Pipeline for Pulsar Observations with PL612 LOFAR Station

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LOw Frequency ARray (LOFAR) is a new generation, digitally controlled interferometric radio telescope consisting of phased array antenna stations, which is operating in still poorly explored part of the radio spectrum between 10-240 MHz. In this work we put particular stress to present the description of the instrument and its parameters related to pulsar observations with particular emphasis on Polish part located in Bałdy near Olsztyn. The most importatnt is the detailed description of the specific pipeline we use for pulsar observations. We also show some spectra as the results of observations with PL612 Station. This paper also allows us to show the great opportunity offered by three LOFAR stations located in Poland and maintained by the POLFAR consortium[1] for conducting unique and independent research of pulsars.

1 Introduction

The first detection of pulsar signal was made in 1967 by Hewish et al. (1968) at the frequency of 81 MHz. It quickly turned out that the pulsating radio signal that was detected is generated by a rapidly rotating neutron star with an extremely high magnetic field. The history of pulsar research, the methods of observation, and their physics are described in details in Lorimer & Kramer (2005). Half a century of pulsar research with radio astronomical methods allowed us to develop a reasonably acceptable model explaining the properties of the pulsar radiation.

Nowadays, after early LOFAR observations of pulsars by Hessels et al. (2010) and latter detailed study of selected pulsars (Bilous et al., 2014), we can be certain that LOFAR is currently one of the best instruments that can be used to study the pulsar's radio signals in great detail, at a level that was previously unattainable.

2 PL612 as the International LOFAR Station

The LOFAR system design, configuration and the signal processing methods were described in detail by de Vos et al. (2009); van Haarlem et al. (2013). The LOFAR interferometer consists of a large number (>100 000) of omnidirectional dipole antennas, that are arranged to form of 51 individual stations across Europe. The majority of the stations are located in the Netherlands, including 24 stations located within a radius of about 2 km the so-called *core*, and a round island of 320 m diameter referred as *Superterp* in the middle of the core region. The remaining 14 Dutch stations referred to as *remote* are located beyond the core in a distance up

[1]The basis of POLFAR foundation can be found in Krankowski et al. (2014)

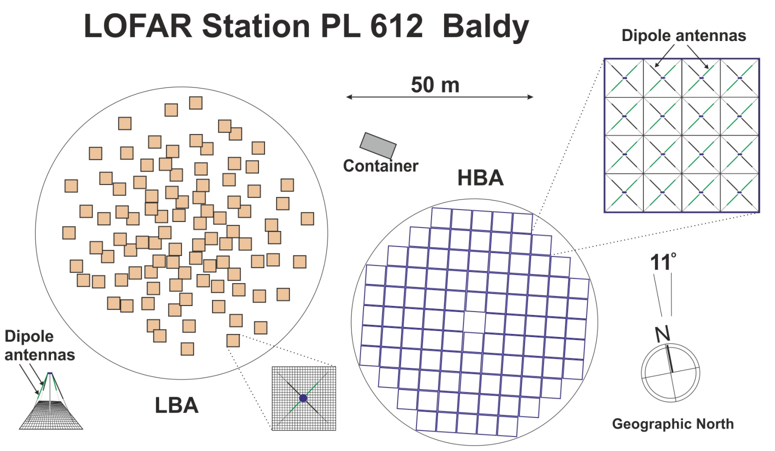

Fig. 1: The international field configuration of elements of LOFAR system is one of the three used (van Haarlem et al., 2013). The presented schematic shows configuration of elements in PL612 station located in Bałdy, Poland. Elements of the station are arranged in two fields: LBA and HBA. Each LBA element (of 96 at the field) consists of two orthogonal dipoles, which gives X and Y polarization. HBA elements are arranged in 96 tiles - each one is the number of 16 pairs of orthogonal dipole elements. For every HBA tile, received radio waves are summed up and sent to filter bank X and Y 200 MHz sampled signals.

to 90 km and placed more or less (depending on land availability) in a logarithmic spiral distribution (van Haarlem et al., 2013). Rest of the stations are the base for ILT - International LOFAR Telescope. Six stations are located in Germany and one station each in UK, France, Sweden and Ireland. The three Polish stations which were constructed in 2015 and from the beginning of 2016 are fully operational part of LOFAR interferometer, called POLFAR (Błaszkiewicz et al., 2016; Dąbrowski et al., 2016). Another LOFAR stations are currently being planned, and their locations are: Irbene in Latvia and Medicina in Italy.

The LOFAR bandwidth spreads from 10 MHz to 240 MHz, but excludes the frequency range from 88 up to 108 MHz because of the expected Earth-bound interference. Each individual station consists of two antenna fields: (i) the Low Band Antennas (LBAs) which are sensitive to the wavelengths from 30 to 4 m (10–90 MHz); a single station LBA field contains 48 or 96 antennas; antennas of the LBA field in full configuration occupy a circular area with a radius of about 40 m; (ii) the High Band Antennas (HBAs) are collected in tiles, and operate in the wavelength range between 3 and 1.2 m (110–240 MHz); 48 or 96 tiles per station. In the full 96 tiles configuration the diameter of the HBA field is 62 m. The configuration of a typical international LOFAR station (the PL612 station in Bałdy is one of them) is shown in Fig. 1.

3 Pulsar observation pipeline in PL612

The pipeline of the pulsar observations used in PL612 LOFAR station presented here later uses mode 5 of LOFAR observations. This mode uses HBA antennas signal as the Receiver Unit input and sets receiver band in the range of 100 – 200 MHz. The

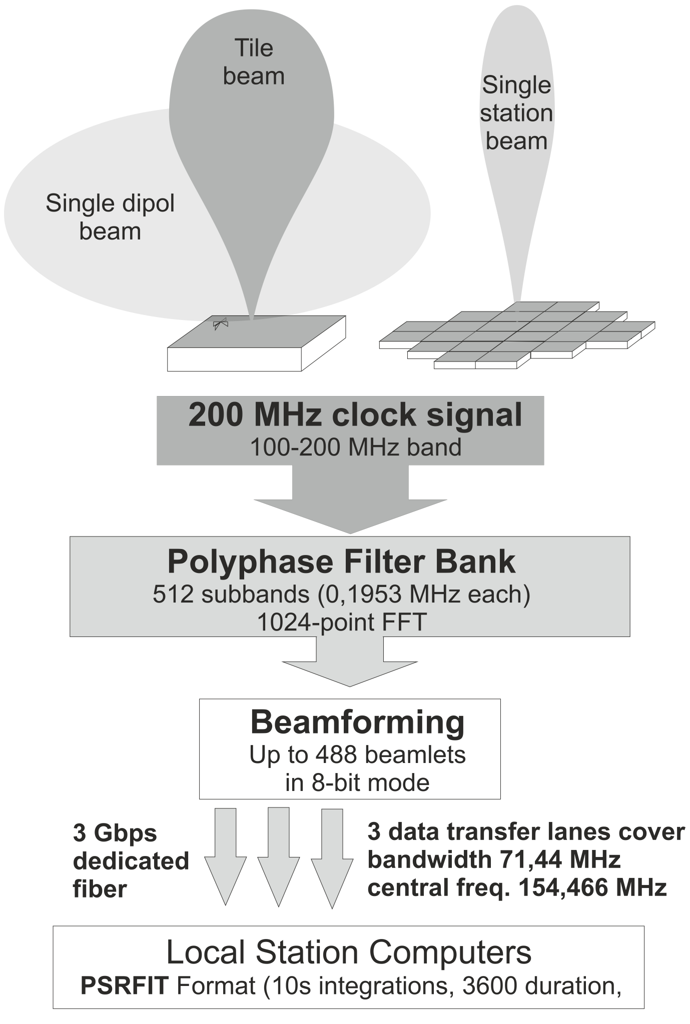

Fig. 2: The idea of beam-forming and essential processes on the way of the signal. Radio waves excite the signal received by the individual LOFAR station components. The set of dipoles arranged as the HBA tiles field lets us form the beam in desired direction. The 200 MHz sampling and subsequent operations let us obtain information in the form we need.

X an Y signal from bow-tie dipoles (16 at each of 96 tiles) is sampled with clock time/frequency of 5ns/200MHz. The signal is passed through the Polyphase Filter Bank with 512 subbands, each of 195.3125 kHz wide. Then the process of beam-forming takes place. System is ready to create up to 488 beamlets (for 8-bit mode), each acting as a single beam for a single subband. Subbands can cover different or the same frequencies for each beamlet. The Polyphase Filter Bank uses 1024 points fast Fourier transform, FFT to divide data stream into 512 subbands, so, the sampling time for 200 MHz clock is 5.12 μs. In our observation, the whole raw data stream is sent to local computers in a specific way. All 488 beamlets are typically

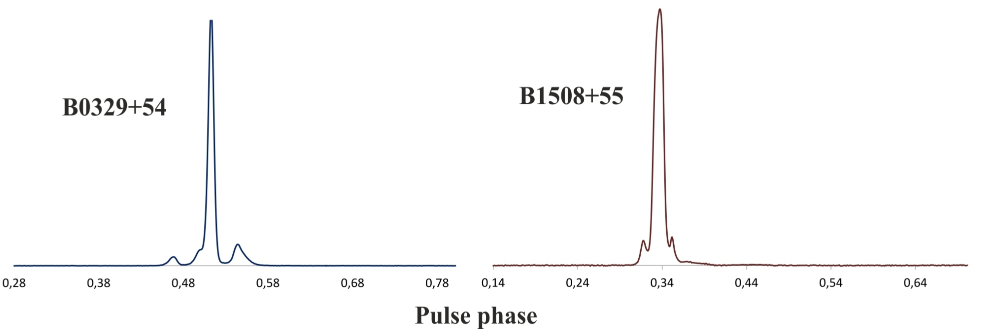

Fig. 3: Integrated pulse profiles of B1508+55 and B0329+54. Signal to noise (S/N) ratio after one hour integration at elevation 70° is ∼4000.

split into 4 lanes, 122 beamlets each. For the purposes of pulsar observations we are utilizing usually only three lanes shifted towards the middle of the band (since the sensitivity at the edges of the band is much lower and hence the data carries less of useful information), starting with beamlet 93, and ending on 459 (93-215, 215-337 and 337-459). The central frequency for our observations was 154.466 MHz and the bandwidth was 71.4844 MHz. The data reduction package DSPRS, The Digital Signal Processing for Pulsars (van Straten & Bailes, 2011) which reduces radio pulsar astronomical time series, producing one or more folded pulse profiles is very important necessary step. Finally, the recorded data are reduced to the full Stockes parameters in TIMER format which is very similar to PSRFITS format (Hotan et al., 2004) and accepted by the PSRCHIVE package. The plot with a schematic of pipeline used for PL612 pulsar observations is presented in Fig. 2.

4 Observational results

Until now LOFAR PL612 station had observed nearly a hundred of pulsars and we have used our instrument for this type of observation almost 700 h. For our purposes we usually observe pulsars for one or two hours with sub-integration time of 10 s. We are also able to record observations in the single pulse mode. Typical bright pulsar profiles obtained after one hour of observations are shown in Fig. 3. Our main goal is to study the effects of variations in the morphology of pulsar radio profiles (see article by Białkowski et al. in these proceedings). We are also investigating the effects of pulsar signal propagation. The main propagation effects observed in pulsar data and caused by the ionized matter of the interstellar medium (ISM) are the dispersion, scattering, scintillation and Faraday rotation. Observations of these phenomena are definitely possible in the LOFAR frequency range, as was demonstrated by Stappers et al. (2011); Bilous et al. (2014). In our research we aim to put particular stress on the long-term monitoring (lasting from a few months to several years) of a few selected sources, which will help us to improve our understanding of the interstellar medium as well as the physics of processes occurring near the neutron star.

5 Conclusions

The LOFAR telescope is fully operational and the first results for pulsars survey were already published by Coenen et al. (2014); Bilous et al. (2014) and Noutsos et al. (2015). It shows the great potential of observations of pulsars in the single station mode. The construction of three stations in Poland was finished and a few more in the rest of Europe are also planned. The revolutionary design of this instrument is an important step towards the future of radio astronomy and space research. At stations belonging to the POLFAR consortium, the pulsar observation and data analysis pipeline (see Fig. 2) based on the system developed by German GLOW consortium was introduced and modernized. The specialized equipment hardware and software which is continuously being further developed and improved raises hopes for great possibilities in the future in the fields of the scrutiny of pulsars. The LOFAR single station mode pulsar observations provide the opportunity to perform long-term monitoring of interesting pulsars, as well as single pulse and variability studies over very wide bandwidths.

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References

Bilous, A. V., et al., *A&A* **572**, A52 (2014)

Błaszkiewicz, L., et al., *Acta Geophysica* **64**, 293 (2016)

Coenen, T., et al., *A&A* **570**, A60 (2014)

Dąbrowski, B. P., Krankowski, A., Błaszkiewicz, L., Rothkaehl, H., *Acta Geophysica* **64**, 825 (2016)

de Vos, M., Gunst, A. W., Nijboer, R., *IEEE Proceedings* **97**, 1431 (2009)

Hessels, J. W. T., et al., in ISKAF2010 Science Meeting, 25 (2010)

Hewish, A., et al., *Nature* **217**, 709 (1968)

Hotan, A. W., van Straten, W., Manchester, R. N., *PASA* **21**, 302 (2004)

Krankowski, A., et al., in Microwaves, Radar, and Wireless Communication (MIKON), 2014 20th International Conference on, 1–4 (2014)

Lorimer, D., Kramer, M., in Handbook of Pulsar Astronomy, Cambridge University Press (2005)

Noutsos, A., et al., *A&A* **576**, A62 (2015)

Stappers, B. W., et al., *A&A* **530**, A80 (2011)

van Haarlem, M. P., et al., *A&A* **556**, A2 (2013)

van Straten, W., Bailes, M., *PASA* **28**, 1 (2011)