Pulse-to-pulse intensity modulation and drifting subpulses in recycled pulsars

R. T. Edwards1 B. W. Stappers2,1

1Pulse intensity modulation in recycled pulsars
Astronomical Institute “Anton Pannekoek”, University of Amsterdam, Kruislaan 403, 1098 SJ Amsterdam, The Netherlands
Stichting ASTRON, Postbus 2, 7990 AA Dwingeloo, The Netherlands
R. T. Edwards, redwards@astro.uva.nl

We report the detection of pulse-to-pulse periodic intensity modulations, in observations of recycled pulsars. Even though the detection of individual pulses was generally not possible due to their low flux density and short duration, through the accumulation of statistics over sequences of \(10^5\)–\(10^6\) pulses we were able to determine the presence and properties of the pulse-to-pulse intensity variations of six pulsars. In most cases we found that the modulation included a weak, broadly quasi-periodic component. For two pulsars the sensitivity was high enough to ascertain that the modulation phase apparently varies systematically across the profile, indicating that the modulation appears as drifting subpulses. We detected brighter than average individual pulses in several pulsars, with energies up to 2–7 times higher than the mean, similar to results from normal pulsars. We were sensitive to giant pulses of a rate of occurrence equal to (and in many instances much lower than) that of PSR B1937+21 at 1400 MHz (\(\sim 30\) times lower than at 430 MHz), but none were detected, indicating that the phenomenon is rare in recycled pulsars.

Introduction

Pulsar science is perhaps unusual in astronomy, in that progress in the theoretical understanding of the emission mechanism is not limited by a lack of data, but rather by an overabundance of complex observable phenomenology. Pulsar signals are seen to vary on every observable timescale from nanoseconds (e.g. hkwe03) to decades (e.g. wt02), with variations associated with such phenomena as microstructure, subpulses, periodic/drifting subpulses, giant pulses, pulse nulling, mode changing, interstellar scintillation and geodetic spin precession. All of these phenomena have been important in shaping ideas concerning the radio pulsar emission process, however to date a complete explanation of radio pulsar emission remains elusive.

This discovery of PSR B1937+21 bhk+82 posed further challenges due to its very short spin period of 1.56 ms. As more “millisecond pulsars” (MSPs) were discovered, the rapid spin and low inferred surface magnetic field strength grew to be understood as the end product of accretion from a binary companion, “recycling” pulsars that had earlier evolved into radio silence (e.g. pk94). However, the question of how the radio emission mechanism is related to that of ordinary pulsars remained open. With a difference of 2–3 orders of magnitude in rotation period and 3–4 orders of magnitude in magnetic field strength, a common emission mechanism might not be expected, yet a good argument can be made for this through the comparison of (polarimetric) average pulse profile morphologies and their frequency dependence (kx00 and references therein).

As noted above, the true pulsar signal varies on all timescales and much has been learned about “ordinary” pulsars from studying aspects of the signal other than the basic average profile. This has not been the case with MSPs because their typically lower flux densities and shorter pulses make the detection of individual pulses difficult. An exception has been the study of so-called “giant” pulses, in PSR B1937+21 wcs84,bac95,cstt96,k100,viv02,ps03, and PSR B1821−24 rj01. Studies of the properties of pulses of normal intensity have thus far been limited to three pulsars. sb95 used the 305-m Arecibo dish to obtain sensitivity to individual pulses of PSR B1534+12 of average and above-average energy and found that their distribution in energy was similar to that of some ordinary pulsars. On the basis of the detection of pulses of above-average intensity, both jak+98 and vam98 found that the properties of the brightest known MSP, PSR J0437−4715, were similar to those of ordinary pulsars, although to good significance neither nulling nor the presence of preferred timescales within individual pulses (e.g. microstructure, subpulses) was detected. Both studies report the detection of quasi-periodic pulse-to-pulse intensity modulations with a period of \(\sim 4\) pulses, and vam98 report (we believe potentially erroneously; see Sect. sec:discussion) that the modulation is not associated with drifting subpulses, as it often is in ordinary pulsars. Finally, jap01 used data with an average single-pulse signal-to-noise (S/N) ratio less than one to show that on a statistical basis and with the exception of giant pulses, the emission of PSR B1937+21 is extremely stable, showing to high significance a complete lack of pulse-to-pulse variations and no difference between the shape of individual pulses and that...
of the average profile.

As shown by jap01, poor single-pulse S/N does not eliminate the possibility of obtaining useful information regarding single pulses. The average profile can of course be measured in such cases, but there is no reason why collection of statistics cannot be extended beyond the first moment to include higher-order moments and correlations. Of primary interest are the second momentSince they worked from voltage samples instead of intensity samples, jap01 referred to this as the fourth moment, giving access to the modulation index, and the second order correlations. A variety of useful correlation statistics can be derived; jap01 integrated the single-pulse autocorrelation function (ACF) to show that every pulse appeared to be identical to the average profile. We extend this approach here to include the Longitude-Resolved Fluctuation Spectrum (LRFS; bac70b), the Two-Dimensional Fluctuation Spectrum (2DFS; es02) and the Longitude-Resolved Cross-Correlation Function (LRCCF; pop86). Applying these techniques to archival observations made at the Westerbork Synthesis Radio Telescope (WSRT), we have detected and characterised pulse modulation behaviour in several recycled pulsars.

Observations and Methods of Analysis
Observations

The data used in this project were selected from archival data taken at WSRT. For many pulsars numerous observations were available, allowing us to take advantage of fortuitous scintillation conditions for substantial enhancements in sensitivity. For all observations, dual linear polarization signals from fourteen 25-m dishes were added using previously determined phase and gain factors and the resultant signal was digitally processed by the PuMa pulsar backend to form a two-dimensional array of total power samples, as a function of time and radio frequency; for details see vkv02. In offline processing, frequency channels containing periodic interference were flagged and a de-dispersed time series was produced by combining remaining channels, aligned using previously published dispersion measures. In Table tab:obs we list parameters of the observations used, including the date of observation as a Modified Julian Day (MJD), the observation duration (\(T_{\text{obs}}\)) in seconds, the centre frequency (\(\nu\)) and total bandwidth (\(\Delta\nu\)) in megahertz, the number of frequency channels used, the resultant dispersion smearing (\(\tau_{\text{smear}}\)) near the center frequency and output sample interval (\(\tau_{\text{samp}}\)) in microseconds, and the number of pulses recorded. The rightmost four columns refer to the sensitivity, see Sect. sec:nondet.

<table>
<thead>
<tr>
<th>(T_{\text{obs}})</th>
<th>(\nu)</th>
<th>(\Delta\nu)</th>
<th>(N_{\text{chan}})</th>
<th>2(c\tau_{\text{smear}})</th>
<th>2(c\tau_{\text{samp}})</th>
<th>(N_{\text{pulses}})</th>
<th>2(c\sigma_{g})</th>
<th>2(c\sigma_{m})</th>
<th>(E_{\text{min}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\text{name date})</td>
<td>(T_{\text{obs}})</td>
<td>(\nu)</td>
<td>(\Delta\nu)</td>
<td>(N_{\text{chan}})</td>
<td>2(c\tau_{\text{smear}})</td>
<td>2(c\tau_{\text{samp}})</td>
<td>(N_{\text{pulses}})</td>
<td>2(c\sigma_{g})</td>
<td>2(c\sigma_{m})</td>
</tr>
</tbody>
</table>

Production of a Longitude/Time-dependent Array
For many techniques of single pulse analysis including those used in this work, the data need to be treated as a sequence of sampled pulses, with a consistent sampling lattice within each pulse. The simplest approach to producing a such two-dimensional (i.e. longitude- and time-resolved) representation of the pulse sequence is to bin each sample according to its longitude phase, as calculated using an ephemeris (for which purpose we used the TEMPO software package http://pulsar.princeton.edu/tempo/). When the time resolution is close to the interval corresponding to the desired longitude resolution, a problem arises with this method. In the simplest case, where the longitude bin width is chosen to correspond to one sample interval (at some point during the observation), each pulse as it appears in the binned sequence is effectively shifted by an amount corresponding to the offset between each sample and the bin centers. This offset advances (modulo one bin) by a constant amount each pulse due to the fact that the apparent pulse period does not (in general) equal an integer number of sample intervals. The pulse shape distortion (longitude shift) is thus periodic from pulse to pulse, and gives rise to a sequence of harmonics in the LRFS. This problem was encountered by vam98 in their analysis of data from PSR J0437−1715, but no attempt was made to remove it.

In this work we avoided the effect by compensating for the shift in each pulse using a frequency-domain time shift. Formally, we may view the time series as a sampled signal that represents the source intensity signal, convolved with a function representing the applied integration. By using a sequence of samples that is offset from the required set of bin centers (longitude samples) by some fraction of a sample \(\epsilon \in [-0.5, 0.5]\), and assigning those samples to the nearest bin, we arrive at a version of the pulse signal that is apparently longitude-shifted by \(\epsilon\) samples. This can be simply corrected by convolution with an offset sinc function, which by virtue of Fast Fourier Transform algorithms is efficiently performed by multiplying the Discrete Fourier Transform (DFT) of the pulse by \(\Delta(\nu) = \exp(2\pi i \epsilon\nu)\) and taking the inverse DFT. Since this performs a cyclical convolution, it is necessary to discard some samples from the ends of the sequence. This is most
noticable in the presence of strong interference, when the apparent step between the last sample and the first can cause ringing at the Nyquist frequency when the sampling lattice is offset by this process. We found that discarding 32 samples from each end of the result was sufficient to avoid this effect. If this correction is made to each pulse, the artifact is removed completely from the signal and all fluctuation statistics can generally be interpreted correctly.

In some circumstances, extension of the approach to effect a change in sampling interval (by dropping coefficients in the frequency domain) might be indicated. This is often necessary in the analysis of simultaneous multi-observatory data sets due to the employment of different sampling intervals, and may also become important in future high-resolution studies of close-orbit binary pulsars where the apparent period can change significantly over the course of an observation. We suggest the technique be investigated as a means for avoiding the deleterious effects of time-domain re-sampling noticed by khk+01. Although we also note that for some purposes, including application of the LRCCF between observatories as in khk+01, the synthesis of synchronous samples is unnecessary and should be avoided.

In theory, the above procedure allows absolute alignment in longitude of observations at different epochs and frequencies. In practice, the published dispersion measure may derive from arbitrary profile alignment procedures, and previously published timing ephemerides may not extrapolate beyond the date range from which they derive accurately enough for phase alignment between different epochs. For these reasons, we did not attempt absolute alignment, and our longitude axes include an arbitrary offset.

Accumulation of Statistics The first step of processing after forming the longitude/time array was to correct for an absolute offset due to the system noise power. To reduce the effect of slow variations in the system temperature we subtracted a running baseline, computed as the mean over the surrounding ± 1000 pulses of all samples in a defined “off-pulse” longitude interval. Denoting the result as $S_{ij}$ where $i$ and $j$ are indices in pulse longitude and pulse number, we then computed the (normalized) average pulse profile as

$$\mu_i = \frac{1}{N} \sum_{j=0}^{N-1} S_{ij},$$

where $N$ is the number of pulses in the interval.