Revisiting the Pushchino RRAT search using a neural network

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ABSTRACT

The search for rotating radio transients (RRAT) at declinations from $-9^\circ$ to $+42^\circ$ was carried out based on the semi-annual monitoring data obtained on the Large Phased Array (LPA) radio telescope at a frequency of 111 MHz. A neural network was used to search for candidates. Four new RRATs were detected; they have dispersion measures of 5–16 pc cm$^{-3}$. A comparison with an earlier RRAT search that was conducted using the same data shows that the neural network reduced the amount of interference by 80 times. It is now down to 1.3% of the initial amount of interference. The loss of real pulsar pulses does not exceed 6% of their total number.

Key words. stars: neutron – pulsars: general

1. Introduction

Rotating radio transients (RRAT) are pulsars with sporadic radiation. They were discovered 15 years ago (McLaughlin et al. 2005). The average time intervals between the emitted pulses start from minutes and can reach up to many hours (McLaughlin et al. 2006; Logvinenko et al. 2020). Despite the actively ongoing search for new pulsars, including the search for RRATs (Deneva et al. 2016; Tyul’bashev et al. 2018a; Sanidas et al. 2019; Han et al. 2021; Good et al. 2021), as well as re-processing of archived data (Keane et al. 2010, 2011; Burke-Spolaor & Bâiles 2010; Karako-Argaman et al. 2015), in the Australia Telescope National Facility (ATNF) catalogue\textsuperscript{1} (Manchester et al. 2005) as of November 2021, there are only 109 RRATs.

There is no unambiguous understanding so far what an RRAT is, nor is there consensus about the reasons for the rare appearance of its impulses. There are a number of phenomenological hypotheses about the nature of RRATs. The four simplest hypotheses suggest that RRATs are ordinary pulsars (Weltevrede et al. 2006; Zhang et al. 2007; Wang et al. 2007; Brylyakova & Tyul’basheva 2021). These hypotheses are based on the properties of the detected pulses: the distribution of pulses by energy, frequency of pulses occurrence, the observed flux density, and other objective indicators. For example, RRATs can be ordinary pulsars with long tails of pulse energy distribution (Weltevrede et al. 2006), or RRATs can be pulsars with very long nullings (Zhang et al. 2007), RRATs are pulsars with an extreme case of switching modes (Wang et al. 2007), or RRATs may be pulsars with giant pulses (Brylyakova & Tyul’basheva 2021; Tyul’basheva et al. 2021a). Burke-Spolaor & Bâiles (2010) reported the assumption that there is some type of “uncompromising” version of the RRAT, but not a single example of such a RRAT was given.

The RRAT search is challenging. The field of view of full-rotation or stationary spherical or parabolic mirrors is small, and therefore, little time is allocated to viewing one direction on the sky. For example, in surveys conducted on the radio telescopes (RT) RT-64 (Parks), RT-100 (Effelsberg and Green-Bank), RT-300 (Arecibo), RT-500 (Five-hundred-meter Aperture Spherical radio Telescope – FAST) (Lorimer et al. 2006; Deneva et al. 2009; Barr et al. 2013; Boyles et al. 2013; Han et al. 2021), the typical observation session time for the selected direction is one minute or several minutes, and therefore transients whose intervals between successive pulses are much longer than a few minutes will be skipped. The sensitivity of these radio telescopes is high, since in the decimeter wavelength range (typically 327–1400 MHz), where the search is carried out, the background temperature of the Galaxy is low, and the frequency bands used for observations are wide. Therefore, pulses similar to those of ordinary strong pulsars are recorded with high confidence.

Separately, we mention the Canadian Hydrogen Intensity Mapping Experiment (CHIME). This radio telescope operates in the decimeter range and has detected pulsars and RRATs\textsuperscript{2} (Good et al. 2021). They are a by-product of searches for fast radio bursts (FRBs). However, CHIME wide field of view, the effective area, which is comparable to the area of hundred-meter mirrors, and the wide reception band suggest its likely high efficiency in organising a targeted search for RRAT pulsars.

Antenna arrays of meter wavelength range that are used to search for pulsars, for example, the Large phased Array (LPA; 16 384 dipoles Tyul’basheva et al. 2016, 2018b) and the LOw Frequency ARray (LOFAR; central core of 4096 dipoles Sanidas et al. 2019), can have a field of view of up to several dozen square degrees. RRAT search surveys on these telescopes

\textsuperscript{1} https://www.atnf.csiro.au/people/pulsar/psrcat/

\textsuperscript{2} https://www.chime-frb.ca/galactic
should be more time-efficient than on spherical or parabolic mirrors. However, when searching for RRAT, the main parameter is the instantaneous sensitivity of the antenna, and this is determined primarily by the effective area and the Galaxy background temperature. Unfortunately, the Galaxy background temperature is high in the meter wavelength range, and therefore the listed arrays can be real competitors of conventional mirrors operating in the decimeter wavelength range, either due to the large effective area (LOFAR antenna) or due to the wide reception band (PARKS). When the long time intervals between successive pulses are taken into account, dozens of observation hours of each point in the sky are needed in a search for RRAT. It is not surprising that about half of RRATs were found during the reprocessing of archived data and not during the targeted search. For example, when Green-Bank Telescope (GBT) data were reprocessed, 21 RRATs were found (Karaka-Argaman et al. 2015), and when Parks telescope data were reprocessed, 28 RRATs were found (McLaughlin et al. 2006; Keane et al. 2010; Burke-Spolaor & Bailes 2010). In addition to the longer time intervals that are required in a search for RRATs, search algorithms that guarantee a high reliability of detecting new objects are also very important. In the work of searching for RRATs using 48 LPA beams covering declinations \(21^\circ < \delta < +42^\circ\), and processing one month of around-the-clock monitoring observations, 107 candidates were thus found Tyul’bashev et al. (2018b). As noted in this paper, different digital filters reduced the number of candidates to 105, and subsequent visual inspection allowed the selection of new RRATs. When searching for RRAT in monitoring data for an interval of six months, the number of candidates increased up to \(6 \times 10^5\), and when additional digital filters were involved, it decreased to \(3 \times 10^5\), which were confirmed visually (Tyul’bashev et al. 2018a). Currently, the daily monitoring survey has been going on for 7.5 years and, therefore, the expected number of candidates being tested may increase up to \(5 \times 10^6\). It is not realistic to visually check this number of candidates. In this paper, we consider the possibility of using a recurrent neural network (RNN) to identify reliable candidates and filter out false sources.

2. Using a neural network to select sources

Tyul’bashev et al. (2018b) reported that the initial search for dispersed pulses was carried out in a standard way: (a) dispersion measures (DM) were sorted out from 3 to 100 pc cm\(^{-3}\); (b) frequency channels were added up for each sorted out DM, and the baselines were subtracted; (c) the standard deviations of noise \((\sigma_n)\) were estimated; and (d) the points of the array obtained from different DMs were checked sequentially. If for some point the signal-to-noise ratio \(S/N = A/\sigma_n\), where \(A\) is the signal amplitude) was higher than five on this DM, the picture of the dynamic spectrum and the added-up profile was memorized; (e) during visual inspection, interferences were eliminated, and candidates for RRAT were additionally checked if at least one pulse having \(S/N \geq 7\) was detected.

In the processing method used, strong pulses are recorded at different DM as long as the \(S/N\) of the assemblage profile remains higher than the set level. With DM close to actual, the profile amplitude will be higher, and the profile width will be less. The higher the observed \(S/N\) for the pulse, the more frequently it will be detected on different DMs, and the more pictures of the same pulse will be memorized.

When viewing one image of the dynamic spectrum per one second, the full viewing time of the semi-annual processing of observations on the RRAT search \((6 \times 10^5\) images) will take 600 thousand seconds or, approximately, one working month. In practice, the initial viewing of images was done quickly. The processing program can sequentially display all dynamic spectra for a given direction on the sky in ascending order of DM, or for a given sidereal time in an interval of about 3.5 min, sequentially going through all the beams, and in each beam, in ascending order, all DM. When we quickly flip through the dynamic spectra, inclined lines are visible on the screen, indicating signals with a dispersion delay.

When we noted an inclined line when viewing, we returned to this picture (or pictures) and evaluated the characteristics of the pulse (coordinates, DM). These characteristics allow us to make a subsequent identification of the source in ATNF. For clarity, we give an example of processing in the dispersed pulse search process.

Tyul’bashev et al. (2018a) reported that when they processed semi-annual data, about a quarter of all dynamic spectra indicated real pulsar pulses and RRATs, and three quarters of the detected pulses were associated with interferences. Some of these interferences are similar to the pulses of ordinary pulsars, whose DM, as a rule, lies in the range from 3 to 10 pc cm\(^{-3}\). The elimination of such interferences is based on the fact that these interference signals can be observed simultaneously in many beams, or, during the day, they are observed at very different right ascensions beyond the dimensions of the receiving beam of the LPA of the Lebedev Physical Institute (LPI). The total transit time of the source through the meridian is approximately seven minutes. Therefore, if the pulses with the same DM are located on a given day far from each other in time (\(>7\) min), then we can talk about detecting an interference. Some other types of interference are discussed below. Neural networks can be used to reduce the number of interferences in visually verified images. For example, convolutional neural networks (CNN), which were previously used to analyze data obtained from LPA LPI, have shown a high efficiency (baev et al. 2019). When processing data using the CNN model, the time series was divided into fixed-length frames, which made it possible to use CNN, which works well in a search for objects in images.

In this paper, in the pictures of dynamic spectra, a found transient is a line of dark pixels starting in frequency channels at a high frequency and shifting in time to a lower frequency. The magnitude of the line slope is related to the DM. That is, from the point of view of pattern recognition, we have simple images of lines at different slopes, “diagonals”, that the network should “see”. The length of this diagonal is the higher the larger the DM, and this means that we must be able to process frames of different lengths with the network. However, on frames of different lengths, there may be a sharp decrease in the quality of CNN learning, and, consequently, in recognition.

The neural network model is written in Python and based on a Google Tensorflow\(^4\) end-to-end open-source platform for machine learning. The Pandas and Numpy libraries were used for a basic extract-transform-load (ETL) processing. Keras is a more generalised approach to design and train a particular neural network model for the classification problem. In addition, a distributed cloud web system was designed on Python/MongoDB stack for ETL and visualisation.

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3. http://pra2.ru/online%20data/onlinedata.html
4. https://www.tensorflow.org/api_docs/python/tf
A core architecture of the model is a long-short-term memory (LSTM; Hochreiter & Schmidhuber 1997), which in turn is based on a concept of artificial RNN that is often used in the field of deep learning (DL). To train the model, a common approach was used. The raw data were converted into a unified format during the ETL procedure, and were combined into Pandas data frames to speed up access and optimize storage.

The trained model accepts a tensor in a unified format and converts it into a resulting value, ranging from 0.00 (probably not positive) to 1.00 (probably positive). To obtain a resulting value, which is Boolean by nature, we need to determine a threshold at which the model values below are interpreted as a false and at which values above are interpreted as a true. To finally tune the model, the threshold was therefore estimated to minimise a number of type I and type II errors on the test dataset. The final model testing was made on real production data with manual checks of the model execution results.

For the network train, we took approximately 9000 images from the 6 × 10^5 that were obtained during the processing of semi-annual observations, and entered the following information into the database: “YES” means we see a transient in the image, and “NO” means we see an interference. The numbers of “YES” and “NO” means were about equal. These images were divided into a ratio of two-thirds and one-third, and the two-thirds of the images were used for network training (training data), and the one-third was used to test the network after training (test data).

After receiving the model, different thresholds for making the right decision were obtained based on the test data. These thresholds were tested on all the processed data. Testing of these thresholds showed that at the level of the threshold for making the right decision equal to 0.8 and with an acceptable number of remaining interferences, a small number of transients is missed (some details are given below in this section).

After the end of the network training process, the sample images used for training were deleted, and the search for transients was carried out throughout the remaining samples of candidates. Since in the new search we used previously processed data (Tyul’bashev et al. 2018a), namely, images of dynamic spectra and pulse profiles for each direction in the sky, the number of observed interferences and the number of detected pulses were already known. Consequently, after the operation of the neural network, it was possible to view the remaining images and determine how many interferences the network took for real pulses, and how many real pulses the network threw out because it considered them as interferences. In other words, it is possible to estimate in practice the probability of a false-positive detection (a second-kind error) and the probability of missing a real signal (a first-kind error).

When processing observation data, we divided the entire sky into pixels, the size of which was slightly smaller than the size of the LPA LPI receiving beam. We performed an independent search in each pixel. Since the exact coordinate of a transient is not known, its pulses can be detected in several nearby pixels by right ascension and declination. For the configuration of the LPA we used, the entire available sky consists of 96 beams divided by declination (−9° < δ < +42°), with a distance between the beams of about 0.5°, and located in the meridian plane, as well as from 422 pieces with a duration of approximately 3.5 min by right ascension: (3.5 × 422)/60 = 24 h. Thus, the sky is divided into 96 × 422 = 40 512 pixels.

After the neural network operation, we found that for 97% of all pixels, less than one interference record per pixel was detected on average. Almost half of all pixels did not have a single image of the dynamic spectrum left. The median value of the remaining interferences number per 96 pixels (corresponding to 96 beams in the meridian) is 12.

Three percent of the recordings show from dozens to hundreds of interference recordings per pixel. We missed one type of interference when we trained the neural network, and this type takes these interferences for transients. We were not able to determine the nature of these interferences, but we hope to learn how to eliminate them with further improvements of the neural network when we process data that accumulated over an interval of seven years. In Fig. 1e, we present the dynamic spectrum and the average profile of these interferences. Excluding 3% of pixels from the analysis, we obtain that the neural network removed almost 99% of all interferences that the original processing program took for dispersed pulses.

Another important question is how many real pulses are removed by the neural network. To estimate the number of pulses removed by the network that were detected during early processing of the semi-annual data (Tyul’bashev et al. 2018a), we visually checked the number of pulses that is visible in known pulsars before and after the neural network operation. The neural network removed 6% of previously detected pulses.

In addition to the known pulsars and RRATs, the network detected pulses that were missed during visual viewing in the earlier search. Some of these missed pulses turned out to be interferences, some were pulses of known pulsars recorded in the side lobes, and some presumably were new RRATs. Figures 1a–e show examples of interferences that the neural network considered transients.
During the visual check, the candidates selected by the neural network, shown in Figs. 1a–e, would have been eliminated. We now consider the reasons for screening out these candidates. To obtain an estimate of the $S/N$, it is necessary to calculate $\sigma_s$. The processing program calculated for each beam $\sigma_s$ at an interval of one hour, after equalising the gain in the frequency channels, adding them on DM = 0 pc cm$^{-3}$ and removing pulse interference. For the profile in Fig. 1a, the $S/N$ is approximately five. In the published papers, $S/N \geq 7$ was used for the RRATs. Candidates up to $S/N = 5$ were recorded in the search program. Practical work has shown that at $S/N = 5 − 6$, an inclined line of dark pixels is still visible on the dynamic spectrum. This distinguishes an RRAT candidate from interference. When we detected a RRAT candidate with $S/N \geq 7$, then the weaker pulses observed in the candidate’s direction were used to confirm it and search for a period. For the case considered in Fig. 1a, the root mean square (RMS) deviations of the noise on the profile were apparently slightly higher than the value determined on the hourly interval, but an inclined line is still visible in the drawing. We cannot say unequivocally that we observe an interference, but the $S/N$ estimate is still lower than the $S/N > 6 − 7$ criterion that is generally accepted in radio astronomy, which does not allow us to publish these RRATs as new open sources without additional good reasons. About 500–700 candidates remain with an $S/N < 6$ and a visually detectable dispersion delay line remains after the neural network processed all the images, and we reject them as unreliable. At the same time, the fact that the neural network finds candidates that visually have a weakly pronounced line in the dynamic spectrum indicates that it operates reliably. We are sure that some of these candidates with $S/N < 6$ are new RRATs, and we are developing ways to confirm them.

Figure 1b shows the case of an interference located in the frequency domain. The processing program was unable to remove this frequency interference. Figure 1c shows interference that is generally accepted in radio astronomy, which does not allow us to publish these RRATs as new open sources without additional good reasons. About 500–700 candidates remain with an $S/N < 6$ and a visually detectable dispersion delay line remains after the neural network processed all the images, and we reject them as unreliable. At the same time, the fact that the neural network finds candidates that visually have a weakly pronounced line in the dynamic spectrum indicates that it operates reliably. We are sure that some of these candidates with $S/N < 6$ are new RRATs, and we are developing ways to confirm them.

$N_2$ in the ninth column is the total number of pulses found between 110.25 MHz and 110.27 MHz. The neural network was unable to remove this frequency interference. Figure 1c shows interference that is generally accepted in radio astronomy, which does not allow us to publish these RRATs as new open sources without additional good reasons. About 500–700 candidates remain with an $S/N < 6$ and a visually detectable dispersion delay line remains after the neural network processed all the images, and we reject them as unreliable. At the same time, the fact that the neural network finds candidates that visually have a weakly pronounced line in the dynamic spectrum indicates that it operates reliably. We are sure that some of these candidates with $S/N < 6$ are new RRATs, and we are developing ways to confirm them.

The neural network also found new pulses of known strong pulsars that were observed in the side lobes of the LPA antenna. These pulsars were detected by the network once, and were missed earlier during our visual search (Tyul’bashev et al. 2018a). Generally speaking, the leakage of sources into the side lobes of the LPA LPI is a serious problem. For example, Fig. 2 in Tyul’bashev et al. (2021b) shows the detected pulses of known pulsars located outside the boundaries of the investigated area. The figure shows that in the studied area with declination $+56^\circ < \delta < +87^\circ$, pulsars in the side lobes in different directions in the sky were observed more often than pulsars caught in the main lobe of the antenna. Detection of previously undetected pulses of real pulsars in the side lobes of the antenna again indicates a higher efficiency of the neural network compared to the human eye.

In addition to interferences and pulses of known pulsars, the neural network found objects that could not be identified with either known pulsars and RRATs or with interference (Fig. 2). The found pulses were detected in one beam and their $S/N > 7$. Table 1 shows the characteristics of the detected pulses. The first column lists the name of a source, and the second and third columns list coordinates for the year 2000. The declination error for all sources is defined as half the distance between adjacent rays and is equal to $\pm 15^\circ$. The error in right ascension is defined as the size of the receiving beam of the LPA at half-power and is equal to $\pm 1.5^\circ$. In Cols. 4–7, DM pulses, half-widths of profiles (W$_0$ s), $S/N$ of strongest pulses, and peak flux density (S$_{\text{peak}}$) are given. In the eighth column, an upper estimate of the integral flux density (S$_{\text{int}}$) is given. The search for the regular pulsar emission in the direction of the RRAT to obtain an estimate of S$_{\text{int}}$ was carried out using summed power spectra and summed periodograms (Tyul’bashev et al. 2022). Monitoring data were used for the search, for which the full frequency band was 2.5 MHz, the frequency channel width was 78 kHz, and the sampling time of one point was 12.5 ms. The absence of signals with a known DM in the summed power spectra allowed us to give upper estimates of S$_{\text{int}}$. S$_{\text{peak}}$ estimates and upper estimates of S$_{\text{int}}$ may be underestimated, since the coordinates of the assumed RRATs are known with a large error, and we cannot make corrections to the flux density that take into account the possible divergence of the direction to the centre of the LPA beam and the direction to the source. The values given in columns 7 and 8 can be up to 1.5–2 times higher. Sensitivity, when searching for ordinary pulsar radiation, depends on many factors: frequency channel width, pulse width, pulsar DM, and so on (Tyul’bashev et al. 2022). Our upper estimates of the integral flux density are given under the assumption that the pulsar period is $P > 0.5$ s.
Three pulses have an estimated duration of the entire search interval. During a special search over an interval of 5.5 years, the pulse search scheme was standard: subtraction of the baseline; addition of frequency channels without and with DM; calculation of standard deviations and comparison of the observed peaks with noise; checking the signal height before and after DM compensation; visual control of all obtained dynamic spectra (more about processing in Brylyakova & Tyul'bashev 2021). The search was conducted up to $S/N \geq 5$. The level $S/N \geq 6$ was considered a reliable detection subject to visual detection of a line having a dispersion shift in frequency channels in the dynamic spectrum. The tenth column shows the frequency of occurrence of pulses $(n)$, taking into account the new pulses found during their purposeful search over an interval of 5.5 years.

Comments on candidates for new RRATs after searching by known coordinates and a known DM on the interval of 5.5 years are listed below.

**J0034+27.** Six pulses with a pronounced line of dispersion delays were detected for the transient. Out of these six pulses, two have an $S/N \geq 6$ on the interval 5.5 years. Taking into account the passage of the source through the LPA receiving beam at half-power during 3–4 min, one pulse with a detection threshold $S/N \geq 6$ from this RRAT comes in a time equivalent to 50–60 h of continuous observations.

**J1346+06.** Twenty-six pulses were found for the transient. Ten of these pulses have an $S/N \geq 6$. Three pulses have an $S/N > 10$.

**J1432+09.** Eight pulses were found for the transient. Two pulses have an $S/N \geq 6$.

**J2002+13.** Seventeen pulses were found for the transient. Three pulses have an $S/N \geq 6$.

### Table 1. Characteristics of the RRATs.

| Name          | $\alpha_{2000}$ | $\delta_{2000}$ | DM (pc cm$^{-3}$) | $W_{0.5}$ (ms) | $S/N$ | $S_{\text{peak}}$ (Jy) | $S_{\text{int}}$ (mJy) | $N_1/N_2$ | $n$ (1/h) |
|---------------|-----------------|-----------------|-------------------|--------------|-------|------------------------|------------------------|-----------|----------|
| J0034+27      | $06^34^m57^s$   | $27^\circ47'$   | 16                | 18           | 7.0   | 2.4                    | <0.17                  | 1/2       | 0.017    |
| J1346+06      | $13^34^m11^s$   | $06^\circ10'$   | 9                 | 9            | 12.6  | 5.8                    | <0.23                  | 1/10      | 0.085    |
| J1432+09      | $14^32^m30^s$   | $09^\circ08'$   | 14                | 14           | 20.0  | 8.6                    | <0.22                  | 1/2       | 0.017    |
| J2002+13      | $20^h02^m07^s$  | $13^\circ03'$   | 5                 | 5            | 8.0   | 4.8                    | <0.30                  | 1/3       | 0.026    |

For all detected sources of pulsed emission, the average time between pulses is in the range of 10–60 h. Earlier, Logvinenko et al. (2020) reported RRATs in which the average time between pulses exceeded 10 h. It is known that the appearance of RRAT pulses can obey a Poisson distribution (Meyers et al. 2019). Smirnova et al. (2022) showed that the distribution of nullings (i.e. the duration of intervals without pulses) for some RRATs obeys an exponential law. To obtain a correct estimate of the characteristic time between pulses, it is necessary to know the distribution law. However, we have detected such a small number of pulses that we cannot say anything about their distribution. Therefore, it is impossible to give an unambiguous answer about the existence of an RRAT sample with very long arrival times between successive pulses. We only note that our observations give indications that these RRAT samples may exist.

At present, 45 pulsars are discovered at the Pushchino Radio Astronomy Observatory (PRAO). In the original papers (Shitov et al. 2009; Tyul’bashev et al. 2018b; Logvinenko et al. 2020; Tyul’bashev et al. 2021b; Samodurov et al. 2022, and this paper), they are called rotating transients. After the discovery of these RRATs by sporadically appearing pulses, some of them were found to have ordinary pulsar radiation. The natural question arises about what a rotating transient is, and how it differs from an ordinary pulsar.

In the Introduction to this paper, we described the probability that RRATs, like ordinary pulsars, may have different natures and the same external manifestations in the form of irregularly appearing pulses. According to Weltevrede et al. (2006), RRATs can be ordinary pulsars with an unusually long tail in the histogram of the distribution of pulses by energy. In this case, the pulsar (regular) emission may be too weak to register in the observation session, but strong pulses from the tail of the distribution can be detected. Tyul’bashev et al. (2021b) reported eight known second-duration pulsars (J0141+6009, J0157+6212, J0653+8051, J1059+6459, J1840+5640, J1910+5655, J2337+6151, and J2354+6155), which in observations on the LPA LPI radio telescope will look like an RRAT if they are removed to such a distance that the usual addition of pulsar pulses with a known period, they are not detected in one observation session. In the paper, the search for dispersed pulses on declinations $-56^\circ < \delta < +87^\circ$ was carried out, and the viewing area was 4000 sq. deg. Consequently, when viewing the entire sky at the LPA LPI, the detection of ~80 such pulsars is expected, with a uniform distribution of pulsars in the sky.

An additional example indirectly supporting the hypothesis of Weltevrede et al. (2006) are surveys that search for dispersed pulsars that conducted at close frequencies (111 and 135 MHz; Tyulbashev et al. 2018a; Sanidas et al. 2019). Some of the sources (J0317+13, J1404+11, J1848+15, J2051+12, and J2209+22), determined as RRAT in the Pushchino survey, 5 https://bsa-analytics.prao.ru/en/transients/rrat/
were detected on LOFAR as ordinary pulsars with separate strong pulses. This situation developed because in the one-hour observation session of the LOFAR Tied-Array All-Sky Survey (LOTAAS), the sensitivity of observations was 2–4 times higher than in the 3.5-min observation session in the PSHuchino Multi-beam Pulsar Search (PUMPS; Tyul’bashev et al. 2022), which made it possible to register the Pushchino RRAT as ordinary second-duration pulsars. Therefore, there is no doubt that the Weltevrede et al. (2006) hypothesis is valid for some part of the RRATs.

Another hypothesis was proposed in the paper Zhang et al. (2007). According to this paper, RRATs are an extreme case of nulling. Pulses with nullings have been known since 1970 (Backer 1970). The degree of pulsar nulling varies widely from cases when individual pulses are skipped to cases when the degree of skipping can reach 93% of all expected pulses (Table 2.1, Gajjar 2017). Nulling has been actively investigated in the decimeter wavelength range (Gajjar 2017 and references there), but it is also observed in the meter range. For example, for the pulsar J0810+37 that was studied in Pushchino (Tyul’bashev et al. 2017), the degree of nulling within a 3.5-min observation session is in the range of 10–90% in different observation sessions, with an average degree of nulling of 40% (Teplykh & Malofeev 2019; Teplykh et al. 2022). At the same time, there are cases when not a single pulse was registered for several days in a row in the observation sessions.

We were not able to find any papers with a special study of nulling of RRAT pulsars. However, many papers give an estimate of the number of observed pulses per hour of time, and if the RRAT period is known, then the degree of nulling can be roughly estimated. Using estimates of the pulse arrival rate if the RRAT period is known, then the degree of nulling can reach 93% of all expected pulses (Table 2.1, Gajjar 2017). Nulling has been actively investigated in the decimeter wavelength range (Gajjar 2017 and references there), but it is also observed in the meter range. For example, for the pulsar J0810+37 that was studied in Pushchino (Tyul’bashev et al. 2017), the degree of nulling within a 3.5-min observation session is in the range of 10–90% in different observation sessions, with an average degree of nulling of 40% (Teplykh & Malofeev 2019; Teplykh et al. 2022). At the same time, there are cases when not a single pulse was registered for several days in a row in the observation sessions.

We were not able to find any papers with a special study of nulling of RRAT pulsars. However, many papers give an estimate of the number of observed pulses per hour of time, and if the RRAT period is known, then the degree of nulling can be roughly estimated. Using estimates of the pulse arrival rate and period for 21 RRATs (J0139+33, J0640+07, J1005+30, J1132+25, and J1336+33), discovered on LPA LPI (Brylyakova & Tyul’bashev 2021; Tyul’bashev et al. 2021a). For these RRATs, it is shown that the observed pulses are at least 30 times higher than the expected or observed peak flux densities in the average profiles, and at the same time, the energy distribution of the pulses is described by a power law or lognormal law with a power-law tail, which is typical for pulsars with giant pulses.

The study of 16 sources (Brylyakova & Tyul’bashev 2021; Tyul’bashev et al. 2021a; Smirnova et al. 2022), discovered as RRATs (Tyul’bashev et al. 2018b,a), for which at least 90 pulses were detected over 5.5 years of daily observations, showed that they do not exhibit special properties compared to ordinary, albeit rarely encountered pulsars. It is possible that the fundamental difference with conventional pulsars will be revealed in the P/P diagram.

Finally, in observations in meter wavelength range, as well as in observations in the decimeter wavelength range, hypotheses are confirmed that part of the RRATs are pulsars with a long tail of the energy distribution of pulses, and part of the RRATs cannot be distinguished from pulsars with long nullings. It was also shown that some RRATs appear as pulsars with giant pulses.

During the search for new RRATs on the LPA LPI, transients with pulses that appear increasingly rarely in time are detected. In this paper, two RRATs were detected (J0032+27 and J1434+09), which have an average time between pulses with an S/N ≥ 6 that reaches approximately 60 h.

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