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STATUS OF THE NENUFAR FAST RADIO BURST PROGRAM

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Abstract. The New Extension in Nançay Upgrading LOFAR (NenuFAR) telescope is a newly commissioned SKA pathfinder targeting very low frequencies. The nearly 2000 dual polarized and phased antennas allow for very sensitive observations in the $10 - 85$ MHz range. Therefore, it is very well suited for the hunt of Fast Radio Bursts (FRB) in this frequency domain, where noise, dispersion, and scattering effects can become quite challenging to handle in order to achieve the detection of these extra-galactic events. Since the start of the early science phase of the instrument, a FRB Program is conducted in order to detect, or at least, constrain the existence of FRBs at the very low frequencies. The detection strategy relies on the monitoring of already known and repeating sources. Currently, the program has accumulated more than 2000 h over 11 promising repeaters. No detection has been achieved yet, but the data analysis is still ongoing. In this proceeding, we present the observation and analysis strategies.

Keywords: Fast Radio Burst, Low Frequency Radioastronomy

1 Introduction

Fast Radio Bursts (FRBs) are a new class of extra-galactic radio transients discovered about ten years ago, and for which the origin and physical mechanisms remain unknown yet (Lorimer et al. 2007). In that respect, many radio observatories are trying to observe and characterize these events, however, their nature, very brief events and mostly non-repeating, makes this task challenging (Spitler et al. 2016; Amiri et al. 2019). On the other hand, many theoretical developments have been made with a great profusion of models (Voisin 2021), despite that, the sparsity of the observations does not allow for constraining them robustly yet (Platts et al. 2019). So far, FRBs have been detected from several GHz down to 110 MHz (Pleunis et al. 2021a), and this program intents to observe them below 85MHz. This goal is particularly challenging because of the dilution of the signal during the propagation over the great distances travelled by the radio emissions (Sokolowski et al. 2018; Pleunis et al. 2021b). In particular, the scattering is expected to reach a few seconds at the frequencies of NenuFAR, hence drastically reduces the signal intensities. Nevertheless, the detection and characterization of already known and new FRBs in the low frequency domain can provide critical information on the FRB physics and populations. Hence, it can unveil a bit more the origin of the FRBs, and add new constraints for the many models currently existing (Shannon et al. 2018). Furthermore, this program on NenuFAR represents a pathfinder program for future FRB searches at low frequency at the dawn of the construction of the SKA. Towards this goal we have already performed numerous observations of already known FRB repeaters, as well as blind zenith observations, and Galactic magnetar survey (SGR1935+2154). We present here the progress made so far on the analysis of the data, and the remaining works ahead of us to detect or constrain FRBs in the frequency band of NenuFAR.

2 Observations

The observation strategy of the FRB Program relies on the high sensitivity at low frequency provided by the radio telescope NenuFAR, and the choice of targets. We detail in this section these two aspects of the program.

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2.1 NenuFAR (New Extension in Nançay Upgrading LOFAR)

NenuFAR is a low-frequency radio array located at the Nançay Radio Observatory, designed as a SKA pathfinder. It consists in 1938 dual polarization antennas hierarchically distributed in mini arrays (MA) of 19 antennas in a hexagonal tile pattern, with a step of 5.5 m between any two antennas inside the MA. 96 of these MA are concentrated in a 400 m core and 6 are located at distances up to 3 km. All MA are analog phased with delay lines, and the digital pointing of the whole array is performed quasi-continuously within the analog MA beam. The antennas operate between the Earth ionospheric cut-off at ~ 10 MHz and the radio FM band at ~ 85 MHz. The angular resolution from the core only varies between 2.9° and 0.5°. The two linear polarization (NE-NW) of each antenna are connected in parallel to several receivers, allowing to operate in four distinct modes: a standalone beam-former, a waveform capture mode, a standalone imager and an upgraded LOFAR station mode combining NenuFAR and the International LOFAR Telescope through the Nançay LOFAR station (FR606). The NenuFAR frequency resolution is $\mathrm{d}f \sim 195$ kHz with a time resolution of $\mathrm{d}t \sim 5$ µs, which can be numerically channelled down to $\mathrm{d}f \sim 100$ Hz at a cost of a lower time resolution $\mathrm{d}t \sim 10$ ms. Finally, the sensitivity of NenuFAR varies from 130 mJy at 15 MHz to 9 mJy at 85 MHz for one hour integration time with a frequency bandwidth of $\mathrm{d}f = 10$ MHz. This makes NenuFAR one of the most sensitive radio telescopes below 85 MHz (Zarka et al. 2020).

2.2 Strategy and targets

The FRB Program observes on a regular basis about 12 FRB repeaters among a total of 50 repeaters discovered worldwide. The choice of these targets is constrained by their visibility in the sky of NenuFAR, their dispersion measure (DM) as low as possible, their fluence as high as possible and scattering as small as possible. The program also surveys the Galactic magnetar SGR1935+2154, progenitor of a possible Galactic FRB signal in 2020 (Andersen et al. 2020). The complete list of targets is given in Table 1, with their parameters and total observation time. A number of pulsars (B0329+54, B0809+74, B2217+47, B1919+21, and B1508+55) are also monitored prior to some observations, in order to assess the radio-telescope capabilities at the time of the observation. Furthermore, it conveniently provides a way to test the analysis pipelines. Usually, each FRB observation last for about 4 h in order to collect enough signal across the frequency band, taking into account the dispersion delay.

Targets	Positions	DM	Fluence	Peak flux	RM	Obs (h)
FRB20180916B	$(01:58:00, +65:44:00)$	350	$2-30$	$0.5-4$	-114.6	592.77
FRB20200120E	$(09:57:56.7, +68:49:32)$	87.2	2	1.8	-28.3	179.38
FRB20181030A	$(10:54:07, +73:44:26)$	103.5	$7-30$	3.2		302.60
FRB20180814A	$(04:22:22, +73:04:00)$	190	$10-60$	1		380.74
FRB20180908B	$(12:32:00, +74:12:00)$	196	2.7	0.6		66.50
FRB20220912A	$(23:09:09.6, +48:42:00)$	219.5	$10-779$	$6-181$	$+0.6$	80.22
FRB20190303A	$(13:53:00, +48:15:00)$	222	$2-3$	0.5	-499.9	105.91
FRB151125	$(01:31:00, +30:58:48)$	273	2450	0.54		95.55
FRB190907	$(08:09:00, +46:16:00)$	311	1.7	0.3		42.76
SGR1935+2154	$(19:34:55.68, +21:53:48.2)$	332.7	480k	110k	112.3	105.18
FRB20181017A	$(22:06:00, +08:50:34)$	240	31	89		67.64
FRB20121102A	$(05:32:09, +33:05:13)$	560	0.11	0.03	10^5	6.96
FRB20190425A*	$(10:39:18, +21:33:36)$	128.2	31.6	18.6		20.64
FRB20181223C*	$(07:32:30, +27:34:48)$	112.5	2.84	1.36		23.87
Zenith pointing	local zenith	blind search	-	-	-	115.94
Total						2186.66

Table 1. List of targets and their observational parameters, derived from detection achieved at higher frequencies by other instruments (e.g. CHIME, LOFAR, PARKES...). Position are given in (α h:m:s, δ deg:m:s), DM values in pc.cm^{-3}, fluences in Jy.ms, peak flux Jy in and RM in rad.m^{-2}. FRB20190425A and FRB20181223C are non repeaters events.

Two observation modes are used for all observations: an incoherent time-frequency mode and the PULSAR mode developed and used by the Pulsar Program of NenuFAR (Bondonneau et al. 2021). For specific targets (considered as promising), the frequency range is increased, in order to cover the full range of NenuFAR. These promising targets are: FRB20180916B (a periodic repeater), FRB20181030A (a high fluence, low DM repeater), and SGR1935+2154 (a possible FRB source).

Time-frequency mode:

- incoherent observation mode: no de-dispersion
- frequency range: $35.4 - 72.7$ MHz, and an extended mode: $12 - 85$ MHz
- time and frequency resolutions: $\mathrm{d}t = 21$ ms, $\mathrm{d}f = 1.52$ kHz
- data rate: ~ 60 GB/h (~ 120 GB/h in extended mode)
- output: time-frequency dynamic spectra

PULSAR mode:

- coherent de-dispersion through all sub-bands
- frequency range $35.4 - 72.7$ MHz
- time and frequency resolutions: $\mathrm{d}t = 21$ ms, $\mathrm{d}f = 195$ kHz
- data rate < 1 GB per observations
- output: standard PULSAR mode output (psrfits)

3 Analysis

The analysis of the data from the time-frequency mode follows a distinct procedure from the Pulsar Mode. The goal envisioned is to design a dedicated FRB detection pipeline benefiting from the incoherent observation mode to extract fine features from the FRB spectrum and the time series. The flexibility provided by the incoherent time-frequency spectra (intensity and polarization) allows for testing and implementing new detection strategies and techniques.

3.1 Time-Frequency mode

The strategy followed by the group is standard: a first step consists in cleaning and reducing the data, followed by a second step of refined cleaning and production of de-dispersed time series, and finally a third step to detect the bursts in the obtained time series. The first processing step in the treatment of the time-frequency data is called the "pre-processing". It consists in the mitigation of the RFI, the correction of the instrument response in time and frequency, and the incoherent de-dispersion at the repeater's expected DM within each 195 kHz sub-band. Then the data are integrated over each sub-bands. This strategy cleans the data with remaining fluctuations below the percent level, and reduces significantly the size of the data. The reduction factor is ~ 64, leading to data volumes of $\sim 2 - 5$ GB for a typical observation duration of 4 h, depending on the observation mode. The post-processing step is designed to leave some flexibility after the pre-processing in order to test various refined cleaning tools. Currently, the code consists of frequency and time cleaning methods, a high-pass filter and a frequency comb method. Each tool can be optimized through a few parameters in order to adapt to the quality and the topology of the data. At the end, the time-frequency data are de-dispersed over a range of DM values and integrated over frequencies to produce the time series. Furthermore, the spikes can be flagged depending on their width and signal-to-noise-ratio (SNR). These data can be directly plotted and analyzed to search for bursts, as illustrated on Fig. 1. The burst search focuses on the analysis of the time

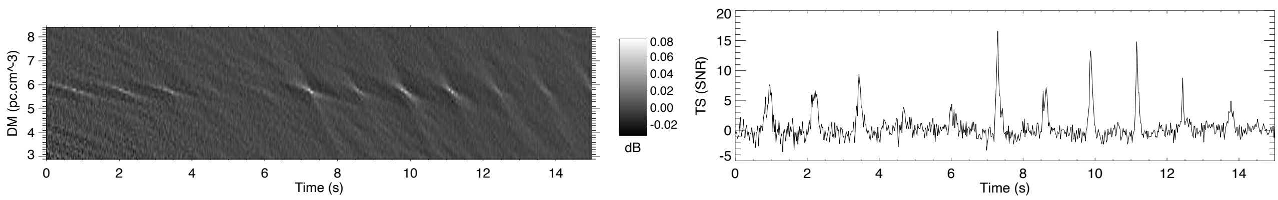

Fig. 1. Detection of single pulses from the pulsar B0809+74. *Left:* DM vs. time plane, where the butterfly shapes associated to all single pulses are clearly visible. *Right:* corresponding time series at the best DM value, where single pulses are detected with signal-to-noise-ratio between 5 and 15. The detection is achieved by using the time-frequency analysis procedures of the FRB Program on time-frequency data.

series via the detection of typical butterfly shapes in the DM vs. time plane. However, due to the length of the observations, the brevity of the expected signals and its scattering, the signal is likely to be buried in the noise. To counter that, a dedicated code helps to discriminate the different peaks present in the data. The code smooths the time series by applying a median filter followed by a convolution of the series with a trapezoid function. Then, it proceeds to search in the DM vs. time plane for clusters of peaks with the "friends of friends" algorithm*. The classification based on the SNR allows for displaying in details the detected peaks, which are then discriminated by eye. The complete detection pipeline has been successfully tested on pulsar observations and FRB simulations (Zarka & Mottez 2016).

3.2 PULSAR mode

The Pulsar Mode analysis has been developed and is maintained by the people involved in the Pulsar Program of NenuFAR (Bondonneau et al. 2021). It provides a robust and independent search strategy for FRB signals. Furthermore, the data analysis is automated and quickly assesses the potential of each observation. The procedure for the analysis is summarized below:

1 normalize the data with respect to the median and the median absolute deviation for each frequency and time window of 10 s

2 clean the data at DM=0: loop, 4 times, over this sequence:
   - compute standard deviation of each data block
   - target blocks with standard deviation fluctuations over $3\,\sigma$
   - compute standard deviation of each data block integrated over time
   - target time integrated blocks with standard deviation fluctuations over $3\,\sigma$
   - compute standard deviation of each data block integrated over frequencies
   - target frequency integrated blocks with standard deviation fluctuations over $3\,\sigma$
   - replace targeted blocks with a synthetic noise following the statistical properties of the data

3 clean the data with RFIFIND (PRESTO Ransom (2001))

4 produce the time series (PRESTO), with reference channel set at the highest frequency for the de-dispersion. One time series is produced for each DM value tested

5 search for bursts (or pulses) with single_pulse_search.py: search for bursts above given $n\,\sigma$ values through a running window with different widths

4 Summary and future prospects

The FRB Program on NenuFAR started during the Early Science Phase of the commissioning of the instrument in 2018. Since then, it regularly observed a list of FRB repeaters already characterized by radio telescopes at higher frequencies. The targets are selected based on their low DM and scattering values, in order to maximize their detection in the frequency band of NenuFAR. The observation strategy is also based on two distinct observation mode: time-frequency and coherent de-dispersion (PULSAR mode). Up to now more than 2000 h of observations have been accumulated, and the analysis is still ongoing. The analysis strategy relies on the two distinct observation modes, for which two distinct analysis are conducted. The time-frequency analysis, while being more flexible, is not automated, unlike the PULSAR mode analysis. These two independent analysis modes can cross-validate any potential discovery robustly. Several improvements and prospects are envisioned, among which we plan to conduct joint observations with the Nançay Radio Telescope for constraining the multi-wavelength emission of FRBs. In addition, real time search algorithms directly fed at the receiver outputs will be deployed soon. The complete analysis of all the data is still undergoing.

The FRB mystery at low frequencies is not unveiled yet, but every observation done with NenuFAR drives us closer to the answer.

References

Amiri, M. et al. 2019, Nature, 566, 235

Andersen, B. C. et al. 2020, Nature, 587, 54

Bondonneau, L. et al. 2021, Astron. Astrophys., 652, A34

Lorimer, D. R. et al. 2007, Science, 318, 777

Platts, E. et al. 2019, Phys. Rept., 821, 1

Pleunis, Z. et al. 2021a, Astrophys. J. Lett., 911, L3

*see: `https://github.com/simongibbons/pyfof`

Pleunis, Z. et al. 2021b, Astrophys. J. Lett., 911, L3
Ransom, S. M. 2001, PhD thesis, Harvard University
Shannon, R. M. et al. 2018, Nature, 562, 386
Sokolowski, M. et al. 2018, Astrophys. J. Lett., 867, L12
Spitler, L. G. et al. 2016, Nature, 531, 202
Voisin, G. 2021, Proceedings SF2A-2021, 405
Zarka, P. & Mottez, F. 2016, Proceedings SF2A-2016, 347
Zarka, P. et al. 2020, URSSI GASS 2020, J01