Multi range study of the radio sources of the RATAN-600 surveys

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Abstract We present the results of the search of variable sources and transient events in the archive data of the sky surveys conducted on 3.9 GHz on the RATAN-600 radio telescope of the Special Astrophysical Observatory of the Russian Academy of Sciences (SAO RAS) in 1980-2000. 17% of the total studied sources can be attributed to the long-term variables in radio range. About half of them has significant variations in optical brightness according to the data of the optical and infra-red catalogs. Variability in the radio range is accompanied by variability in the optical range for the quite bright host objects ($R < 18^m$).

At a level of 3-5 r.m.s. we found three transient events. Using the data from radio and optical surveys and VizieR, SIMBAD, and NED databases, we made assumptions on the possible nature of these events. The first transient is probably associated with AGN activity, the second one — with a cataclysmic GRB event or with a supernova, the origin of the third is not determined. The inference on the possibility of search for variable sources and transients using the data from the RATAN-600 blind surveys was drawn. According to our estimation the surface density of radio transients is 0.03 on one square angular degree with the detection level 8–11 mJy on 3.94 GHz.

Keywords: Keyword One, Keyword Two, Keyword Three, Keyword Four, Keyword Five, Keyword Six

1. Introduction

Many radio sources exhibit flux density variations when observed at different epochs. This variability is due to both external (scintillations) and internal factors, which are associated with the radiation generation processes in the source itself. Variable radio sources are associated with different classes of objects, and their variability has different characteristic time scales. Variable radio emission is observed in active galactic nuclei (AGN), micro quasars, pulsars, and stars. Some AGNs exhibit intra-day variability due to the scintillation of their very compact components, caused by inhomogeneities of the intervening medium between the observer and the object. On time scales of one to several months, the variations of synchrotron emission often correlate with those of optical and/or x-ray radiation because of the nonuniform accretion rate and interaction between the jet and the ambient medium in the immediate vicinity of the nucleus. Variability on time scales of several years may be due to more substantial changes in the accretion rate, heating of the matter, and energy processing in the accretion disk.

Long-term variability of very bright AGNs with fluxes above 1 Jy is a subject of systematic studies; however, few such studies have been carried out for the population of fainter AGNs because of the lack of observational data. At the same time, the study of radio variability of the sources with weak flux densities may prove to be a unique tool for investigating the evolution of AGNs and the nature of this phenomenon.

With the appearance of wide-field optical digital detectors, mass search for variable objects and transients became possible, and the attention to such research methods essentially increased. The same also refers to the radio range. At the end of the 20th century apart from the traditional monitoring of known objects, the archive data were used in searching for variability of radio sources. Thus, the papers [1]–[4] included the analysis of the archive data of the NVSS (NRAO VLA Sky Survey) [5] and FIRST (Faint Images of the Radio Sky at Twenty-Centimeters) [6] surveys. Let us also notice the 22-year survey of the southern sky MOST (Molonglo Observatory Synthesis Telescope) [7], the pilot survey ATCA (Australia Telescope Compact Array) at a frequency of 20 GHz (S_{20GHz} > 100 mJy) [8], the survey ATATS (Allen Telescope Array Twenty-Centimeter Survey), which comprises 12 epochs of observations ($S_{1.4GHz}$ > 20 nJy) [9]-[10], PiGSS (Pi GHz Sky Survey, Allen Telescope Array) [11]-[12], and many others.

The archive data of the surveys are also used for searching and estimating the frequency of radio transients [9]–[15]. Long-term radio transients are frequently thought to be associated with different types of events and objects. They can be supernovae [16–18] or afterglows of gamma-ray bursts [19]–[21]. The activity of stars and compact objects in the Galaxy can be also detected as a transient event in the radio range. For the new generation of radio surveys of the sky, tidal disruption event (TDE) or tidal disruption flares (TDF) are of special interest; they are associated with a sudden increase of the accretion rate due to tidal disruption of a star, appeared too close to an object with a mass of about 10^6–$10^8 M_{\odot}$, which can lead to an explosion in the soft x-ray band or, probably, to radio emission [22]–[24]. A considerable number of radio supernovae, isolated afterglows of gamma-ray bursts, outbursts due to tidal interaction are predicted in surveys with a sensitivity of about 0.1 mJy. All these events generate synchrotron radiation with self-absorption and, consequently, can be more likely observed at high radio frequencies.

There are a number of astrophysical phenomena that may plausibly produce gravitational waves in close coincidence with radio frequency emission [25]-[26]. Detection of transients coincident in these two channels would open up a new field for characterization of astrophysical transients involving massive compact objects. Transient gravitational-wave emission can occur when a temporary deformation of a rapidly rotating neutron star, a merger of a binary system of compact objects, specifically neutron stars or black holes. Recent evidence suggests that neutron star binary mergers may create at least some fraction of FRBs (Fast Radio Burst). Gamma-ray bursts (GRBs) may also result in radio emission. Core-collapse supernovae have also been proposed as plausible sources of short-duration radio pulses and GW emission.

2. Search for variable radio sources in the RATAN-600 blind surveys

We searched for variable radio sources from the archive data of surveys or observation cycles of the “Cold” experiment [27]. As a material for research, we used scans averaged throughout the multi-day runs. The work was carried out in several stages, which included (1) the compilation of a sample of calibration sources [28], (2) the search for candidates for variable radio sources [29]-[30], (3) searches for catalogs of the optical and infrared ranges of optical variability in the candidates we found for variables radio sources [31], (4) search for transient events [32]-[33]. Further, we describe in more detail the methods used by us.

2.1. RATAN-600 blind surveys of the experiment Cold

In 1980 the first 3.94 GHz deep blind survey was performed on the Northern sector of RATAN-600 within the framework of the “Cold” experiment [27] at the declination of the SS 433 source. A radio-source catalog (the RC catalog) with a detection threshold of 10 mJy [34] - [35] was produced based on the data of the survey. To refine the flux densities and coordinates of the RC catalog sources, several more observing runs were carried out at the same wavelength 7.6 cm and at the same declination SS433 ($Dec_{1980} = 4°57′±20′$) with RATAN-600 radio telescope. Soboleva et al. [36] reported the results obtained using data of surveys made in 1988-1999 and newly reduced data of the "Cold" survey (1980 - 1981) in the interval of right ascensions $7^h < RA < 17^h$. The list of objects found in this strip and identified with the objects of the NVSS catalog [5] can be found in the RCR (RATAN Cold Refined) catalog.

The reduction of the data of these surveys revealed that the flux densities of a number of objects vary from one observing run to another. The authors averaged the flux densities over all the observing runs, since identifying variable radio sources was not among their tasks. These averaged flux densities and their errors are reported in the RCR catalog [36].

We try to analyze whether it is possible to discover variable radio sources in the blind surveys. To solve this problem, we use the data of the 7.6-cm surveys carried out in 1980, 1988, 1993, and 1994 at the declination of $Dec_{1980} = 4°57′$ in the $7^h < RA < 17^h$ strip [29] and then in the $2^h < RA < 7^h$ strip [30].

The use of surveys to study the variability of radio sources has a certain advantage due to the fact that in the process of the survey the antenna is focused onto a certain elevation H (declination Dec^0 of the central survey section) and its configuration remains practically unchanged during the runs. This reduces the errors due to the repositioning of the antenna, which is especially important for the determination of flux densities of faint sources.

Another advantage of blind surveys is that due to the specificity of the power beam pattern (PBP) of RATAN-600 its field simultaneously covers many sources in a single run of the sky strip. The number of sources crossing the PBP that can be identified in records increases with the sensitivity of the telescope and integration time. Integration time is determined by the number of repeated transits of the given sky strip (i.e., the number of scans). The number of transits of the observed sky strip in the surveys considered varied from 20 to 35 depending on the survey and hour of observation. Thus repeated scanning of the same sky strip in the surveys not only increases the number of objects, but also makes it possible to study fainter sources.

Note that the data of the considered surveys can be used to study the long-term variability of radio sources on time scales of several years, which is known to be due to the nonstationary processes in AGNs.

2.2. Selection of sources for construction of calibrating curves and estimation of flux density errors

The principal aim of calibration source selection is to derive the calibration curves that can be used to compute the source flux densities and to estimate the flux density errors. We selected RCR radio sources with steep and well-studied spectra with available flux density data at several frequencies. We selected sufficiently bright objects with minimal scatter of data points in their spectra. Radio sources with steep spectra seldom exhibit variations at frequencies greater than 1 GHz. However, such variability is observed in objects where a compact component is found, which is responsible for flux density variations. Our sample does not include known variable sources, which have mostly flat spectra. Most of the selected sources have spectral indices $\alpha_{3.94} < -0.75$ ($F_\nu \sim \nu^\alpha$) and r.m.s. errors of the scatter of data points on the spectrum $RMS^{sp} < 20\%$. According to the data of the used catalogs, the source flux density errors at different frequencies lie in the interval from 6% to 28%. The average flux density error for the entire sample of calibration sources is 15% ± 0.03%.

Let us recall some of the features of the observations on the RATAN-600 radio telescope whose PBP differs significantly from that of a parabolic dish [37]. In the mode of single-sector observations the PBP broadens with increasing angular distance from its central section. Correspondingly, the farther the source is from the central section, the broader is the response width and the weaker the signal. One-dimensional scans are superpositions of the sources that have crossed different horizontal sections of the power beam pattern.

To find variable sources in the data of the deep surveys carried out on the RATAN-600 radio telescope in 1980–1994, we performed a more thorough selection of calibration sources, constructed the experimental dependences F/T_a and computed calibration curves, performed a detailed analysis and estimated the relative standard errors for each survey.

To test the calibration sources for variability, we performed quantitative estimates of the parameters V_R [1], V_F [38], and the long-term variability index V [39] that characterize the variability of objects (our main parameter was the index V) and analyzed the statistical properties of suspected variable objects**.** Out of the entire sample of calibration sources (about 80 objects) 14 had positive long-term variability indices for at least one pair of surveys.

The estimates of relative standard deviations of flux densities from their mean values averaged over all the surveys, RMS^i (i is number of a survey), for the subsamples with $V > 0$ and $V < 0$ showed that they differ significantly. The RMS^i values for suspected variable sources and for “nonvariable” sources, averaged over the entire sample, are equal to $RMS^i = 0.23 \pm 0.07$ and $RMS^i = 0.08 \pm 0.04$, respectively. This leads us to conclude that the flux densities of the overwhelming majority of calibration sources varied only slightly from one survey to another, and that the flux density errors, on average, did not exceed 10%. Thus, we used for the calibration curve constructing only sources with $V < 0$ and with the χ^2 probability $p < 0.6$.

2.3. Candidates for long-term variable radio sources

As the initial data for the analysis of the variability of RCR-catalog sources, we use several-day average observational runs that have undergone primary reduction. After background subtraction we identified the sources on the averaged scans via Gaussian analysis. A detailed description of the technique used to reduce survey data has been published in [36].

We have searched for variable radio sources using the preserved averaged data from the “Cold” blind surveys carried out at RATAN-600 in 1980–1994. We studied those sources in the right ascension interval $2^h < RA_{2000} < 17^h$ which had flux density measurements at a frequency of 3.94 GHz in at least two surveys. We studied objects with 3.94-GHz flux densities $F \geq 15$ mJy, which are easily identifiable in the scans. We did not perform the study of variability of the objects, for which the flux density estimates in different surveys coincided within the measurement errors, or they were detected in a single survey only, as well as blended sources.

To reveal variable sources among the RCR objects of the considered sample, we estimated the long-term variability index V, the relative variability amplitude $V\chi$, the χ^2 probability p, and the parameters V_R and V_F.

In the interval of $2^h < RA_{2000} < 17^h$, 429 of 830 objects of the RCR catalog were studied for variability. We detected significant flux density variations for 73 of 429 objects studied for variability with a probability of $p > 0.6$ by the χ^2 criterion.

From our measurements, there are no significant flux density variations detected for five sources included in the OVRO monitoring program and/or marked as variable in NED database. Taking into account these 5 sources, we detected 78 variable sources in the region studied, which is equal to about 10% of the whole number of sources detected in the interval of $2^h < RA_{2000} < 17^h$, or 18% of the number of objects (429) that were studied for variability. This coincides with estimates for about 10 – 30% when searching for radio variability with the archive data [1, 40].

Radio luminosities of the studied sample of variable sources at 1.4 GHz fall within the range of $10^{24.5}$–$10^{29.5}$WHz^{-1}, i.e., all these objects are powerful radio sources. There are more galaxies (52%) than quasars (40%) among them. The number of objects with steep spectra ($\alpha_{3.94\,GHz} \leq -0.5$) is greater than with flat ones. Variable sources can have different kinds of morphological types, although, there are more point sources and sources with a core by 10 – 17% than among nonvariable objects.

The tenth part of variable objects are not compact and have significant angular and linear sizes (from 100 to 500 kpc), and also there are features in the morphological structure which are probably caused by a recurrent phase of the radio source activity. All the extended sources are associated with galaxies that have neighbors. One possible explanation of their variability is a change of internal jet orientation which does not coincide with the formed jets of a radio galaxy. In a number of cases, such changes could be caused by gravitational interaction with a close massive neighbor.

2.4. Search for optical variability for the candidates for long-term variable radio sources

To search for variability of host galaxies in the optical range [31], we used the USNO-B1 [41], GSC2.3 [42], SSS [43], and SDSS DR12 [44] catalogs, in the infrared range 2MASS [45], LAS and GPS UKIDSS [46]. The USNO-B1, SSS, and GSC-2.3 catalogs are based on the series of photographic sky surveys.

We estimated the V_R parameter which characterizes the amplitude of brightness variations. Fifteen objects from the list of variable radio sources are marked as variable in the optical range in the NED database. Thus, the variability in the optical and/or infrared ranges is observed for 35 (V_R>2.5) of 73 variable radio sources. Accounting for photometry errors, intrinsic for catalogs, the median amplitude of brightness variations of the objects under study is 1.0^m for USNO-B1, SSS, and GSC2.3, 0.15^m for SDSS and 0.36^m for 2MASS and the UKIDSS surveys.

All the host galaxies of the variable sources with brightness in the interval of R filter magnitudes in $13^m \div 18^m$ proved to be variable in the optical range. For the objects fainter than 18^m but brighter than 21^m, the percentage of optically variable objects decreases to 50% – 70%. Among even fainter objects ($R \approx 21^m$), the variability was not detected from the catalog data. The decrease of the percentage of optically variable objects with the brightness decrease is associated with observational selection due to insufficient survey depth and absence of systematic observations of faint objects. In most cases, variability in the radio range is accompanied by variability in the optical range for the quite bright host objects (R < 18^m).

Assuming that emission of an active galaxy is determined by processes generated by the central engine and the core is surrounded by the dust torus, we can suppose that the amount of the observed optical emission depends on the degree of obscuring the central source by the torus, and the radio emission generated by the active core is detected to the full extent.

The ratio of optical luminosity to radio luminosity can be referred to a characteristic of the shading factor of the torus. To check this, we used the RCR sources with a known type of the host object and redshift (about a half of the catalog's objects) which allowed us to estimate their radio luminosity and absolute magnitude. We analyzed to which extent the ratio of absolute magnitude to logarithmic radio luminosity, $k = -M_r/\log(L_{3.94})$, taken with the opposite sign, differs for galaxies and quasars. We found that the quasars demonstrate quite constant value of this ratio, $k \approx 0.94$, independent of the power of a radio source; for the galaxies, it varies from 0.77 to 0.92. The k parameter for strongest galaxies is minimal, then with the radio luminosity decline after some value, it starts to grow up to the values observed for quasars. Different behavior of k for galaxies and quasars shows that there is a relation with obscuring characteristics of a torus. The dependence of this parameter on radio luminosity for radio galaxies indicates that the obscuring properties of the dust torus are different for the sources of different radio luminosity.

The comparison between the RCR sources for which there are no significant flux density variations detected and variable radio sources including those with brightness variations in the optical and/or infrared ranges according to the catalog data showed that the k median value and the proportion of the sources with flat spectra grow from the first group to the last one. If we view this as a manifestation of the dust torus orientation and its shading characteristics, then we can conclude that the core of variable sources is more open to an observer.

3. Search for long-term radio transients in the RATAN-600 blind surveys

Let us note that the sources detected at least in two surveys were included into the RCR catalog [36]. A number of sources detected in one survey only were not included in the RCR catalog. The reason is that due to precession they turned out at different distance in declination from the central cross-section of the survey in different years. With increasing source's distance from the central cross-section, the sensitivity of the survey turned out insufficient for detection. Moreover, the sensitivity of the surveys slightly changed from cycle to cycle. In an additional analysis of the survey scans, which was conducted in order to discover transient signals, we singled out twenty-two sources identified with the NVSS objects. They make about 4%of the number of the sources from the RCR catalog.

As a criterion of the transient nature of a source, apart from its absence in the NVSS and other catalogs, we adopted the condition of its detection in scans of only one single survey of 1980, 1988, 1993, and 1994 provided that the sensitivity of at least one another survey would be enough for its detection.

The characteristics of the surveys, taken from [30, 31], are given in Table 1, where column 1 shows the name of the survey, column 2 - the elevation of antenna positioning H, 3 - the begin and end dates of the survey, 4 - the duration time of the surveys Δt, in days, 5 - the number of scans N from which we obtained the averaged record, 6 - root-mean square error of noises in the averaged scans σ, in mJy, 7 - the detection threshold F_{min} in the averaged scan, in mK. Notice that the search for transient events using the data from the Cold surveys is complicated by different sensitivity of the surveys and precession, due to which the region of the survey slightly shifts.

Table1. *Characteristics of the surveys conducted on RATAN-600 in 1980–1994*

Survey	H	Dates	Δt, days	N	σ, mK	F_{lim}, mJy
1980	51°07'.9	Mar 15, 1980–Jun 06, 1980	84	25-50	0.7	8.0
1988	51°08'.7	Dec 16, 1987–Jan 12, 1988	28	25	1.1	10.6
1993	51°09'.6	Sep 17, 1993–Nov 01, 1993	46	46	1.6	10.4
1994	51°22'.0	Apr 01, 1994–May 25, 1994	55	40	1.2	11.1

Upon the browsing the scans of the surveys in the right ascension range 2^h < RA < 17^h, three transient events were discovered (see Table 2). All of them were found in the scans of the 1980 survey, which differs from the further ones by the best sensitivity, low noise, and also by longer duration (longer accumulation time). The antenna temperatures T_a of the detected events exceed 3–5σ. Transient radio sources completely meet the above requirements. Although the sensitivity of the 1988, 1993, and 1994 surveys suffices for their detection, they are not detected in the scans. The characteristics of transients are given in Table 1, where column 1 shows the name of the event, column 2 – right accession with error, 3 – declination with error, 4 – flux density on 3.94 GHz, in mJy, with error, column 5 shows the estimates of the ratio T_a/σ, which these sources should have had in the records of the 1988–1994 surveys with regard to the sensitivity of these surveys and the flux densities obtained from the 1980 survey.

Table2. *Transients in the interval* 7^h *< RA <* 17^h *in the 1980–1994 surveys*

Name	$R.A._{2000}$, hh mm ss.s	Dec, dd mm ss	F, mJy	T_a/σ, in 1988-1994
J111417+045530	11 14 16.7 ± 0.6	+04 55 30 ± 45	21.0 ± 2.0	5.2–7.5
J113344+045030	11 33 44.1 ± 0.6	+04 50 30 ± 45	24.3 ± 2.5	3.4–4.0
J165433+045457	16 54 33.1 ± 0.3	+04 54 57 ± 45	88.2 ± 8.5	11.1–16.6

Notice that the considered data are the average from 20 to 35 of the processed records of the sky stripe passing, depending on the survey and the observing hours, which excludes the presence of random noise, moreover, the level of man-made noise near the telescope was low in 1980–1994. The scans averaged over all observations of the surveys are time intervals from one to three months. Thus, the transient events detectable in the available data will refer to slow radio transients with the duration of the event from weeks to months. Unfortunately, neither the archive of the RATAN-600 observations nor the authors of the surveys preserved daily records or groups of the averaged records that could be of use for a more detailed analysis of the events and their interpretation.

As far as the goal of the paper is to study the possibilities of detection of transient events using the observed data obtained in the RATAN-600 blind survey mode but not their investigation, we considered it possible to use the preserved scans averaged over the whole set of observations to search for long duration transients.

After the checking of the supernovae list, and the SIMBAD and NED databases including the catalogs of cataclysmic variables, Wolf-Rayet stars, Xray binaries, and M dwarfs, radio sources which are available in VizieR, SIMBAD, and NED databases, we have not found any coordinate coincidence (r = 2). A search for coincidences with detected transient events was also carried out. Using the data from radio, optical and infrared surveys, we made assumptions on the possible nature of these events. The first transient is probably associated with AGN activity, the second with a cataclysmic GRB event or with a supernova, the origin of the third is not determined.

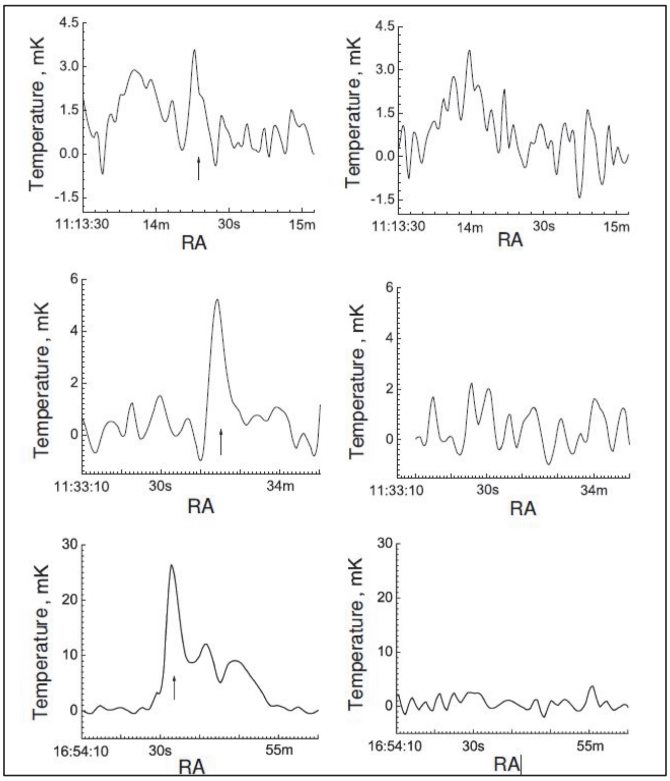

Fig1. *On the left: the regions of the averaged scan of the 1980 survey, which show the supposed transient sources J111417+045530, J113344+045030, and J165433+045457 (top to bottom). In the figures, they are marked with arrows. On the right: for comparison, with the scan of the 1994 survey where the same data regions are given.*

The survey area in the right-ascension interval $2^h < RA_{2000} < 17^h$ is 157.5 square degrees. Total accumulation time of the surveys is about 7 months. So the estimation of the radio transient surface density is $3 \times 10^{-2}deg^{-2}$ with the detection level 8–13.5 mJy on 3.94 GHz and 1 day duration of a transient. If it takes into account only accumulation time of the 1980 survey the density is more than twice higher.

4. Conclusion

Using the processed data from the Cold surveys conducted on RATAN-600 in 1980–1999, in a few our papers we tried to detect variable objects and transient events. The strategy of conducting the deep search Cold surveys was primarily aimed at obtaining data to search for microwave background fluctuations but not at the study of radio sources. Nevertheless, we discovered seventy-three sources suspected in variability, three transient events, and twenty-two radio sources which had not been included in the RCR catalog due to the selection criterion applied: the presence of a source in two surveys at least.

In the attempt to interpret the origin of the detected transient signals, we found that they most likely refer to three different events. One of them can be referred to transient events associated with active galactic nuclei, the second one—to afterglows in the radio band of cataclysmic GRB events or supernova explosions, and the origin of the third one is undetermined.

Thus, taking into account the characteristics of the available radiometers and the observation strategy, the RATAN-600 radio telescope can be used not only for monitoring of the known variable radio sources but also as a tool to search for variable and transient events.

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