

# Investigation of radio pulsar emission features using power spectra

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**Abstract** Since 2013, round-the-clock monitoring of the sky has been carried out simultaneously in 96 beams using a high-sensitivity radio telescope called the Large Phased Array (LPA) at the frequency 110.25 MHz. These observations are made under the program of interplanetary plasma investigation. The same data are used to search for pulsars by means of power spectra. To increase the sensitivity of the pulsar search, 500–600 power spectra corresponding to different days of observations are summed. In the integrated spectra of known pulsars, besides expected improvement in signal-to-noise (S/N) ratio for the frequency harmonics, some features are explored in this paper. We present the 27 strongest pulsars which are in a field with declination  $21^\circ - 42^\circ$ . The observable details in the integrated power spectra are connected with the presence of pulsar periods of the second ( $P_2$ ) and third ( $P_3$ ) class, which have been identified. Empirical relations for calculating these periods are obtained. The value  $P_2$  is estimated for 26 pulsars, and for 15 sources it is made for the first time. The value  $P_3$  is estimated for 13 pulsars, among them these values are given for five sources for the first time.

**Key words:** pulsars: general — pulsars

## 1 INTRODUCTION

A Fourier power spectrum is a good tool for searching for the frequency of a periodic process, therefore it is no wonder that the search for pulsars is made, as a rule, by using power spectra. A Fourier transform is applied to the correlation function, or the Fourier transform of a signal is computed by the square. After detection of the harmonics in a spectrum, the signal is integrated with a period corresponding to the inverse ratio of the first harmonic frequency. Thus, the search for a dispersion measure is carried out in cases with observations in several frequency channels. As a result of averaging, the mean profile of a pulsar is obtained, which is the narrowest for the “correct” dispersion measure. Recurring observations using the same telescope with which the pulsar candidates are found, in addition to other frequencies, are even better than observations by other telescopes, as it is a reliable method to confirm the existence of a pulsar. With small variations, such process of searching for pulsars is accepted everywhere, see the last review of Barr et al. (2013). The power spectrum is only part of the method

applied to search for pulsars, and further operations during pulsar investigation are not generally used.

Round-the-clock monitoring of the sky by the Large Phased Array (LPA) radio telescope began in 2013, under the program for investigating interplanetary plasma, and especially coronal mass ejections (Shishov et al. 2016; project “Space Weather”). Besides this program, review of data was also used in the search for pulsars (Tyul'bashev et al. 2016, Tyul'bashev et al. 2017, Samus & Li 2018), which was part of the project “BSA-Analytics”, <http://bsa-analytics.prao.ru>). As pulsars are objects with small flux densities, the main problem in searching for them is realizing the highest possible sensitivity of observations so that it is possible to identify extremely weak objects. Because daily monitoring is an obvious method of increasing of the sensitivity, the power spectra can be accumulated, corresponding to coordinates of the same points in the sky. In such integrated spectra, with expected improvement in the signal-to-noise (S/N) ratio for the frequency harmonics and the inclusion of multiple values (up to 108 for PSR J0323+3944), the unexpected appearance of several fea-

tures demanded an explanation. In this paper, analysis of the integrated spectra is carried out and the nature of two observable features in the power spectra is considered.

## 2 OBSERVATIONS AND DATA PROCESSING

Observations were made using the LPA of the P.N. Lebedev Physical Institute at the center frequency 110.25 MHz. LPA is a phased array constructed with half-wave dipoles. The geometrical area is 72 000 m<sup>2</sup> and the effective area is about 45 000 m<sup>2</sup> in the zenith direction, which is the configuration used by us. The size of one beam is approximately 0.5° × 1°. The antenna is a meridian instrument, therefore any direction can be observed only once a day for a duration of approximately 7 minutes. The details, concerning radio telescopes created based on the LPA antenna, are given in Shishov et al. (2016); Tyul'bashev et al. (2016). There are two basic modes of data recording. The first mode is a record in the six frequency channels with a channel bandwidth of 430 kHz and a data-sampling interval of 0.1 s. The second mode is to record in a 32-channel frequency mode with bandwidth of a channel being 78 kHz and data-sampling interval 12.5 ms. Since August, 2014 both modes have been used simultaneously during observations in 96 beams of the antenna, overlapping declinations  $-9^\circ < \delta < 42^\circ$ . Data presented in this paper were obtained in declinations  $21^\circ < \delta < 42^\circ$ , where we had peak sensitivity of the radio telescope and a minimum of noise was observed.

Before calculating a power spectrum, pulse interferences were cleaned and the noise level was estimated. If this level was too big, defined as more than a threshold level specially calculated for a given direction, further operations were not applied. In practice, we found that approximately 20% to 30% of all records were rejected by the primary search for pulsars. Part of these rejected data can be used further to examine the search results and, probably, for pulsar investigations. Power spectra were constructed for both the 6-channel “small” data and for the 32-channel “big” data. To obtain the Fourier power spectra, the fast Fourier transform was employed. A temporary file with length of 2048 points was generated for “small” data and one with length of 16 384 points was produced for “big” data, which is approximately half of the temporal beam of the LPA. Further, the spectra obtained independently for each frequency channel were summed and used in a primary search for the periods of new pulsars (Tyul'bashev et al. 2017; Samus & Li 2018). The following stage consisted of a summation

of the power spectra for the different days corresponding to one direction on the celestial sphere. When processing of the “big” data began, two years of observations were already available. There were 500–600 files on average with individual spectra to obtain the integrated power spectrum. An increase of 22–24 times in the S/N ratio is expected for the harmonics of such integrated spectra.

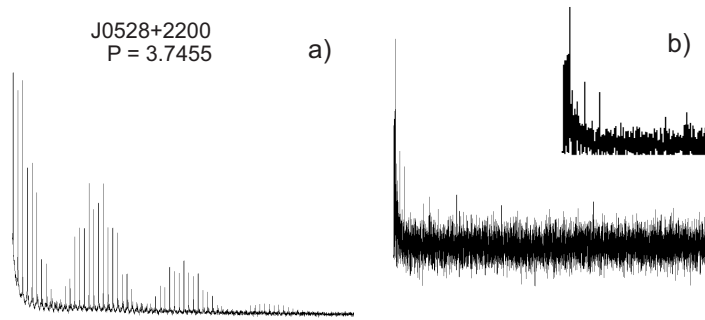
What would be expected from such summation? As exterior radiation from the majority of pulsars can be represented as a set of delta functions, in the obtained power spectrum there should be a set of delta functions. In practice, a series of observations is limited in time and consequently an average power spectrum for the harmonics should be built based on the height, where the first harmonic is the strongest. In reality, such a pattern is broken for an individual power spectrum, as pulses from the same pulsar have different intensities, including sometimes lacking part of the pulses. Frequent unsuccessful subtraction of a baseline in the initial data and strong low-frequency noise lead to the S/N ratio in the first harmonic being lower than the second one.

As a result of summation of an individual power spectrum, we expected to see a certain “ideal” spectrum. However, effects of averaging were absolutely unexpected for almost all pulsars in our list. For 26 of 27 pulsars, a modulation in amplitudes of harmonics with quasi-periods from tens to hundreds of milliseconds is observed. In Figure 1, an example of an integrated (a) and individual (b) power spectrum of the pulsar J0528+2200 in a frequency interval of 40 Hz, corresponding to 25 ms, is displayed.

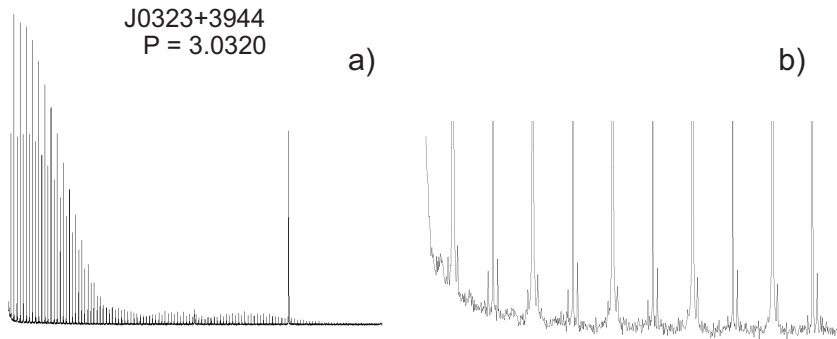
From Figure 1, it is apparent that the individual spectrum does not show any features. In an integrated spectrum, a wavy structure is obvious. A modulation showing periodic increase of the S/N ratio at far harmonics is presented. The pulsar is constantly visible during the most part of days during the monitoring. Its flux density at 400 MHz according to the ATNF Pulsar Catalogue<sup>1</sup> is  $S_{400} = 57$  mJy, and at the frequency 102 MHz,  $S_{102} = 100$  mJy (Malofeev et al. 2000).

By detailed consideration of the integrated power spectra, especially the first harmonics, a second feature has been identified. In Figure 2(a), the integrated power spectrum of pulsar J0323+3944, plotted on a large scale, is displayed, and the 10 first harmonics are shown in Fig. 2(b). The harmonics satellites near the pulsar's main harmonic companions are clearly visible. Such details

<sup>1</sup> <http://www.atnf.siro.au>



**Fig. 1** Example of an integrated (a) and individual (b) power spectrum for pulsar J0528+2200. The insert in panel (b) displays a fragment of the spectrum that illustrates the best representation of the first harmonic.



**Fig. 2** The integrated power spectrum of pulsar J0323+3944. Interference originating from human-caused sources regularly appears (50 and 33 ms) as shown; (b) a fragment from a pulsar spectrum – first ten harmonics. Satellites of the first harmonics are visible.

about this kind of power spectrum were not previously mentioned by other authors in this field.

In Figure 2(a) it is apparent that amplitudes of the harmonics have an obvious wavy structure. For the first harmonics, there is an obvious slope in the power of harmonics, with not so strong modulation, as shown in Figure 1(a). In Figure 2(b) it is clearly visible that near the harmonics, there are harmonics satellites which are not multiples of the pulsar's period. One of these satellites is to the left, and another one is to the right of the main harmonic, but distances to the left and right satellites are not identical. It is interesting that both satellites are not visible in all pulsars, and only one of the satellites is visible more often. This kind of detail is observed in 13 of 27 pulsars.

The power spectra of 25 pulsars are presented in Figure 3, in addition to those of the two pulsars shown in Figures 1 and 2. These figures are plotted such that the axis for the frequencies is constrained to where the harmonics are visible. Therefore, the extreme right frequency on all power spectra is different. The value of a period given together with the name of a pulsar allows

orientation in the frequency domain, as the frequency of the first harmonic is equal to the rotation period of a pulsar. Figure 4 shows fragments of the power spectra from Figure 3 for several pulsars with clearly visible harmonics satellites, except for pulsar J0323+3944 which is displayed in Figure 2(b).

Not all spectra in Figures 3 and 4 show identical details like what is visible in Figures 1–2, but all have typical features. Analysis of the integrated spectra is described in the following paragraph.

### 3 INVESTIGATION OF POWER SPECTRA

As is known, besides a rotation period ( $P_1$ ) in some pulsars, other periodic or quasi-periodic features which are not directly related to the main period are also observed. This is the so-called “drifting subpulse phenomenon” which is characterized by two periods  $P_2$  and  $P_3$ . At the very beginning of pulsar investigation, it was discovered (Drake & Craft 1968) that there were pulsars with inner structure of an individual pulse - subpulses which showed a regular drift in the phase of arrival inside the so-called “pulsar window,” forming “drift bands” on a di-

agram consisting of the number of the period (ordinate) versus the phase of the period (abscissa).  $P_2$  is accepted as a period in the second class. The value  $P_2$  is the horizontal drift band separation in time units. A period of the third class ( $P_3$ ) is a distance which is determined by the number of periods  $P_1$  on the ordinate. Drifting toward the back end of a “window” is defined as positive, and toward the forward one as negative. One of the first pulsars with a very regular and clear drift (PSR J0814+7429) was identified in Vitkevich & Shitov (1970). Now the drift of subpulses is known in about 70 pulsars and, approximately for the same number,  $P_2$  and  $P_3$  have been measured (Weltevrede et al. 2006).

There are some models which attempt to explain the drift effect. The most known are no-radial pulsations of a neutron star (Ruderman 1968), the sparking gap model over a polar cap (Ruderman & Sutherland 1975), rotation of a radiation pattern around a magnetic axis (Sieber & Oster 1975), which was developed in “a rotating carousel” model (Deshpande & Rankin 1999) and applied to PSR B0943+10 (Rankin et al. 2003), and, at last, a feedback model that was proposed by Wright (2003). Unfortunately, none of these models explains all the details related to the effect of subpulse drift.

We have tried to explain the features shown in Figures 1–4 in the integrated power spectra by the presence of  $P_2$  and  $P_3$ . We take, for an example, two pulsars J0528+2200 (Fig. 1) and J0323+3944 (Fig. 2), which, according to the investigation of Weltevrede et al. (2006), have these periods. That paper, containing the most measurements of drifting subpulses, was taken as basis for comparison with our data. It presents the result of detailed investigations of 187 pulsars at a frequency of 1420 MHz, acquired in Westerbork (Netherlands). The one-dimensional and two-dimensional Fourier power spectra in a pulse window have been used for measuring the modulation coefficient, and  $P_2$  and  $P_3$ . In this analysis, the records containing some thousands of pulses were used. In Figure 1(a) it is apparent that the middle or a maximum of the first “hump” of modulation in a power spectrum is necessary for harmonics near the number 19, which corresponds to a period of 200 ms. According to Weltevrede et al. (2006) in this pulsar,  $P_2$  is  $-200$  ms or  $+500$  ms. Our estimate allows selecting the single-valued period 200 ms. We cannot estimate a sign for the drift. Thus, the period of the second class is calculated from a simple relation

$$P_2 = P_1/n, \quad (1)$$

where  $n$  is the harmonic number at which the middle of the first “hump” of modulation in an average power spectrum takes place, and  $P_1$  is a pulsar rotation period. Analyzing the known periods of the third class of some pulsars, we have obtained the empirical formulas for these satellites of the main harmonic

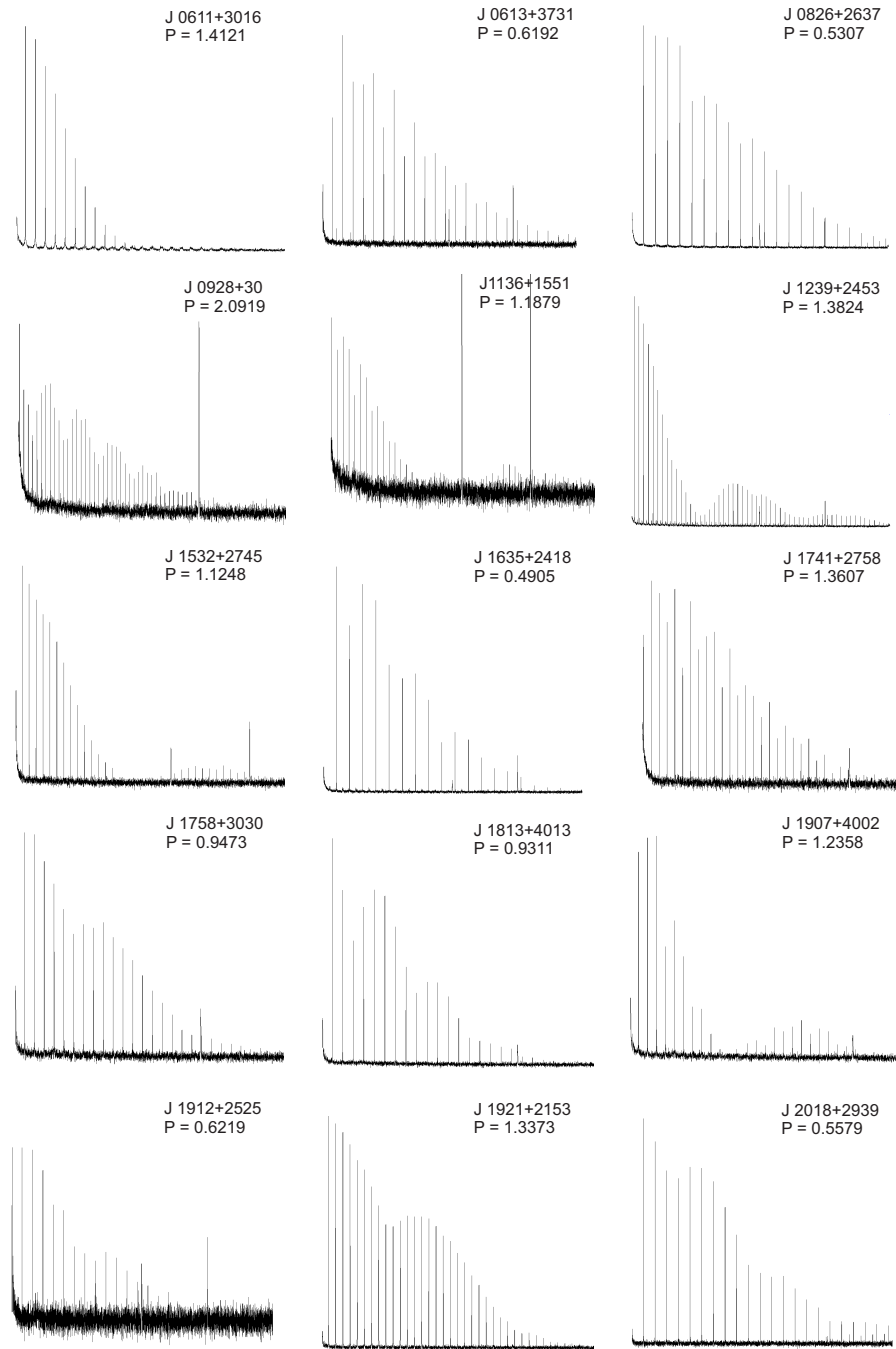
$$\begin{aligned} P_l(n) &= P_1(n) \left( n \times \frac{P_3}{(n \times P_3 - 1)} \right), \\ P_r(n) &= P_1(n) \left( n \times \frac{P_3}{(n \times P_3 + 1)} \right), \end{aligned} \quad (2)$$

where  $P_l$  is a period of the left satellite,  $P_r$  is a period of the right one and  $P_3$  is a period of the third class, in terms of  $P_1$ . It follows from relations (2) that

$$\begin{aligned} P_3 &= P_l(n) \times \frac{1}{n \times \Delta P_l(n)}, \\ P_3 &= P_r(n) \times \frac{1}{n \times \Delta P_r(n)}, \end{aligned} \quad (3)$$

where  $\Delta P_l(n) = P_l(n) - P_1(n)$  and  $\Delta P_r(n) = P_1(n) - P_r(n)$ . Presence of the harmonics satellites in the spectrum, apparently, reflects the presence of beating in two periodic processes with periods  $P_1$  and  $P_3$ . It is necessary to notice that both satellites are not in all pulsars, and in case both are present, the value of  $P_3$  calculated from Equation (3) is slightly more in the left companion (by 7% – 20%), but, as a rule, both values coincide within measurement error. It is interesting to note that in Weltevrede et al. (2006) there are also pulsars with not only one value of  $P_2$ . We will return to our example. Having calculated distance to the left and right satellites at several harmonics of pulsar J0323+3944 (Fig. 2b), according to Equation (3), we calculated the period  $P_3 = 8.4 \pm 1.3$ . Weltevrede et al. (2006) give the same quantity,  $P_3 = 8.4 \pm 0.1$ .

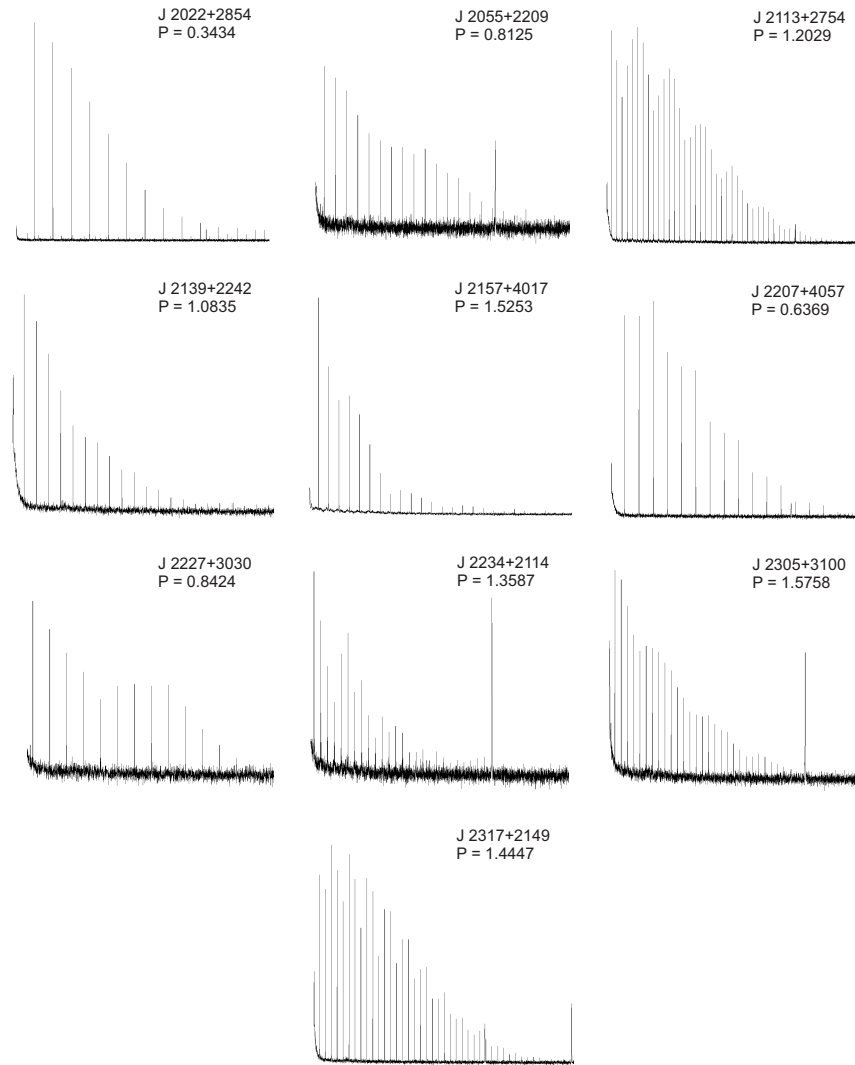
In Table 1, information on 14 pulsars from our sample is presented. These pulsars are the same as those in the list of objects in Weltevrede et al. (2006). In the first column of the table, names of the pulsars in J2000 are given. In the second column, we list the pulsar’s period from the ATNF Pulsar Catalogue, in the third column period  $P_2$  and in the fifth column period  $P_3$  of the pulsars, measured in our observations. For comparison, in columns four and six the data from Weltevrede et al. (2006) are given. The measurement errors of  $P_2$  are related to how a harmonic is defined in terms of where the middle of the first maximum of the amplitude modulation appears. The error is defined as  $\pm 0.5$  of a harmonic number in the basic spectrum. The error of a measurement for  $P_3$  is related to the dispersion of the values  $P_l(n)$  and  $P_r(n)$ , measured for not less than three satellites at the first several harmonics. As a rule, the number of measurements made is from 6 to 20. The first measurements



**Fig. 3** Integrated power spectra of 25 pulsars.

of  $P_2$  and  $P_3$  for 13 pulsars are presented in Table 2. These pulsars were not included in the paper Weltevrede et al. (2006). In the first, second and third columns, the same quantities as in Table 1 are given, and in the fourth one values for  $P_3$  are presented.  $P_3$ , given in Tables 1 and 2, is mainly obtained as the mean value between  $P_l(n)$  and  $P_r(n)$ .

The comparison of our estimates of the periods  $P_2$  and  $P_3$  with data in Weltevrede et al. (2006) shows good agreement. Moreover, in our estimates of period  $P_2$ , for some pulsars, it is possible to remove cases with multiple values in a direction of subpulse motion in a pulse window. Our accuracy for the evaluation of  $P_2$  in most cases is high, but for  $P_3$  we see comparable values.



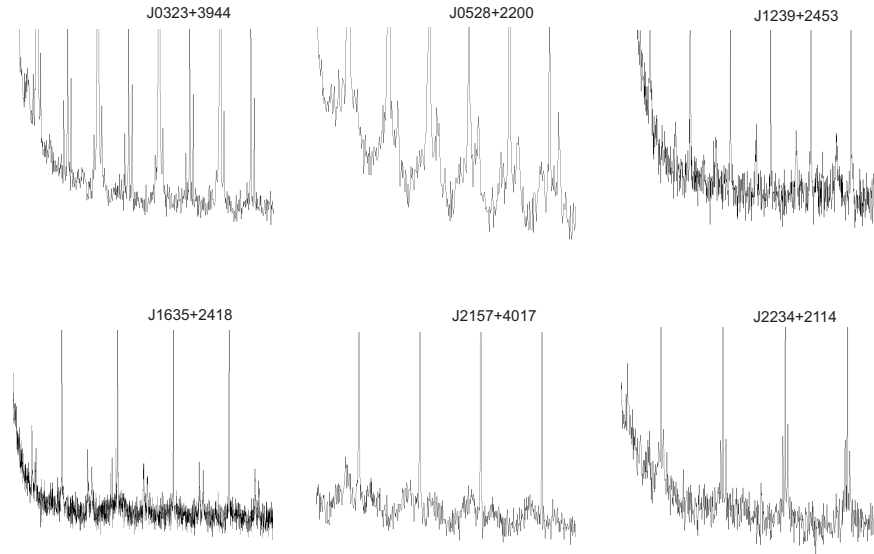
**Fig. 3** — *Continued.*

#### 4 SUMMARY AND DISCUSSION

Investigations of the integrated Fourier power spectra became possible because there were data from monitoring a large part of a sky spanning four years. The volume of these data has already exceeded 100 terabytes. The continuous accumulation time of each point in the sky, after rejecting the data with interferences, exceeds two days. These rich data have already provided a series of interesting results from investigation of the solar wind (Chashei et al. 2015, Shishov et al. 2016), on the search for pulsars (Tyul'bashev et al. 2016, Tyul'bashev et al. 2017) and on the search for prompt radio transients (Tyul'bashev & Tyul'bashev 2017). The integrated power spectra also reveal two new, unexpected features which we interpret

as a manifestation of the periodic processes in radiation associated with the pulsar pulses.

If our interpretation is true for all 14 pulsars in Table 1, we have obtained an estimate of  $P_2$ . For seven pulsars, our results agree well with data given from Weltevrede et al. (2006), and for four sources there is a discrepancy in the measurements. Thus for three pulsars among these four (J1921+2153, J2157+4070 and J2305+3103), values of  $P_3$  coincide with Weltevrede et al. (2006). Only for J2113+2754 do we not see the satellites at the first harmonic. For two pulsars, we cannot exactly determine the first “hump” in their spectra. Therefore for pulsars J1907+4002 and J1921+2153, we give two values of this quantity (Table 1). For three pulsars (J1813+4013, J1907+4002 and J2317+2149) we made, for the first time, an estimate of  $P_2$ , because such



**Fig. 4** Fragments of the integrated power spectra of pulsars are presented, with the most obvious harmonics satellites, except for pulsar J0528+2200 which is in Fig. 1(b).

**Table 1** Estimates of the Periods  $P_2$  and  $P_3$  from Fourier Power Spectra and According to Weltevrede et al. (2006)

Name	$P_1$ (s)	$P_{2(LPA)}$ (ms)	$P_{2(W)}$ (ms)	$P_{3(LPA)}$	$P_{3(W)}$
J0323+3944	3.03	112±12	152 <sup>+42</sup> <sub>-25</sub>	8.4±1.3	8.4±0.1
J0528+2200	3.75	200±10	-208 <sup>+20</sup> <sub>-90</sub> 520 <sup>+580</sup> <sub>-105</sub>	4.9±0.5	3.8±0.7 3.7±0.4
J0826+2637	0.53	150±25	80 <sup>+60</sup> <sub>-10</sub>	5.7±0.4	7±2
J1136+1551	1.19	400±70	430 <sup>+400</sup> <sub>-50</sub> 660 <sup>+180</sup> <sub>-300</sub>		3±1
J1239+2453	1.38	60±3	61 <sup>+4</sup> <sub>-9</sub> 77 <sup>+5</sup> <sub>-11</sub>	2.7±0.1	2.7±0.1
J1813+4013	0.93	170±15			
J1907+4002	1.24	65±4 250±50			
J1921+2153	1.34	33±1 100±3	13 <sup>+1</sup> <sub>-1</sub> 41±4	4.2±0.5	4.4±0.1
J2018+2839	0.56	93±8	-19 <sup>+2</sup> <sub>-12</sub> -108 <sup>+23</sup> <sub>-44</sub>	4.1±0.4	4±4
J2022+2854	0.34	26±3	24 <sup>+14</sup> <sub>-2</sub> -52 <sup>+5</sup> <sub>-14</sub>		2.3±0.1 2.5±0.2
J2113+2754	1.2	200±15	470 <sup>+60</sup> <sub>-50</sub>		4.4±0.1
J2157+4017	1.53	300±40	470 <sup>+370</sup> <sub>-45</sub>	4.5±0.7	3.1±0.8
J2305+3100	1.58	190±30	66 <sup>+14</sup> <sub>-1</sub>	2.2±0.4	2.1±0.1
J2317+2149	1.44	470±30			

**Table 2** Estimates of  $P_2$  and  $P_3$  for the Pulsars which were not included in Weltevrede et al. (2006).

Name	$P_1$ (s)	$P_2$ (LPA) (ms)	$P_3$ (LPA)
J0611+3016	1.41		2.5±0.2
J0613+3731	0.62	180±70	
J0928+3037	2.09	280±20	4.8±0.5
J1532+2745	1.12	39±2	4.6±0.5
J1635+2418	0.49	140±30	2.0±0.15
J1741+2758	1.36	270 <sup>+120</sup> <sub>-60</sub>	
J1758+3030	0.95	105±15	
J1912+2525	0.62	70±8	
J2055+2209	0.81	80±10	
J2139+2242	1.08	160±20	
J2207+4057	0.63	210±40	
J2227+3030	0.84	105±15	
J2234+2114	1.38	230±20	23.3±3.5

data are not in Weltevrede et al. (2006). Such a situation can indicate that additional investigations of these pulsars are necessary, or the nature of the modulations which we observe is related not only to period  $P_2$ . The values of  $P_3$  have been confirmed for eight of 11 pulsars from the list in Weltevrede et al. (2006), and in the three remaining sources we do not see significant harmonics of the satellites in their integrated power spectra (Table 1). The data for 13 pulsars, given in Table 2, are new and they give estimates of  $P_2$  for 12 sources and estimates of  $P_3$  for five pulsars, including pulsar J0928+3037 recently discovered by us (Tyul'bashev et al. 2016). The values for  $P_2$  are in the range 26–470 ms and the values of  $P_3$  lie in a range from 2 to 23.3  $P_1$  (Tables 1–2). All new estimates of both  $P_2$  and  $P_3$  need to be confirmed by other methods.

Thus, as a result of the analysis of integrated power spectra obtained by a summation of 500–600 daily spectra, some new features are discovered. It is shown that two of them, namely a modulation with periods from 3 to 40 for first harmonics reflect the period of the second class ( $P_2$ ), and the presence of harmonic satellites is verified by the period of the third class ( $P_3$ ). We find empirical relations (1–3) for the calculation of both periods. As a result of the analysis, measurements of these periods and a comparison with the data in Weltevrede et al. (2006), the value  $P_2$  is estimated for 26 pulsars, and for 15 sources it is made for the first time. The value  $P_3$  is estimated for 13 pulsars, among these, for five sources, they are given for the first time.

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