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## РАДИОАСТРОНОМИЯ И АСТРОФИЗИКА

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# DECAMETER PULSAR/TRANSIENT SURVEY OF NORTHEN SKY. FIRST RESULTS

*The decameter pulsar/transient survey is now being made using the UTR-2 radio telescope. The survey strategy and parameters, equipment characteristics, data processing algorithms as well as preliminary results are described. The very first result was the discovery of decameter emission of the pulsar J0240+62. Test measurements have shown the sensitivity, reached in the present survey, being 5 Jy for the transient signals, and several mJy – for the periodic pulsar emission.*

*Key words:* survey, decameter range, pulsar, transient

## 1. Introduction

The discovery of pulsars [1] has had an enormous importance for astronomy and astrophysics. In addition to studying this new class of objects directly (their internal structure, main characteristics and radiation models), pulsar science has built connections to various problems in other fields of astrophysics. Pulsar timing, especially the study of the Hulse–Taylor pulsar [2] and the binary pulsar J0737-3039(A/B) [3], established the most strict tests of the relativity theory. A precise measurement of period of the pulsar B1257+12 [4] has led to the discovery of a planetary system around a pulsar. Study of repetitive and sporadic emission of neutron stars has revealed new branches of their evolution: magnetars [5], XDINSs [6], RRATs [7], intermittent pulsars [8] and X-ray link to radio pulsars [9]. Powerful pulsed emission of neutron stars can be used as a probe of electron density in the Galaxy [10]. Timing of millisecond pulsars is an attempt to detect gravitational waves [11]. There is no doubt that future theoretical and experimental studies of neutron stars will bring more and more new discoveries.



Ultra-broadband emission (from low-frequency radio waves to highest energy gamma range) makes neutron stars unique objects of studying, within all electromagnetic spectrum. Dozens of surveys have been made [12–15] in various wavelength ranges – from meter waves to gamma range, in order to find new targets for studies. Nevertheless, the relevance of new surveys does not diminish. Whereas the high-frequency range is well suited for studies of distant neutron stars in the Galaxy, and the extragalactic transient events, the most low-frequency region of the electromagnetic spectrum, on the contrary, carries the information about the closest pulsars and transient sources of radio emission. The discovery of new neutron stars in our neighborhood, which were left out in the high-frequency surveys, is possible due to the expansion of their emitting cone and increase in the beaming fraction, as compared to higher frequencies. Thus, one of the most relevant tasks for the lowest end of electromagnetic spectrum (decameter wave range) is a survey of the pulsed and transient emission sources, accessible in this range. It is especially important, because such a survey has never been made at these frequencies before. Formerly, this task could hardly be considered feasible, but at present, due to improvement of telescopes, receiving equipment, computer hardware and methods of search, such a survey has become possible. After a successful re-detection of 40 known pulsars at decameter wavelengths [16], which has demonstrated the potential of the decameter wavelength range, we commenced a survey of the entire Northern sky at the most sensitive UTR-2 decameter wave radio telescope.

Present work describes the survey concept, equipment and software used, and the very first results. Section 2 summarizes information about instrumentation and parameters of the survey. Section 3 describes the main stages of data processing pipeline and the corresponding software. Section 4 demonstrates (as a testing result) the detection of known pulsars in survey data, in a form of summary plots produced by data processing routines. Section 5 presents the analysis of detected transient signals, in particular, the detection of decameter emission of recently discovered [12] nearby pulsar J0240+62. The last Section provides the conclusions and prospects.

## 2. Instrumentation and Survey Parameters

The largest decameter wavelength radio telescope UTR-2 [17], equipped with a broadband preamplification system [18] and a set of digital receiving equipment [19], can operate in a five-beam mode, with the width of each beam $\sim 24'$ at 25 MHz, and the angular distance between the beams $\sim 23'$. In this case, five beams, directed along the meridian, capture the angle range of about $2.5^\circ$ by declination. A drift-scan survey (driven by the Earth's rotation), allows to cover the whole northern celestial hemisphere during 80 nights of observations.

Concept of the survey is designed to gain the maximum use of the UTR-2 advantages. It necessitates making a compromise between the integration time for each source (which should be as longer as possible) and the total observation time (which is restricted). A broad directional pattern of "North–South" antenna allows keeping sources within the beam for 40–60 min. Sum, Difference and Product of directional patterns of the two antennae ("North–South" and "East–West") can be used, ensuring the flexibility of data analysis.

Here are some considerations that we have followed, choosing the survey parameters. In order to have a high sensitivity, the effective area of the telescope $(A_E)$ must be large. But it decreases with growth of zenith angle ($z$). Therefore we have limited the declination $(\delta)$ of surveyed parts of the sky from $-10^\circ$ to $+90^\circ$ (coordinates of UTR-2: $49^\circ 38' 10''$ N, $36^\circ 56' 29''$ E). Decrease in the effective area at $\delta = -10^\circ$ in this case does not exceed 2 times, compared to zenith direction. Choice of the time resolution ($\Delta t = 8$ ms), is based on measurements of the scattering time constant $(\tau_{SC})$ of nearby pulsars, only two of which (B0950+08 and B0809+74), have the $\tau_{SC}$ less than the selected $\Delta t$ at decameter wavelengths. Another key parameter is the highest accessible dispersion measure (DM), which we take into account while processing the data. As an integral of the electron density along the line of sight, it is directly related to the distance from the Earth, at which we search for the source of pulsed signals. We chose it the same as in [16]: $30\ \text{pc}\cdot\text{cm}^{-3}$ (which corresponds to $1-2$ kpc maximum distances to the sources with low galactic latitudes $|b| < 5^\circ$). It is related to a very time-consuming and computationally expensive nature of dedispersion procedure. In the near future (having larger computing capabilities), the raw data can be reprocessed with increased maximum DM up to $60-100\ \text{pc}\cdot\text{cm}^{-3}$, in order to search for more distant sources of pulsed signals. The selected frequency range is $16.5-33.0$ MHz. It is divided into 4096 partial frequency channels. This part of the UTR-2 frequency range is least affected by interference.

## 3. Data Processing Pipeline

The total amount of raw survey data will be about 100 terabytes. In addition, all the events that resemble signatures of pulsar or transient emission (we call them "candidates" hereafter), must be re-observed, in order to confirm or refute the detection. This will result in even larger data sets to be processed. Therefore, fast and efficient data processing techniques should be used.

The data processing pipeline includes 3 main stages:

– interference mitigation (including normalizing and calibration),

– compensation for dispersion delays between frequency channels, and further integration over the frequency band,

– search for sources of repetitive and transient emission.

The last step is flexible. It implies having a toolkit with several processing procedures, which can be adjusted to the specific multi-parametric search. Due to a fragmented structure of raw data, we can start processing almost on the fly – immediately after the recording of the first file (about 9 min after the start of observation). For the alignment of processing time between all the steps, parallelization can be used.

## 3.1. Interference Mitigation

Decameter range is extremely polluted with the radio frequency interference (RFI) of natural and artificial origin. Their signatures in the data can result in a false-positive detection of spurious signals in both the time domain and the Fourier image domain.

The RFI level depends on time of the day, season, etc. Therefore the processing algorithms with different depth of RFI mitigation should be used. At this stage, the calibration is taken into account. The applied RFI mitigation algorithm is described in more detail in work [20]. The plots of raw and cleaned dynamic spectra, as well as the map of contaminated pixels are kept to check the following stages of processing.

## 3.2 Dedispersion

According to the dispersion equation of electromagnetic wave propagation in cold plasma, the $\Delta T$ delay of signal at a certain frequency $f$ with respect to infinitely high frequency is:

$$\Delta T = 10^{16}\frac{\mathrm{DM}}{2.410331}f^{-2}. \qquad (1)$$

In this case, we compensate for a propagation delay between the upper (33 MHz) and the current frequency of the spectrogram and then integrate over all frequency channels. The data is processed by looking through a "trial" DM within 0 to $30\ \mathrm{pc\cdot cm^{-3}}$ with a step $0.01\ \mathrm{pc\cdot cm^{-3}}$. A step between adjacent DM trials has been chosen as a compromise between the accuracy of dispersion compensation and the processing time. Nevertheless, under these conditions, the processing time on a personal computer still exceeds the observation time by a factor of 100.

We have developed the programs which parallelize calculations, and thus increase 50-fold the processing speed (on a computer with the Intel Core i7 CPU and 32GB RAM, it takes approximately 23 hours to process a 12-hour observation). Given that the telescope works in a five-beam mode, this step requires further increase in productivity, use of parallelism and processing power of GPUs. For efficient pipelining we still need acceleration of about 10 times compared to the results already achieved.

### 3.3.1 Search for Individual Transient Signals

The next step of the pipeline is a search for transient signals in the "time – dispersion measure" plane. Here we examine each of 3000 time series, integrated over frequency, whether they exceed a certain threshold. At this stage, we can potentially find giant or anomalously intense pulses of pulsars, RRAT-like signals, etc. Radio emission of strong pulsars will be displayed as a series of consecutive pulses at the same trial value of DM.

In order to suppress the background noise fluctuations and highlight the useful signal, we filtered out low frequency components, lower than a cutoff frequency of the high pass filter, i.e. 0.2 Hz. To increase sensitivity, we also use integration of 4 adjacent time samples (i.e. the effective time resolution becomes 32 ms). The samples that exceed the threshold ($5.5\sigma_{\mathrm{DM}}$ – a standard deviation, calculated for each integrated time series with corresponding trial DM), are put down to the database, indicating their DM, S/N ratio of the event and the time elapsed from the beginning of the file. They are marked on the "time – dispersion measure" plane by circles, with radii proportional to the S/N value of the event. To check for false-positive detections, the pre-processed data are examined in different ways, introducing different input parameter values (e.g. checking in different frequency bands) and also are checked visually. Fig. 1 shows the example of false-positive detection. The dynamic spectrum (after the dispersion delay compensation) shows the frequency sweep of the signal, different from the dispersion relation (1).

### 3.3.2 Periodicity Search

As mentioned above, the search for weak pulsar signals is possible due to their periodic nature and the accumulation of the source through signal within a wide "North–South" antenna pattern, during $40-60$ min. We make the Fourier transform of the data for this time window, i.e. $40-60$ min. In the same way as when searching for transient signals, for each value of trial DM, we calculate the standard deviation ($\sigma_{\mathrm{FFT}}$). Values, exceeding a certain threshold ($6\sigma_{\mathrm{FFT}}-10\sigma_{\mathrm{FFT}}$), are also put down in the output file and marked with circles on the "frequency – dispersion measure" plane. The radii of the circles are in

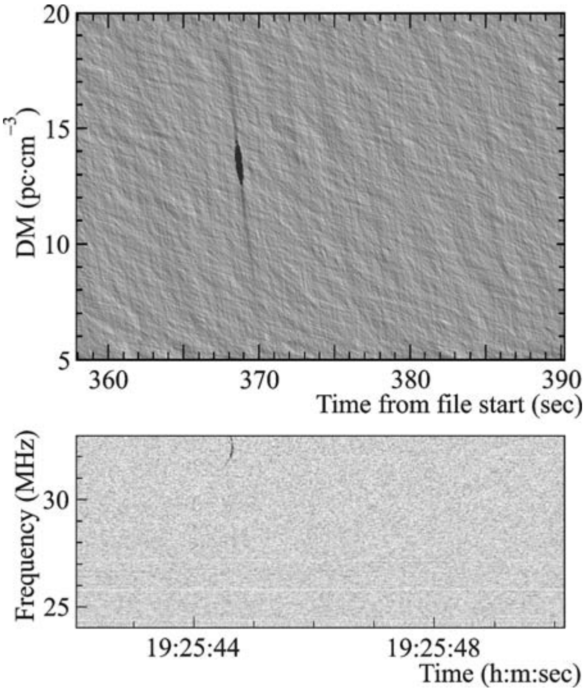


***Fig. 1.*** False-positive detection in the "time – dispersion measure" plane (upper panel). The test has shown the presence of a signal (lower panel) with time-frequency dependence different from the dispersion law (1)

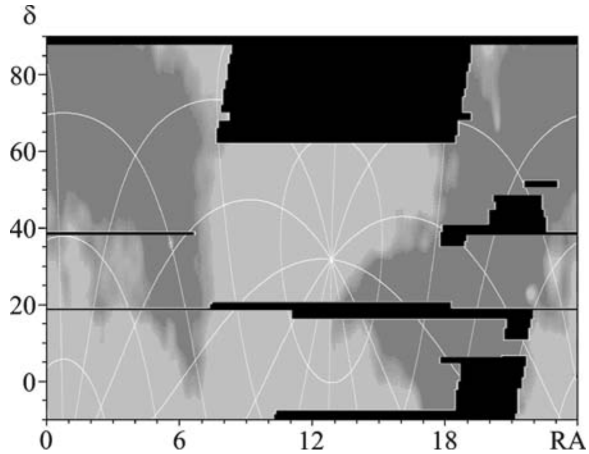


***Fig. 2.*** Surveyed sky region in the RA–δ coordinates

this case proportional to the S/N ratio logarithm. Thus we can detect a wide range of variations of harmonic intensity values for the weak and strong pulsars.

## 4. Methodology of Pulsar and Transient Search

By the beginning of 2014, the initial observations, which began in April 2010, were almost completed. We have obtained the records of more than 90 % of the Northern sky. For the remaining areas (gaps between the strips, which were recorded with a six-month shift, and the circumpolar regions), one more short-term observational session is required. Fig. 2 shows the map of surveyed sky regions.

The survey database includes:

– raw data,

– normalized data after RFI mitigation,

– intermediate files with compensated dispersion delay,

– outputs of repetitive and transient search routines.

Preprocessing (steps 1 and 2 of the pipeline) is now completed for a half of the raw data. Using the aforesaid search routines, we have processed the survey data that contain recordings of radio emission of known pulsars, such as PSR B0809+74, B0834+06, B0950+08.

To clearly represent the transient events that occurred during the night of observations, the data might be depicted as shown in Fig. 3. The upper panel of the Figure shows in the "dispersion measure – signal-to-noise ratio" coordinates the data points, exceeding the selected threshold $5.5\sigma_{DM}$ ($\approx 5$ Jy, under the selected observational parameters). The peak corresponds to the DM of $12.88\ \text{pc}\cdot\text{cm}^{-3}$ (pulsar B0834+06). The bottom panel "time (in hours from the start of recording) – dispersion measure" serves to determine the time of signal maximum. Also, both panels show clearly the interference, left out during the cleaning procedure, which are noticeable at low values of DM.

As aforesaid, another processing step is a search for repetitive pulses. Example of processing of 1-hour records of pulsar B0809+74 in the survey mode is shown in Fig. 4.

The upper panel shows the variations of individual pulse intensity (with respect to the noise) integrated over the entire frequency range 16.5 – 33.0 MHz, in 6 consecutive 520-sec files. Individual pulses, with respect to pulsar rotational phase, are shown in the second panel, where each vertical line is one period of neutron star rotation. The dark "corridor" in the middle is the beaming fraction of the pulsar. The third panel shows the S/N ratio of the first harmonic of the pulsar signal being inverse to its rotational period. The fourth panel shows the normalized directional pattern of the sum of the UTR-2 "North–South" and "East–West" antennae towards the pulsar.

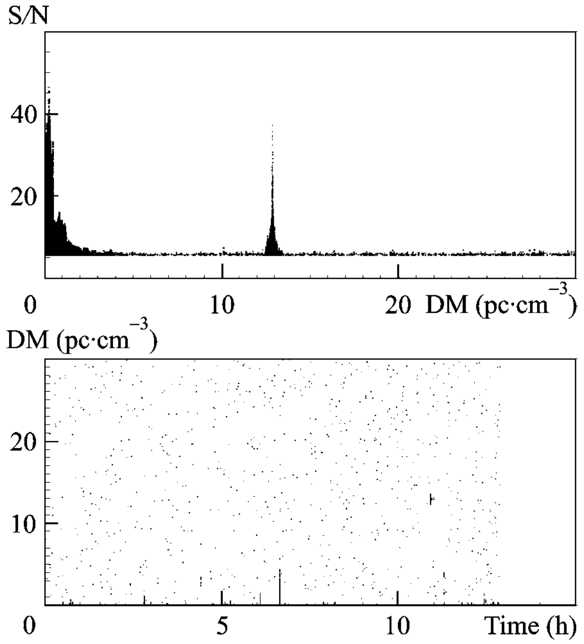


***Fig. 3.*** Principal output of the transient search program. The lower panel shows all the events during one night of observations which exceed a 5.5 $\sigma_{DM}$ level (dots). The upper panel represents the same events, sorted by DM, in the coordinates "signal-to-noise ratio versus dispersion measure"

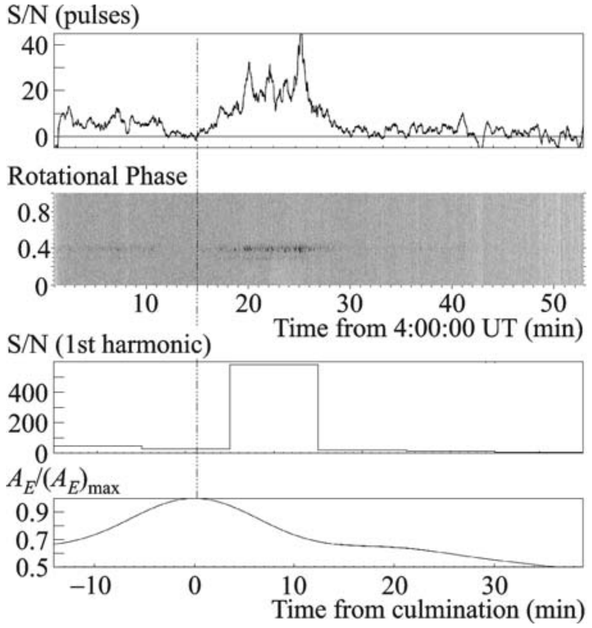


***Fig. 4.*** An example of detection of pulsar B0809+74 in surveyed data. The panels from top to bottom: power of individual pulses integrated over entire frequency range, dependence of intensity on the rotational phase of pulsar, S/N of the first harmonic in the 6 consecutive 520-sec files, normalized directional pattern of the sum of the UTR-2 "North–South" and "East–West" antennae towards the pulsar

The Figure helps understand that the time of maximum intensity of the pulsar radio emission does not coincide with culmination time (maximum of the antenna pattern and a dash-dot line). Only the use of the sum (not multiplication) of two antennae could result in capture and integrating the first harmonic of the pulsar radio emission up to the impressive value of S/N ratio $\sim 600$. Further processing is also aimed at S/N increasing. Fig. 5 shows first 17 harmonics of the pulsar: at the top – S/N of harmonics at the trial DM value of $5.75\ \text{pc}\cdot\text{cm}^{-3}$, in the middle – the layout of harmonics in several adjacent values of trial DM. It is evident from this panel, that there is an additional resource to accumulate the pulsar power, which can be vital for detection of weak periodic sources.

Summing of 100 adjacent values of DM (lower panel, left), we can raise the S/N up to 2000 (lower panel, right – the value of the first harmonic is highlighted by the solid line). Adding of all higher harmonics' power to the first harmonic value (dotted line) gives about a twofold S/N increase for this pulsar. Note that during the transition of a pulsar across the directional pattern (up to 60 min), if its emission is constantly present in the beam, the S/N ratio might be additionally two-fold higher than the obtained one.

Thus, the way the data are recorded in the survey, provides a high sensitivity to the periodic emission of weak radio sources. Flux density of the aforesaid pulsar is about 1.2 Jy. A reserve in the S/N ratio gives hope for detection of repetitive radio emission sources at the level of several mJy.

## 5. Detected Transient Signals. Decameter Radio Emission of Pulsar J0240+62

To date, by means of the transient signal search program, we have processed 30 % of records of the Northern sky. We have found about 70 events with S/N ratio above 6.5 $\sigma_{DM}$, more than 60 of which have a DM value that does not coincide with DM of any known pulsar. Their time-frequency behavior obeys the dispersion law (1), which is a strong argument to put them into the "candidates" list. At the next step of the search we will run the follow-up observations, targeted at these "candidates".

By now, the most important result has become a detection of decameter emission of the recently discovered pulsar J0240+62 [12]. Fig. 6 shows results of the transient search program: $\text{DM} = 3.83 \pm 0.01\ \text{pc}\cdot\text{cm}^{-3}$,

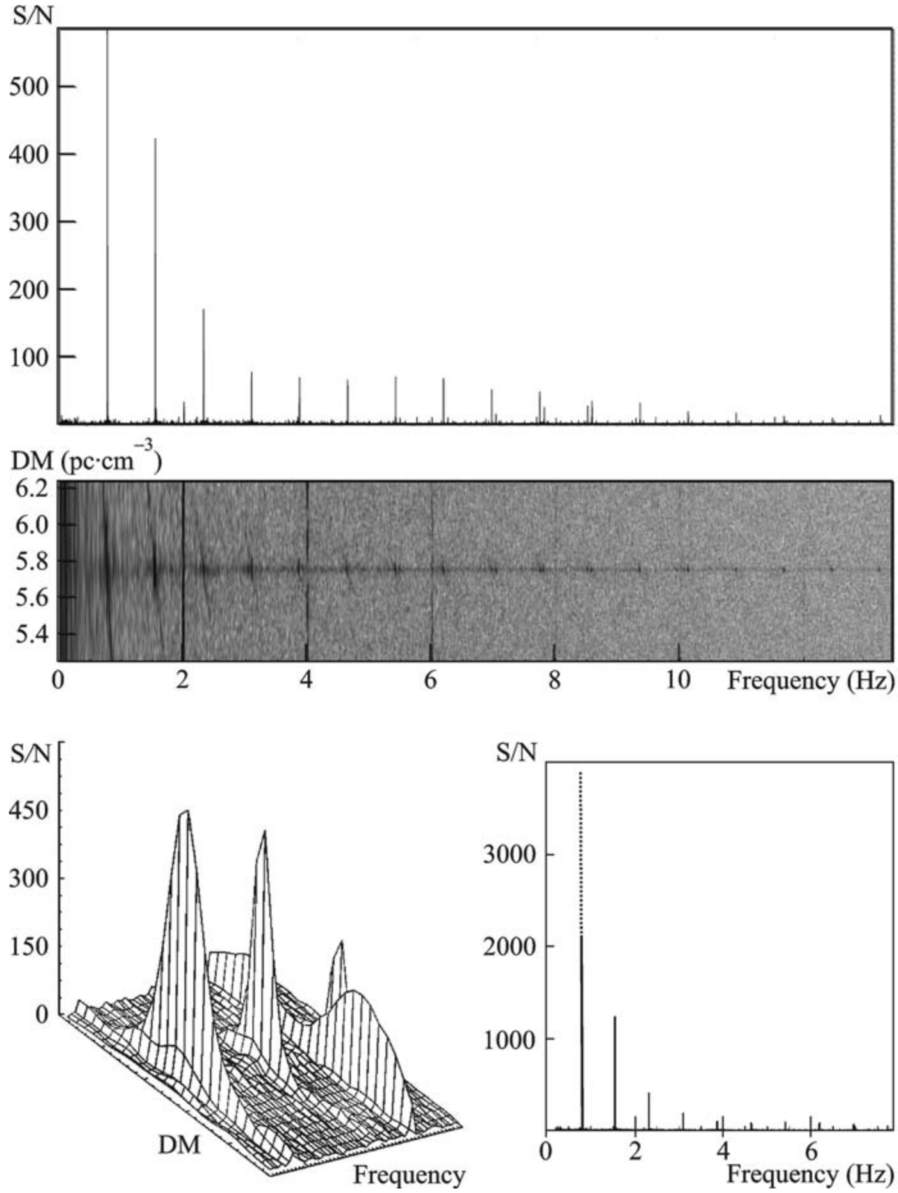


***Fig. 5.*** Power of harmonics of PSR B0809+74 radio emission versus DM. The upper panel: intensity of first 17 harmonics at the true value of pulsar DM (which is known). The middle panel: the harmonic power at several adjacent DM values. The lower panel, left, shows how the harmonic power decreases as the trial DM value shifts away from the true value $(5.75\ \text{pc}\cdot\text{cm}^{-3})$. The lower panel, right, shows the result of averaging of 100 adjacent DM values (dash-dot line – the result of addition of the higher harmonics power to the first harmonic value)

$S/N = 21.9$. Given that the maximum was detected at 2 h and 7 min of local time on October 8, 2013, the Right Ascension (RA) of the source was 2 h and 41 min (total time, when the pulsed emission at this DM is present in beam C of the UTR-2 makes more than one hour).

Declination, corresponding to the center of beam C was $\delta = 63.14°$. Having determined the approximate values of RA, $\delta$ and DM, we had no doubt that it was a record of the decameter radio emission of the aforementioned pulsar. In adjacent beams (B, D, and E) the emission was also present, but only within the time interval of 2 h 7 min to 2 h 11 min. This effect can be explained as follows. The directional pattern of the sum of antennas "North–South" and "East–West" has a crosswise form. "Knife-like" patterns of antenna "North–South" in a five-beam mode are separated, as aforesaid, by $23'$. But a "knife-like"

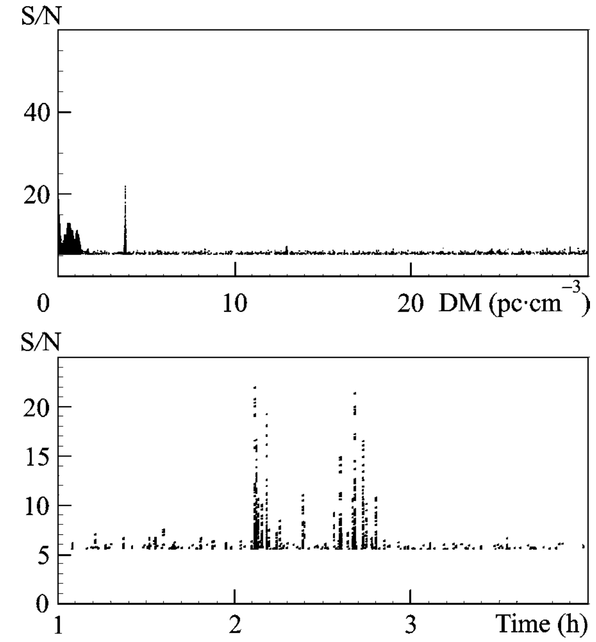


***Fig. 6.*** Detection of pulsar J0240+62. The upper panel shows S/N ratio with respect to DM with a maximum at $\mathrm{DM} = 3.83\ \mathrm{pc \cdot cm^{-3}}$. The lower panel shows pulsar's pulses within the DM range of $3.83 \pm 0.05\ \mathrm{pc \cdot cm^{-3}}$ in the C beam versus local time

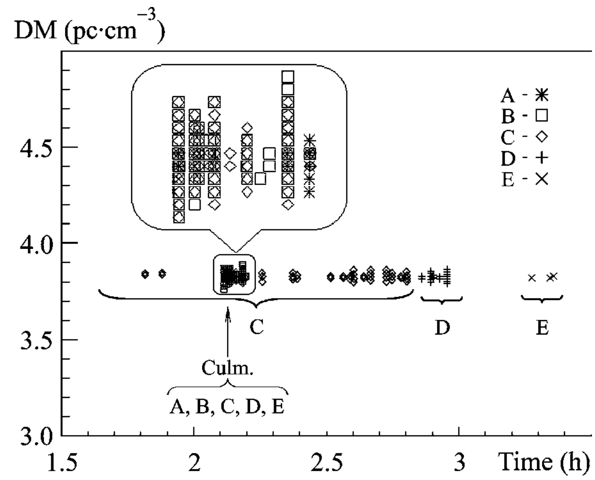


***Fig. 7.*** Upper panel: track of a simulated source through the beams of UTR-2. Lower panel: pulsar detection in all beams of the telescope (A–E). The most intense pulses take place in the B and C beams. At the expected culmination time of PSR J0240+62, its emission was present in all beams of UTR-2

pattern of "East–West" antenna, with a width of 1°, is common. The transition of the source over the "East–West" antenna had to occur exactly between 2 h 7 min through 2 h 11 min.

Fig. 7 shows a simulated source transit, having $\delta = 60°$ through the center of beam C in the coordinates "hour angle (in minutes from culmination) – Code V (directional cosine of UTR-2 pointing)". Calculation shows that far from the culmination, the source will cross the center of beam D (40 min before and after the culmination) and the center of beam E (60 min before and after the culmination). Antenna gain will be less than $0.5(A_E)_{\max}$, but still non-zero. And as is seen above, the most intense pulses can occur apart from the source's culmination. The lower part of the figure shows how the detected pulses are allocated in all five beams. In each beam, pulses have been detected with the S/N ratio of more than $8\sigma_{\mathrm{DM}}$.

## 6. Discussion and Prospects

Thus, we can claim about a high detection efficiency of individual pulses as well as their repetitive sequences. The large relative bandwidth ($f_{\mathrm{up}}/f_{\mathrm{low}}$) enables high precision distinguishing between the dispersion law, inherent in cold interstellar plasma from other time–frequency dependences, such as man-made interference. Whereas, for the high-frequency surveys the preliminary determination of RA an $\delta$ of a source is accurate, and the third coordinate – the distance to the source defined by the dispersion delay in the interstellar medium – is determined poorly, then at low frequencies, the situation is just the opposite. Surely, during the follow-up observations all these three parameters will be essentially refined.

Developed preprocessing routines and automatic transient signal search pipeline can successfully carry out a blind search for individual and repetitive pulses. Preprocessing has already been done on approximately 50 % of data. The number of "candidates" is already quite large (dozens with a flux density of 5 Jy and higher).

For multiparameter checks of "candidates", an online access to the intermediate processing results is needed. This requires enhancement of the processing cluster(s) (currently, these are the Institute of Radio Astronomy and UTR-2 clusters) and increasing the disk space available.

High sensitivity to repetitive pulse sequences allows detection of sources with a flux density ranging from a few mJy to a few Jy. This sensitivity is very high for the decameter wavelength range. If we take into account that along with increasing beaming fraction at lower frequencies some pulsars might have a broad "plateau" with intensity of a few percent of the main pulse, then the ability to detect such pulsars oriented past the Earth with their narrow main pulse is much higher in the decameter wavelength range.

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ДЕКАМЕТРОВИЙ ОГЛЯД ПІВНІЧНОГО НЕБА З МЕТОЮ ПОШУКУ ПУЛЬСАРІВ І ДЖЕРЕЛ ТРАНЗІЄНТНОГО ВИПРОМІНЮВАННЯ. ПЕРШІ РЕЗУЛЬТАТИ

Наразі на радіотелескопі УТР-2 здійснюється декаметровий огляд пульсарів і джерел транзієнтного випромінювання. Описано стратегію та параметри огляду, характеристики обладнання, алгоритми обробки даних, а також попередні результати дослідження. Першим важливим результатом стало відкриття декаметрового випромінювання пульсара J0240+62. Тестові вимірювання показали, що чутливість, досяжна в цьому дослідженні, становить 5 Ян для транзієнтних сигналів та кілька міліянських для періодичного пульсарного випромінювання.

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ДЕКАМЕТРОВЫЙ ОБЗОР СЕВЕРНОГО НЕБА С ЦЕЛЬЮ ПОИСКА ПУЛЬСАРОВ И ИСТОЧНИКОВ ТРАНЗИЕНТНОГО ИЗЛУЧЕНИЯ. ПЕРВЫЕ РЕЗУЛЬТАТЫ

В настоящее время на радиотелескопе УТР-2 проводится декаметровый обзор пульсаров и источников транзиентного излучения. Описана стратегия и параметры обзора, характеристики оборудования, алгоритмы обработки данных, а также предварительные результаты исследования. Первым важным результатом стало открытие декаметрового излучения пульсара J0240+62. Тестовые измерения показали, что чувствительность, достигаемая в настоящем исследовании, составляет 5 Ян для транзиентных сигналов и несколько миллиянских для периодического пульсарного излучения.

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