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The search of radio transients in the RATAN-600 radio telescope 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 1980-1994. 17% of the total studied sources can be attributed to the variables in radio range. About half of them has significant variations in optical brightness according to the data of the catalogs. At the level of 3-5 r.m.s. we found three transient events. Two weak events probably associated with AGN activities or with cataclysmic events such as GRB and a supernova flash. The nature of the third event has not been established. 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. radio continuum: astronomical data bases: miscellaneous, surveys, galaxies: active, radio continuum: galaxies, methods: data analysis

1. Introduction

The strategy of conducting of the deep blind survey of the "Cold-80" experiment on the RATAN-600 radio telescope in 1980 was primarily aimed at obtaining data to search for microwave background fluctuations. The survey covered the strip of sky centered on SS 433 ($Dec_{2000} = +4°54'$) with width of 40 arc minutes on declination and 24 hours range on right accession. The catalog RC (RATAN Cold) with a detection threshold of 10 mJy on 3.94 GHz was produced based on the observations of the survey (Parijskij *et al.* 1991, Parijskij *et al.* 1992). To refine flux densities and coordinates of the sources of the catalog, several more observing runs were carried out in 1982–1999 on RATAN-600 at the same frequency and declination.

The RCR (RATAN Cold Refined) (Soboleva *et al.* 2010, Zhelenkova *et al.* 2017) catalog was obtained using newly re-proccesing scans of the "Cold-80" experiment and runs in 1982–1999, which underwent primary processing with the RATAN-600 standard software. The catalog contains the right ascensions and fluxes of about 800 objects identified with those of the NVSS (Condon *et al.* 1998) catalog in the right-ascension interval $2^h < RA_{2000} < 17^h$. The sky surveys made with RATAN-600 is to obtain more comprehensive information about the spectral indices of decimeter-wave sources. The main and important conclusion of such surveys is that we found no objects within the right ascension interval considered at least at the about 13 mJy level on 3.94 GHz that had not been previously included into decimeter-wave catalogs.

The reduction of the data of these surveys revealed that flux densities of a number of the objects vary from one observing run to another. To examine this issue, we use the data of the surveys carried out in 1980, 1988, 1993, and 1994. We conducted this work in several successive stages, which included an evaluation of the detection opportunity and development of the search technique of variable sources by means of these surveys (Majorova & Zhelenkova 2012), the selection of sources with significant variations in flux density (Majorova & Zhelenkova 2013, Majorova *et al.* 2015), the search for transient events (Zhelenkova & Majorova 2016a), as well as the search for variability in optics on all available optical and infrared sky surveys (Zhelenkova & Majorova 2016b).

2. The search of variable radio sources

We studied those sources which had flux density measurements at 3.94 GHz in at least two surveys. 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.

The RATAN-600 power beam pattern (PBP) differs from that of a parabolic dish. The PBP broadens with increasing angular distance from its central section. The farther the sources is from the PBP center the broader the responce width and weaker the signal. One-dimensional scan is a superposition of the sources that have crossed different horizontal sections of PBP. We needed to derive the calibration curves that can be used to compute the source flux densities and to estimate the flux density errors.

To find variable sources in the data of the deep surveys we performed a more thorough selection of calibration sources. We then constructed for each survey the dependences of $F^i_{3.94}/T^i_a$ on dH. Here $F^i_{3.94}$ is the is the 3.94-GHz flux density of the calibration source and T^i_a is its antenna temperature. We determined $F^i_{3.94}$ from the approximating curve of the spectrum of the corresponding source, and T^i_a from the Gaussian analysis of the averaged survey record. And with the computed calibration curves we performed a detailed analysis and estimated the relative standard errors for each survey. To derive these curves, we selected RCR radio sources with steep and well-studied spectra with available flux density data at several frequencies.

The detection thresholds (or average 3 r.m.s. values) in these surveys were equal to 8.0±0.5 mJy for the 1980 survey; 10.6±1.3 (1988); 10.4±3.7 (1993); 11.1±2.0 (1994).

We estimated the long-term variability index V of each studied source, its relative variability amplitude V_χ , and the χ^2 probability p. We detected significant flux density variations for 73 objects with a probability of $p > 0.6$ by the χ^2 criterion in the studied region, which is equal to 17% of the number of the sources (429 objects) that were studied for variability.

Let us note that the sources detected at least in two surveys were included into the RCR catalog (Soboleva *et al.* 2010). A number of sources detected in one survey only were not included in the 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 22 sources identified with the NVSS objects. They make about 3% of the number of the sources from the RCR catalog.

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Table 1. Transients in the interval $2^h < RA < 17^h$ in the 1980–1994 surveys.

Name	RA, hh mm ss.s	Dec, dd mm ss	$F_{3.94\,GHz}$ 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

3. The search of transient events

The archive data of the surveys are also used for searching and estimating the frequency of radio transients. They are frequently thought to be associated with different types of events and objects. They can be supernovae or afterglows of gamma-ray bursts, tidal disruption events (TDE), tidal disruption flares (TDF) and others. The activity of stars and compact objects in the Galaxy can be also detected as a transient event in the radio range.

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. We detected three events at a level of 3–5 r.m.s. (Tab. 1). 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, about 3 months). The antenna temperatures T_a of the detected events exceed 3–5 r.m.s. 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. After the checking of the supernovae list, and the SIMBAD and NED databases including the catalogs of cataclysmic variables, Wolf-Rayet stars, X-ray 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.

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. Optical variability of the discovered variable candidates

We used FIRST radio maps (Helfand *et al.* 2015) to cross identify the radio sources of the RCR catalog with available digital optical and infrared sky surveys (Zhelenkova *et al.* 2012, Zhelenkova 2013a, Zhelenkova *et al.* 2013b). Digital images in various filters and the coadded in a few bands images, are analyzed for the sources with no optical candidates found in the catalogs. We failed to find any optical counterparts only for 6% of the sources because their host objects proved to be fainter than the limiting magnitude of the corresponding surveys. A little over half of all the identifications proved to be galaxies; about one quarter were quasars, and the types of the remaining objects were difficult to determine because of their faintness.

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To search for variability of host galaxies of the studied radio sources in the optical range, we used all available catalogs in the optical and infrared ranges. Typically photometry errors of the photographic survey are estimated at $0.^m3$ and for digital surveys they are $0.^m01 - 0.^m85$, though they can be greater for fainter objects. We converted the optical magnitudes of the hosts to the R band values, and the infared magnitudes to the K band values.

We estimated the V_R and V_K long-term variability coefficients. Host objects of the radio sources under study, for which at least one of the calculated variability coefficients exceeds 2.5, are included in the subsample of the objects suspected of variability in the optical and/or infrared ranges.

Thus, the variability in the optical and/or infrared ranges is observed for 35 of 73 variable radio sources. It follows from our analysis that all the host galaxies of the variable sources with brightness in the interval of magnitudes in R band $13^m - 18^m$ 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 ($> 21^m$), 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.

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