Hunter J. D., 2007, Computing in Science & Engineering, 9, 90
Joseph A., et al., 2019, ApJ, 882, L18
Kirsten F., et al., 2021, arXiv e-prints, p. arXiv:2105.11445
Kumar P., Lu W., Bhattacharya M., 2017, MNRAS, 468, 2726
Kumar P., Shannon R. M., Moss V., Qiu H., Bhandari S., 2021, The Astronomer’s Telegram, 14502, 1
Lanman A. E., et al., 2021, arXiv e-prints, p. arXiv:2109.09254
Law C., Tendulkar S., Clarke T., Aggarwal K., Bethapudy S., 2021, The Astronomer’s Telegram, 14526, 1
Locatelli N. T., et al., 2020, MNRAS, 494, 1229
Lorimer D. R., 2011, Astrophysics Source Code Library (ascl:1107.016)
Lorimer D., Kramer M., 2005, Handbook of Pulsar Astronomy. Cambridge Observing Handbooks for Research Astronomers, Cambridge Press
Lu W., Kumar P., Zhang B., 2020, arXiv e-prints, p. arXiv:2005.06736
Lyubarsky Y., 2014, MNRAS, 442, L9
Lyutikov M., Popov S., 2020, arXiv e-prints, p. arXiv:2005.05093
Macquart J. P., Shannon R. M., Bannister K. W., James C. W., Ekers R. D., Bunton J. D., 2019, ApJ, 872, L19
Marcote B. et al., 2017, ApJ, 834, L8
Marcote B., et al., 2020, Nature, 577, 190
Marcote B., et al., 2021, The Astronomer’s Telegram, 14603, 1
Martin V. R., et al., 2021, arXiv e-prints, p. arXiv:2108.00697
McKinnon M. M., 2014, PASP, 126, 476
Metzger B. D., Margalit B., Sironi L., 2019, MNRAS, 485, 4091
Michilli D., et al., 2018, Nature, 553, 182
Nicastro L., Guidorzi C., Palazzi E., Zamponi L., Turatto M., Gardini A., 2021, Universe, 7, 76
Nimmo K., et al., 2021a, arXiv e-prints, p. arXiv:2105.11446
Nimmo K., et al., 2021b, arXiv e-prints, p. arXiv:2111.01600
Pastor-Marazuela I., et al., 2020, arXiv e-prints, p. arXiv:2012.08348
Pearlman A. B., Majid W. A., Prince T. A., Nimmo K., Hessels J. W. T., Naudet C. J., Kocz J., 2020, ApJ, 905, L27
Perley R. A., Butler B. J., 2017, ApJS, 230, 7
Petroff E., Hessels J. W. T., Lorimer D. R., 2019, A&ARv, 27, 4
Petroff E., Hessels J. W. T., Lorimer D. R., 2021, arXiv e-prints, p. arXiv:2107.10113
Pilia M., et al., 2020, ApJ, 896, L40
Piro L., et al., 2021, arXiv e-prints, p. arXiv:2107.14339
Pleunis Z., et al., 2021, ApJ, 911, L3
Rajwade K. M., et al., 2020, MNRAS, 495, 3551
Ransom S. M., Eikenberry S. S., Middleditch J., 2002, The Astronomical Journal, 124, 1788
Spitler L. G., et al., 2016, ApJ, 830, 121
Spitler L. G., et al., 2014, ApJ, 790, 101
Tavani M., et al., 2020b, ApJ, 893, L42
Tavani M., et al., 2020a, arXiv e-prints, p. arXiv:2005.12164
Tavani M., et al., 2021, arXiv e-prints, p. arXiv:2107.00000
van Straten W., Bailes M., 2011, Publ. Astron. Soc. Australia, 28, 1
This paper has been typeset from a \TeX/\LaTeX file prepared by the author.