PROCEEDINGS OF SCIENCE

Pushchino Multibeam Pulsar Search: First Results

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Since the discovery of pulsars, dozens of surveys have already been conducted to search for them. In the course of the surveys, sky areas from thousands to tens of thousands of square degrees have been explored. Despite repeating observations of the same areas, new pulsars are constantly being discovered. We present the Pushchino Multibeam Pulsar Search (PUMPS), having a sensitivity that is an order of magnitude higher than the sensitivity of all previously made pulsar search surveys. In PUMPS, daily round-the-clock observations are carried out of the area located at declinations $-9^o < \delta < +42^o$. The survey is carried out with the 96 beams of the Pushchino Large Phased Array (LPA) at a frequency of 111 MHz. During the observation period of August 2014 – August 2022, the survey was repeated approximately 3 000 times. The expected sensitivity in the survey reaches up to 0.1 mJy. The paper considers some problems that can be solved when processing the received data.

The Multifaceted Universe: Theory and Observations - 2022 (MUTO2022)
23-27 May 2022
SAO RAS, Nizhny Arkhyz, Russia

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PoS(MUTO2022)043

1. Introduction

The pulsar search surveys have been conducted since their discovery in 1967 [1] and have already led to the discovery of more than 3 300 pulsars[1] [2]. The estimate of the expected number of radio pulsars is 30 000 objects with a luminosity higher than 0.1 mJy per kpc^2 [3]. The estimate of the pulsars available for observations on the Square Kilometer Array (SKA) radio telescope under construction is 20 000 pulsars [4]. That is, about 10–15% of the radio pulsars available for observation have been discovered so far.

In [5], it was shown that the number of new major discoveries in pulsar searches increases as a natural logarithm of the number of discovered pulsars. For each subsequent discovery, it is necessary to discover many times more pulsars than there were known at the time of the previous discovery. A natural question arises about the point of conducting new surveys. Having more and more time and financial expenditures for conducting the observations and processing them, the experimental scientist has less and less chance for a major discovery.

Surveys conducted with high sensitivity make it possible not only to discover new types of pulsars [6, 7] but also to study pulsar populations in detail to explore the interstellar medium both in the Galactic plane and in the halo. Therefore, if expenditures of time and other resources are acceptable, the surveys should be carried out, because they improve our knowledge about the evolution of pulsars and their properties.

The surveys are conducted on the sky area accessible to the telescope, i.e., on about half of the celestial sphere. Taking into account the small, as a rule, dimension of the antenna beam pattern and the number of simultaneously available beams, the survey is an extremely long and, taking into account the cost of an hour of observations, also extremely expensive task for almost all large telescopes. However, for the Large Phased Array (LPA) radio telescope located in the Pushchino Radio Astronomy Observatory (PRAO), a survey of the entire sky is a daily routine task. In this paper, we consider the PUshchino Multibeams Pulsar Search (PUMPS) and some of the problems that can be solved in the course of this survey.

2. Survey and tasks

The survey on the LPA transit radio telescope (an observation frequency of 111 MHz) has been carried out daily around the clock since August 2014 with 96 beams, and since January 2022 with 128 beams aligned in the meridian plane and covering declinations $-9^\circ < \delta < +55^\circ$. The data are recorded in a 2.5 MHz band in 32 frequency channels 78-kHz wide with a point reading time of 12.5 ms. The amount of data recorded per year is almost 45 terabytes. The work on the pulsar search started in 2015, and to date 42 pulsars and 46 rotating radio transients (RRATs) have been discovered (see the website[2] and references thereon). Since we have not had a good computation server, processing of all the data was impossible. We expect that the new server to be purchased, which has a terabyte of RAM and 128 full-fledged cores, starts operation this year and allows the processing in a reasonable time the accumulated data with a volume of about 300 terabytes.

[1] https://www.atnf.csiro.au/research/pulsar/psrcat/
[2] https://bsa-analytics.prao.ru/en/

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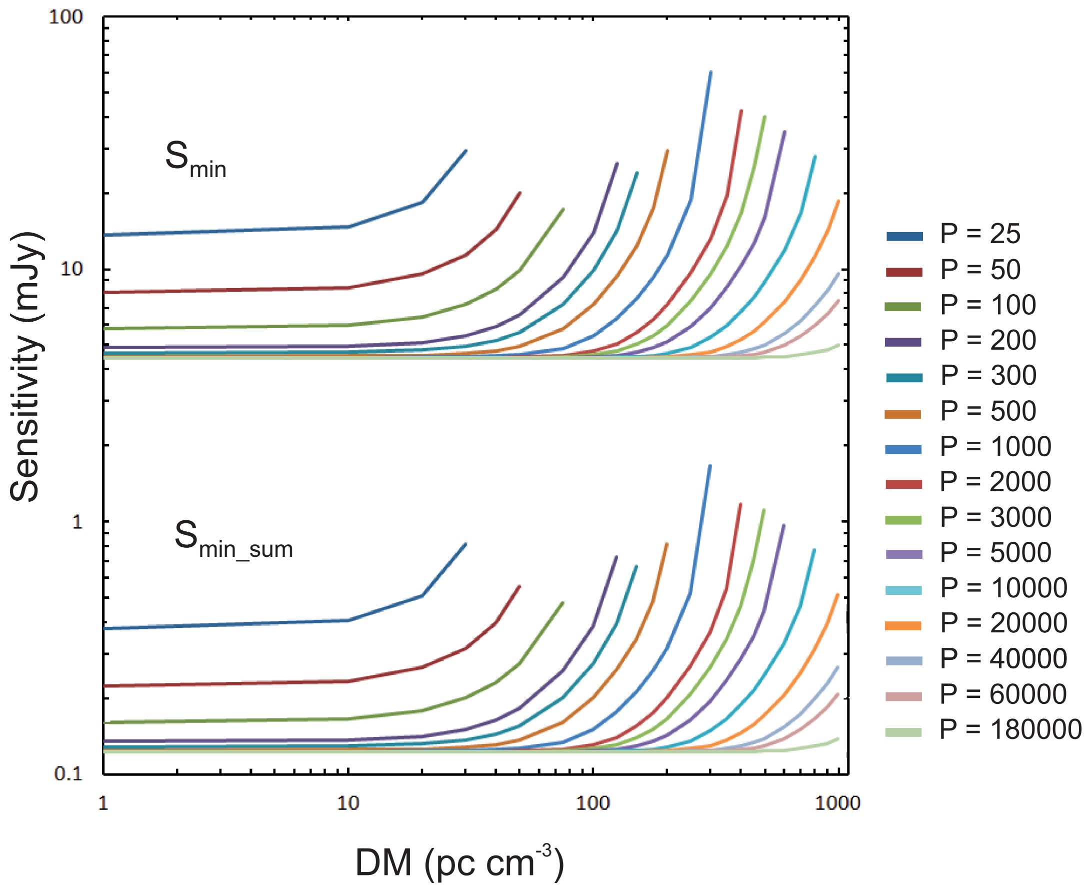

Figure 1: The sensitivity in searching for pulsars (vertical axis) depending on DM (horizontal axis) for different periods of pulsars. The upper and lower parts of the figure show the sensitivities S_{min} and $S_{min-sum}$ respectively. The colors on the right indicate the periods in ms displayed by the curves.

Based on the PUMPS data, a search for classical pulsars and transients with periods of several seconds (hereafter second-period pulsars) is carried out. As was shown in [8], the sensitivity of the LPA in one 3.5-minute duration observing session, when the source passes through the meridian at half the power of the beam pattern, is inferior to the surveys conducted on the aperture synthesis Low Frequency Array (LOFAR) system and on the Five-hundred-meter Aperture Spherical Telescope (FAST).

The accumulation of the periodical signal by summing up power spectra and periodograms allows us to improve the sensitivity by tens of times with the dispersion measures $DM < 100$ pc/cm^3. To search for transients, the instantaneous sensitivity is primarily important, and this sensitivity is provided by a large effective area of the LPA equal to 45 000 sq.m.

In [8], we considered the sensitivity in searching for second-period pulsars and limited ourselves to the PUMPS sensitivity estimates $DM \leq 200$ pc/cm^3. However, the discovery of the pulsar with a period of 77 seconds and a pulse half-width of 300 ms [7] allows us to seriously consider the search for pulsars at significantly higher DM. For such DM, the main factor reducing the sensitivity of the search is the interstellar scattering (τ_s). In the experimental dependencies $\tau_s(DM)$, it can be seen that for the same DM the scattering can differ by three orders of magnitude [9–12]. So, in observations at a frequency 111 MHz, the scattering can be from ten seconds to ten minutes. We have recalculated the sensitivity curves up to $DM = 1\,000$ pc/cm^3. The following formula was used for estimating the scattering [9]:

$$\log(\tau_s) = 3.59 + 0.129\log(DM) + 1.02\log(DM)^2 - 4.4log(f), \qquad (1)$$

where τ_s is obtained in microseconds, DM is expressed in pc/cm^3, f is the central frequency of observations in GHz. Since the estimates of τ_s may be significantly higher than those obtained from formula 1, this may lead to a deterioration in the sensitivity assessment both in single observation sessions (S_{min}) and when summing up power spectra and periodograms ($S_{min-sum}$).

Fig. 1 shows sensitivity estimates for pulsars with different periods after the evaluation of τ_s using formula 1. The sensitivities in search for pulsars with different periods and dispersion measures shown in the figure differ slightly from the sensitivities shown in Fig. 4 of [8]. These differences are related to the fact that in [8] the scattering was estimated according to the empirical formula from [11].

The sensitivity in PUMPS, equal to 0.2–0.3 mJy, is about 16 times better than the sensitivity of 3–4 mJy in the LOTAAS survey made on LOFAR [13], when recalculated into a frequency of 111 MHz [8]. This means that, all other things being equal, 4 times more distant pulsars can be detected on the LPA than on LOFAR. In addition, there is, in principle, a possibility to find pulsars with long (> 10–20 s) periods at high DM. Since the luminosity decreases in proportion to the square of the distance and the volume increases in proportion to the cube of the distance, the number of pulsars available in the survey can grow up to 64 times. There are 73 pulsars discovered in the LOTAAS survey, and the possible number of new pulsars in the PUMPS survey may reach $64 \times 73 \approx 4\,500$. This fantastic assessment is most likely very far from reality. The sensitivities indicated in Fig. 1 are achieved only for pulsars that do not have pulse gaps and with very stable (not variable) radiation. Let us note, however, that when we conduct the search, the sensitivity is several times lower than expected with the accumulation of 8 years of observations (see the website,[3] references thereon, and [8]); for the same areas in the sky, we detect **all** pulsars discovered on LOFAR and almost the same number of new pulsars in these areas that were not detected in the LOTAAS survey (see Fig. 6 in [8]). Our conservative scenario is the discovery of 200–300 new pulsars in PUMPS, the optimistic scenario is 1 000–1 500 new pulsars.

The sensitivity in the search for pulsed radiation of transients for the LPA radio telescope is fixed because we cannot change neither the area of the antenna nor the temperature of the system nor the band. However, for a year of observations, taking into account the 3.5-minute passage through the meridian at half power, approximately 20 hours of recording are accumulated for each point in the sky. The survey started in August 2014 and is planned at least until December 2024. This means the accumulation of approximately 8.5 days of data for each point entering the observation area. In [15, 16] the existence of RRATs is shown, between the pulses of which 10 or more hours can pass. To detect and study such transients, it is necessary to conduct very long-term observations, which naturally appear during the monitoring.

The field of view of the LPA with 128 antenna beams is approximately 50 sq.deg. The field of view estimates of other large telescopes used for the RRAT detection are: for 64-meter-mirror

[3] https://bsa-analytics.prao.ru/en/

Parkes (Australia)—0.7 sq.deg. with 13 beams at a frequency of 1.4 GHz; for 100-meter-mirror Green-Bank (USA)—0.35 sq.deg. with one beam at a frequency of 350 MHz; for 300-meter-mirror Arecibo (USA)—1 sq.deg. with 7 beams at a frequency of 327 MHz; for 500-meter-mirror FAST (China)—0.16 sq.deg. with 19 beams at a frequency of 1.2 GHz. The instant sensitivity for FAST [14] after recalculation of the frequency 1.2 GHz into the frequency 111 MHz with an assumed spectral index 1.7 ($S \sim \nu^{-\alpha}$) exceeds the sensitivity of the LPA by about an order of magnitude. However, if we talk about RRATs, for which hours can pass between the appearance of successive pulses, the second main factor for searching, after the instantaneous sensitivity, becomes the time of observations at one point on the sky. If the average time between RRAT pulses is one hour, then FAST will need to view half of the sky once per hour: [20 000 sq.deg. (half of the celestial sphere) / 0.7 sq.deg. (FAST field of view)] × 1 hour = 28 570 hours, or 3.3 years, of round-the-clock observations. Due to the FAST availability, even for a single examination of the sky the task looks hardly realizable.

Thus, for the search both for second-period pulsars and RRATs, the LPA radio telescope turned out to be surprisingly suitable despite all its obvious disadvantages: observations in one linear polarization (entire classes of scientific problems fall out, and a loss of sensitivity in $2^{1/2}$ times appears), a narrow full band (leads to the low accuracy of DM estimation and the deterioration of sensitivity obtained on modern broadband recorders), the lack of right ascension diagram control (leads to the low accuracy in determining the pulsar period at an interval of 3.5 minutes, there are problems in obtaining timing, it is impossible or very difficult to investigate weak sources), the too large size of the LPA beam $0.^{\circ}5 \times 1^{\circ}$ (leads to the low coordinate accuracy of detected objects).

Despite the mentioned disadvantages of the instrument, the data obtained at the LPA can be used to research many scientific problems. We list some of the planned PUMPS projects without going into details of their realization. The search projects: search for pulsars with periods from 25 ms up to minutes, search for RRATs and Fast Radio Bursts (FRBs), search for pulsars in nearby galaxies, search for pulsars with small DM down to 0 pc/cm^3, search for pulsars with sporadic radiation. Research of the interplanetary, interstellar, intergalactic environments: pulsar variability induced by scintillations (the diffraction and refraction of radio emission in different media), pulse scattering of pulsars and FRBs, Faraday rotation. Research of pulsed and periodic radiation sources: the nature of RRATs and FRBs, statistics of pulsars with inter-pulses, inter-pulse radiation of pulsars, intermittent pulsars, intrinsic variability, targeted search for gamma, X-ray, and other radio-quiet pulsars, spatial distribution of pulsars in the Galaxy as a whole and for different samples, pulse energy distribution at a frequency of 111 MHz, timing, and others.

Let us look at three examples of using the monitoring data.

– There are opposite hypotheses about the evolution of the pulsar's "magnetic axis" relative to its axis of rotation. There are hypotheses according to which, over time, the directions of the pulsar's "magnetic axis" and its axis of rotation become perpendicular to each other (orthogonal rotator), other hypotheses suggest that the directions of the axes become coincide with time (coaxial rotator) (see [17] and references therein). For the orthogonal rotator the pulse takes the smallest possible fraction of the period, for coaxial rotators, on the contrary, the pulse takes the maximum possible fraction of the period. Pulsars with long periods are old pulsars (see, for example, the handbook [18]). Their evolution took longer time compared to

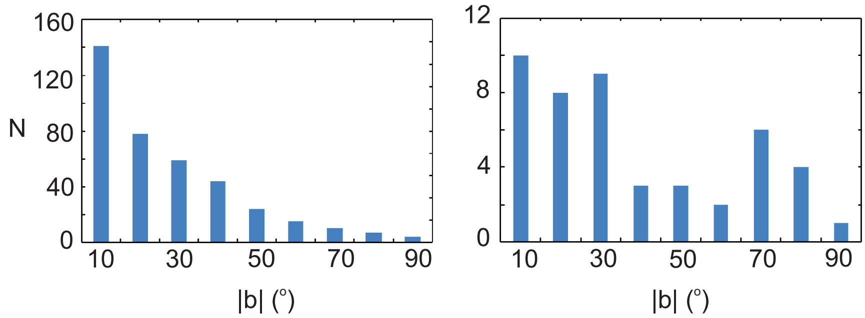

Figure 2: The histograms show the dependence of the observed number of pulsars on the galactic latitude. The left part of the figure shows the dependence for the second-period pulsars from ATNF with $P > 0.4$ s, $DM < 100$ pc/cm^3, $-9^\circ < \delta < +55^\circ$. The right part shows the dependence for the RRATs detected in PUMPS. The vertical axis shows the number of pulsars in the bins of the histogram, the horizontal axis is the galactic latitude. The size of the histogram bin is 10°. For negative latitudes, their modulus was used.

ordinary second-period pulsars. Therefore, a simple comparison of the relative pulse duration (duty cycles), i.e., the fraction of the period occupied by the pulse for ordinary second-period pulsars and for pulsars with extra-long periods (> 10–20 s), which are going to be discovered in the survey, should give an answer to the question whether radio pulsars become coaxial or orthogonal rotators by the end of their life in the active phase.

– Since pulsars form during supernova explosions and the exploded stars are in the plane of the Galaxy, pulsars at birth should be located in the Galaxy plane as well. As a result of the explosion, pulsars can acquire a velocity component perpendicular to the plane of the Galaxy and go into the halo. Pulsar lifetime in the active phase (as a radio pulsar) can be from millions to tens of millions of years, and the pulsar can move away from the plane of the Galaxy by some distance. However, the farther away from the Galactic plane, the fewer pulsars should be detected. Fig. 2 presents histograms showing the number of pulsars and RRATs at different galactic latitudes (at different elevations above the plane of the Galaxy). It is obvious that the distributions for the second-period pulsars with small DM located in the same area where all Pushchino RRATs were detected[4] and the distribution for Pushchino RRATs are different in appearance. We do not discuss this difference, which can be explained by a number of hypotheses from insufficient RRAT statistics and selection effects to the discovery of relic pulsars inherited from the previous Universe [19]. We are only presenting here one of the problems associated with the strange RRAT distribution over Galactic latitudes.

– Daily observations allow us to obtain average profiles for hundreds of pulsars. The peak or integral flux density estimated from the average profile allows us to construct the dependence of the observed flux density estimate on time. The observed variability may be related to scintillations on interstellar plasma. If the variability cannot be explained by the interstellar medium, it is related to internal factors. Fig. 3 shows the "light curve" of the pulsar J0323+3944 (B0320+39). The figure shows variations in the flux density over time. We do

[4]https://bsa-analytics.prao.ru/en/transients/rrat/

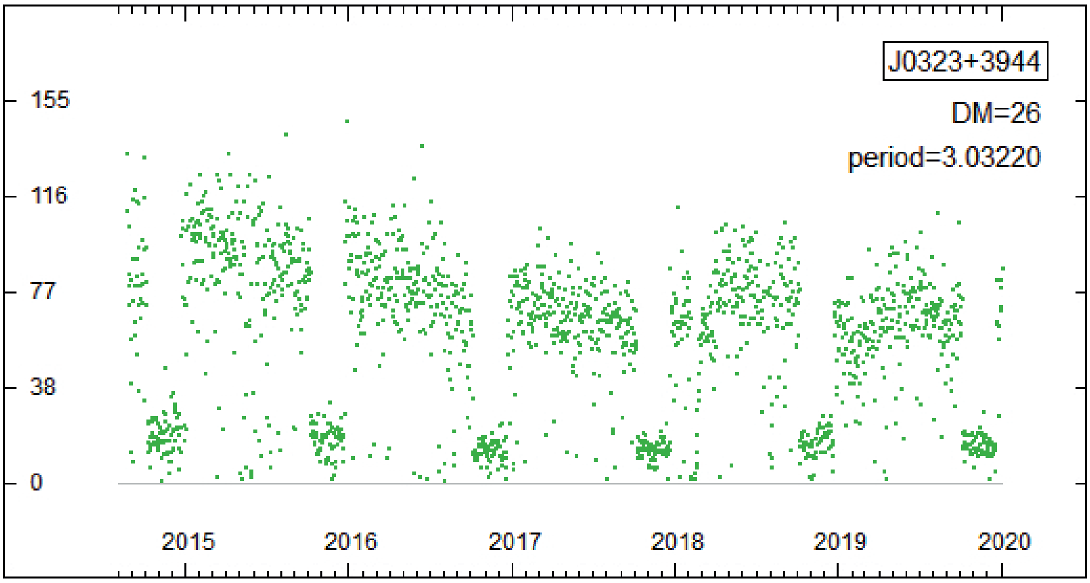

Figure 3: The estimates of the average profile height for J0323+3944 (B0320+39) depending on time. Each point is an estimate for one day. The vertical axis shows the S/N ratio, on the horizontal axis the date of observations is shown.

not investigate in this paper the causes of the apparent variability of J0323+3944 but only show that the problem of studying the variability can be solved using the PUMPS data.

In the present paper there are no solutions of the problems discussed above in the examples, this is a matter of the future. We only show the fundamental possibility of performing various tasks based on the data received in PUMPS.

3. Conclusion

Up to date, 88 pulsars have been discovered in the PUMPS survey. Having a sensitivity an order of magnitude higher than in the surveys presently conducted, we can expect the detection of more than 1 000 new pulsars. The main thing, in our opinion, is that with the radical increase in sensitivity, we begin to exploit the area that is called the "unknown unknowns" in [20]. When working in this area, there is no guarantee that major discoveries are going to be made, however, as we believe, this kind of work is the real academic science.

Acknowledgments

The study was carried out at the expense of Russian Science Foundation grant 22-12-00236, https://rscf.ru/project/22-12-00236/.

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