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The impact of technical constraints on the possibility of resolving the pulsar magnetosphere by observing its scintillations

E. Fadeev[1], A. Andrianov[1], M. Burgin[1], M. Popov[1], A. Rudnitskiy[1], T. Smirnova[2], and V. Soglasnov[1]

[1] Lebedev Physical Institute, Astro Space Center, 84/32 Profsoyuznaya, Moscow, 117997 Russia
[2] Lebedev Physical Institute, Pushchino Radio Astronomy Observatory, Pushchino, 142290 Russia

Abstract. Variation in the pulsar dynamic spectra with pulse longitude had in the past been interpreted as a result of the spatial motion of the pulsar emission region and led to some conclusions about the altitude of the emission regions or the magnetosphere structure. Motivated by this research, we used the VLBI observations of PSR B1237+25 with the Arecibo and Green Bank radio telescopes at 324 MHz, performed as part of a RadioAstron observing program, and analyzed scintillations at separate longitudes of the pulse profile. We have found that the fringe phase characteristics of the visibility function vary quasi-sinusoidally as a function of longitude. Also, the dynamic spectra from each of the telescopes shift in frequency as a function of longitude. However, we have found that these shifts arise from the low-level digitizing of the pulsar signal. After correcting for these digital effects, the frequency shifts have largely disappeared. The residual effects may be of instrumental origin or indicate the pulse emission altitudes well below the pulsar light cylinder radius.

Keywords: scattering; pulsars: individual: B1237+25; ISM: general; techniques: high angular resolution; methods: data analysis

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1 Introduction

Pulsars are observed through the inhomogeneous interstellar plasma, which acts as a lens or an interferometer with an extremely long baseline, potentially providing extremely high spatial resolution. The first evidence of resolving the magnetosphere of a pulsar with interstellar interferometry was reported by Wolszczan & Cordes (1987), who estimated the altitude of the emission region close to the light cylinder radius r_{LC}. Since then, there have been a few apparently successful attempts to spatially resolve this region, but so far no a consistent picture has been obtained as to the altitude of the emission regions near the pulsar or close to r_{LC}.

2 Observations

We carried out VLBI observations of PSR B1237+25 the with the Arecibo Telescope and the Green Bank Telescope (GBT) at 324 MHz in a bandwidth of 16 MHz in right and left circular polarizations. The observations were made as part of the RadioAstron space VLBI science program on December 22, 2017, and February 26, 2018. The data were processed at the Astro Space Center (ASC) using the ASC software correlator with gating and incoherent dedispersion applied.

3 Data processing

The pulse profiles are shown in Fig. 1a. We divided the pulse window into nine subwindows w_k with $0 \leqslant k \leqslant 8$. Then, in each window we computed a complex cross-spectrum for the Arecibo–GBT baseline and an autospectrum (dynamic spectrum) for each of the two radio telescopes.

For every single pulse and every subwindow, we computed the complex visibility function $V_k(\tau)$ as the inverse Fourier transform of the cross-spectrum. Then we computed for each subwindow in the pulse profile the phase φ_k of $V_k(\tau)$ relative to the phase in the subwindow w_4: $(\varphi_k - \varphi_4)$. We found that in a delay window of approximately ± 125 ns the curves of phase differences could be approximated by straight lines with a fitted slope. In Fig. 1b we plot for the two polarizations and two days of observations the values of the varying slopes and their standard errors derived from the fitting for each subwindow with respect to the value for the window w_4. We note that this pattern is very similar to the comparable pattern of phase versus longitude presented by Wolszczan & Cordes (1987).

We can also see the frequency shift in our dynamic spectra as a function of longitude for each of the two telescopes separately. In Fig. 1c, d, we show the dynamic spectra in the windows w_0 and w_8 respectively. The latter one is slightly but clearly

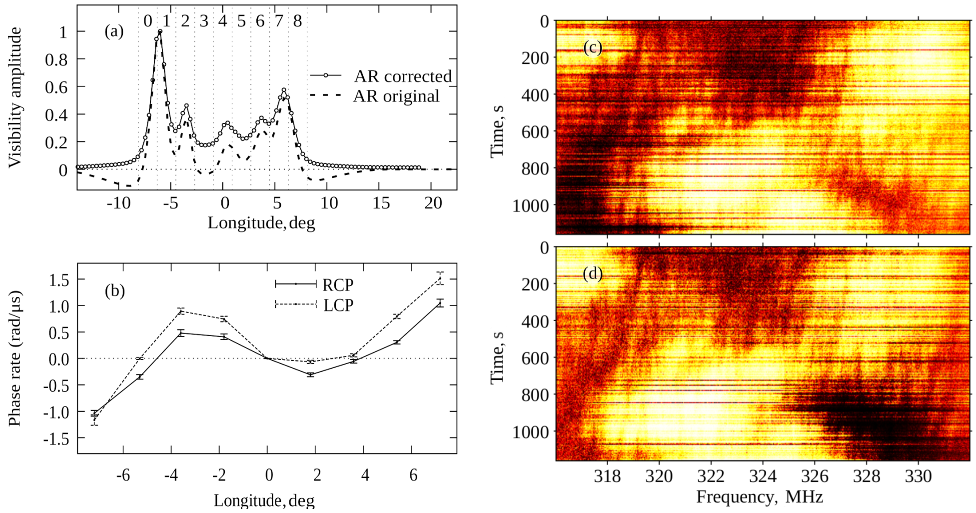

Fig. 1. (a) Average profile of PSR B1237+25 for the original data and the profile after correction. The vertical dashed lines indicate the nine on-pulse subwindows, w_0 to w_8, used as gates for the correlation and for our analysis. (b) The variation rate of the visibility phases as a function of pulsar longitude for both senses of polarization for the observing epoch December 22, 2017. (c, d) The dynamic spectra observed with the Arecibo Telescope in the longitude windows w_0 (top) and w_8 (bottom). A shift of about 1 MHz toward lower frequencies from w_0 to w_8 is clearly visible.

shifted toward lower frequencies with respect to the former. The time-averaged spectrum in the window w_0 has an excess at higher frequencies, while the spectrum in the window w_8 has the opposite distortion as it is shown in Fig. 2 (left).

The reason for the distortions can be traced back to the effects of digitizing a non-stationary stochastic signal like the pulsar signals studied in Jenet & Anderson (1998). For one-bit digitizing, the excess of spectral power density at relatively high frequencies leads to a false deficiency of spectral power density at relatively low frequencies. The same effect can be seen under saturation conditions for the two-bit (four-level) digitizing used at both the Arecibo Telescope and the GBT. We switched off the automatic gain control on both telescopes as it would have not worked correctly for pulsar observations due to its inertia. In these circumstances, the digitizer was saturated by strong pulses which were turning it into a pseudo-two-level system.

Due to interstellar dispersion, the pulsar signal arrives at the telescope earlier at higher frequencies, affecting the energy redistribution within the bandwidth. The incoherent dedispersion algorithm used by the correlator was not able to fully compensate for the dispersion delay. Since all the VLBI observations of the RadioAstron mission had been archived, we applied the corrections of two-bit sampling to the

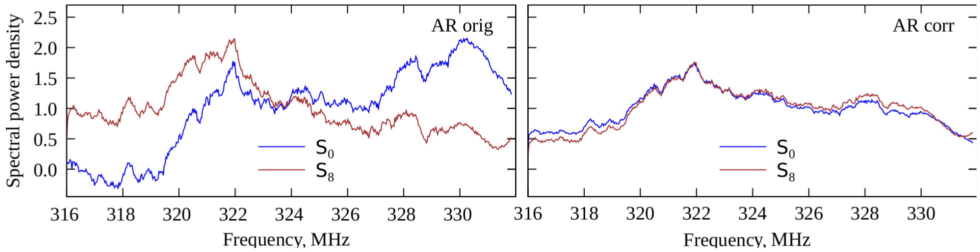

Fig. 2. Time-averaged left circular polarization spectra for the leading (S_0) and trailing (S_8) windows, each with the spectrum for the off-pulse subtracted. The left and right panels show the spectra before correction and the corrected spectra, respectively.

original VLBI data. Moreover, we also dedispersed the data coherently (Girin et al. 2023). As a result, most of the frequency effects disappeared (see Fig. 1a and Fig. 2, right panel). We did not investigate the nature of the residual effects. These effects could be instrumental or caused by the actual motion of the emission region. For further information see Popov et al. (2023).

4 Summary

- In the VLBI data as well as in the data from a particular telescope, the frequency shift demonstrates a non-monotonic pattern as a function of pulsar longitude.
- We attribute the distortions and frequency shifts of the longitude-dependent dynamic spectra mostly to the uncorrected low-level digitizing of the data.
- Upper limits of any astrophysics-related frequency shifts suggest that the altitude of the emission regions for PSR B1237+25 is well below r_{LC}.
- In view of our analysis, we think that observations with the intent to resolve the pulsar magnetosphere need to be critically evaluated in terms of these constraints on interstellar interferometry.

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