

Low frequency pulsar observations with NenuFAR

Observation de pulsars à basse fréquence avec NenuFAR

L. Bondonneau¹, J.-M. Grießmeier^{1,2}, G. Theureau^{1,2,3}, I. Cognard^{1,2}, and the NenuFAR-France collaboration^{1,2,3}

¹*LPC2E - Université d'Orléans / CNRS, France*

²*Station de Radioastronomie de Nançay, Observatoire de Paris - CNRS/INSU, USR 704 - Univ. Orléans, OSUC, route de Souesmes, 18330 Nançay, France*

³*Laboratoire Univers et Théories LUTH, Observatoire de Paris, CNRS/INSU, Université Paris Diderot, 5 place Jules Janssen, 92190 Meudon, France*

Keywords: NenuFAR, Pulsar, Low frequency

Mots-clefs: NenuFAR, Pulsar, Basses fréquences

Abstract:

NenuFAR (New Extension in Nançay Upgrading loFAR) is the new radiotelescope developed and built in Nançay. Designed to observe the largely unexplored frequency window from 10 to 85 MHz, it has a high sensitivity across the bandpass. Still in the construction phase today, it already has more than 1000 antennas and is better suitable for large band observation than the European low frequency network LOFAR. The scientific exploitation is about to start.

Pulsar observations require a real-time pipeline able to cope with a high data rate in order to significantly reduce the required dedicated storage. The data are reduced by taking care of the interstellar medium through coherent dedispersion and by folding the data to the apparent rotation period of the neutron star. We will end by presenting the first results obtained using the pulsar instrumentation of NenuFAR.

Résumé:

NenuFAR (New Extension in Nançay Upgrading loFAR) est le nouveau radiotélescope développé et en cours de construction sur le site de Nançay. Conçu pour observer dans une fenêtre radio encore très peu étudiée de 10 à 85 MHz il est très sensible sur toute sa bande passante. Encore en phase de construction aujourd'hui il dépasse déjà les 1000 antennes et est plus adapté pour les observations large bande que le réseau basse fréquence européen de LOFAR. L'exploitation scientifique est sur le point de commencer.

L'observation des pulsars demande un traitement des données très haut débit en temps réel afin de considérablement diminuer le stockage nécessaire aux observations. Les données sont réduites en prenant soin de corriger de façon cohérente la dispersion du milieu interstellaire et par le repliement des données à la période de rotation apparente de l'étoile à neutron. Nous présenterons les premiers résultats de l'instrumentation pulsar de NenuFAR.



Figure 1 – Left picture: Satellite picture of NenuFAR. Green points are mini-arrays of 19 antennas. White points are future mini-arrays. Right picture: Picture of NenuFAR antennas (see [1]).

1 NenuFAR

NenuFAR is officially labelled as SKA pathfinder. In its present state NenuFAR-1, it is composed of 56 mini-arrays of 19 antennas (see left picture in Figure 1). The final NenuFAR will be composed of 96 such mini-arrays.

Because NenuFAR has a high gain across the full band, the sensitivity relative to the LOFAR core is especially high at low frequencies. For example, at 20 MHz, NenuFAR-1 is 5 times as sensitive as the LOFAR core. This is mainly due to the new design of NenuFAR antennas, optimized preamplifiers and the antenna spacing. Observations shown in this paper were made in commissioning mode, without proper coherent summation between mini-arrays. When the calibration phase will be completed with a proper coherent summation and pointing correction table the sensitivity of NenuFAR-1 will reach that of the LOFAR core. The final version will exceed the sensitivity of the LOFAR core by a factor 1.7.

2 Pulsar Backend

A pulsar backend is fed by the beamformer with waveform data through a User Datagram Protocol (UDP) connection corresponding to 300 MB/s. To be able to process this data stream in real time on a single machine all calculations have to be performed on Graphical Processing Units (GPUs) to optimise the parallelization. The backend has two main objectives: correct for the dispersion of the interstellar medium in the Fourier domain (coherent dedispersion [2]) and fold the observation at the period of the neutron star. Finally the output of the backend is saved as a Flexible Image Transport System (FITS) file a thousand time smaller than the original waveform data.

2.1 Low frequency Pulsar Backend

Low frequency coherent dedispersion in real time is a challenge due to the long time delay within the lowest frequency channel. For example, with a single channel of 195 kHz and for an observation at 20 MHz, B0329+54 (at a dispersion measure of 26.7 pc.cm^{-3}) has a intrachannel dispersive delay of 5 seconds, which corresponds to several times the pulse period. In the pulsar pipeline we need to double this dispersive delay to get an overlap. In consequence, for each channel and complex polarization we need an FFT (Fast Fourier Transform) on 2^{21} complex values of 5.12 microseconds, corresponding to more than 10.7 seconds of waveform data in a single FFT. For the total bandwidth (384 channels) we need 8 GB of memory in a single GPU.

If we look at the frequency resolved pulse profile of Figure 2 the difference is clearly visible between a dispersed profile (left plot) and a coherently dedispersed profile of B0950+08 (right plot). Note that the dispersion of this pulsar is low only 2.97 pc.cm^{-3} , which is the fifth lowest DM value of 2659 known pulsars.

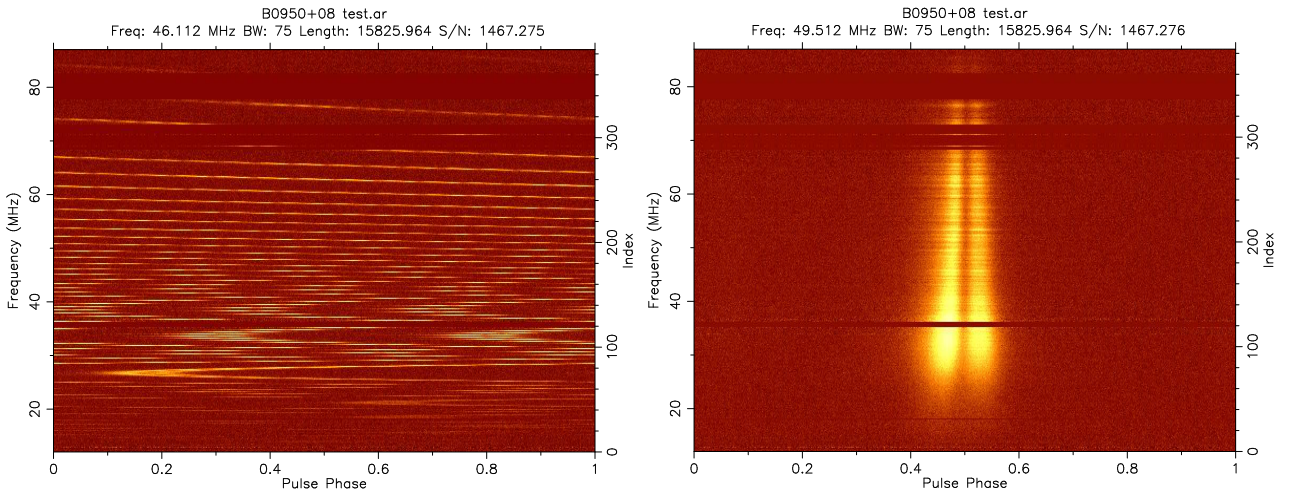


Figure 2 – Frequency resolved pulse profile for an observation of B0950+08 with 56 mini-arrays of NenuFAR. Left plot: The dispersed pulsar as observed by the radiotelescope. Right plot: The same observation coherently dedispersed.

UnDySPuTeD is the beamformed high rate backend of Nenufar on which the software LUPPI (Low frequency Ultimate Pulsar Processing Instrument) is installed. LUPPI is installed on two machines with in total 4 GPUs (GTX 1080 8 GB). It has been designed coherently dedisperse and fold up to 4 numerical beams of 37.5 MHz of bandwidth simultaneously (192 channels per beam).

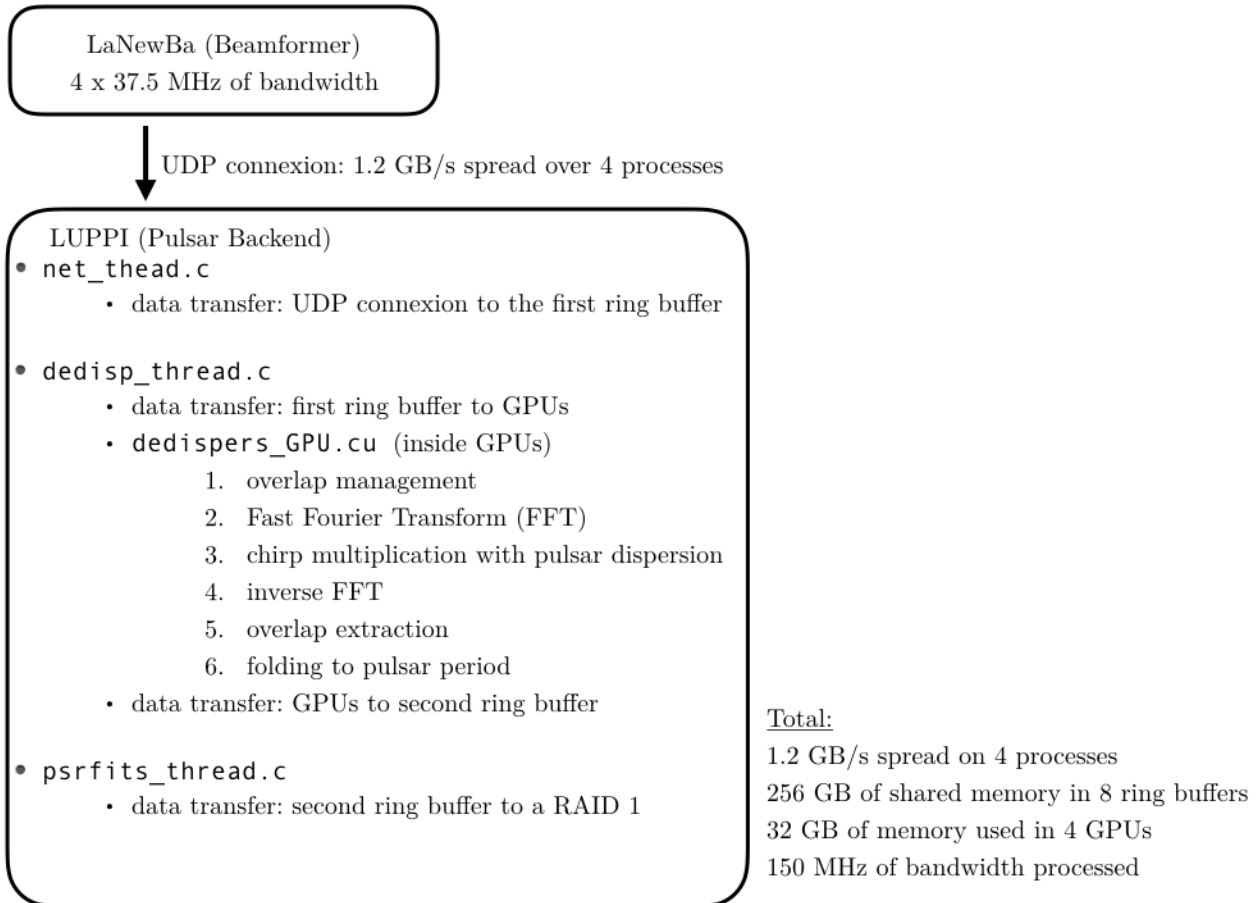


Figure 3 – Sketch of the Low frequency Pulsar Processing Instrument (LUPPI) describing how the data are processed from the beamformer to the final Flexible Image Transport System (FITS) file through the three main threads: `net_thread`, `dedisp_thread` and `psrfits_thread`.

2.2 LUPPI

This section will detail the data processing applied by the Low frequency Ultimate Pulsar Processing Instrument (LUPPI) (see Figure 3). LUPPI is a dedispersing and folding algorithm working with GPU parallelization. This software is a low frequency adaptation of NUPPI¹ (Nançay Ultimate Pulsar Processing Instrument) which is the software used on the decimeter Radio Telescope of Nançay (NRT). NUPPI is directly inspired by GUPPI (Green Bank Ultimate Pulsar Processing Instrument, [3]).

The NenuFAR beamformer LaNewBa, uses Field-Programmable Gate Array (FPGA) boards and is able to broadcast 4x37.5 MHz of bandwidth in 768 channels of 195 kHz to Undysputed and LUPPI via four UDP links. LUPPI works with three main threads: The `net_thread` is bound to the UDP port and writes waveform packets for all channels to a first ring buffer. Secondly, `dedisp_thread` is the heart of the program, in which the waveform data is transmitted to the GPUs where most of calculations are done (FFT, management of the overlap, coherent dedispersion by multiplication of the waveform with the chirp function in the Fourier domain, inverse FFT, overlap extraction and folding of the subintegration by the pulsar period). Finally, the folded data stream is send in a second ring-buffer to be written to a RAID (Redundant Array of Independent Disks) in FITS format by `psrfits_thread`.

3 Observations

In this section we present the folding mode where the pulsar signal is integrated in time to increase the signal to noise ratio and show the frequency variations of the profiles. The total bandwidth is 75 MHz for all observations. The observation length is variable: from 32 minutes for B0809+74 to 5 hours for B1133+16.

¹G. Desvignes, <https://github.com/gdesvignes/NUPPI>

The aim of this section is to illustrate the low frequency pulsar population by showing iconic low frequency pulsars (see on Figure 4 and 5).

These observations show high variations of pulsars profiles due to the interstellar medium and intrinsic magnetospheric properties of the pulsar.

3.1 B0809+74

This pulsar was already observed and studied with LOFAR [4], [5], [6] and with UTR-2 [7]. Two pulsations are apparent in Figure 4. It is particularly interesting for two reason: it exhibits impressive drifting subpulses (see [4]) and the ratio between the amplitudes of both pulsations reverses at 50 MHz as can be seen in Figure 4.

3.2 B0834+06

Observed by LOFAR [6] and UTR-2 [7]. This pulsar shows an exponential tail in the lowest part of the band below 29 MHz, which is the signature of the multi-path propagation in the interstellar medium [2].

3.3 B0950+08

This pulsar was observed with LOFAR [5] and with the MWA [8]. Defined as one of the least scattered pulsar in [9] there is no scattering tail visible in Figure 4.

3.4 B1133+16

Observed with UTR-2 [7], LOFAR [5], [6] and the MWA [8]. This pulsar is well know in low frequency for the increasing of the separation between both pulsations, which is the signature of the emission height in a bipolar model see [10] and [11], [2].

3.5 B1237+25

Observed with UTR-2 [7], the LWA [12] and LOFAR [5], [6]. B1237+25 is the first pulsar for which mode-changing behaviour was detected [13].

3.6 B1508+55

Studied with LOFAR [10] it is well know to have a low rotation measure (see [2]). Osłowski et al. (in prep.) as in [14] observed a profile variation in time interpreted as an echo of the main pulsation on a plasma bubble in the interstellar medium. This echo can be seen in Figure 5 just after the main pulse.

3.7 B1919+21

B1919+21 is the first pulsar discovered by Jocelyn Bell in 1967 [15]. Below 100 MHz it is the strongest pulsar in the north sky. In Figure 5 we can observe its three main components easily distinguishable at 40 MHz. It is interesting to observe that only the central component is visible below 30 MHz see in Figure 5. This could be a signature of a modification in the emission mechanism.

3.8 B2217+47

This pulsar is observed by LOFAR and discussed in [14], it is the best example of scattering tail for the low band (see Figure 5).

4 Conclusion

In this paper we go through the first real-time low-frequency pulsar backend working on Graphical Processing Units (LUPPI). We described the challenge of low frequency coherent dedispersion due the high dispersive delay. Finally we presented the first observations of iconic pulsars with NenuFAR.

Today with NenuFAR and Undysputed with LUPPI we have started to observe, coherently dedisperse and fold pulsars of the north sky (with limits of -10 degrees in declination and a maximum DM of 100 pc.cm^{-3}) to characterized the low frequency pulsar population. This will also be used to provide targets for future observations.

This new instrumentation allows us to deeply study the low-frequency variabilities of the flux density, the polarizations, the evolution of the profile in time and frequency which allows to constrain models of the emission mechanism and probing the interstellar medium via measurements of the DM and scattering.

5 References

- [1] <https://www.obs-nancay.fr/NenuFAR-45-.html>, “observatoire de nancay.”
- [2] D. Lorimer and M. Kramer, “Handbook Of Pulsar Astronomy,” Dec. 2004.
- [3] R. DuPlain, S. Ransom, P. Demorest, P. Brandt, J. Ford, and A. L. Shelton, “Launching GUPPI: the Green Bank Ultimate Pulsar Processing Instrument,” (Marseille, France), p. 70191D, Aug. 2008.
- [4] T. E. Hassall, B. W. Stappers, P. Weltevrede, J. W. T. Hessels, A. Alexov, T. Coenen, A. Karastergiou, M. Kramer, E. F. Keane, V. I. Kondratiev, J. van Leeuwen, A. Noutsos, M. Pilia, M. Serylak, C. Sobey, K. Zagkouris, R. Fender, M. E. Bell, J. Broderick, J. Eisloffel, H. Falcke, J.-M. Griessmeier, M. Kuniyoshi, J. C. A. Miller-Jones, M. W. Wise, O. Wucknitz, P. Zarka, A. Asgekar, F. Batejat, M. J. Bentum, G. Bernardi, P. Best, A. Bonafede, F. Breitling, M. Bruggen, H. R. Butcher, B. Ciardi, F. de Gasperin, J.-P. de Reijer, S. Duscha, R. A. Fallows, C. Ferrari, W. Frieswijk, M. A. Garrett, A. W. Gunst, G. Heald, M. Hoeft, E. Juette, P. Maat, J. P. McKean, M. J. Norden, M. Pandey-Pommier, R. Pizzo, A. G. Polatidis, W. Reich, H. Rottgering, J. Sluman, Y. Tang, C. Tasse, R. Vermeulen, R. J. van Weeren, S. J. Wijnholds, and S. Yatawatta, “Differential Frequency-dependent Delay from the Pulsar Magnetosphere,” *Astronomy & Astrophysics*, vol. 552, p. A61, Apr. 2013. arXiv: 1302.2321.
- [5] A. Bilous, V. Kondratiev, M. Kramer, E. Keane, J. Hessels, B. Stappers, V. Malofeev, C. Sobey, R. Breton, S. Cooper, H. Falcke, A. Karastergiou, D. Michilli, S. Osłowski, S. Sanidas, S. ter Veen, J. van Leeuwen, J. Verbiest, P. Weltevrede, P. Zarka, J.-M. Grießmeier, M. Serylak, M. Bell, J. Broderick, J. Eisloffel, S. Markoff, and A. Rowlinson, “A LOFAR census of non-recycled pulsars: average profiles, dispersion measures, flux densities, and spectra,” *Astronomy & Astrophysics*, vol. 591, p. A134, July 2016. arXiv: 1511.01767.
- [6] M. Pilia, J. W. T. Hessels, B. W. Stappers, V. I. Kondratiev, M. Kramer, J. van Leeuwen, P. Weltevrede, A. G. Lyne, K. Zagkouris, T. E. Hassall, A. V. Bilous, R. P. Breton, H. Falcke, J.-M. Grießmeier, E. Keane, A. Karastergiou, M. Kuniyoshi, A. Noutsos, S. Osłowski, M. Serylak, C. Sobey, S. ter Veen, A. Alexov, J. Anderson, A. Asgekar, I. M. Avruch, M. E. Bell, M. J. Bentum, G. Bernardi, L. Birzan, A. Bonafede, F. Breitling, J. W. Broderick, M. Brügger, B. Ciardi, S. Corbel, E. de Geus, A. de Jong, A. Deller, S. Duscha, J. Eisloffel, R. A. Fallows, R. Fender, C. Ferrari, W. Frieswijk, M. A. Garrett, A. W. Gunst, J. P. Hamaker, G. Heald, A. Horneffer, P. Jonker, E. Juette, G. Kuper, P. Maat, G. Mann, S. Markoff, R. McFadden, D. McKay-Bukowski, J. C. A. Miller-Jones, A. Nelles, H. Paas, M. Pandey-Pommier, M. Pietka, R. Pizzo, A. G. Polatidis, W. Reich, H. Röttgering, A. Rowlinson, D. Schwarz, O. Smirnov, M. Steinmetz, A. Stewart, J. D. Swinbank, M. Tagger, Y. Tang, C. Tasse, S. Thoudam, M. C. Toribio, A. J. van der Horst, R. Vermeulen, C. Vocks, R. J. van Weeren, R. A. M. J. Wijers, R. Wijnands, S. J. Wijnholds, O. Wucknitz, and P. Zarka, “Wide-band, low-frequency pulse profiles of 100 radio pulsars with LOFAR,” *Astronomy & Astrophysics*, vol. 586, p. A92, Feb. 2016.
- [7] V. V. Zakharenko, I. Y. Vasylieva, A. A. Konovalenko, O. M. Ulyanov, M. Serylak, P. Zarka, J.-M. Grießmeier, I. Cognard, and V. S. Nikolaenko, “Detection of decametre-wavelength pulsed radio emission of 40 known pulsars,” *Monthly Notices of the Royal Astronomical Society*, vol. 431, pp. 3624–3641, June 2013.
- [8] T. Murphy, D. L. Kaplan, M. E. Bell, J. R. Callingham, S. Croft, S. Johnston, D. Dobie, A. Zic, J. Hughes, C. Lynch, P. Hancock, N. Hurley-Walker, E. Lenc, K. S. Dwarakanath, B.-Q. For, B. M. Gaensler, L. Hindson, M. Johnston-Hollitt, A. D. Kapińska, B. McKinley, J. Morgan, A. R. Offringa, P. Procopio, L. Staveley-Smith, R. Wayth, C. Wu, and Q. Zheng, “Low-Frequency Spectral Energy Distributions of Radio Pulsars Detected with the Murchison Widefield Array,” *Publications of the Astronomical Society of Australia*, vol. 34, 2017.
- [9] J. A. Phillips and A. W. Clegg, “Electron density fluctuations in the local interstellar bubble,” *Nature*, vol. 360, pp. 137–139, Nov. 1992.
- [10] A. Noutsos, C. Sobey, V. I. Kondratiev, P. Weltevrede, J. P. W. Verbiest, A. Karastergiou, M. Kramer, M. Kuniyoshi, A. Alexov, R. P. Breton, A. V. Bilous, S. Cooper, H. Falcke, J.-M. Grießmeier, T. E. Hassall, J. W. T. Hessels, E. F. Keane, S. Osłowski, M. Pilia, M. Serylak, B. W. Stappers, S. ter Veen, J. van Leeuwen, K. Zagkouris, K. Anderson, L. Bähren, M. Bell, J. Broderick, D. Carbone, Y. Cendes, T. Coenen, S. Corbel, J. Eisloffel, R. Fender, H. Garsden, P. Jonker, C. Law, S. Markoff, J. Masters, J. Miller-Jones, G. Molenaar, R. Osten, M. Pietka, E. Rol, A. Rowlinson, B. Scheers, H. Spreuw, T. Staley, A. Stewart, J. Swinbank, R. Wijers, R. Wijnands, M. Wise, P. Zarka, and A. van der Horst, “Pulsar polarisation below 200 MHz: Average profiles and propagation effects,” *Astronomy & Astrophysics*, vol. 576, p. A62, Apr. 2015.

- [11] T. E. Hassall, B. W. Stappers, J. W. T. Hessels, M. Kramer, A. Alexov, K. Anderson, T. Coenen, A. Karastergiou, E. F. Keane, V. I. Kondratiev, K. Lazaridis, J. van Leeuwen, A. Noutsos, M. Serylak, C. Sobey, J. P. W. Verbiest, P. Weltevrede, K. Zagkouris, R. Fender, R. A. M. J. Wijers, L. Bähren, M. E. Bell, J. W. Broderick, S. Corbel, E. J. Daw, V. S. Dhillon, J. Eislöffel, H. Falcke, J.-M. Grießmeier, P. Jonker, C. Law, S. Markoff, J. C. A. Miller-Jones, R. Osten, E. Rol, A. M. M. Scaife, B. Scheers, P. Schellart, H. Spreeuw, J. Swinbank, S. ter Veen, M. W. Wise, R. Wijnands, O. Wucknitz, P. Zarka, A. Asekar, M. R. Bell, M. J. Bentum, G. Bernardi, P. Best, A. Bonafede, A. J. Boonstra, M. Brentjens, W. N. Brouw, M. Brüggen, H. R. Butcher, B. Ciardi, M. A. Garrett, M. Gerbers, A. W. Gunst, M. P. van Haarlem, G. Heald, M. Hoeft, H. Holties, A. de Jong, L. V. E. Koopmans, M. Kuniyoshi, G. Kuper, G. M. Loose, P. Maat, J. Masters, J. P. McKean, H. Meulman, M. Mevius, H. Munk, J. E. Noordam, E. Orrú, H. Paas, M. Pandey-Pommier, V. N. Pandey, R. Pizzo, A. Polatidis, W. Reich, H. Röttgering, J. Sluman, M. Steinmetz, C. G. M. Sterks, M. Tagger, Y. Tang, C. Tasse, R. Vermeulen, R. J. van Weeren, S. J. Wijnholds, and S. Yatawatta, “Wide-band simultaneous observations of pulsars: disentangling dispersion measure and profile variations,” *Astronomy & Astrophysics*, vol. 543, p. A66, July 2012.
- [12] K. Stovall, P. S. Ray, J. Blythe, J. Dowell, T. Eftekhari, A. Garcia, T. J. W. Lazio, M. McCrackan, F. K. Schinzel, and G. B. Taylor, “Pulsar observations using the first station of the long wavelength array and the LWA pulsar data archive,” *The Astrophysical Journal*, vol. 808, p. 156, July 2015.
- [13] D. C. Backer, “Pulsar Nulling Phenomena,” *Nature*, vol. 228, p. 42, Oct. 1970.
- [14] D. Michilli, J. W. T. Hessels, J. Y. Donner, J.-M. Grießmeier, M. Serylak, B. Shaw, B. W. Stappers, J. P. W. Verbiest, A. T. Deller, L. N. Driessen, D. R. Stinebring, L. Bondonneau, M. Geyer, M. Hoeft, A. Karastergiou, M. Kramer, S. Osłowski, M. Pilia, S. Sanidas, and P. Weltevrede, “Low-frequency pulse profile variation in PSR B2217+47: evidence for echoes from the interstellar medium,” *Monthly Notices of the Royal Astronomical Society*, vol. 476, pp. 2704–2716, May 2018. arXiv: 1802.03473.
- [15] A. Hewish, S. J. Bell, J. D. H. Pilkington, P. F. Scott, and R. A. Collins, “Observation of a Rapidly Pulsating Radio Source,” *Nature*, vol. 217, pp. 709–713, Feb. 1968.

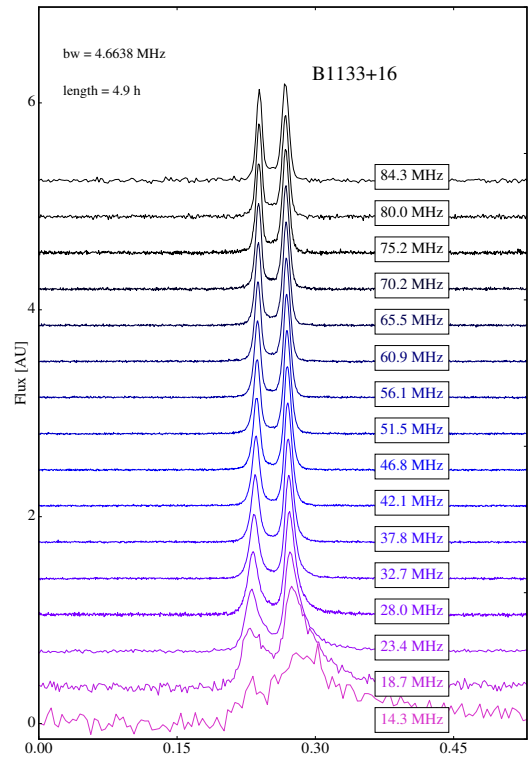
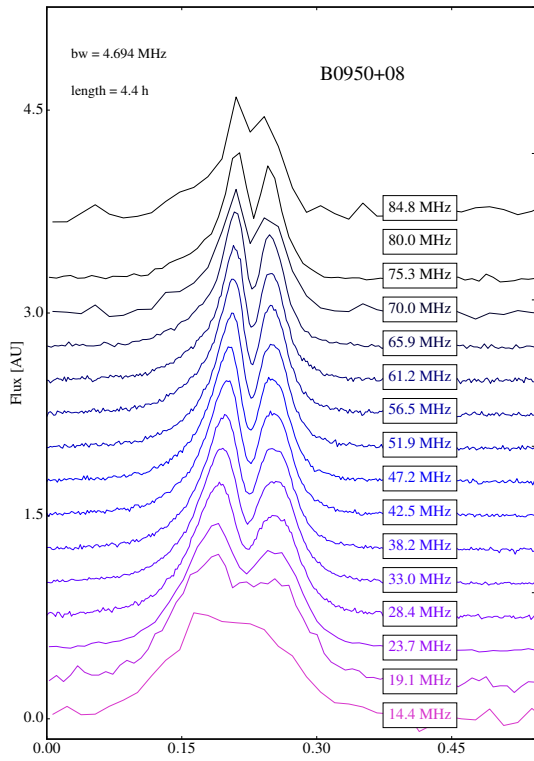
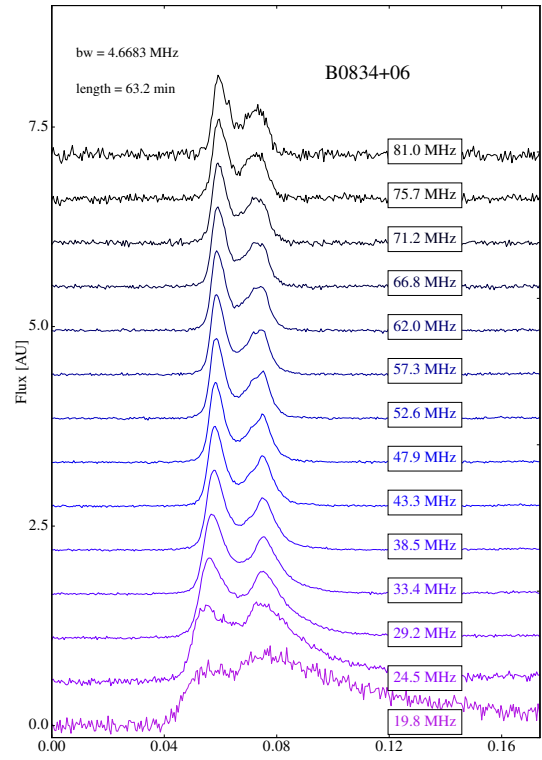
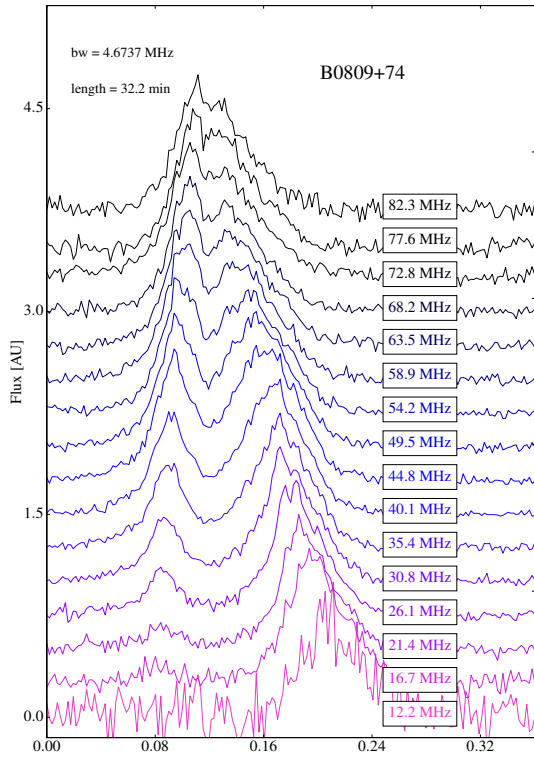


Figure 4 – Frequency stacked profiles for four pulsars: *B0809+74*, *B0834+06*, *B0950+08* and *B1133+16*.

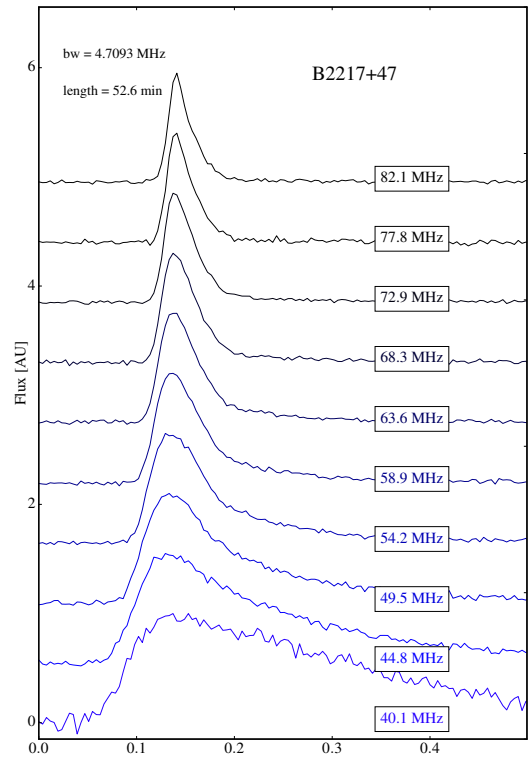
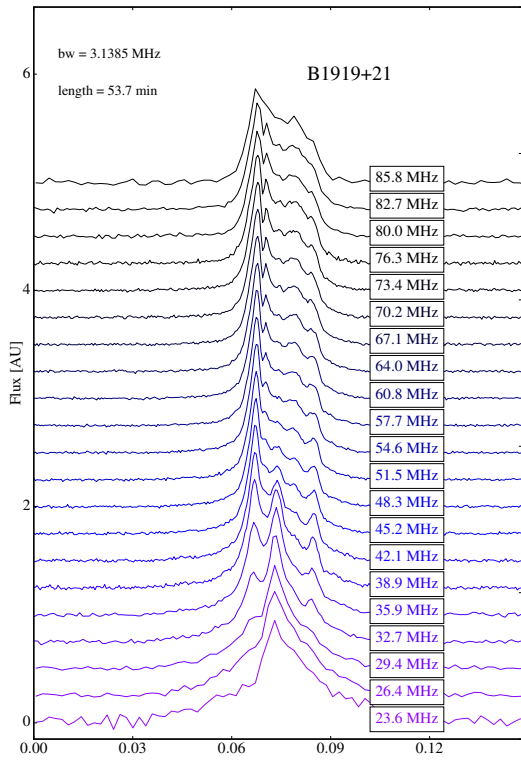
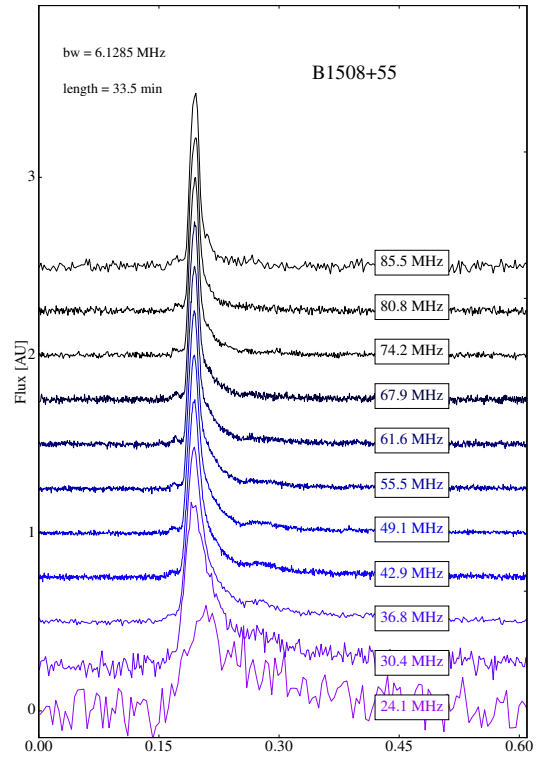
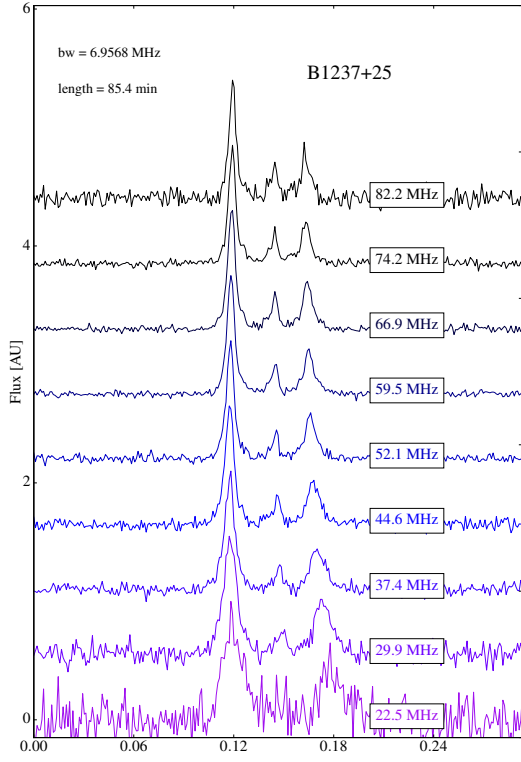


Figure 5 – Frequency stacked profiles for four pulsars: *B1237+25*, *B1508+55*, *B1919+21* and *B2217+47*.