Search for Periodic Emission from Five Gamma-Ray Pulsars at the Frequency of 111 MHz

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Abstract—The search for pulsar (periodic) radiation of five gamma-ray pulsars was carried out using the summed power spectra and summed periodograms. No harmonics corresponding to the known periods of the pulsars were found. An upper estimate was obtained for the integral flux density of pulsars J0357+3205 (<0.5 mJy), J0554+3107 (<0.5 mJy), J1958+2846 (<0.5 mJy), J2021+4026 (<0.4 mJy), and J2055+2539 (<0.55 mJy).

Keywords: gamma-ray pulsar, radio emission

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1. INTRODUCTION

An estimate of 3000 pulsars have been discovered (https://www.atnf.csiro.au/research/pulsar/psrcat/) since the discovery of the first pulsar 74 years ago [1]. The overwhelming majority of these sources are found in the radio range. In 1970, a paper was published indicating the probable detection of pulsating gamma-ray emission in a young pulsar located in the Crab Nebula [2].

Until 2008, gamma rays were detected in pulsars that were originally found in other ranges. In 2009, the first papers with observations of gamma-ray source samples with the Fermi orbiting telescope appeared [3]. It turned out that many of the previously discovered gamma-ray sources are gamma-ray pulsars. The overwhelming majority of these pulsars have no radio emission. It is customary to use the term “radio quiet pulsars” for such pulsars. It is assumed that they have a thermal radiation mechanism, in contrast to radio pulsars, the radiation of which is associated with the motion of electrons in strong electric and magnetic fields.

For several gamma-ray pulsars, which were considered to be radio quiet, radiation was detected in the radio range at wavelengths from centimeters to decimeters [4–8]. In particular, in [8], the search for the periodic emission of the pulsar J0357+3205 was carried out in daily observations over an interval of 5 years, and the pulsar was discovered in some sessions only once. It is possible that the luminosity of gamma-ray pulsars in the radio range is very low, and the sensitivity of modern radio telescopes is insufficient for their regular detection.

In this paper, an attempt is made to detect weak periodic radio emission from several gamma-ray pulsars in observations with the Large Phased Array (LPA) radio telescope of the Lebedev Physics Institute (LPI) of Russian Academy of Sciences. Monitoring observations with the radio telescope have been going on around-the-clock for six years. In the direction of each LPA beam, approximately five days of observations were accumulated. To increase the sensitivity of observations, the summation of the power spectra and the summation of periodograms are used, and a new presentation of the visualization of the processed data is used to detect periodic radiation.

2. OBSERVATIONS AND PROCESSING PROGRAM

After the reconstruction of the LPA LPI, which ended in 2012, its effective area has increased by 2–3 times and is approximately equal to 45000–50000 square meters towards the zenith. The central observation frequency is 110.3 MHz, and the total observation bandwidth is 2.5 MHz. Several independent radio telescopes have been created on the basis of the antenna field, which consists of 16384 dipoles. One of them is used for round-the-clock monitoring observations. This radio telescope has 128 unguided beams that overlap in the meridian plane of declination from −9° to +55°. Until the end of 2020, observa-
tions were made in 96 spatial beams covering declination from $-9^\circ$ to $+42^\circ$. Since the beginning of 2021, 24 more spatial beams have been added in the test mode, and now monitoring observations are being carried out for declination up to $+52^\circ$.

The number of beams served by one recorder is related to its ability to digitize the input data stream. One recorder is used for 48 beams and the total input data rate is approximately 12 gigabits per second. The sampling rate formed by the recorder and the number of frequency channels are related to the physical capabilities of the RAM of an industrial computer used and the speed of writing information to the hard disk. In monitoring observations, the mode is used when the band is divided into 32 frequency channels with a bandwidth of 78 kHz, and the recording is carried out with a sampling rate of 12.5 ms. Even for observations of second pulsars, this mode is not optimal. In the meter wavelength range, for most of the known pulsar problems, it is preferable to have frequency channels with a bandwidth of 5–20 kHz and a sampling rate of 1–3 ms. However, in the non-optimal mode used, 35 terabytes of data are recorded per year in 96 beams. Optimally, it would need to record up to 6 petabytes per year, which exceeds the observatory’s data storage capacity.

More details about the reconstruction of the LPA LPI meridian radio telescope and about the monitoring scientific programs running on it can be found in [9, 10]. Additional details about the recorder can be found in [10, 11].

As is known, the sensitivity of observations with a radio telescope is determined by the temperature of the system, the effective area of the antenna, the receiving band, the sampling frequency, and the observation time. For the LPA LPI, the observation time in one session is determined by the transit time of the investigated source through the meridian and is about 3.5 min at the equator at half power. According to [10], the average sensitivity at the zenith for observations of second pulsars outside the galactic plane is 6–8 mJy, and in the galactic plane, 15–20 mJy. The best and worst sensitivity may differ from these values by about 1.5 times due to the fact that the coordinates of sources do not coincide with the coordinates of the beams. Therefore, the full flux is not observed in the beam, but only a part of it. There are also other corrections that consider the peculiarities of the antenna array of the LPA LPI.

The sensitivity can be increased by increasing the observation time. For example, if the period and derivative of the pulsar period are known with high accuracy, then the pulsar pulses observed on different days, months and years can be summed up. Unfortunately, although the recorders for monitoring observations are launched according to the atomic frequency standard, after starting the time is counted by a quartz oscillator, which gives a possible time error of about $\pm 25$ ms at a time interval of one hour. Attempts to implement the addition of pulsar pulses in phase at large time intervals remain unsuccessful so far.

In papers [12, 13] on the search for second pulsars at the LPA LPI, it was proposed to increase the sensitivity of observations due to the incoherent addition of the power spectra. Information about the pulse phase is lost in the power spectrum, but the location of the harmonics in the spectrum for a given pulsar is the same, regardless of the observation day. If we approach in a strict manner, then the period of the pulsar likely changes with time, but since the accuracy of the period determined from the power spectrum in a 3.5-minute record is no better than one in the third decimal place, then we will not feel changes in the period of the pulsar at intervals of a hundred years. Pulsar harmonics will always fall on the same point numbers in the power spectrum. By obtaining the power spectra for different observation days and adding them, it is possible to increase the signal-to-noise ratio (S/N) of the harmonics observed in the spectrum. The sensitivity should increase as the square root of the number of stacked spectra if the original noise was white, and the antenna gain remained unchanged throughout the observation interval. However, sensitivity may vary slightly from day to day due to different antenna physical conditions and weather conditions. Note also that not all interferencies can be removed during processing. For these reasons, the actual sensitivity grows less than expected. To calculate the estimate of the growth of real sensitivity in the summed power spectra, we obtain independent estimates of the magnitude of the initial noise and the increase in sensitivity for each direction in the sky (details in [13]).

As is known, the search for pulsars can also be carried out using periodograms. According to [14–16], the sensitivity in searching using periodograms can be higher than when searching using power spectra. Both methods of searching for periodic radiation are implemented in the program for processing monitoring data of the LPA LPI.

There are general standards for the search for new pulsars. In search programs, power spectra or periodograms are first built, while enumerating possible dispersion measures (DMs), harmonics are searched for that, the S/N level of which is greater than a given value. False sources are eliminated according to various criteria, and the remaining candidates are viewed visually. For visual viewing, pictures are created that show the resulting average profile, dynamic spectrum, dependence of peak flux density in SN units on DM. For the sources that have passed the visual check, additional observations are carried out, and, if possible, their period and the derivative of the period are specified.

Such a scheme for processing observations will work adequately if sources are observed, the flux den-
sity of which is such that they are visible in one observation session. As shown in [13], when searching for very weak pulsars, situations arise when harmonics with S/N > 7 are observed in the summed power spectra, including for pulsars discovered in observations with other telescopes, but there is not a single session when we can obtain the average profile of the pulsar.

A new program for processing and visualizing the processed data has been created to search for pulsars in which radiation is not detected in individual sessions. The right ascension and declination of pulsars according to the catalog for 2000 are used as input parameters. The program recalculates the coordinates for the given day and evaluates the quality of the noise track at the pulsar location. If the quality of the noise track is low, then this day does not participate in further work. If the quality of the observations is good, then a piece of the record with a length of 16384 points (approximately 204.8 s) is cut out and the power spectra are constructed by enumerating the DMs from 0 to 1000 pc/cm\(^3\). An additional enumeration is also performed, considering that the pulse width of the pulsar can be greater than one point of the original (raw) data. For this, addition is performed over 2, 4, and so on points in the raw data, and the power spectra are rebuilt. There are six such enumerations in total, and they make it possible to obtain the maximum SN ratio in the power spectrum for an assumed pulse width of 12.5 ms to 800 ms. For each tested dispersion measure and for each enumeration considering the pulse width, the corresponding power spectra are added for all observation days. In each summed power spectrum, the S/N of each point is determined and tables are created in which the harmonic amplitudes with S/N > 4 are stored. These tables are used for visualization when searching for new pulsars.

In the central window of the visualization program (Fig. 1), we can see a map, where the location of the circle on the abscissa axis reflects the pulsar period (P), and on the ordinate axis the observed measure of dispersion. The size of the circle reflects the S/N of the harmonic in the summed power spectrum. Obviously, the maximum S/N in the harmonic will be observed in the power spectrum, which was calculated after adding the frequency channels with the dispersion measure of the pulsar and averaging the initial data, which correspond to the width of the average pulsar profile. However, a strong pulsar will be visible both at DMs close to the true one, and on averages that do not coincide with the pulse width of the pulsar. Therefore, on the P/DM map, the pulsar should be observed in the form of vertical stripes, narrowing towards the edges and limited in height. The maximum size of the circle on this strip should be at the true dispersion measure of the pulsar. Smaller stripes can appear at multiples of harmonics corresponding to half a period, a third of a period, and so on.

The map generated by the data visualization software is interactive. When we click on the circle of interest, we can view the power spectrum corresponding to the selected circle, plot the dependence of SN on DM for the selected harmonic. Thus, the program allows us to see the pulsar on the P/DM map, estimate its dispersion measure, S/N of the harmonic and expected pulse width. Some additional details concerning the processing and visualization program can be found in the paper on the search for weak pulsars in the monitoring survey at the LPA LPI [17]. Analogos of the search program and visualization of the processed data are made for searching using periodograms. The routine for constructing periodograms is taken from [16] (https://github.com/v-morello/riptide).

Figure 1 presents an example of visualization when processing observations of the well-known pulsar J1638+4005 at an interval of 3 years for the summed power spectrum and at an interval of 5.5 years for the summed periodograms. The pulsar J1638+4005, which has P = 0.76772 s and DM = 33.4 ps/cm\(^3\) [18], was discovered in observations at the LPA LPI [12] in the summed power spectra and was noted in the original paper as a weak pulsar. The average profile of the pulsar presented in this paper, obtained in one observational session with a duration of 3.5 min, shows S/N = 6. In [18], the integral flux density of this pulsar is estimated from observations with LOFAR and with the 76-m Jodrell-Bank telescope: 128 MHz (S = 3.1 mJy), 167 MHz (S = 1.7 mJy), 334 MHz (S = 0.34 mJy), and 1532 MHz (S < 0.06 mJy). Based on the estimate of the spectral index (α = 2.3, S ~ ν\(^{-α}\)) given in this paper, one can estimate the expected integral flux density of this pulsar at the central frequency of the LPA LPI antenna (S\(_{10.7\text{ MHz}}\) = 5.7 mJy). The flux density of 5.7 mJy is very close to the limiting sensitivity of LPA in one observation session [10].

We can see in Fig. 1 that the pulsar J1638+4005 has 13 harmonics with S/N ≥ 6. All signals with SN ≥ 10 are represented by circles of the same size. Therefore, the width of the vertical segments changes insignificantly. The rightmost stripe corresponds to a period of 0.7695 s (OX axis), and the center of the stripe corresponds to DM = 33–34 ps/cm (OY axis). In the S/N/DM dependence for the first observed harmonic, the maximum falls on DM = 33–34 pc/cm. The period of the pulsar, determined from point 532 in the power spectrum, is 0.7695 s. It does not coincide with the catalog value of the period 0.7677 s. The period difference is associated with low frequency resolution in the power spectrum. We estimate the period accuracy as determined from the power spectrum as 0.001 s. When working with the visualization program, we can select any point on the power spectrum and see what period this point corresponds to, as well as the S/N of this point. If we add up the heights of all harmonics visible in the power spectrum, then the S/N of
sals than pulsars detected from power spectra. This is especially noticeable for pulsars, which have very narrow pulses in relation to the pulsar period. There is also a gain when using periodograms when searching for pulsars with large periods. It is known that low-frequency noise is observed in the power spectra, which is difficult to subtract. An example of such noise at the beginning of the recording is shown in Fig. 1c. The periodogram in Fig. 1d was obtained by summing up 5 years of observations (approximately 1800 observation sessions of 3.5 min each). The maxima marked by arrows in the periodogram correspond to the pulsar period $P = 0.7678$ s and multiple periods. Dim gray in the figure shows the characteristic triangular struc-
tures that appear for strong pulsars when using periodograms. The peak marked in the figure has \( S/N = 183 \). Proceeding from the fact that the pulsar J1638+4005 was detected earlier with \( S/N = 6 \) [12], and its expected integral flux density is 5.7 mJy (see above in this section), we can recalculate the minimum detectable signal in the summed periodogram and give an experimental estimate of the integral flux density of extremely weak pulsars 

\[
S = 5.7/(183/6) = 0.19 \text{ mJy}.
\]

This estimate is close to the theoretical estimate of the flux density of extremely weak for detection pulsars observed at the zenith exactly in the center of the beam, 

\[
S = 5/(1800)^{1/2} = 0.12 \text{ mJy}.
\]

Considering the typical loss of sensitivity 1.5–2 times of theoretical values due to weather conditions, lack of observations due to routine maintenance on the antenna, corrections for the features of the antenna array, which has a fixed direction of beams in the sky, and other reasons [13], the obtained estimates are good and consistent. Thus, the program for searching for periodic signals using the summed power spectra and summed periodograms can with a high degree of reliability detect pulsars for which it is impossible to construct an average profile from observations in one session at the LPA LPI.

3. RESULTS AND DISCUSSION

The search for regular radiation was carried out for five gamma-ray pulsars that entered the monitoring area. Pulsars J0357+3205, J0554+3107, J1958+2846, J2021+4026, and J2055+2539 were discovered in observations with the Fermi satellite [3, 20, 21]. Radio emission was detected only from the pulsar J0357+3205 in the FAST/Arecibo observations [7] and at the LPA LPI [8]. The FAST/Arecibo observations are published in a presentation at the conference, and the details of periodic signal detection are practically unavailable. In the search for radio emission at the LPA LPI, a pulsar was detected once in 1700 observation sessions with \( S/N > 7 \). The flux density in FAST/Arecibo observations is 0.04 mJy at a frequency of 1250 MHz, and at a frequency of 110.3 MHz it is 14 mJy. The search for periodic radiation in the monitoring data of the LPA LPI was carried out in the summed power spectra and in the summed periodograms in observations over an interval of 5.5 years. Densification of points, that is, points located along a line at known pulsar periods and related to close DMs, were not detected for any pulsar. On search maps, in contrast to the one shown in Fig. 1a, signals with \( S/N > 4 \) are shown. Even if the studied gamma-ray pulsars had harmonics with \( S/N = 4–5 \), then small vertical segments should have been observed. The absence of harmonics corresponding to the pulsar periods makes it possible to obtain an upper estimate of the flux density under the assumption that the pulsar has a constant, albeit very weak, radiation in the radio-wave range. Data processing shows that for none of the five studied pulsars there are any signs of periodic signals with \( S/N > 4 \).

Since we know the exact coordinates of the pulsars, we can calculate their position with respect to the stationary beams of the LPA and make corrections that allow us to obtain upper estimates of the flux density taking into account the peculiarities of the antenna array.

Let us consider the processing of observations using the example of the pulsar J0357+3205. In the gamma-ray band, the half-power main component occupies a quarter of the period [3], i.e., about 100 ms. In the radio range at a frequency of 1250 MHz, the profile is two-component [7]. Based on the profile in the figure, one of the components is wide, and its half-width \( (W_e) \) is approximately 90 ms. The second component is narrow, has a comparable height, and its half-width is approximately 35 ms. The distance between the components is 165 ms. The expected distance to the pulsar is 270–900 ps [19]. According to FAST observations \( DM = 47 \text{ pc/cm}^3 \). In LPA observations, only one narrow component with \( DM = 46–48 \text{ pc/cm}^3 \) is visible, with \( S/N = 10 \) [8]. In the middle profile in the gamma-ray band, the narrow component visible in the radio range is also guessed, but its height is significantly less than that of the wide component.

The expected increase in sensitivity in summed power spectra and in summed periodograms is proportional to the square root of the number of observation sessions. In 5.5 years, the pulsar should be observed almost 2000 times. However, as mentioned in the previous paragraph, some observations disappear due to strong interference, there are days when there were no observations due to technical maintenance of the antenna. On the remaining days, the background noise may change due to weather conditions. To obtain an estimate of the real \( S/N \) growth depending on the number of observation sessions, the noise variance was estimated every day over the time interval corresponding to the passage of the pulsar through the meridian. All noise variances were lined up in ascending order and normalized to the minimum variance. Thus, the minimum variance turned out to be equal to one, and the total variance is equal to the square root of the sum of the squares of individual variances [13]. The change in the \( S/N \) ratio depends on how many individual power spectra were added and what normalized noise variances they had. 1334 sessions were used to add the individual power spectra. The theoretical value of the growth of the \( S/N \) should be \( 1334^{1/2} = 36.5 \) times, the real growth of the \( S/N \) from the experiment is 32.1 times.

There are no prominent details at the location of the harmonic of J0357+3205. The absence of a signal in the summed power spectrum allows us to give an upper limit estimate of the integral flux density of the
pulsar. Since the LPA LPI is an antenna array with beams fixed in declination, formed using the Butler matrix, a number of corrections must be made to estimate the flux density, considering the antenna characteristics. These corrections are due to the fact that the coordinate of the pulsar does not coincide with the location of the beams, the pulsar is not observed at the zenith, and therefore the effective antenna area is less than 45000 square meters, each Butler matrix forms 8 beams, and they have a common envelope. For the pulsar J0357+3205, these three corrections give a factor of 0.3. That is, for a given pulsar, only a third of the energy coming from the sky is observed on the LPA antenna. Assuming that the minimum noise variance determines “ideal” observations and, based on an estimate of the sensitivity of 5 mJy when observing pulsars outside the galactic plane, towards the zenith [10], we can give an upper estimate of the pulsar flux density: \( S_{\text{int}} < 5/(32.1 \times 0.3) < 0.5 \text{ mJy} \). The obtained estimate indicates that the integral flux density over the long-term observation interval is less than 0.5 mJy, but cannot guarantee that there were no periods of short flare activity during this observation interval.

For the remaining four pulsars, the same analysis was done as for J0357+3205. For all pulsars, no harmonics were found at known periods either. The distances to the pulsars were estimated indirectly by different authors. Usually, the authors proceeded from the assumption that the pulsars are young and should be located near the supernova remnants that gave rise to the pulsars. Estimated distances to the remaining gamma-ray pulsars: 3.5 kpc (J0554+3107; [21]), 9.2 kpc (J1958+2846; [22]), 2 kpc (J0201+4026; [23]), and 0.6 kpc (J2055+2539; [24]). Unlike the pulsar J0357+3205, the pulsars J0554+3107, J1958+2846, J0201+4026, and J2055+2539 lie in the galactic plane at galactic latitudes not exceeding 10°. Therefore, in obtaining the upper estimate of the flux density, we assumed that in the direction toward the zenith, the minimum detectable integral flux density in a single observation session for these four pulsars is not 5, but 10 mJy [10].

Having done the same procedures for the remaining pulsars as for J0358+3205, we obtained upper limits for the integral flux density for all sources in the sample. The results are shown in Table 1. The first column of this table contains the name of the pulsar in J2000 notation, the second column presents its period, the third column indicates the expected gain of the S/N in the accumulated power spectra and periodograms, and the fourth column shows multiplied corrections taking into account the signal loss. The fifth column gives the upper estimate of the integral flux density of the pulsar at a frequency 110.3 MHz under the assumption that the broadening of the pulse within the frequency channel due to the dispersion measure is insignificant.

The absence of harmonics in the averaged power spectra and in periodograms can be due to several reasons. First, the level of the integral flux density can be lower than the obtained upper estimate. Second, when obtaining the upper estimate of the flux density, we considered the factors associated with the peculiarities of observations on a diffraction grating with a fixed position of the beams in the sky, but further the sensitivity was estimated using the standard formula of the radiometric gain. If there are some additional unaccounted factors that decrease the sensitivity in the search for new pulsars, then the upper estimate of the flux density may increase. Third, the obtained estimates of the flux density were made under the assumption that the dispersion measure does not introduce additional broadening of the pulse within the frequency channel. Based on the width of the frequency channel, it is easy to calculate that the intra-channel broadening of the pulse at DM = 100 pc/cm³ degrades by half the estimates given by us in Table 1. Fourth, we assumed that the pulse duration was <0.1 of the period. If the pulse width in the radio range is equal to half the period, then the upper estimates of the flux density in Table 1 will change by a factor of two and amount to approximately 1 mJy for all five pulsars. Fifth, if the radiation of gamma-ray pulsars has a flare pattern in the radio range, or they have a strong variability associated with other reasons, then a situation may arise when the integrated flux density determined over the entire observation interval is less than 0.5 mJy, and at certain time intervals the pulsar is still visible.

### Table 1. Upper limit estimates of the integral flux density from gamma-ray pulsars

| Name              | \( P \) (s) | \( S/N \) growth | Correction | \( S_{\text{int}} \) (mJy) |
|-------------------|------------|-------------------|------------|--------------------------|
| J0357+3205        | 0.44410    | 32.1              | 0.30       | <0.5                     |
| J0554+3107        | 0.46496    | 27.5              | 0.70       | <0.5                     |
| J1958+2846        | 0.29040    | 25.6              | 0.80       | <0.5                     |
| J0201+4026        | 0.26532    | 34.3              | 0.70       | <0.4                     |
| J2055+2539        | 0.31956    | 30.4              | 0.60       | <0.55                    |

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