The Significance of Low-frequency Interferometric Observations for the GPS Pulsar Flux Estimation: The Case of J1740+1000

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Abstract

In this paper we present recent Low Frequency Array observations of the pulsar J1740+1000. We confirm that its spectrum has a turnover at 260 MHz, which is unusual for a typical pulsar. We argue that in this case interferometric imaging provides more accurate pulsar flux estimates than other, more traditional, means such as beamformed observations. We conclude that existing calibration and imaging techniques can be used for a more comprehensive study of the influence of the interstellar medium on the point-like sources at very low frequencies in the near future.

Unified Astronomy Thesaurus concepts: Radio pulsars (1353); Interstellar medium (847)

1. Introduction

The flux of the majority of pulsars increases with decreasing frequency at least down to about 100 MHz. Their spectra are well described by a single power-law function with the population average spectral index close to −1.6 (Lorimer et al. 1995; Jankowski et al. 2018). However, for some pulsars low-frequency observations made by the standard technique (i.e., recording pulsars profiles, Lorimer & Kramer 2012) have been shown to be inaccurate at measuring the pulsar’s flux. The main reason for that is the influence of the interstellar medium (ISM), which introduces a scattering tail on the trailing side of the pulsar profile. In extreme cases the characteristic scattering time may approach or exceed pulse period, substantially hindering source detection. In even more extreme cases the pulsar’s flux can be absorbed via free–free thermal absorption caused by an ionized medium in the vicinity of the pulsar (i.e., dense filaments in supernova remnants, bow-shock pulsar wind nebulae, or H II regions). The absorption becomes more severe at lower frequencies and this results in an observed turnover in the apparent pulsar spectrum and a peak flux at around 1 GHz (Kijak et al. 2011a, 2011b, 2013, 2017). These sources were called the gigahertz-peaked spectra (GPS) pulsars and currently ~30 such objects are known (see Dembska et al. 2015; Basu et al. 2016, 2018; Kijak et al. 2017, 2018; Jankowski et al. 2018, and references therein).

It is well known that some pulsars exhibit a genuine low-frequency turnover i.e., below 500 MHz (see, for example, Sieber 1973; Malofeev 1996; Kramer et al. 2003, and references therein). The most recent observational studies include those by Murphy et al. (2017), Bilous et al. (2016), Bilous et al. (2020), and Bondonneau et al. (2020). To date several mechanisms have been proposed to explain this phenomenon, as described in the review article by Sieber (2002).

The PSR J1740+1000 spectrum was classified by Dembska et al. (2014) as a GPS; however, the recent 150 MHz Low Frequency Array (LOFAR) beamformed measurements by Bilous et al. (2016) challenged the GPS interpretation. Their flux density estimate suggests that the PSR J1740+1000 spectrum can be described by a single power-law function. Other recent wide frequency (from 325 to 5900 MHz) observations indicate a turnover at the frequency around 550 MHz, but the low-frequency (<325 MHz) behavior still remains unclear (Rożko et al. 2018).

Interferometric imaging is usually more accurate than beamforming techniques for the low-frequency flux estimation of GPS pulsars (Basu et al. 2016; Kijak et al. 2017). The most important advantage is that instrumental and atmospheric gain fluctuations can be corrected on very short timescales by self-calibrating the interferometric data, which is not feasible for beamformed pulsar observations.

In this paper, we present new 120–168 MHz observations (project LC9_004) of PSR J1740+1000 obtained with LOFAR (van Haarlem et al. 2013). We utilized the multibeam capability of LOFAR and observed our target for 2 × 4 hr simultaneously with one of the LOFAR Two-Metre Sky Survey (LoTSS; Shimwell et al. 2017) fields. PSR J1740+1000 was also independently observed for 2 × 4 hr as part of LoTSS (pointing P265+10, proposal code LT10_010). This LoTSS pointing is centered 0°8 from the target, which lies approximately at the 50% level of the power primary beam. We use these observations to study the low-frequency behavior of PSR J1740+1000. With this example we also highlight the capability of interferometric imaging observations at low frequencies and advocate using this to study all pulsars where the flux density is strongly affected by the ISM.

The outline of the paper is as follows. In the Section 2 we describe our observations and the calibration techniques we used. In Section 3 we compare the maps we obtained using different calibration procedures and also the different observations. In Section 4 we discuss the PSR J1740+1000 spectrum.
and the implications of our new measurements. In Section 5 we conclude.

2. Observations and Data Reduction

2.1. LOFAR Observations and Preprocessing

We observed PSR J1740+1000 using the LOFAR High Band Antenna (HBA) for four hours on both 2017 December 12 and 2018 February 1. Each observation was bracketed by short scans of flux density calibrators. In addition to these targeted observations, we made use of data from LoTSS. For an overview of LoTSS and a detailed description of the observation and processing strategy, we refer the reader to Shimwell et al. (2017). Parameters related to the three observations are listed in Table 1.

The observational setup of all three runs were identical. The observing bandwidth covers the frequency range from 120 to 187 MHz and was split into 243 subbands (SBs), which were subdivided into 64 channels of 3 kHz width. The correlator integration time was set to 1 s. After the observation, radio frequency interference (RFI) excision was carried out on the high time and frequency resolution data before they were averaged in frequency to 16 channels per subband. RFI excision was carried out using AOFlagger (Offringa et al. 2010, 2012) and averaging was done with the New Default PreProcessing Pipeline (NDPPP van Diepen & Dijkema 2018). Only the averaged visibility data are stored in the LOFAR Long Term Archive (LTA).

LOFAR HBA data are first calibrated to correct for direction independent effects such as clock offsets and bandpass, which can be derived from calibrator observations and transferred to the target field (see, e.g., de Gasperin et al. 2019). After the direction independent calibration is performed the image fidelity is still low and direction-dependent calibration is needed to correct for ionospheric distortions that are severe at low frequencies. Currently, there are two widely used routines to perform direction-dependent calibration on LOFAR imaging data, namely Factor (van Weeren et al. 2016) and DDF-pipeline (Shimwell et al. 2019). In this project, we process our data using both techniques as summarized below.

2.2. Factor Data Analysis

We calibrated and imaged data from the targeted observation using Factor (van Weeren et al. 2016; Williams et al. 2016). In our Factor processing we divided the field of view into multiple facets such that each facet has at least a point source with integrated flux density greater than 0.4 Jy. For each facet, we derived calibration solutions by self-calibrating a small region around the facet calibrator and applied the solutions to the other sources in that facet. Once calibrated, we imaged the calibrated visibilities from the facet containing PSR J1740+1000 using the wideband deconvolution algorithm available in WSClean (Offringa et al. 2014).

2.3. KillMS and DDFacet Data Analysis

Both the targeted data set and the LoTSS data set were processed using the latest version of the LoTSS pipeline (as used for LoTSS-DR2). This pipeline utilizes DDFacet (Tasse et al. 2018) and KillMS (Tasse 2014; Smirnov & Tasse 2015) and will be described in detail in C. Tasse et al. (2020, in preparation) but is also summarized in Section 2.3.3 of Shimwell et al. (2019). To further enhance the image fidelity in the region of the pulsar, we used the direction-dependent calibration solutions to remove all sources away from the target and then performed an additional self-calibration cycle on this region. This postprocessing, which will be described in detail in R. J. van Weeren et al. (2020, in preparation), allows us to optimize the calibration toward the pulsar and to produce a data set calibrated in the direction of the target that can be easily reimaged.

3. Image Analysis

In this section we compare three maps: two from our targeted observations (their resolution is $16^\prime\times 5^\prime/2$ and $6^\prime\times 6^\prime$, respectively), and one from LoTSS observations (its resolution is $12^\prime/33 \times 57^\prime$).

The flux density values and the rms of the maps were measured using the The Astronomical Image Processing System (AIPS) software tasks JMFIT and IMSTAT, respectively. Even though the pulsar is a point-like source we find a discrepancy between the peak and integral intensity measurements that is likely caused by residual ionospheric phase errors (Shimwell et al. 2017)—we only use the integrated flux values for further analysis.

To ensure an accurate flux scale of our LOFAR images the integrated flux densities of 60 bright, compact sources in our field of view were cross-checked with TGSS-ADR1 (Intema et al. 2017). We found that the median ratio of the integrated DDF-pipeline flux densities to the integrated TGSS-ADR1 flux densities is 1.09 (1.22 for LoTSS pointing observations), which lies within the typical range for LOFAR observations (see, e.g., Shimwell et al. 2019). Shimwell et al. (2019) suggested that a conservative uncertainty of 20% should be used on the LoTSS-DR1 integrated flux density measurements, but the dominant error in a flux density estimate comes from the signal-to-noise

| Table 1 | Observations and Imaging Parameters |
|--------|-----------------------------------|
| Observation Type | Targeted Factor | Targeted Factor | LoTSS Pointing |
| Calibration Method | Pipeline | DDF-pipeline | DDF-pipeline |
| Observation Date | 2017 Dec 12 (4 hr) | 2017 Dec 12 (4 hr) | 2018 Sep 24 |
| | 2018 Feb 1 (4 hr) | 2018 Feb 1 (4 hr) | |
| Map resolution [arcsec] | 16.5 $\times$ 6.2 | 6.0 $\times$ 6.0 | 12.33 $\times$ 5.00 |
| rms [mJy/beam] | 0.27 | 0.25 | 0.47 |
| Integral intensity [mJy] | 2.85 $\pm$ 0.98 | 3.42 $\pm$ 1.65 | 3.45 $\pm$ 0.98 |

Note. The local noise in the pulsar region (rms) and integrated flux density measurements were made using the AIPS task JMFIT.
As is seen in Table 1 our flux density errors are much greater than proposed survey uncertainty, which is unsurprising since our source is very weak at 150 MHz and it was close to the detection threshold. More surprisingly, the median ratio of the integrated LoTTS-Factor flux densities to the integrated TGSS-ADR1 flux densities is 0.72. This discrepancy is consistent with the PSR J1740+1000 Factor pipeline flux density estimate being lower than the flux density estimates obtained with DDF-pipeline.

The map obtained from the Factor pipeline is shown in the left panel of Figure 1. The noise level is similar to that obtained with DDF-pipeline. However, the detection of the pulsar in the Factor map was quite challenging but the detection is clear in the higher quality DDF-pipeline map (Figure 1 right panel) where the measured flux is $3.42 \pm 1.65$ mJy (see also Table 1).

In the LoTSS observation (Figure 2) the target was $\sim 0^\circ.8$ away from the pointing center, which corresponds to 50% of the primary beamwidth from the center, but this should not have any effect on our results besides the increased noise. Nevertheless, from this map we made an independent measurement of pulsar flux that agreed with our targeted observation.

4. PSR J1740+1000 Spectrum Analysis

The pulsar J1740+1000 was discovered by McLaughlin et al. (2000) using the Arecibo telescope. It is a young pulsar with a period of 154 ms that is located at a relatively large distance from the galactic plane, along a line of sight that includes the North Polar Spur (Loop I) and the Gould Belt, which is an expanding disk of gas and young stars (McLaughlin et al. 2002). This pulsar also hosts an unconfirmed Pulsar Wind Nebulae (Kargaltsev et al. 2008; Kargaltsev & Pavlov 2010). Due to its location on the sky, diffractive interstellar scintillation makes flux measurements challenging and significantly different measurements have been made, especially at frequencies between 1 and 2 GHz. Figure 3 shows all flux measurements we have found in the literature together with two new values: the weighted arithmetic mean flux value obtained from our two different processing methods used on the targeted observations, and the independent flux measurement from the LoTSS pointing.

Generally, two observational techniques are used to estimate pulsar flux density: beamforming or single dish observations and interferometric imaging observations. For the beamforming or single dish observations the pulsar flux density is generally
Figure 3. Pulsar spectrum with a free–free thermal absorption model fitted to all available flux density measurements. The open red star denotes the flux density value that was averaged over 1–2 GHz observations. The two values at 150 MHz were slightly displaced in frequency in order to be more visible in the plot. The dashed lines correspond to 1σ errors of the model. The values of the fitted parameters are presented in Section 4. The acronyms point to the following publications: B16—Bilous et al. (2016), GMRT—Rozko et al. (2018), MCL02Ar—McLaughlin et al. (2002), K11—Kijak et al. (2011b), D14—Demb ska et al. (2014), R18—Rozko et al. (2018).

estimated from the pulsar mean profile that is accumulated over many pulses (Lorimer & Kramer 2012). The flux is determined by comparing the on pulse and off pulse emission levels. There are different ways of determining the baseline level that allow the measured on and off emission ratio to be translated into physical units. One method is to record the flux calibrator before and/or after pulsar observations. Another method uses the radiometer equation. For the interferometric observations the standard approach is to observe a flux calibrator before and at the end of each observational session for the data to be calibrated so that the intensity can be measured from the map. In case of the LOFAR this flux calibration is more complicated due to inaccuracies in the beam model (e.g., Shimwell et al. 2019). Observational details and the flux density estimation methods for previously published PSR J1740+1000 studies can be found in Rozko et al. (2018).

PSR J1740+1000 flux density values were estimated by different observational methods, which have different advantages and disadvantages. Dembska et al. (2015) showed, based on a study of four pulsars that were heavily affected by scattering, that the flux measurements obtained using beam-formed methods were underestimated in comparison with flux density measurements from interferometric imaging observations. However, in cases where the scattering time is very small or negligible both flux density estimates are consistent within measurement errors (Demb ska et al. 2015; Basu et al. 2016). The mean profiles of PSR J1740+1000 published in the appendix of Rozko et al. (2018) showed that with decreasing frequency the mean profile weakens but does not significantly broaden, i.e., no scattering tail appears on the trailing side of pulsar profile. This implies that both methods of the flux density estimation at frequencies exceeding ~300 MHz should give the same result.

Regardless of the method, the pulsar flux density measurements should be affected by the scintillation-driven flux variation in exactly the same way. The typical timescale for the diffusive scintillations at LOFAR frequencies is around a few minutes. For our 8 hr LOFAR observations we thus average over these possible flux variations. In the case of refractive scintillations the time variation scale can vary from days to months. Targeted and LoTSS observations were separated around a half a year, so any significant refractive scintillations should manifest in different flux density levels in both observations, but instead we observed very similar flux density values.

To check the GPS interpretation of the pulsar spectrum we fitted a free–free thermal absorption model to all available flux density values. We follow the approach of Lewandowski et al. (2015; which is similar to that employed by Rajwade et al. 2016), and use the following formula of the flux ($S_\nu$) at any frequency ($\nu$):

$$S_\nu = A \left(\frac{\nu}{10}\right)^\alpha e^{-B\nu^{-2.1}},$$

where $A$ is the pulsar intrinsic flux at 10 GHz, $\alpha$ is the pulsar intrinsic spectral index, and $\nu$ is a frequency in GHz. The parameter $B$ is defined as:

$$B = 0.08235 \times \left(\frac{T_e}{K}\right)^{-1.35} \left(\frac{\text{EM}}{\text{pc cm}^{-6}}\right).$$

where $T_e$ is the electron temperature and EM is the emission measure. In the fitting procedure $A$, $\alpha$, and $B$ were free parameters and $\nu_p$ is the frequency corresponding to the maximum pulsar flux. To fit the data we used the Levenberg–Marquardt nonlinear least squares algorithm (Levenberg 1944; Marquardt 1963) and estimated the errors using $\chi^2$ mapping (Press et al. 1996).

The fitted parameters are $A = 0.40^{+0.31}_{-0.27}$, $B = 0.020^{+0.23}_{-0.020}$, $\alpha = -0.75^{+0.36}_{-0.72}$, $\chi^2 = 2.01$, and $\nu_p = 0.26$. Figure 3 shows the pulsar spectra with the fitted model and 1σ errors in this. According to new estimated parameters the peak frequency shifted toward lower frequency ($\nu_p = 260$ MHz), which is lower than that deduced in Rozko et al. (2018) ($\nu_p = 540$ MHz). Our result also confirms that the spectrum of PSR J1740+1000 is not a power law.

We used the pulsar dispersion measure (DM) to constrain the electron density and temperature of the absorber (see Rozko et al. 2018, and references therein). Assuming that half of the DM is contributed by the absorber we calculated the EM for three different absorber cases: a dense supernova remnant filament (with size equal 0.1 pc), a pulsar wind nebula (with size equal to 1.0 pc), and a warm H II region (with size equal 10.0 pc). For each case from the fitted value of parameter $B$ we obtained constraints on the electron temperature: 460$^{+520}_{-460}$ K (for 0.1 pc), 113$^{+960}_{-113}$ K (for 1 pc), and 20$^{+728}_{-174}$ K (for 10 pc). The derived temperatures are a little larger than those previously published, but they are consistent within the error, thus we still believe that the most probable absorber is a partially ionized small molecular cloud along the line of sight of the pulsar, because the derived electron temperature for the 10 pc absorber is too low for a H II region, and a presence of the PWN around the pulsars is still unconfirmed.

Our flux density estimate at 150 MHz has fewer uncertainties than the flux density value reported by Bilous et al. (2016). The main reason is that the PSR J1740+1000 profile is very weak and significantly broadened at 150 MHz (see Figure C.8. in Bilous et al. 2016) which makes the task of finding the correct baseline level very difficult—their reported signal-to-noise ratio is 6 but the flux density error is larger than 50%.
For the reasons stated above we believe that the interferometric method is better suited for low-frequency flux density measurements of this pulsar, as it is independent of the pulse broadening. However, our flux density estimate suggests that the simplest free–free absorption model with a single absorbing medium may be insufficient to explain observed spectrum shape.

One possibility may be that with interferometric imaging observations we are measuring not only the pulsar flux, but also some additional flux density that comes from the pulsar wind nebula around the pulsar. If that was the case one can expect that while the pulsar flux would continue to sharply decrease at lower frequencies (due to effects such as thermal absorption), the total flux may behave differently because of the emission from the nebula itself. However, in this scenario the emission from the pulsar wind nebulae may experience synchrotron self-absorption at low frequencies. To check this hypothesis we need more measurements in the low-frequency part of the spectrum and a more complex model where synchrotron self-absorption is fitted together with thermal absorption.

Another possibility is that there are two absorbers along the line of sight that can also explain the observed spectrum shape. This is not unlikely as J1740+1000 lies behind the North Polar Spur Region, and we need additional knowledge of structures along the line of sight to the pulsar to ascertain if this is the case. Further exploration of the multicomponent free–free absorption model is beyond the scope of this paper and requires additional measurements below 300 MHz. It is worth mentioning that more complex spectra with free–free thermal absorption have been observed like the radio galaxies with two turnovers (see, e.g., Callingham et al. 2017, and references therein).

The free–free thermal absorption in the pulsar magnetosphere was proposed to explain turnovers at low frequencies (i.e., around 100 MHz) by Malov (1979). Today we know that the pulsar radio emission is coherent and their magnetosphere is filled with highly relativistic electrons that should not absorb their emission (Mitra 2017). We cannot be sure that the observed total flux comes only from the coherent mechanism: it could be the sum of the pulsed and unpulsed emission (Basu et al. 2011); however, we believe that this is very unlikely to be the case.

The case of PSR J1740+1000 shows that the current techniques to calibrate imaging data open up the possibility of conducting a comprehensive study of the spectra for pulsars that are GPS candidates or are heavily affected by scattering at low frequencies. The interferometric observations are crucial for these studies as they are not impacted by scattering. In some cases beamformed observations may suffer from scattering that mimics a turnover feature (see, i.e., the case of PSR B1815-14 presented in Dembska et al. 2015). In such cases the interferometry method could be the only way to estimate pulsar flux density.

5. Summary

In this paper we presented the results of the LOFAR interferometric imaging observations of the PSR J1740+1000. We have shown that two independent LOFAR observations (i.e., targeted and from LoTSS pointing) confirmed a low flux density at 150 MHz. Due to its relatively low peak frequency ($\nu_p = 260$ MHz) obtained from the model it should not be classified as a typical GPS pulsar. However, flux measurements themselves still show a maximum flux around 600 MHz. We believe that in this case the mechanism responsible for the low-frequency flux density may be similar to the mechanism responsible for turnovers of GPS pulsars.

We claim that measuring fluxes from interferometric imaging data is important for the GPS pulsar population in general and also for other pulsars that exhibit low-frequency turnovers (below 500 MHz). While this is not the case of PSR J1740+1000, for other GPS candidates it could help to distinguish the true turnover from the “artificial” flux density drop that may result from the strong pulse broadening caused by the scattering. Moreover, the existing calibration techniques should make interferometric pulsar observations possible at frequencies below 150 MHz, which will in turn allow for a more comprehensive study of the influence of the ISM at very low frequencies (de Gasperin et al. 2018).

Our study shows that in the case of PSR J1740+1000 the simple free–free absorption model seems to be insufficient to describe the whole spectrum shape and a more complex model may be required.

We analyzed the LOFAR data with two different direction-dependent imaging pipelines, DDF-pipeline and Factor. In this particular case our target was detected at higher significance in the DDF-pipeline processed data, however, a detailed comparison between the pipelines is beyond the scope of this paper.

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