Methodology and the System of automated processing of the RATAN-600 multi-frequency 1–22 GHz observations

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Abstract. The data processing and analysis are carried out at the Astro Space Center of the Lebedev Physical Institute using the YURZUF software package developed and periodically updated by the authors since 1990. The useful signal is separated from the noise by matching the model and observed responses, which is equivalent to the optimal signal filtering mode. For the model response, the RATAN-600 beam is calculated (taking into account real aberrations caused by the transverse displacement of the input feeds from the antenna focus). To reduce errors in the machine inversion of the matrix when approximating the observed response, the well-known SVD program is used. Based on observations of 10–15 known generally accepted secondary calibration sources, the amplitude response of a highly stable noise signal generator (NS) at each wavelength is calibrated in spectral flux density units (in Jansky units) depending on the source height. If necessary, corrections are introduced for the angular sizes and polarization of the calibrators. The core software of the YURZUF multifrequency processing package is described.

Keywords: software; active galaxies: quasars; general radio continuum

1. Introduction

Oleg Verkhodanov and the RATAN-600 Data Processing: Oleg was the first to create a publicly available automated program for step-by-step processing of the RATAN-600 data from the feed cabin No.1 to obtain instantaneous multi-frequency spectra of radio emission for sources in the range of 1–22 GHz — during several years of his working at the radio telescope after graduating from the Leningrad University. This his work, as well as the automation of processing sky survey by the SAI-group, "spurred" also the development of automated processing our joint observations with the SAO at the RATAN-600 in the same years, the results of which are used up to today, and the main software packages are discussed here.

2. Methodology of observations and data processing

The method of obtaining and processing data for many years since the 1990s, in the main, has practically not changed, despite the obvious progress in the operational technology and the modernization of receiver and processing complexes. Due to the horizontal arrangement of the input horns and observations along the meridian with a fixed antenna, practically instantaneous radio spectra are measured in the range from 1 to 22 GHz — by a standard high-sensitivity complex on the RATAN-600 feed cabin №1, consisting of 5–7 broadband radiometers, — at wavelengths of 1.4, 2.1, 2.7, 3.9, 6.2, 7.6, 8.2, 13, 24 and 31 cm (some of them were temporary and today are absent — see Fig. 1–6). Processing the observations and analyzing the results are performed on modern computers using a software package developed and updated by the authors. The useful signal is extracted from the background noise by "fitting" (matching) the model response to the observed one, which is equivalent to the optimal signal filtering mode. In this case, the code by V.R. Amirkhanyan for the formulas by Stotsky is used to calculate the RATAN-600 radiation pattern (taking into account real aberrations due to the transverse offset of the input feeds from the antenna focus) and the well-known SVD singular value analysis program (Forsite et al. 1980) to reduce the errors of machine matrix inversion when approximating the observed response. A number of other processing programs, all programs for statistical and model analysis of the spectra and structure were developed by Y.Y. Kovalev. The signals from all radiometers are recorded simultaneously and independently (see an example in Fig. 2). The multi-frequency response to the passage of the source is obtained in a few minutes due to the daily rotation of the Earth. Each observation at each frequency, usually 3–5–7 minutes long, begins and ends with a series of responses to the switching on of a highly stable noise signal generator (NS) of constant power. As usual, the amplitude of the NS-signal plays the role of the division value of a high-precision ruler (of variable length due to variations of the gain),"applied"' to different records for the relative measurement of the amplitude for the antenna temperatures responses $T/T_{\rm NS}$. Based on observations of known calibration objects — generally accepted standards of the spectral flux density scale — the amplitude of the NS-response is calibrated in units of this scale (at the heights of the calibrators, after averaging repeated observations and taking into account corrections for partial angular resolution and polarization), and then, using regression analysis methods, the calibration dependence $F_{\rm NS}(h)$ is approximated over the entire interval of observation heights h (Fig. 3). After this, the measured spectral flux density F of the object under study is calculated as $F = (T/T_{\rm NS})F_{\rm NS}(h)$. If necessary, the $T/T_{\rm NS}$ value of the objects under study and calibration is corrected for atmospheric absorption by calculations using meteorological parameters. Errors are estimated using the mean error propagation method and the value of the residual sum of squares. All average values are calculated as weighted averages using the method recommended by Agekyan (Agekyan 1972). Their error was further increased by the Student's correction due to the finite number of measurements, to bring the probability characterizing the root-mean-square interval of one sigma to the standard value of 0.683.

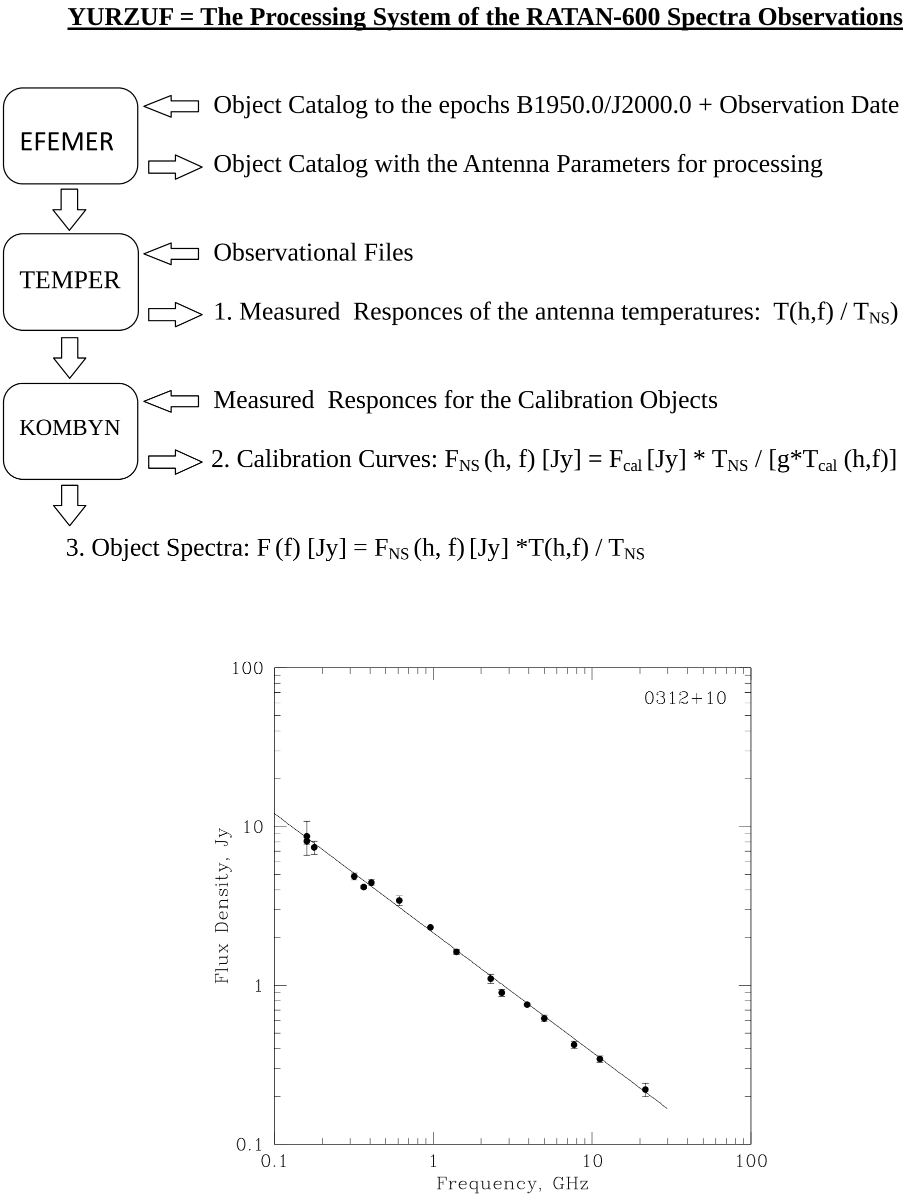

Figure 1. The block diagram of the YURZUF system (top) and the test results of its work (bottom): the RATAN-600 (1–22) GHz data are in agreement with the spectrum (Verkhodanov et al. 2005) out of (1–22) GHz. Top we have defined: T and F — antenna temperature (in K) and spectral flux density (in Jy), $T_{\rm NS}$ — the temperature of the Noise Source, g — correction for angular size and polarization, f — frequency, h — height of the object above the horizon; the calibration curve $F_{\rm NS}(h,f) = 2kT_{\rm NS}/A_{\rm eff}(h,f)$, where $A_{\rm eff}(h,f)$ — the antenna effective area.

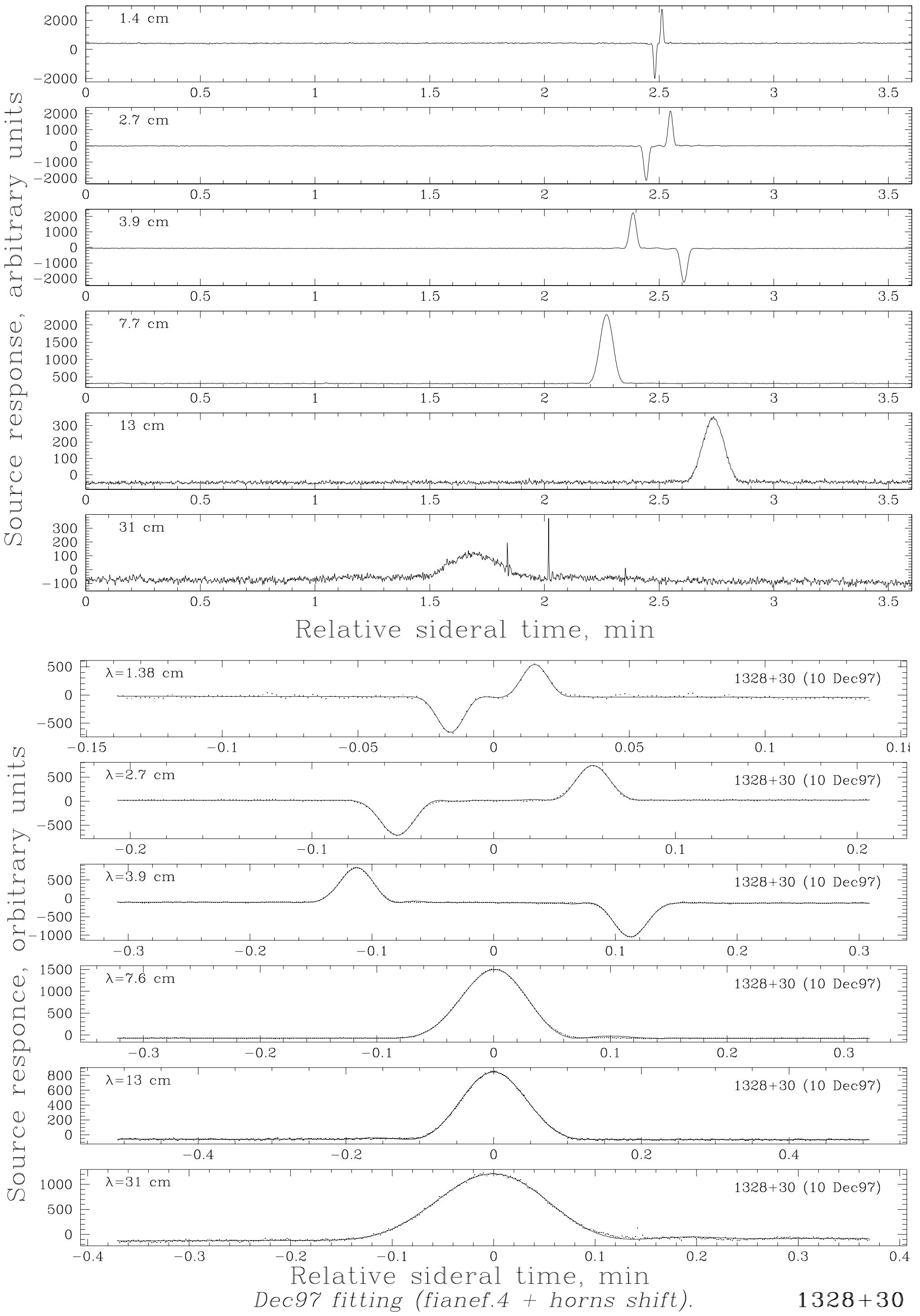

Figure 2. Top (Kovalev et al. 1999): examples of the RATAN-600 radio telescope responce to the passage of the source B0923+39 through fixed antenna patterns during the Earth's daily rotation. Observations were made on December 16, 1997, at 6 wavelengths from 1.4 to 31 cm with an integration time of 0.1 s. Bottom (Kovalev et al. 1999): examples of processing the B1328+30 calibrator. Approximations of the observed responses (dots) by the calculated RATAN-600 radiation pattern (solid line). Two responses at wavelengths of 1.4, 2.7 and 3.9 cm display the diagram modulation of the signal.

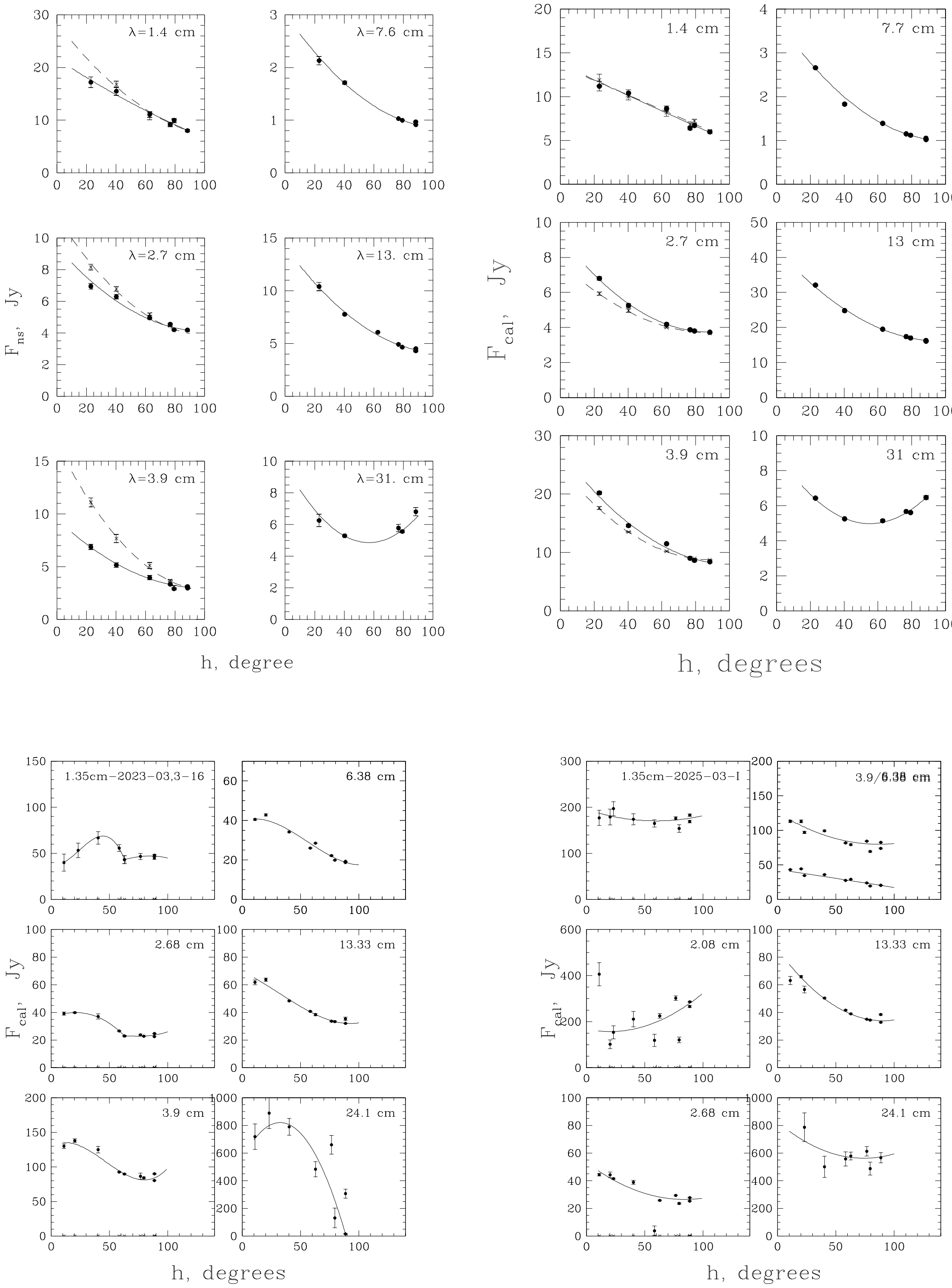

Figure 3. Examples of calibration curves obtained by the program KOMBYN for 4 sets in July 1996 (two columns on the left, top), December 1997 (two columns on the right, top), 3–16 March 2023 (two columns on the left bottom), 2–15 March 2025 (two columns on the right bottom). Calibration curves $F_{\rm ns}(h) = 2kT_{\rm ns}g_{{\rm atm}(h)}/A_{\rm eff}(h)$ display the averaged over the cycle time dependence of the Noise Signal amplitude $F_{\rm cal} = F_{\rm ns}$ on the height h above the horizon at the working wavelengths, obtained by the calibrators. The calibrations of the each of two modulated responces of the signal (top) are different. Such signals are averaged later.

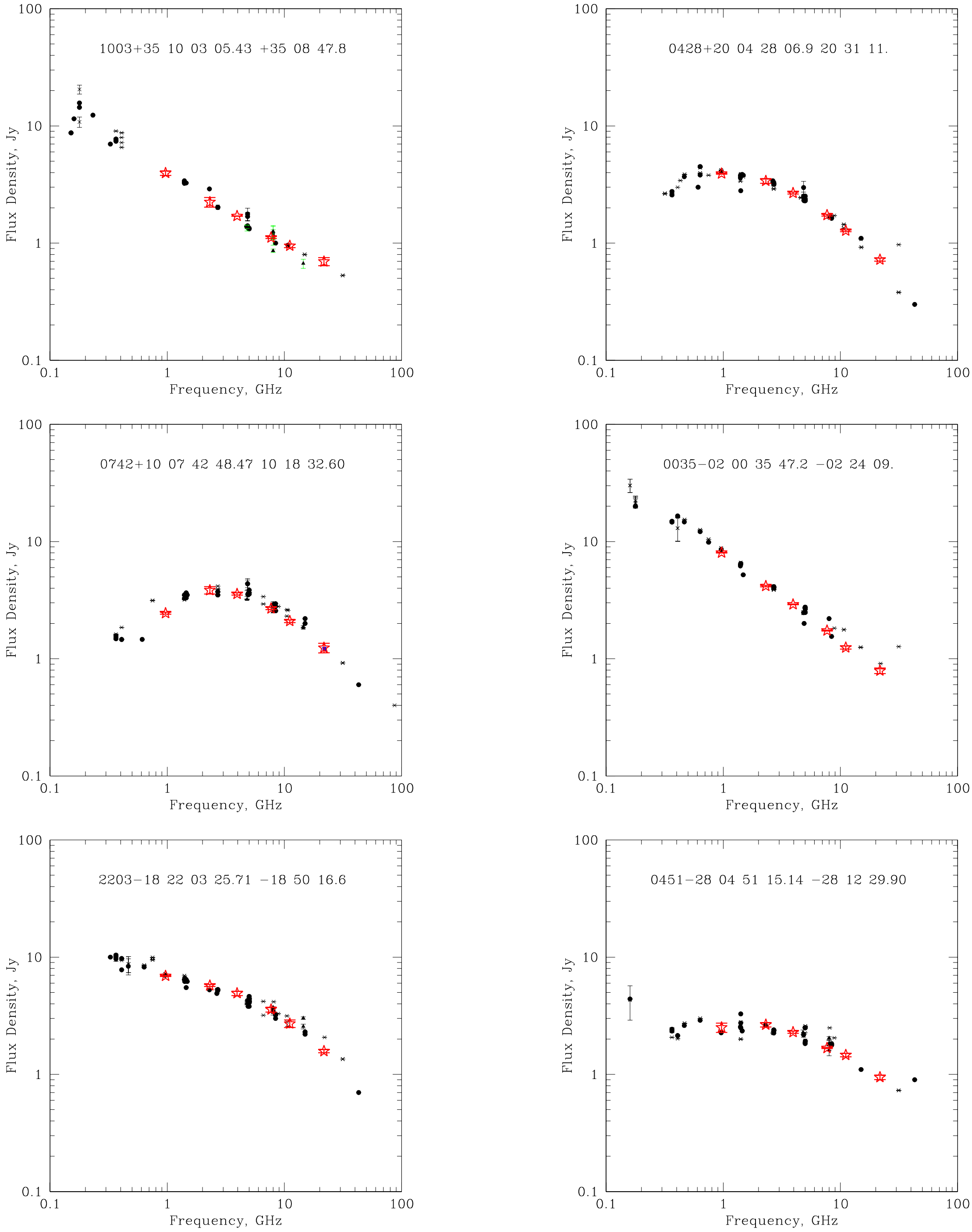

Figure 4. Examples of testing the RATAN-600 calibration solutions in (1–22) GHz using 6 objects with different heights and wide spectra measured by other telescopes (similar to Fig. 1, bottom). RATAN-600 data are marked with a red "asterisk". The rest of the data are from the CATS database (Verkhodanov et al. 2005). To the right of the source name in each window are the source coordinates for the epoch B1950.0.

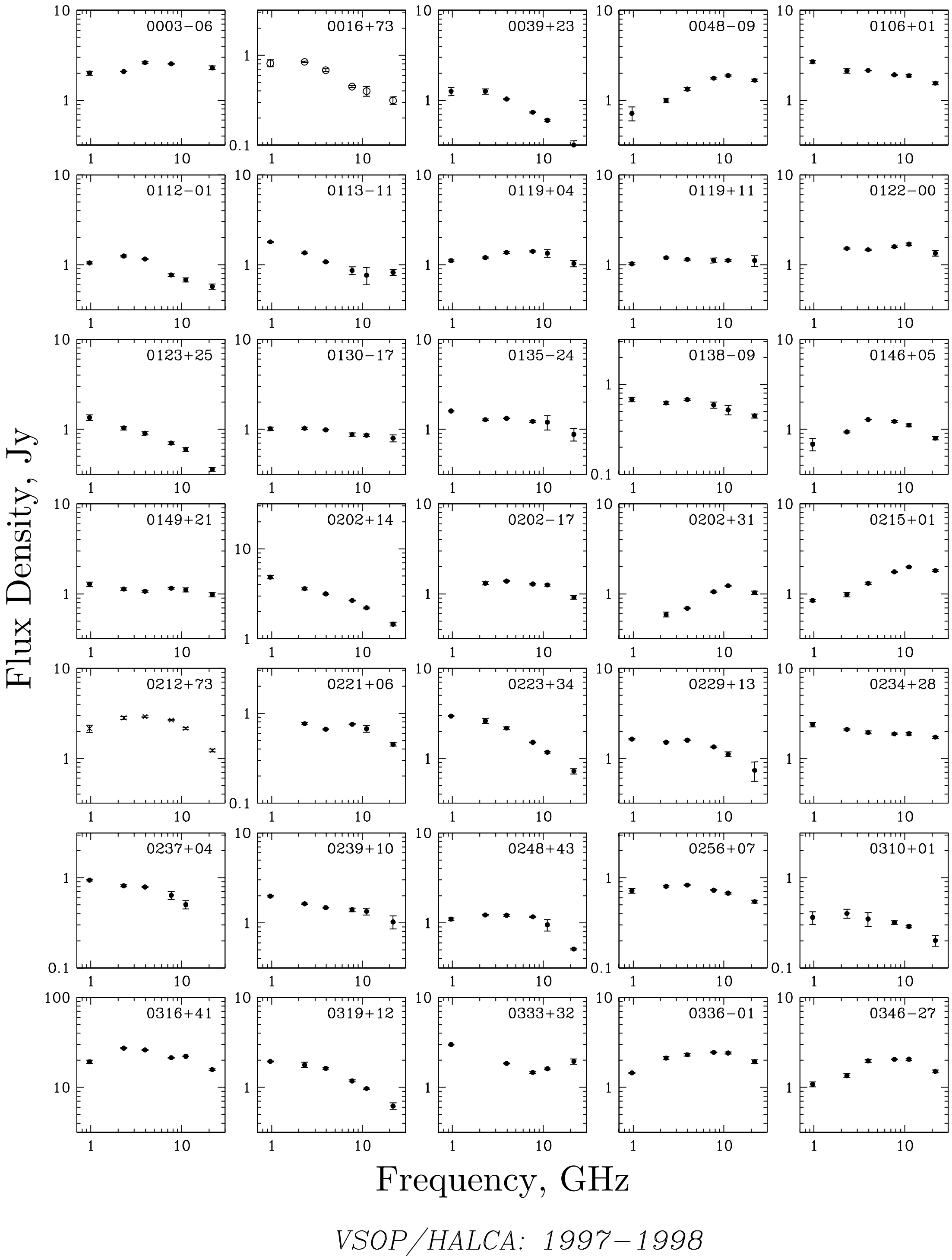

Figure 5. Some examples of reducing the RATAN-600 1–22 GHz spectra observations by the YURZUF package: the instantaneous spectra for 35 VSOP/HALCA objects in 1997–1998 (Kovalev et al. 2000).

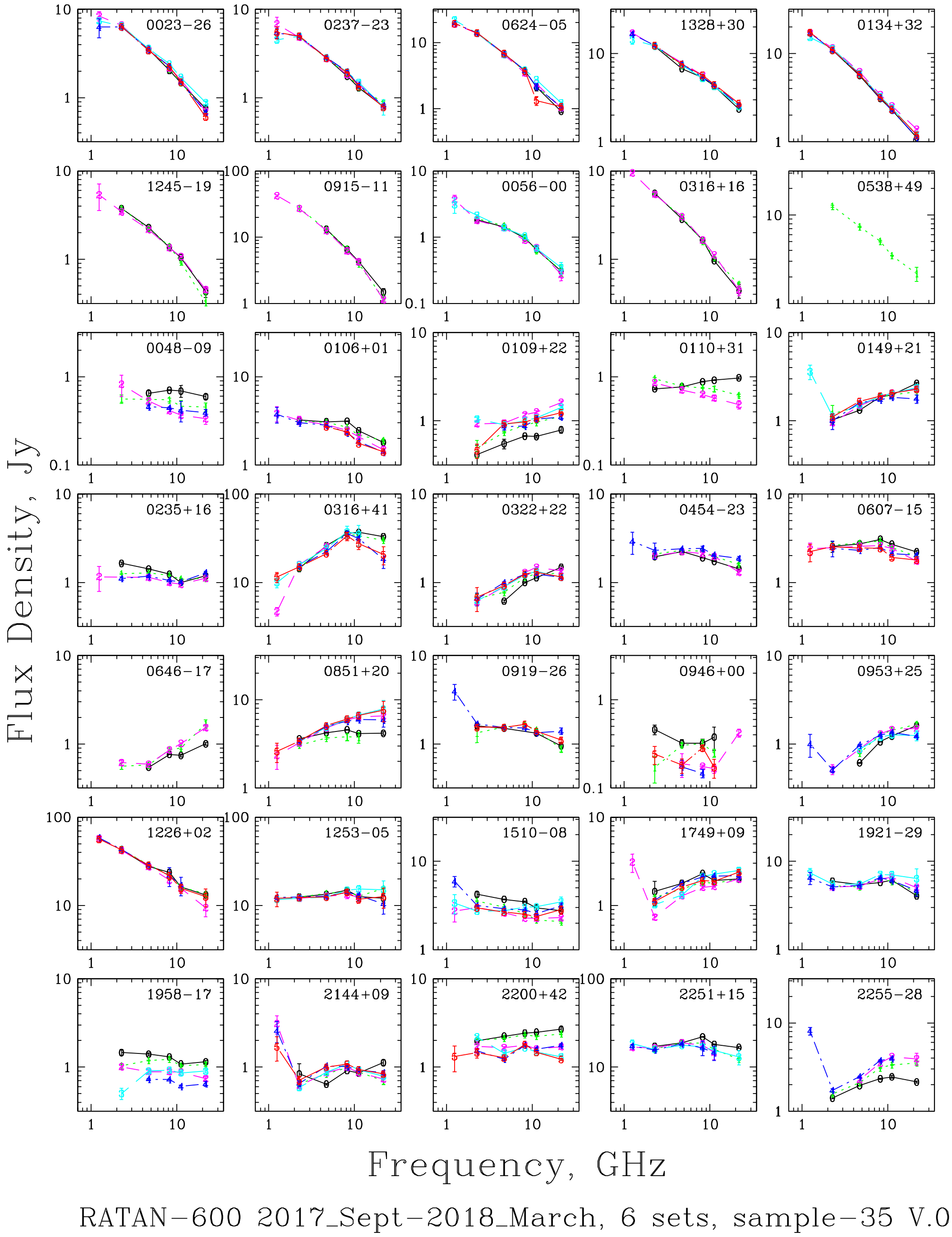

Figure 6. Checking the quality of the RATAN-600 flux density calibrations: 1–22 GHz spectra at 6 frequencies for 10 calibration objects (first 10 objects, top) and for 25 quasars and galaxies from the RadioAstron sample in 6 sets of 2017–2018. The interferences are visible in some cases.

3. The YURZUF software package

The package is intended for automatic processing of instantaneous spectra of radio emission of discrete objects measured on the RATAN-600 radio telescope, and includes the entire set of basic and utility programs and batch scripts necessary for this — from calculating the used parameters of the radio telescope and isolating the signal from the primary noise recording of the telescope response in ADC units to generate a table with the final results of measuring instantaneous and averaged over a cycle spectra for each source.

The package consists of 3 basic processing programs EFEMER, TEMPER and KOMBYN, written in FORTRAN-77, the sequential operation of which implements the processing task, several utilities and command files (see Fig 1). The utilities facilitate the preparation or modification of service files and the conversion of the data format to a form convenient for graphical display of results.

The EFEMER program for each object in the list for a given observation date calculates the coordinates of the source, its height and the speed of image movement in the focal plane (due to the Earth's rotation), as well as the focal parameter of the radio telescope (the distance from the antenna focus on top of the feed cabin to the center of the antenna ring reflector). The results are written to the same table, which is then used as a service file by the TEMPER and KOMBYN programs.

The TEMPER program extracts the desired signal from the original noise record of measurements and normalizes it to the amplitude of the calibration signal from the internal stable noise generator for calibration by antenna temperature. The results for each source at each frequency (channel) are written to a separate output file, which serves as an input for the KOMBYN program.

The KOMBYN program combines 5 independent programs and performs 8 functions: 5 functions for processing calibration objects in order to obtain an approximation of the calibration dependence — of the normalized effective area of the antenna on the source height in order to calibrate measurements in units of the spectral flux density, — and 3 functions for processing measurements of each object from the initial list (specified by the EFEMER program), using this calibration dependence and the output files of the TEMPER program. The final results are obtained for the instantaneous and cycle-averaged flux density spectra (in Jy-units), which are written in tabular form to the corresponding output files (Fig. 5–6).

4. Summary

1. The results demonstrate a high quality of approximation of real responses of quasi-point sources by calculated responses.
2. More details on the methods of observations and data processing can be obtained in Agekyan (1972); Forsite et al. (1980); Kuzmin et al. (1964); Kraus (1966); Esepkina et al. (1973); Konnikova et al. (2011); Kovalev et al. (1999, 2000, 2002); Kovalev (1997); Verkhodanov et al. (2005).

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