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IKI/ASC at the RATAN–600 in 1979–1996: spectra monitoring and the nature of long–term variability of extragalactic radio sources[1]

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Abstract. A brief survey of the Programme for studying the long-term variability of extragalactic radio sources, based on the 5–7 frequency monitoring observations of the instantaneous 1–22 GHz spectra at the radio telescope RATAN–600 is presented. The principal obtained results and plans are discussed.

Key words: multifrequency monitoring – instantaneous spectra — variability – compact objects – modelling — VLBI – structure – cosmological parameters

1. Introduction

Since the discovery of the radio emission variability of compact extragalactic radio sources (Sholomitsky, 1965; Dent, 1965) the interest in this phenomena has not abated for more than 30 years. A multitude of unexpected and to a large extent still unexplained peculiarities have been found. The variability on different time scales (from hours to several years [2]) over a wide frequency band (from radio to optical and higher frequencies) indicates extremely high compactness in the central engines of active galaxies and apparent brightness temperatures exceeding the theoretical Compton limit of 10^{12} K for noncoherent synchrotron emission in stationary objects. The apparent superluminal velocities also indicate the presence of relativistic plasma and motions in the AGN compact cores. The variable radio sources are connected with VLBI-compact sources on milli–arcsecond scales.

If we take into consideration also the applied importance of the system of compact sources with highly accurate coordinates on the sky to use this system for the aims of geodesy, geophysics and navigation, then the role of such objects and multifrequency monitoring and physical modelling the spectra and structure of many sources in a wide frequency band become more important.

Research has demonstrated that the nature of HF variability (at frequencies higher than 2–3 GHz) and LF variability (at frequencies lower than 1–2 GHz) can be different, because the HF and LF variations, if both exist, are probably not correlated (Padrielli et al., 1987; Mitchel et al., 1994). It is believed that the HF variability is due to intrinsic processes in the sources, while the LF variability is caused by processes in the interstellar matter. However, some sources do show correlated HF and LF variability, and, for example, mutifrequency long–term LF and HF variations between 0.3 and 15 GHz for the quasar 0235+16 and, possibly, between 0.3 and 300 GHz for the quasar 2145+16 have been modelled by the processes inside the sources (O'Dell, 1988; Kovalev and Larionov, 1994; Kovalev, 1996a).

The nature of HF variability is usually explained by eruptions from the compact nucleus of an object — by expanding synchrotron clouds (Shklovsky, 1960, 1965) or jets (Kovalev and Mikhailutsa, 1980), as well as shocks in the jets (Blandford and Königl, 1979). The models can generally explain variations in a narrow frequency band, but the difficulties enhance rapidly with increasing bandwidth or adding structure variations to analysis. Conversely, only observations covering a wide frequency range can discriminate between various proposed models. Nevertheless, most of the monitoring of multi–frequency observations have been concentrated only either on the spectral or on the structural behaviour because of the problems in techniques or coordination of observations, and only in some special cases spectra and structures both have been observed at several epochs (for more details see Altschuler, 1989; Kellermann, 1994).

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[1] The paper has been prepared using the oral report on the 30th anniversary SAO Conference in October 1996.

[2] Flux variations ∼30% for ∼3 years scale at the centimetre wavelengths are typical.

For example, Teräsranta et al. (1992) presented the results of 10-year HF monitoring at 22, 37 and 87 GHz. Gear et al. (1994) presented the results of analysis for a few selected sources at 10 frequencies from 5 to 375 GHz at 3 epochs. Mitchel et al. (1994) showed the results of a 5–year study of LF variability at 5 frequencies from 0.318 to 1.40 GHz.. Padrielli et al. (1987) study characteristics of LF variable sources. Bondi et al. (1996) summarize the results of 15-year monitoring at 408 MHz. Aller et al. (1985) have weekly monitored polarization of several dozens of variable radio sources at 3 centimeter wavelengths for many years. The discussed monitoring at 5–7 frequencies between 1 and 22 GHz (Kovalev, 1991; Berlin et al., 1992) connects both regions of variability by the instantaneous spectra, but still higher and lower frequencies are necessary for an adequate study. Broadband (from radio to optical) quasimultaneous spectra of 25 extragalactic sources for one epoch have been studied by Landau et al. (1986). Radio–optical observations give also the rapidest variations of the emission — on the scales of days and hours (Wagner & Witzel, 1995).

The relation between specific spectral and structural parameters has been studied by Wehrle et al. (1992) for many sources using the total flux densities at up to 3 frequencies and VLBI maps at 5 GHz for 3 epochs. Eight VLBI observations for six years as well as multifrequency VLA, VLBI and single dish observations of the superluminal quasar 4C 39.25 have been performed by Shaffer et al. (1987) and Marsher et al. (1991). Involving 3–frequency radio spectra, Gabuzda et al. (1994) have studied polarized maps of the BL Lacertae object 0735+17 at 2 frequencies for 3 epochs, and Kovalev (1997) has studied the polarized structure of the rapidly variable BL Lacertae object 0716+714 at 3 frequencies for 2 epochs using the world's VLBI and VLBA arrays. Kellermann et al. (1994) have searched for compact cores using images with resolutions 0.5 and 18 milli-arcseconds. Kellermann (1993) uses the VLBI compact objects for estimations of the deceleration parameter of the Universe, while Ma et al. (1990) — for geodesic purposes.

Presenting new important information, radio images are the material which is difficult to successfully compare with the model images. By the present time only a few papers have been known with a numerical simulation of the milli–arcsecond structure and with more or less successful comparison of the observed and simulated maps for variable sources, using various models: Hughes et al. (1991) studied BL Lac and 3C 279, Gomez et al. (1993) — 3C 279B, Kovalev (1995a, 1996) — 0454+84, 2145+06 and typical maps.

The objective of this Programme to improve the situation is to study the nature of variability of extragalactic compact objects by observations and their interpretation by modelling the physical processes in the sources.

2. History and general outlines

The monitoring at the radio telescope RATAN–600 has been performed since 1979 by the astrophysical department (headed by I.S. Shklovsky) of the Space Research Institute of the USSR Academy of Sciences (IKI AS USSR) together with the Special Astrophysical Observatory. In 1990 the department was transformed to the Astro Space Centre of the Lebedev Physical Institute (ASC FIAN, headed by N.S. Kardashev).

In 1978 N.S. Kardashev advised the author to submit to the Programme Committee of the RATAN–600 a Proposal to perform this task (it was believed that time that the "Hedgehog" model of variable radio sources could be relatively quickly tested by observations; the model was popular with some circles of IKI (I.S. Shklovsky, N.S. Kardashev, G.B. Sholomitsky et al. — at our department), FIAN (L.M. Ozernoy), GAISH (the Sternberg Astronomical Institute, V.N. Kurilchik) and with their students). The first set of spectrum measurements was carried out on May 1–22, 1979 for 5 calibrators and 6 well-known variable sources BL Lac, OJ 287, 3C 279, 3C 345, 3C 454.3 and 1510–08. In September of that year the first results of 20–days' observations — results for BL Lac at 4 wavelengths from 2.1 to 13 cm — were reported at a USSR radio astronomy conference and published by Kovalev and Pustilnik (1979). The data were sufficient to disprove the belief of sceptics (V.I. Slysh) that it is impossible to obtain reliable results on variability by using an antenna with variable surface like the RATAN–600. The observations have been continued under support of Yu.N. Parijskij.

11 variable extragalactic objects and 6 calibrators were monitored with various recurrence in the course of 11 runs of the first 3 years[3] (Berlin et al., 1983). In the middle of the period discussed the number of monitored sources increased up to 115, in 1996[4] —

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[3] Setting of the cabin with the secondary mirror and as many as 222 elements of the ring reflector of the radio telescope was done "semi-automatically" by 3–4 operators. *Under the quota of one observation per an hour, they had to read from the table and manually introduce the counts for 6 mechanical limbs (with points) for each element,* and then the values of these counts were realized automatically. The cabin was located at a point on the rails, marked by an operator after he had measured the distance (with a 20 m measuring reel) from one of 8 geodetic indicators.

[4] The radio telescope had been strongly modernized: the height of the elements of the ring reflector has been increased by 30%; the sensitivity had been increased by using the LNA with improved HEMT-transistors for all the 6 receivers, including LNA, cooled to a physical temperature of 20 K for 4

Years, 1900 +	79–82	82–87	87–92	94–96
Total objects	11–16	16–60	115	200
Total frequencies	5–6	6–7	6–7	6
Runs per year	4	3–4	3–4	5
Days per run	6–20	6–7	6–7	10
Objects per day	15–20	20–40	60	60
Registration	P	P–M	Mmera	Mpc
Antenna	S	S	A	A+F
2-nd mirror cabin	H	H	H	H

Table 1: *Information on the monitoring.* Designations: P — paper tape of the recorder; M — magnetic tape of a computer of the type of "Elektronika-60" with manual control of data recording; Mmera/pc — hard magnetic disk of a PC like MERA/PC IBM with a packet data registration; S, A and F — pointing of the antenna elements is Semi-automatic, Automatic and with the auto save of results in a File, accordingly; H — manual measuring of the focal distance by a 20-m measuring reel. Observations from February, 1992 to December, 1994 are absent because of technical work on modernization of the antenna.

up to 200 (see Tabl. 1), in 1997 — up to 600.

3. Observations and data reduction

In general, the methods of observations and data reduction were not changed for all the years, in spite of the progress in the equipment (in 1979 — a pencil and a ruler in the process of manual reduction of the data recorded on paper tape of a recorder; in 1996 — computer automatic packet reducing data written on hard magnetic disk by a system of automatic registration). Practically instantaneous, 1–22 GHz spectra at 5–7 frequencies are measured due to the horisontal location of the receiver horns and meridional observations with the motionless antenna. The regular 5–7 high sensitive radiometers in the cabin No.1 of the secondary reflector are used at the wavelengths of 1.0 (earlier), 1.4, 2.1 (earlier), 2.7, 3.9, 6.0 (earlier), 7.6, 8.2 (earlier), 13 and 31 cm. The parameters of the radiometers are given by Nizhelsky (1996).

The data reduction and analysis of the results are made in the ASC/IKI using computers such as IBM PC (HP 9821A in the eighties) and the original software package, developed by the author and modified with the help of V.R. Amirkhanyan and Y.Y. Kovalev (junior). A signal is extracted from a noise by fitting a model responce to an observed one. There are also used the programme developed by V.R. Amirkhanyan to calculate the diagram pattern of the RATAN–600 with the main beam and secondary lobes (taking into consideration the real aberrations caused by transversal shifts of the receiver horns from the antenna focus), and the FORTRAN programme SVD (Forsythe et al., 1980) to reduce the computer errors of matrix transformations for regression of the responce. Some other programmes of the new software package for data reduction as well as full software for statistical and model analysis of the spectra and structure have been developed by Y.Y. Kovalev (junior).

Output signals from the radiometers are recorded simultaneously and independently. A multifrequency responce to movement of a source is obtained for 1–2 minutes because of the daily rotation of the Earth. Each observation at each frequency (for 5–7 minutes generally) starts and finishes by a sequence of responces to switching on and off a noise signal generator (NS) with a stable constant power level. Here (as is the case in radio astronomy) the amplitude of NS is used as a high accuracy scale of "a ruler" (with a variable length due to the variable gain of a radiometer) to put it to different observational responces and, in such a way, to measure the amplitude T of a source responce relative to the amplitude T_{ns} of the NS responce, T/T_{ns}.

Using observations of known calibration objects — generally accepted secondary standard calibrators of the spectral flux density scale (Baars et al., 1977; Ott et al., 1994), — the amplitude of the NS responce is calibrated to the units of this scale (to $F_{ns}(h_i)$ at the heights h_i of calibrator observations, after averaging the repeated observations and including the corrections for the linear polarization and the angle resolution). Then the calibration curve $F_{ns}(h)$ is approximated over these points to all intervals of the heights h of observations, using the known method of regression analysis (see the example in Fig. 1).

Finally, the measured spectral flux density F_ν is calculated as $F_\nu = (T/T_{ns})F_{ns}(h)$. The values of T/T_{ns} for sources under study and calibration (and also $F_{ns}(h)$ as a result) are corrected for the atmosphere extinction in the ordinary way of calculations using the meteorology parameters, if necessary. The method of spreading the average error as well as the value of the rest squares sum are used to estimate the errors. All mean values are calculated as weighted values. In most cases the main part of the errors of F_ν were the calibration errors of $F_{ns}(h)$ because relatively strong objects were monitored ($F_\nu > 0.5$ Jy as a rule), or the rest errors caused by the industry interferences.

Due to averaging and frequent daily observations of 5–7 calibration objects (with wittingly stationary emission), the calibration errors include "automatically" also the errors caused by the instability of parameters of the atmosphere, antenna and radiome-

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radiometers; registration of the output data as well as setting the elements of the ring reflector was done automatically — in a packet regime, creating a file with the result of actual setting the antenna elements (whilst still without the cabin with the second mirror).

ters. The mean relative errors of calibration in the first 3 years of observations (11 runs since 1979) at the wavelengths 31, 13, 8.2, 3.9, 2.1 and 1.4 cm were (3.3 ± 0.7)%, (3.6 ± 0.7)%, (2.3 ± 0.4)%, (3.0 ± 0.3)%, (4.0 ± 0.5)%, and (8.4 ± 1.7)%, respectively (Kovalev, 1985: Tabl. 4,5). In two recent runs of 1996 (in June and July) at the middle heights they were typically within 1–3 %, depending on the wavelength (excluding the errors of the flux density scale itself). The errors of absolute calibration of the used scale are estimated by Baars et al. (1977), Ott et al. (1994) as 10% at 22 GHz and 5 % at lower frequencies.

4. Principal tasks and results

The major task of the first part of the monitoring was to study several dozens of the well–known variable objects to investigate the observed quantities of the temporal variability of the instantaneous spectra as well as the possibility of their physical modelling. It was first found (and explained by the "Hedgehog" model for the first example — outbursts in BL Lac in [illegible]) the presence of "r–type" waves of perturbation, moving along the spectrum from the high to the low frequencies and resulting in the observed outburst of the flux from such waves of opposite polarities (Kovalev, 1984, 1985, 1991; Berlin et al., 1992).

The tasks for the second part of the monitoring were to study statistically complete samples of [illegible]–200 objects of the wider types — VLBI compact sources from the catalog by Preston et al. (1985), which is also the base catalog to select objects for study by the space project "RadioAstron", — for a statistical and model analysis of the instantaneous spectra of the sources of various subtypes, an investigation of connection between the variable and compact objects and a possibility of theoretical calculations of the observed VLBI structure within the same model (see Figs. 2–5). It was first obtained:

1. As a rule, the instantaneous spectra of about [illegible] VLBI compact sources are "smooth" most of the time and may be emitted by the "double" sources, one of the components of which is dominated at the high frequencies of the spectra and must be compact for the VLBI (Nizhelsky et al., 1994; Kovalev et al., [illegible], 1997).

2. A statistical analysis of the istantaneous spectra (Kovalev, 1996b) shows that:

a) the value of the frequency for the spectrum maximum in the local frame is about 10 GHz;

b) a correlation between this frequency and the spectrum maximum is absent;

c) the nature of QSO and BL Lacs may be common.

3. A statistical and model analysis of the obtained spectra provide strong arguments in favour of a single compact component (a jet) in most of the studied objects, in contrast to the often discussed alternative of many single compact clouds — "the multi component structure" can only be seeming, and it may be caused by the complicated profile of the brightness distribution along a *single persistent* jet at the phases of its quasi–stationary or nonstationary flowing out of the active nucleus of an object (Kovalev, 1996a; Kovalev & Kovalev, 1996).

4. The theoretically calculated VLBI structures for some cases of the model of a nonstationary jet are in qualitative agreement with a typical structure observed in VLBI experiments (Kovalev, 1995a) as well as with the spectra of outbursts at the millimeter wavelengths (Nesterov et al., 1994).

5. The discovery of compact objects whose spectra, structure, polarization and variability are explained by the "Hedgehog" jet model (Kovalev & Mikhailutsa, 1980) will allow these objects to be used as cosmological indicators to measure extragalactic distances and fundamental parameters of the Universe — the Hubble and the deceleration parameters (Kovalev, 1994, 1995); three first candidates have been found: these are BL Lac (Kovalev, 1984), 0235+16 (Kovalev & Larionov, 1994) and 2145+06 (Kovalev, 1996a).

5. Strategy up to 2000

Since 1997 a new task has been planned — *a united mass monitoring and analysis of a big sample of compact extragalactic objects: cooperative multi–frequency study of radio–optical spectra and VLBI structure.*

The new comprehensive Programme consists in monitoring, statistical and model analysis of multi–frequency radio spectra, radio–optical spectra and VLBI structure of as many as 1000 compact objects, including about 555 objects of the complete sample from the VLBI catalog of Preston et al. (1985) (with a correlated flux of higher than 0.1 Jy at the wavelength of 13 cm, within the limits of declinations from −30° to +43°), and supercompact objects the milliarcsecond structure of which is observed by the first ground–space radio interferometer in the VSOP survey.

The Programme unites up to 6 scientific tasks due to a new principle of optimization of daily lists of sources, a common method of observations, data reduction and analysis. The base is the monitoring of the instantaneous 1–22 GHz spectra at the RATAN–600 and the cooperation in studying compact objects (including "lensed" extragalactic objects, full samples of BL Lac's and objects from the γ–survey EGRET), using the quasi–simultaneous observations of:

a) the flux density at the other radio and optical frequencies — first of all, with telescopes in Italy (0.4 GHz), Crimea and Finland (22, 37 and 90 GHz),

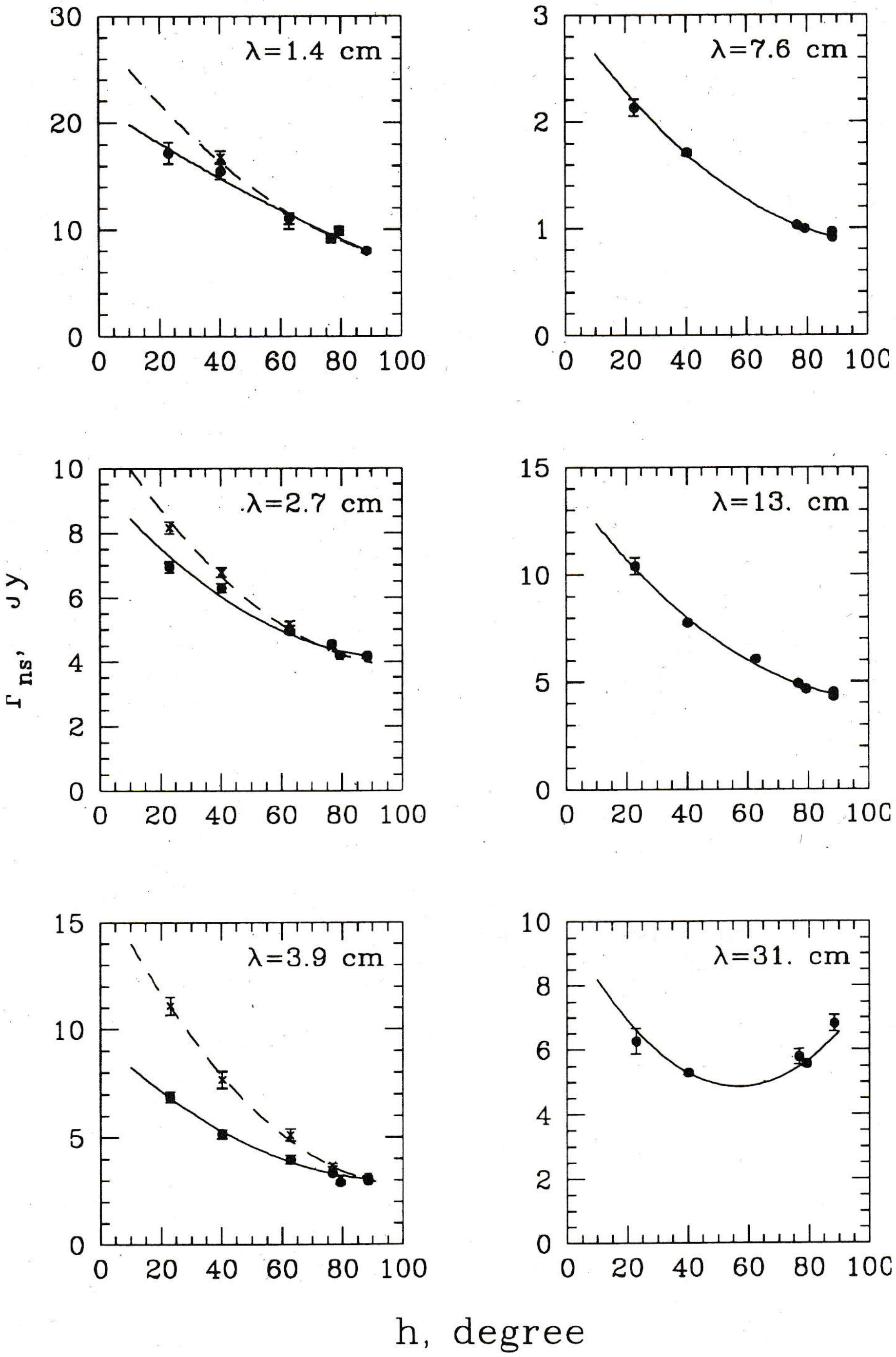

Figure 1: *An example of calibration in 1996, July.*
The flux density F_{ns} corresponds to a measured antenna temperature $T_{ns,\lambda}$ at the angle h above the horizon a a wavelength λ. Calibration curves $F_{ns}(h)$ represent in fact the resulted common dependence on h (averaged ove a run) for a factor $k_{atm}(h)$ (because of atmosphere extinction) and an effective antenna area $A_{eff}(h)$: $F_{ns}(h) =$ $2kT_{ns,\lambda}k_{atm}(h)/A_{eff}(h)$ (k is Boltsman's constant). $A_{eff}(h)$ includes also the real aberration additional dependenc on h because of transversal shifts of the receiver horns from the antenna focus. Curves for 2 horns are shown for th receivers, used a diagram modulation (shifts of horns at $\lambda = 3.9$ cm were very different in the shown run).

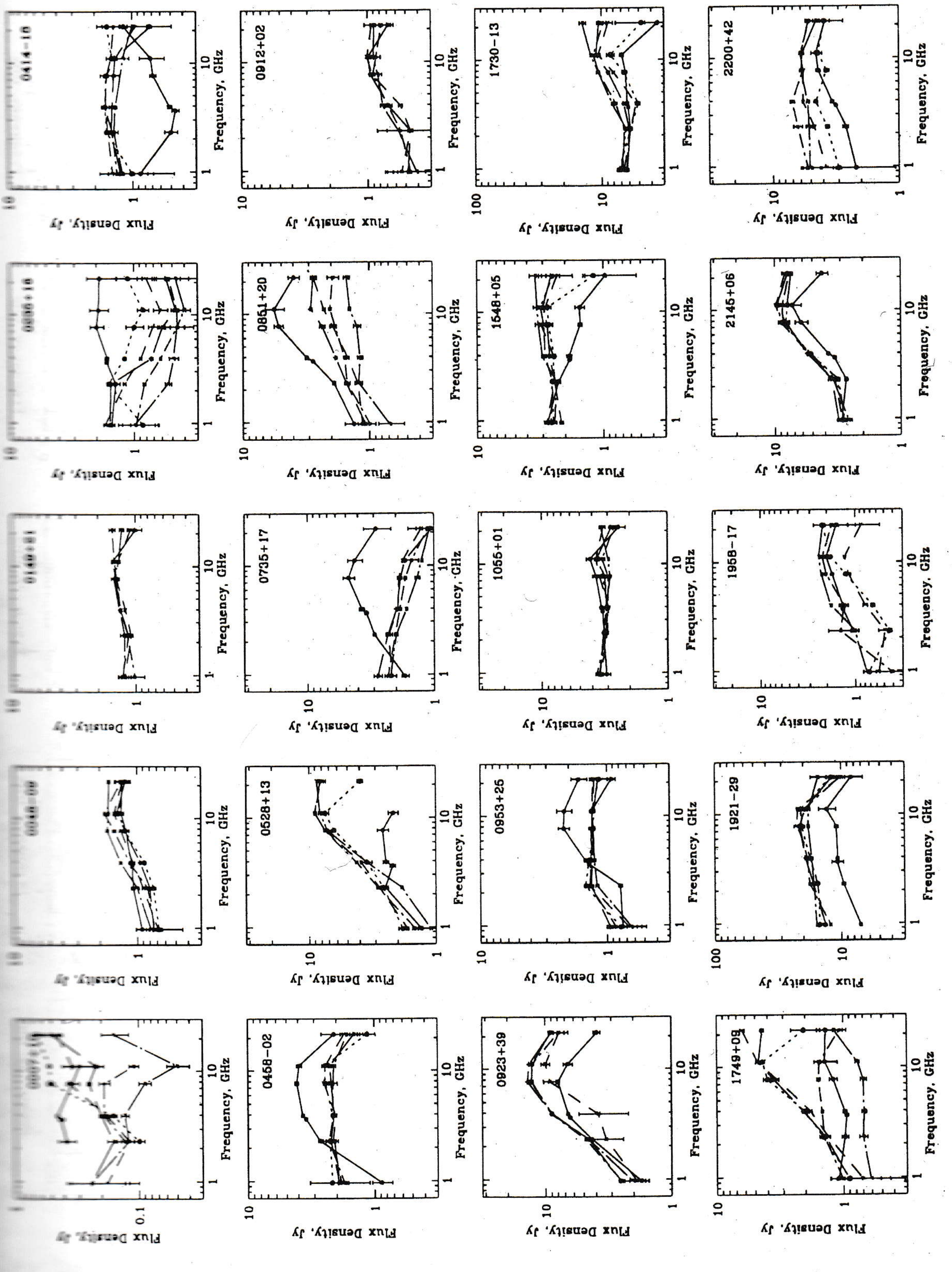

Figure 2: *An example of strong and weak spectrum variability over 7 years.* November, 1989 — solid line; August/October/December, 1995 — dots/short-dash line/long-dash line; March/July, 1996 — short/long-dash-and-dot lines (Kovalev et al., 1996, 1997).

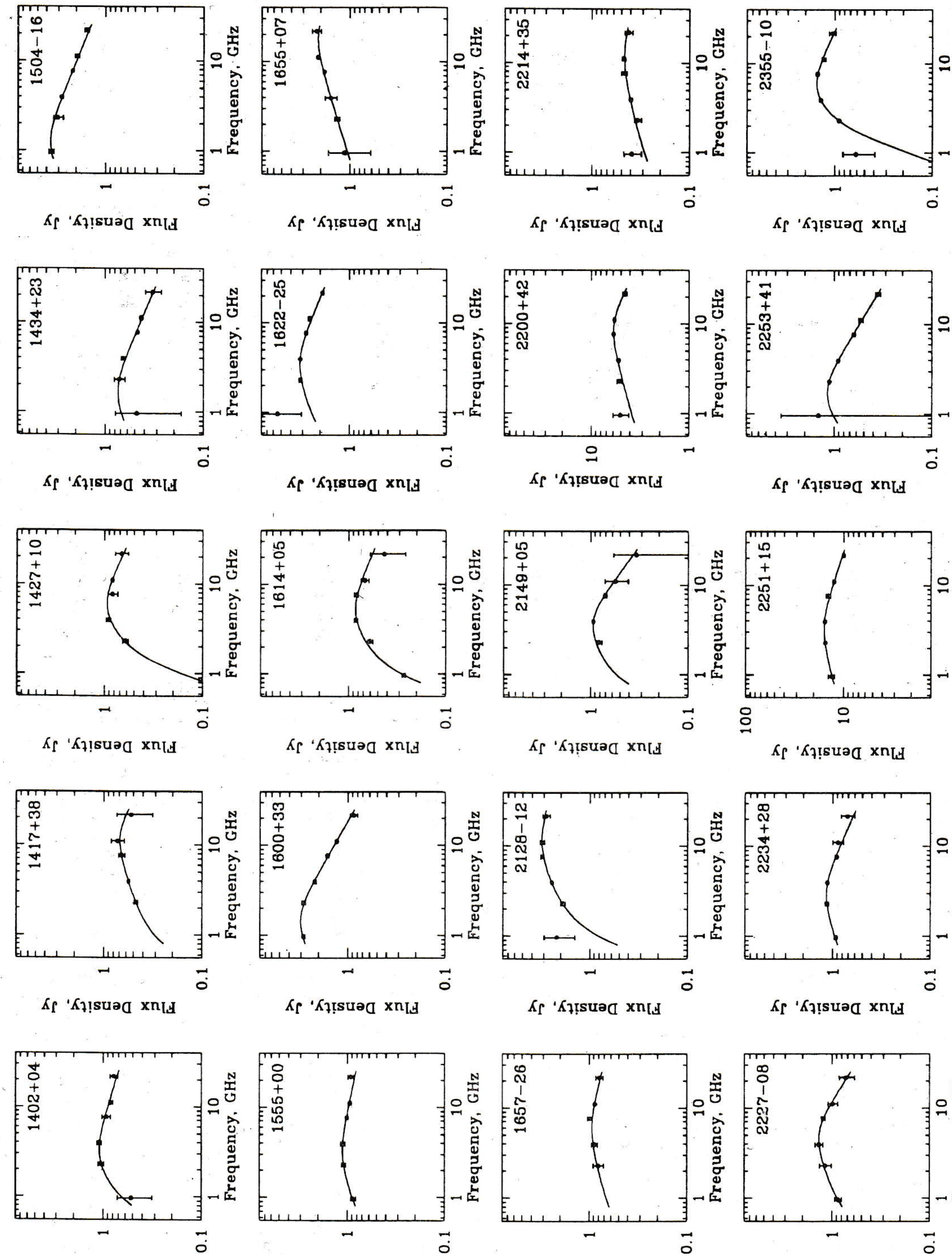

Figure 3: *An example of model analysis of the spectra, measured in July, 1996.*
20 out of 50 objects with the positive results of fitting the "Hedgehog" model to observations (Kovalev and K valev, 1996): solid line — the result of calculations, dots — data of observations. Criteria of χ^2 is satisfied at significa level of 0.05. Each calculated spectrum corresponds to synchrotron emission of a single persistent VLBI–compact of relativistic particles, which stationary flows out of an active nucleus of an object in a quasi–radial magnetic field some angle to an observer.

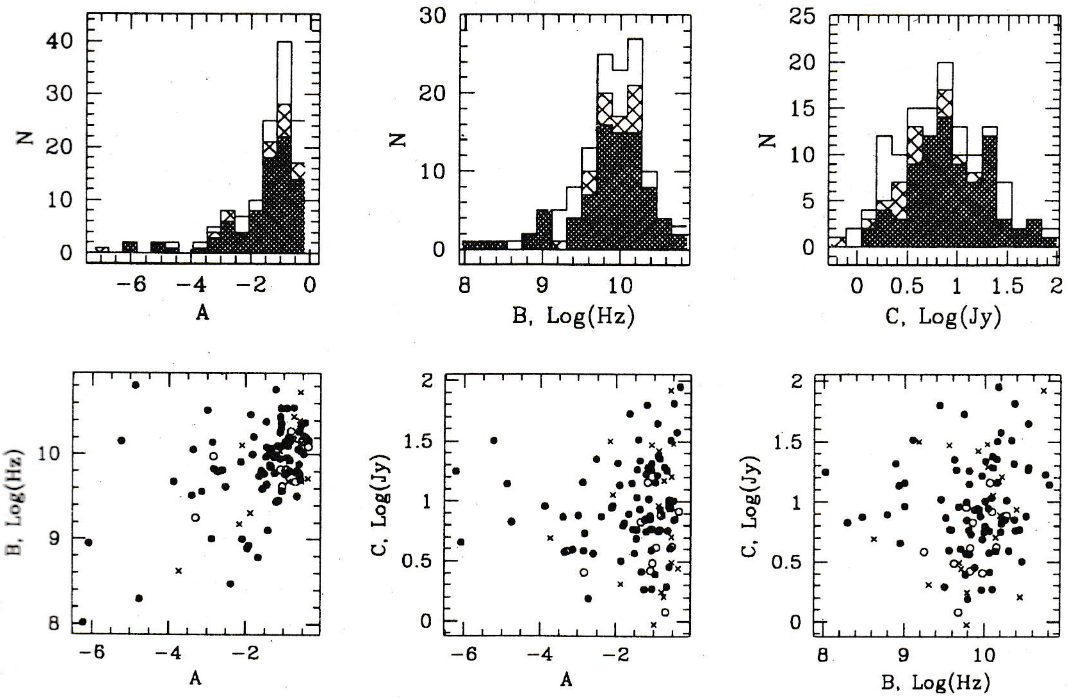

Figure 4: *An example of statistical analysis of spectra for 2 runs — in June and July, 1996.* Results for the mean spectral parameters A (effective width of a spectrum), B (frequency of the spectrum maximum) and C (flux density of the spectrum maximum), Kovalev (1996b). On top: distribution of A, B C (shaded for quasars, crossed for BL Lac's, open for the other objects). On bottom: interdependences of A, B and C (filled circles for quasars, open circles for BL Lac's, crosses for other sources).

small optical telescopes at the SAO RAS and 0.71 m telescope in Germany;

5) milli-arcsecond structures (ASC works, VSOP survey) with the help of the system VLBA and global VLBI network.

In 1996 we started the ground-based support of the VSOP survey by obtaining instantaneous spectra at the RATAN-600. Before the satellite launch about 100 objects were measured in 1996, and after the launch of the satellite with the 8 m antenna in 1997, our spectral monitoring of about 200 objects of the VSOP survey was started. First cooperative results on the radio-optical monitoring for several variable sources have been obtained. We hope that the space-ground network VSOP–VLBA–VLBI will also actively react to measure the structure of the objects on which the interesting outbursts will be registered by spectrum monitoring.

6. Conclusions

Having some experience in observations at the RATAN-600 ("the total length of work" at the RATAN-600 is equal to about 3 years) as well as due to personal impression from a cursory acquaintance with the other excellent telescopes in the world, the author runs the risk to draw the following conclusion (to the point double because of the jubilee of the observatory): the RATAN-600 is today the best radio telescope *for the spectra monitoring of the Programme discussed* in spite of the main problem — the want of long tracking an object. The arguments are as follows: 1) the sensitivity *over one scan* is high enough to do observations of many interesting variable and compact objects at all wavelengths (more than 1000 relatively strong interesting objects), 2) spectra obtained are instantaneous, multi-frequency, and wide-range, 3) the known problems with pointing and tracking the sources are absent because of scanning the "knife-like" beam pattern of the antenna by an object.

Some results of Section 4 may be distorted by the selection effect. It is important to check them using the deeper sample planned in Section 5. For this work to be done, the following points in the plans of the observatory are of paramount importance:

1) increase in stability and interference protection of the radiometers in the cabin No.1; auto monitoring of the meteorology parameters and the radiometer parameters to check the stability of a noise source generator and a receiver tract as well as to save the

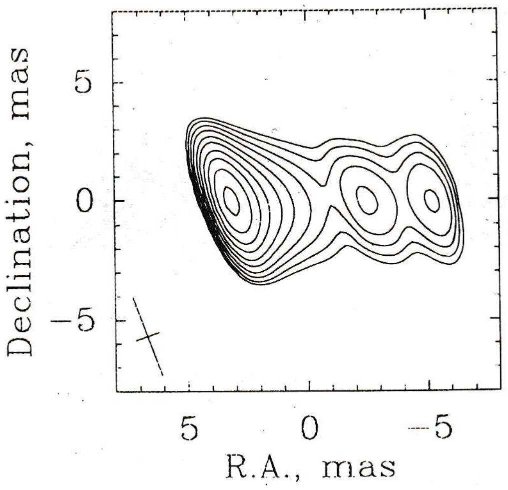

Figure 5: *An example of modelling the VLBI structure.*
3 visual components represent 3 bright parts of *one nonstationary* jet in the "Hedgehog" model but not separate compact clouds (a version of the map from Kovalev, 1995a). The contours are shown at levels of 4, 5.6, 8, 11, 16, 22, 32, 45, 64, 91 % of the maximum value. The map and spectrum of emission of such a jet must be variable in time because of the nonstationary brightness distribution along the jet, caused by the nonstationary character of flowing of relativistic particles out of the active nucleus of the object.

results into the head of a file with observational data;

2) modernization of the procedure of measurements of the focal distance for the secondary mirror — by means of laser distance measurements (this will also allow one to check and register the errors of pointing the secondary mirror *automatically*, for the first time in the 30–year history of the SAO, — which is very important because of difficulties of today's manual checking the results during mass observations);

3) modernization of control by both the "Southern sector" and the "Flat reflector" of the antenna which will decrease 1.5–2 times the observational load on the "Northern sector" of the radio telescope.

If most of the plan is realized, this work may be the widest on regular mass observations of multi–frequency spectra and structure of many hundreds of VLBI compact sources, sensitive on temporal scales from months to several years. Results will be important both for the study of the nature of compact objects and their variability and for their use for practical purposes — in astrometry, geophysics and navigation: for formation of an inercial coordinate frame, studying movement of the Earth's continents, as well as for monitoring of the RATAN–600 parameters.

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