Astronomical and Astrophysical Transactions (*AApTr*), 2022, Vol. 33, Issue 2, pp. 149–174,
ISSN 1055-6796, Photocopying permitted by license only, ©Cambridge Scientific Publishers

Investigation of intra-day variability of the radio galaxy 3C 84 (Perseus A) flux density in centimeter range on the RT-32 VIRAC (Latvia) and RT-32 NSFCTC (Ukraine) radio telescopes

A. Sukharev[1,2,*], M. Ryabov[1,2], V. Bezrukovs[2], A. Orbidans[2]

[1] *Institute of Radio Astronomy, National Academy of Sciences of Ukraine, 4 Mystetstv Str., Kharkiv, 61002, Ukraine*
[2] *Ventspils International Radio Astronomy Centre, Ventspils University of Applied Sciences, 101 Inzenieru Str., Ventspils, LV-3601, Latvia*

Received 15 February, 2022

Extragalactic radio source 3C 84 (also known as Perseus A) is the active nucleus of the giant galaxy NGC 1275, the largest in the Perseus galaxy cluster (Abell 426). It is one of the brightest X-ray galaxy clusters. The nucleus of galaxy NGC 1275 (Seyfert II type) is a powerful radio source in the Northern Sky (flux density at frequency 8 GHz is about 30 Jy). 3C 84 has a long-term variability in the radio band, with a "wave-like" change in the flux density on a time scale of several decades. The purpose of our work was to search for and study the properties and features of the appearance of fast variability of the 3C 84 radio source in the centimeter radio range. For this, as part of the international Ukrainian–Latvian cooperation between the Institute of Radio Astronomy NAS of Ukraine and the Ventspils International Radio Astronomy Centre, many observation sessions were performed (October 2020 – September 2021) at the 32-m radio telescopes in Ukraine (Zolochiv) and Latvia (Irbene), with additional observations at the 16-m radio telescope (Irbene). As a result, the following main results were obtained: the 3C 84 radio source exhibits manifestations of episodic intra-day variability, with characteristic times, usually in the range 3–8 hours, as well as "calm phases", when there is no significant variability, and the source flux density does not change over several observation sessions. The most likely cause of this variability could be interstellar scintillations, but some quasi-simultaneous observations of 3C 84 carried out at the 32-m radio telescopes in Ukraine and Latvia showed the presence of a correlation in cross-Fourier spectra, with a characteristic time about 6 hours. In addition, the appearance of 3C 84 flux variability with characteristic times from 1–3 hours to several tens of minutes were recorded, which were not associated with radio-interference or hardware effects. They were detected in observations both in Ukraine and in Latvia, in different seasons of the year.

Keywords: 3C 84, flux density, intra-day variability, Perseus A, radio galaxy, wavelet analysis

*Email: magister.phys@gmail.com

1 Introduction

The extragalactic radio source 3C 84 (Perseus A), also known as the giant lenticular galaxy NGC 1275 (Seyfert 2 type), is one of the popular objects for study. One of the reasons for the ongoing interest in this object is its location in a large cluster of galaxies in constellation Perseus (Abell 426). The cluster, which is one of the most massive objects in the Universe, contains thousands of galaxies immersed in a huge cloud of gas with a temperature of several million degrees. The Perseus Cluster of galaxies is the brightest such cluster in the sky in X-ray range. In 2003, long-periodic shock waves were discovered, which are generated by inflation of bubbles of relativistic plasma by central active nucleus of the galaxy NGC 1275. Those bubbles are visible as ripples in the X-ray range, since brightness of X-ray emission of the medium filling of the cluster space strongly depends on the density of the plasma. More detailed information about the cluster of galaxies in Perseus is presented in the works [1], [2]. 3C 84 shows polarization variability of the radio emission, emitted by the active nucleus. Circular polarization reverses sign along the jet, making 3C 84 also the first radio source to exhibit both signs of circular polarization simultaneously. There are indications that NGC 1275 is interacting gravitationally with the engulfing galaxy. In the optical range, a system of high-speed optical emission lines of absorbed galaxy and bright gaseous filaments, probably held by the magnetic field, are visible. Also, an interesting feature of 3C 84 are enormous radio-emitting bubble-like structures [3], [4]. The analysis of data of long-term observations of the 3C 84 source in radio range showed the presence of a characteristic wave-like change in the flux density. Approximation of these data by two models made it possible to determine the approximate period of the wave, caused by precessional motion of the relativistic jet. For the model with a lower second flux density maximum, the period of about 88 years was obtained. For the model with a symmetrical second maximum, the period turned out to be about 40 years. The presence of precessional rotation of the 3C 84 jet in the radio range was also detected from long-term VLBI observations [5].

In the optical range, 3C 84 also exhibits both long-term and fast variability, which manifests itself even within individual observation nights. Fast variability, on time scales of several hours, has also been found in the gamma range. For example, in [6], flare activity was detected in energy range above 100 GeV, according to data of the MAGIC ground-based gamma-ray telescopes. The source flux density changed significantly from day to day, the shortest characteristic doubling time was about 611 minutes (about 10.2 hours). Also in this work, a significant correlation was found between gamma and optical (R filter) light curves. This correlation was increased at the moments of absence of flare activity of the source 3C 84. In [7], based on observations in V, R, I filters, the characteristic time of change in brightness of NGC 1275 nucleus was determined to be approximately 3 and 6 days. The work [8] shows presence of significant variability in the core of galaxy NGC 1275 within individual nights of observations (1982–1994). Characteristic times of these changes were about 4–9 hours. There were about 8% of such nights in 1982–1987, and about 40% of nights showed presence of rapid intensity fluctuations during 1989–1994.

In the millimeter radio range, the 3C 84 source has a quasi-periodic change in flux density, which is superimposed on the main, slow long-term trend. Thus, it was shown in [9] that the observational data (2002–2021) of the NGC 1275 galaxy

at a wavelength 1.3 mm contains a double, split quasi-period, with similar peak values of 345 and 386 days, which were well determined by the wavelet transform method for non-uniform time series (WWZ). Both peaks were of high significance, and trigonometric polynomial based on these periods described NGC 1275's core flux density very well, after subtracting the long-term trend. Those authors explain the detected effect by possible precession of the accretion disk and oscillation of relativistic jets, which gives the observed effect of period bifurcation.

At the same time, observations in the radio range of the 3C 84 source with a high registration frequency (one measurement of flux density per 1 second) are still quite small. This makes it difficult to determine the parameters of short-periodic variability. In turn, the properties of intra-day variability are also insufficiently studied. Therefore, obtaining information about intra-day and inter-day variability became the main goal of this work. Observations from three radio telescopes, at the observatories of Latvia (Irbene) and Ukraine (Zolochiv, Lviv region), separated from each other by a distance of about 1000 km, made it possible to register more reliably the manifestations of the intra-day variability of the Seyfert galaxy NGC 1275 (radio source 3C 84). This work is the next in a series of articles about the results of a joint study of fast radio and optical variability of extragalactic radio sources, which is jointly carried out at the astronomical observatories of Ukraine, Slovakia and Latvia [10], [11], [12], [13].

2 Observation technique and methods of their processing

Due to the presence of discontinuities and small gaps in the observational data, the search for the presence of quasi-periodic variability was carried out using the following approach. At the first stage, Lomb–Scargle periodograms were calculated (using "classical" method, which was described in [14]. This method provides a more accurate determination of the periods and spectral power of harmonics. It is less susceptible to periodogram distortion due to spectrum spreading and data noise for estimates of the periods of quasi-sinusoidal components in the radio data. At the second stage, a linear fit of the data curves was performed. This approximation was performed to determine the magnitude and phase of one or more dominant variability components using the least squares method. The results obtained were used as initial parameter estimates for the third stage of optimization. It consisted iterative fitting by the least-squares method of approximating data curve in the form of one sinusoid or trigonometric polynomial to real data by selecting the optimal values of its initial parameters: frequency, amplitude and phase. That algorithm allows us to refine the initial values of periods for each light curve, making their assessment more meaningful and believable. This procedure is presented in more detail in [15]. Smoothing of the original data for noise reduction was performed using a polynomial moving average [16].

In the case of uniform data set, to extract components of intra-day variability from time series of flux density variations of the radio source 3C 84, Fourier filtering and reconstruction of the data was used, with the Hamming spectral window, which gives weak edge distortions, in comparison with other spectral windows [17].

For time-frequency data analysis, the fast wavelet transform method was used, but this method is only suitable for uniform time series. The fast continuous wavelet

transform was necessary due to the quite large size of the analyzed time series of radio observations, and gave a very large increase in speed of data analysis and redrawing of wavelet spectrograms. Details about the fast wavelet transform can be found in [18], [19].

3 Radio telescopes of VIRAC, Latvia

Ventspils International Radio Astronomy Center (VIRAC) of Ventspils University of Applied Sciences, Latvia is the only major radio astronomy observatory in the Baltics. The observatory is located in the village of Irbene near Ventspils city and is equipped with two radio telescopes with parabolic mirrors with diameters of 32 and 16 meters, Cassegrain systems, which are fully automated and equipped with remote control. At the central office of VIRAC, it is possible to remotely control antennas and automatically observe target radio sources and calibration radio sources according to a predetermined observation program. In the observations, we used a full-power receiver (in two circular polarizations, right (RCP) and left (LCP)), cooled by liquid helium, with a back-end SDR detector (software-defined radio), which made it possible to quite accurately tune the receiving parameters, taking into account possible radio-interference. The operating frequencies for both radio telescopes are in the ranges 5, 6.1, 6.7, 8–8.8 GHz. Additionally, an uncooled "warm" receiver was used on the 32-m antenna, with an operating frequency 1.6 GHz in a frequency range of 1.3–1.7 GHz. This receiver has good characteristics, a quite small noise track width, and is often used to observe ionospheric scintillations of powerful cosmic radio sources. The main technique for measuring the flux density on the VIRAC radio telescopes, which is the same for the 16-m and 32-m antennas, is as follows. After pointing the telescope at the source and selecting the observation frequency, the power of source response is recorded (TP_{src1}), then the background power of the sky area is recorded similarly (TP_{sky}), then the background power is recorded in the sky area with the noise generator turned on (calibrated noise diode) (TP_{cal}) and control registration of the power of the source (TP_{src2}), to reduce effect of some external noise and take into account changes in elevation angle of the radio telescope. The flux density of the studied radio source in janskys is determined from the following equations:

$$S_j = \frac{T_{cal}}{DPFU \cdot G\,(el)} \cdot \frac{TP_{src_{avg}} - TP_{sky}}{TP_{cal} - TP_{sky}},$$

at $DPFU = \frac{T_{sys}}{S_f} \cdot \frac{TP_{src} - TP_{sky}}{TP_{sky}}$ and $T_{sys} = T_{cal} \cdot \frac{TP_{sky}}{TP_{cal} - TP_{sky}}$, where T_{cal} – noise generator signal temperature, $DPFU$ – receiver temperature increment per unit flux density in K/Jy (gain), T_{sys} – system temperature in K, $G(el)$ – gain versus elevation angle of antenna, S_f – flux density of the calibration radio source.

As a result, according to the formula for S_j, the samples of flux density in janskys, as well as its standard deviation, are written to the output file. One measurement of the flux density of a radio source takes about 20 seconds. Seven consecutive measurements at the same frequency were averaged to reduce atmospheric effects (for example, light clouds) and radio interference. The following calibration sources, with a constant flux density, were used to control the stability of the receiving equipment

and the accuracy of the radio telescope pointing system: 3C 295, 3C 286, 3C 123, 3C 48, as well as Cas A and Cyg A. Detailed studies of parameters of the 16-m VIRAC antenna and the control system and receiving methods are described in [20]. The 32-m VIRAC antenna has fairly similar positioning system parameters. More details about the RT-32 VIRAC antenna can be found in [21].

When radio telescopes operate in the jansky flux density measurement mode, 200–400 measurement points can be obtained per observation session. But for a qualitative "drawing" of the curve of variations in the flux density of the 3C 84 source, a much larger number of measurements per session is needed. To do this, radio telescopes can measure in decibels (dB), with relatively to a highly stable noise generator calibrated in Kelvins at all operating frequencies. Let Raw_{on} and Raw_{off} be the source measurements with the noise generator on and off, respectively (Raw here means dimensionless numbers linearly proportional to the total received power obtained from the analog-to-digital converter after FFT and averaging). Then the "relative" intensity of the radio source in dB was calculated as:

$$Sf_{rel} = 10 \cdot lg \left(\frac{Raw_{off}}{Raw_{on} - Raw_{off}} \right) ,$$

where lg is the decimal logarithm.

The use of such a technique does not allow us to immediately obtain values of the flux density in janskys, however it makes it possible to check more accurately the presence or absence of very fast variability of the studied radio source. At the same time, it is possible to obtain high-quality curves of changes in the flux density of 3C 84 for almost a day, but here it is necessary to take into account the influence of the sky background, and a strong influence of cloudiness is also possible. The influence of the sky background was estimated in two ways. With the first method, the radio telescope recorded flux with the antenna beam passing along the path of the 3C 84 radio source, but with a shift to 0.6 degrees from it for 12–18 hours. Thus, before the observation session, a record of change in the sky background was obtained, which was then taken into account. The second method consisted in alternately recording the source and the sky background. Usually, after 20 minutes of recording the source, the antenna beam was shifted by 0.3 degrees and the background was recorded for 10 minutes, then the cycle was repeated. Further, based on a series of measurements of the sky background, an "average" background curve was constructed using cubic spline interpolation, which was then taken into account.

4 Radio telescope of National Space Facilities Control and Test Center, Ukraine

This parabolic Ukrainian radio telescope with a mirror diameter of 32 meters is located near Zolochiv city, Lviv region. Initially, like the Latvian antennas in Irbene, it was a telecommunications antenna for receiving television programs via geostationary satellites in the 4–6 GHz radio band. Now the antenna belongs to the Center for Space Research and Communications of the National Space Facilities Control and Test Center. At present, when the development of high-speed Internet and 4G mobile

data transmission has significantly reduced the demand for satellite television communications, this MARK-4B antenna system was upgraded in 2019 to the level of a professional and high-precision radio telescope, which today in many parameters is one of best-in-class 32-m radio telescopes. The MARK-4V antenna system was produced by the Japanese company NEC in the 1980s. It belongs to the type of Beam Wave-Guides (BWG) antennas. After the upgrade, the RT-32 Zolochiv antenna is one of the best in Europe (in the class of 32-m radio telescopes) in terms of sensitivity and noise immunity. A remarkable advantage of this BWG antenna is the ability to observe simultaneously in two frequency bands 4–8 GHz and 18–26 GHz (C and K bands), without the need for additional switching. Another advantage of the antenna is the ability to conduct observations with a time resolution from 0.1 to 1 second while maintaining a narrow noise track, which is extremely important when studying the intra-day variability of active galactic nuclei. The effective frequency range of the antenna today is 2.3–26 GHz. Now, a wideband cryogenic receiver (frequency range 4.6–6.8 GHz and 18–26 GHz) is installed on the MARK-4B antenna system, which operates in the detection mode, spectrum analyzer or wave-form mode. The inherent noise of the receiving and recording system in the C range at the zenith is not higher than 45 K. Due to the more efficient irradiation of the subreflector, the main reflector and, accordingly, the higher effective area of the RT-32 Zolochiv radio telescope, fluctuation sensitivity at a frequency of 5 GHz is approximately the same as the best samples of modern 32-m radio telescopes. When studying AGN intensity variations, the signals received by the RT-32 Zolochiv antenna are detected in the 500 MHz band. Further, their power is digitized and converted into decibels. Calibration of the signal received by the antenna for the RT-32 Zolochiv was done using a highly stable noise generator and/or using reference space radio sources. The procedure for calibrating and estimating the intrinsic noise of the RT-32 is described in detail in [22], [23].

5 Results

The radio source 3C 84 has a pronounced long-term variability with a large amplitude and a wavy appearance. That variability was discovered based on the results of four years of observations of the Seyfert galaxy NGC 1275 (active nucleus of which is a powerful radio source, better known as 3C 84), which were published in 1966 [24]. Usually, in the observation time interval of 2–3 years, the 3C 84 flux density curve has a smooth increase or decrease, depending on the phase of radio source activity. An example of data from long-term monitoring of 3C 84, over the time interval from 2009 to 2012, which was carried out at the 26-m radio telescope UMRAO (University of Michigan, USA) is shown in Figure 1.

At the same time, information about the intra-day variability and day-to-day variability of the 3C 84 source, in the centimeter range, are practically absent. While the long-term variability of this source is relatively well understood, the nature of the fast radio variability of this object remains unclear to the present time. Given this fact, and the short duration of the research grant supporting this work, we decided to focus on finding and highlighting the features of the fast variability of 3C 84 on intra-day and day-to-day time scales, from several hours to several days. The main

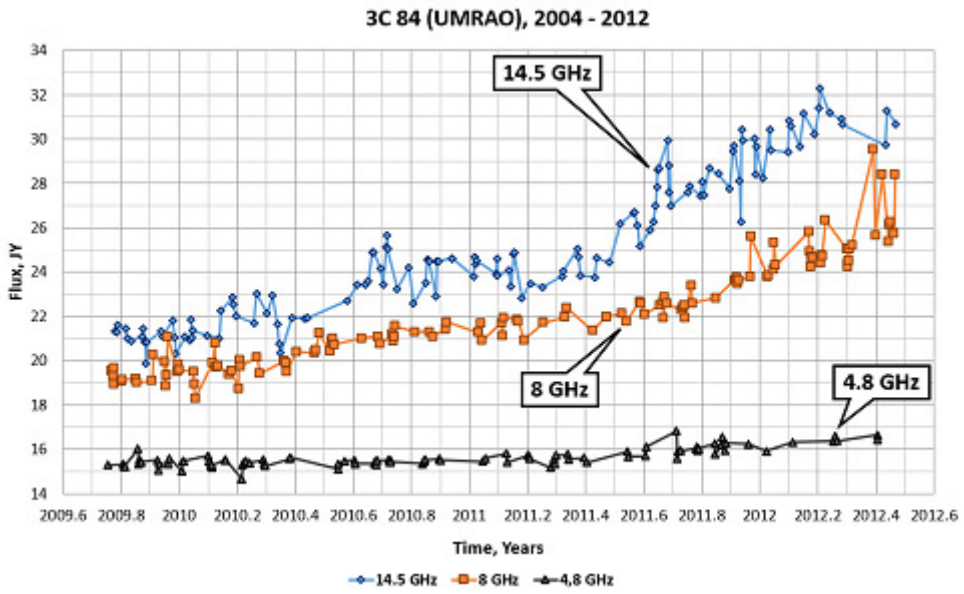


Figure 1 An example of a long-term change in the flux density of the radio source 3C 84, according to observations at UMRAO (USA), at frequencies 4.8, 8, 14.5 GHz in the time interval 2009–2012. A smooth increase in the flux density with increasing frequency can be seen. Variability amplitude in this example: 2.15 Jy (4.8 GHz), 11.25 Jy (8 GHz), 12.42 (14.5 GHz). This shows that 3C 84 does not have a quasi-cyclic appearance of variability over a time interval of observations of several years.

results and progress of research into the 3C 84 variability properties, on the radio telescopes in Latvia and Ukraine are shown in the next sections.

6 Observations of the radio source 3C 84 on radio telescope in Zolochiv, Ukraine

During the time from October 2020 to September 2021, about 90 days of observations of the radio source 3C 84 were carried out at the RT-32 Zolochiv radio telescope. Basically, the signal was recorded on a four-channel radiometer, at two frequencies, usually 5 and 6 GHz, with two circular polarizations for each frequency (left (LCP) and right (RCP)). In the original data tables, 10 flux density samples per second were recorded, however, data with an output sampling rate of 1 Hz (1 flux density sample per second) was actually used. This made it possible to record quite accurately the curve of intra-day flux variations of the 3C 84 source, which made it possible to reliably determine weak low-amplitude variations with characteristic times of about 1 hour or even less. Observations at the radio telescope in Zolochev, due to the very low level of noise and radio-interference, are excellent for studying the intra-day variability of active galactic nuclei, in particular, the 3C 84 source.

At the first stage of data processing, radio interference and outliers were removed,

since their number is usually small, data cleaning from radio-interference was done manually. Next, interpolation and pre-smoothing of the data was performed using a cubic smoothing spline with cross-validation. This procedure is a highly effective means of reducing noise in the observational data [26]. Interpolation was necessary because the methods of wavelet and Fourier analysis, as well as Fourier filtering, were mainly used for uniform time series. The next step was to determine the trend of "flux density – antenna elevation angle" dependence (when operating at low antenna elevation angles, the antenna temperature increases due to penetration of the near-surface noise of the Earth into the side lobes of antenna beam pattern, at higher angles this effect decreases) in the case of the RT-32 Zolochiv, it usually has a smooth arcuate appearance and is well described by a polynomial of the third degree.

After fitting the trend, it was subtracted from the original data (alignment), resulting in records of the flux density 3C 84 during each observation session. Example of such records from source 3C 84, after subtracting the inscribed polynomial of the third degree, is shown in Figure 2. Further, already obtained data on intra-day variations of the flux density of source 3C 84 were additionally smoothed by Savitzky–Golay polynomial filter to suppress variations with characteristic times less than 10 minutes (example of smoothing is shown in Figure 3). This made it possible to remove very small fluctuations in the flux density, which occurred in some cases when the electric drive increased the angle of the antenna. Since the polarization of 3C 84 radio emission was not investigated in this work, and the data in channels of left (LCP) and right (RCP) circular polarizations for each observation frequency were very well correlated, the data for two channels for each observation frequency were averaged.

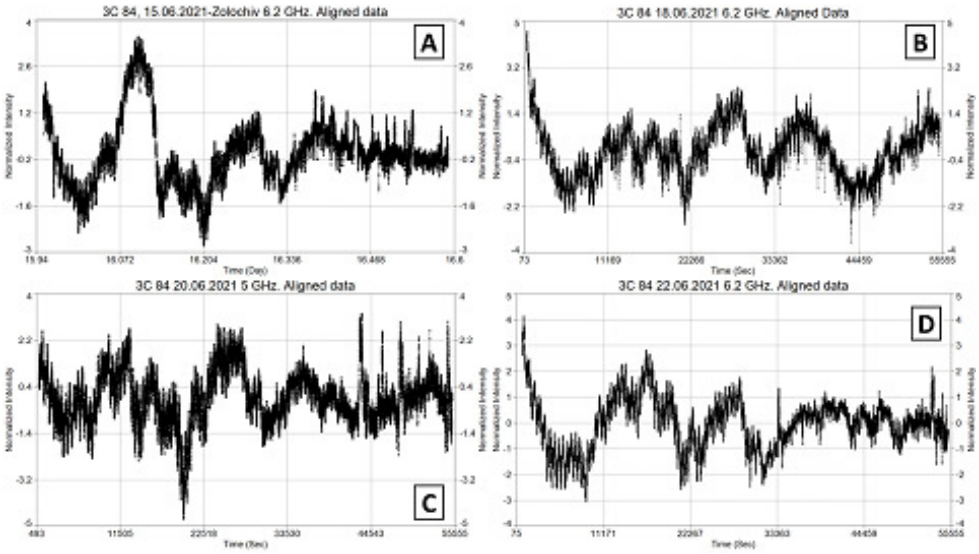


Figure 2 Examples of flux density recordings for the 3C 84 source, made on the RT-32 Zolochiv antenna. A) 6.2 GHz recording received on June 15, 2021, B) 6.2 GHz recording received on June 18, 2021, C) 5 GHz recording received on June 20, 2021, D) 6.2 GHz recording received on June 22, 2021. In this example, along the Y axis, measurements of the flux density in arbitrary power values are normalized (average value is subtracted, followed by dividing by the standard deviation); along the X axis, observation time in seconds.

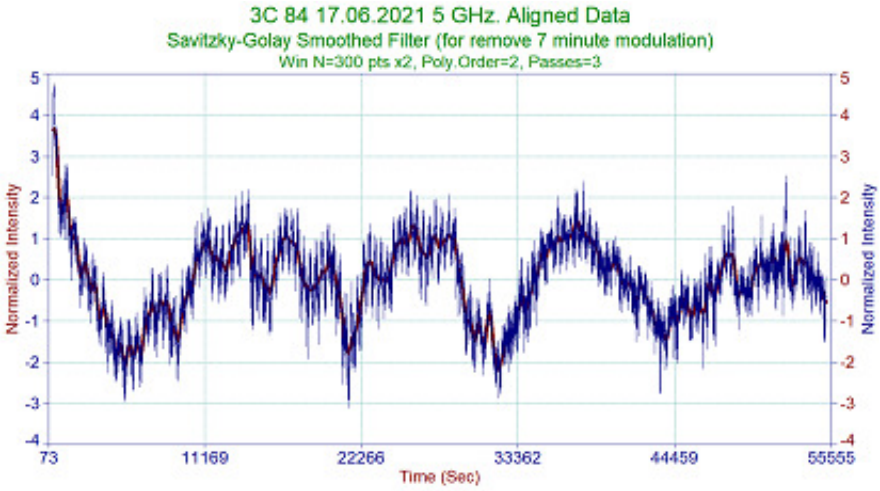


Figure 3 Flux density record of the 3C 84 received on June 17, 2021, at a frequency of 5 GHz. The data were smoothed by Savitzky–Golay filter with a smoothing window of 300 points, a polynomial degree of 2, and a number of passes of 3 (thick line in the figure). It can be seen that this method effectively removes the parasitic signal modulation caused by vibrations of the radio telescope mirror.

After all the data pre-processing, the obtained "clean" 3C 84 flux density curves were analyzed using fast wavelet transform and FFT method. Fast wavelet transform provides undoubted advantages in the analysis of radio variability data of extragalactic radio sources, since the presence of noise or cyclic components is immediately visible on the spectrograms, as well as the approximate time of their existence in the analyzed signal. Unlike the "classic" Fourier transform, whose analyzing function covers the entire time axis, two-parameter analyzing function of the one-dimensional wavelet transform is well localized both in time and in frequency. This allows us to see the detailed structure of process and the evolution of harmonic and noise components of the signal, over time. Therefore the use of wavelet analysis allows us to obtain more information about the structure of signal at different periods than, when using Fourier analysis. To better determine the time-localization of radio flux density variations, we used a wavelet transform based on the Gaussian Derivative function and Paul Wavelet in our work. This made it possible to highlight individual harmonic components at different scales, to trace their change over time and duration of their existence. In general, the wavelet transform works by using definition of the wavelet transform directly, that is, convolution of signal with scaled wavelet is calculated. For each scale, a set of the same length N as the input signal is obtained in this way. Using M arbitrarily chosen wavelet scales, an N×M field is obtained that directly represents the time-frequency plane, and the wavelet transform coefficients give Z-axis of the surface. In our case, a fast wavelet transform was used to speed up the calculation time, because the input data was quite large.

As a result of the calculations, matrices of wavelet transform coefficients were obtained, representing surfaces in three-dimensional space. Since surface images are not very informative when studying the signal structure, they are replaced by projections

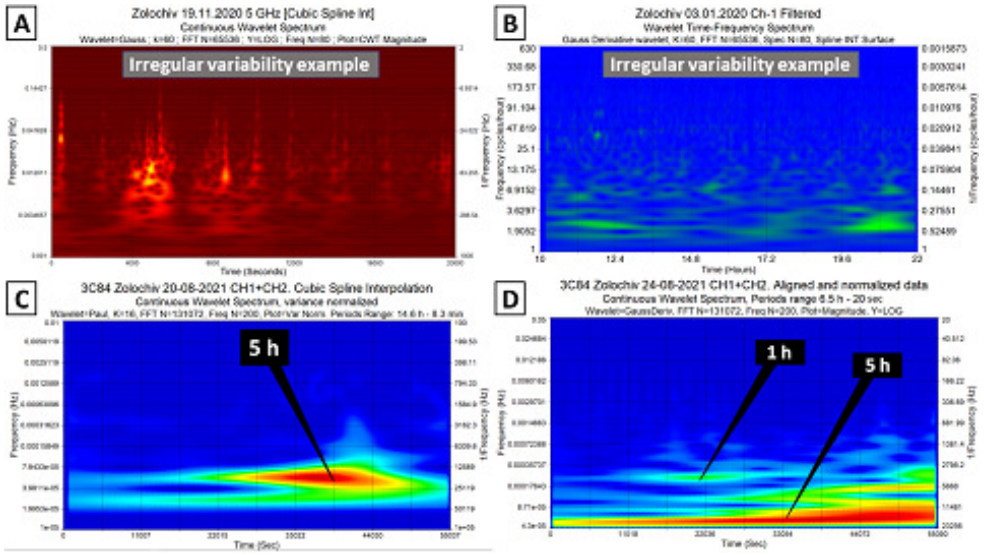


Figure 4 Wavelet spectrograms for the 3C 84 source obtained from the RT-32 Zolochiv data. Panels of the figure show: A) Noise-like signal with irregular variability, which was received on November 19, 2020. B) Signal with irregular variability, which was received on January 03, 2021. C) Signal with a quasi-period of about 5 hours, recorded on August 20, 2021 (in this example, the spectrogram is normalized as $\frac{\Re^2 + \Im^2}{V}$, where $\Re^2$ is the real part of the wavelet transform, $\Im^2$ is the imaginary part of the wavelet transform, V is the variance of the data series, for each element of the spectrogram. D) Signal with a quasi-period of about 5 hours and a weaker quasi-period of about 1 hour.

on the "frequency-time" plane with isolevels, which allow us to trace the changes in intensity of the wavelet transform amplitudes at different scales (frequencies / periods) and over time. Because it is necessary to show a very wide range of scales, from several hours to several minutes, the visualization was performed in logarithmic coordinates along the Y axis. Examples of the obtained wavelet spectra of intra-day variations in the 3C 84 flux density for different calendar dates are shown in Figures 4 and 5. For wavelet spectrograms, amplitude visualization was used in the form $\sqrt{\Re^2 + \Im^2}$, for each element of the spectrogram, where $\Re, \Im$ – real and imaginary parts of the wavelet transform, respectively. However, in some cases, visualization was used taking into account dispersion of the time series (example in Figure 4), which made it possible to significantly suppress background noise on the spectrogram.

As can be seen from the examples of wavelet spectrograms, obtained from the RT-32 Zolochiv, the source 3C 84 has days when regular variability within individual observation days is completely absent, and there are days when weak low-amplitude variations appear, sometimes quite close to quasi-periodic ones, with characteristic times, most often 3–4 hours, 5 hours, and less often 8 hours. Also, sometimes there are weak variability components with characteristic times of about an hour or a little less than an hour. As will be shown below, variations in the flux density of 3C 84 source, with close characteristic times, were also observed in Irbene, Latvia, on the

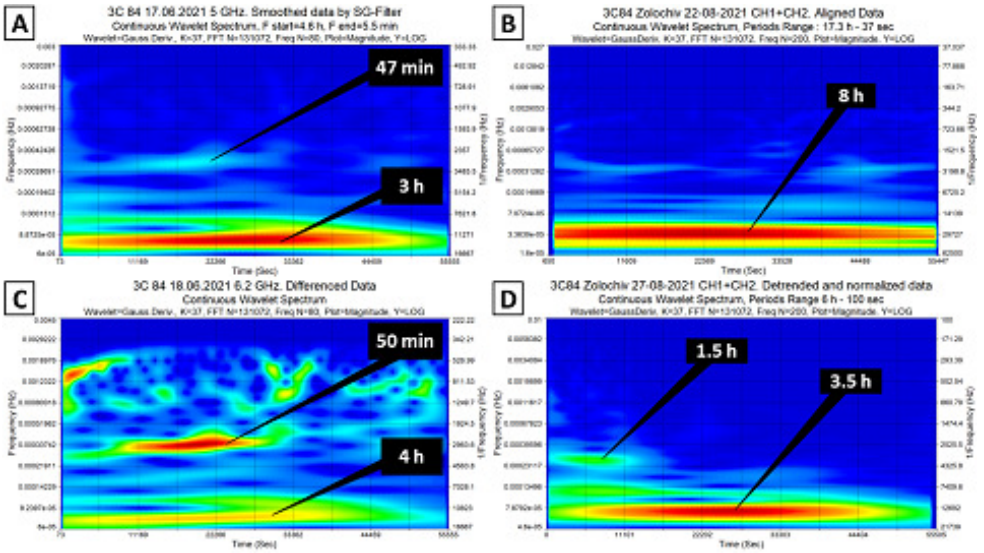


Figure 5 Wavelet spectrograms for the 3C 84 source, obtained from RT-32 Zolochiv data. The panels of the figure show: A) Example of a signal recording with a quasi-period of about 3 hours and a weak variability component with a quasi-period of about 47 minutes. B) Example of a signal recording with a quasi-period of about 8 hours. C) Example of a signal recording with a quasi-period of about 4 hours and a quasi-period of about 50 minutes. D) Example of a signal recording with a quasi-period of about 3.5 hours and a weak variability component at the beginning of an observation session with a characteristic time of about 1.5 hours.

VIRAC radio telescopes, which are located at a distance of about 1000 kilometers from RT-32 Zolochiv.

Similar results are obtained when considering the "classic" FFT spectra for the 3C 84 source signal records, obtained with the RT-32 Zolochiv. As a confirmatory method, to determine whether there is variability in the data under study (in other words, whether there is a "memory effect" in the data in the form of repeatability, the Hurst exponent calculation method was used (detailed description is given in [27]). This method is convenient for approximate understanding of the presence or absence of cyclical variability, hidden by noise. In the case $H = 0.5$ the data is white noise, in the case $H < 0.5$ the data series is anti-constant (any trend tendency to be reversed) and each data value is likely to have a negative correlation with previous values. If the time series has a "memory", that is, subsequent values depend on the previous ones, which is a normal consequence of variability, the values of the Hurst exponents move to 1. Usually, when the H value equal to, or greater than 0.8 indicates a pronounced "memory effect", or the presence of variability in the time series. Some examples are shown in Figure 6, for 3C 84 signal at 5 GHz, received on 05 January 2021 on RT-32 Zolochiv.

From Figure 6C it follows that in the time series there is some "memory effect" in the form of cyclic variability. It is most likely that in this example of analyzed intra-day data from RT-32 Zolochiv, variability in the flux density of the 3C 84 source was

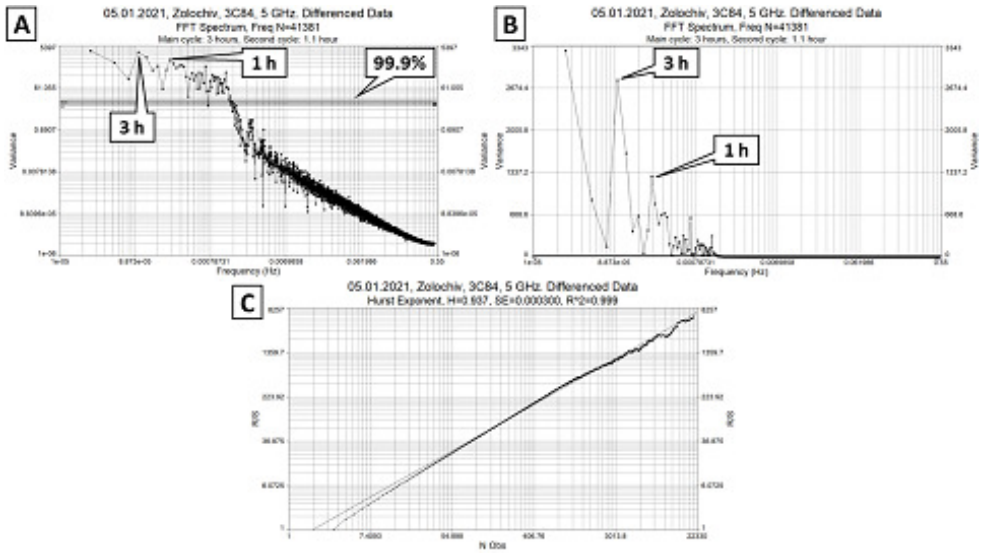


Figure 6 Signal spectrum of the radio source 3C 84, which was received on January 05, 2021 at a frequency of 5 GHz on the RT-32 Zolochiv. Panels of the figure show the following plots: A) Spectrum on a double logarithmic scale, flags indicate the maxima corresponding to flux density variations with characteristic times of about 3 hours and 1 hour, as well as a critical level of 99.9%. C) The same spectrum, but with a logarithmic scale only along the X-axis. In both of these spectra, the Y-axis is the spectral power normalized by variance of time series. C) Plot of Hurst exponent, here can see the good quality of straight-line approximation, with the value $H = 0.937$ with the standard error coefficient derived from the fit $SE = 0.000300$ and the coefficient of determination $R^2 = 0.999$.

indeed observed. 1000 separate sets of random noise, the largest peak can reach the height of this level strictly by chance.

Thus, over more than a year of observations at frequencies of 5 and 6.2 GHz, at different times of the year, many manifestations of the fast variability of radio source 3C 84, determined by different methods, have accumulated, according to observations on the Ukrainian RT-32 Zolochiv, which is an indicator of the actual presence of non-random flux density variations. However, observations with a single radio telescope often do not allow us to obtain full confidence in registering actual variability of a radio source against the background of other disturbing factors such as radio-interference, including ionospheric and weather effects. Therefore, as additional confirmation, monitoring observations of the 3C 84 source were carried out during the year at the 32-m and 16-m radio telescopes of VIRAC, Latvia, in a wider frequency range of 1.6, 5, 6.1, 6.7, 8–8.8 GHz.

7 Observations of the radio source 3C 84 on radio telescopes VIRAC, Latvia

Observations at the 32-m and 16-m VIRAC radio telescopes were performed in two measurement modes. The jansky flux density measurement mode was used for multi-day successive measurements of the 3C 84 radio source. For faster and more complete recording of intra-day variations in the 3C 84 flux density, the decibel (dB) measurement mode was used relative to a calibrated highly stable noise generator. In the mode of recording spectral flux density in decibels, in the output file, one measurement was recorded in two seconds. This made it possible to prescribe quite well the shape of 3C 84 variations and also to filter out radio interference and randomly dropping measurement points. Figure 7 shows the example of a recording of radio source 3C 84 in janskys, which was obtained on the 16-m antenna of VIRAC, from September 23 to 26, 2020 at a frequency of 6.1 GHz in left (LCP) and right (RCP) circular polarizations.

As a result, based on many records of variations in the flux density of the radio source, a picture is formed similar to that seen from the observations of 3C 84 on RT-32 Zolochiv. Specifically, 3C 84 has "calm" phases when regular flux density variability is either absent altogether, or only a daily 24-hour harmonic and a semi-diurnal 12-hour harmonic appear. However, "activity" phases are observed less often, when flux density variations appear in the records with characteristic times of about 3–4–5 hours or little more, including fast and clearly visible fluctuations in the flux density with characteristic times of about 1 hour, which were recorded even at a frequency of

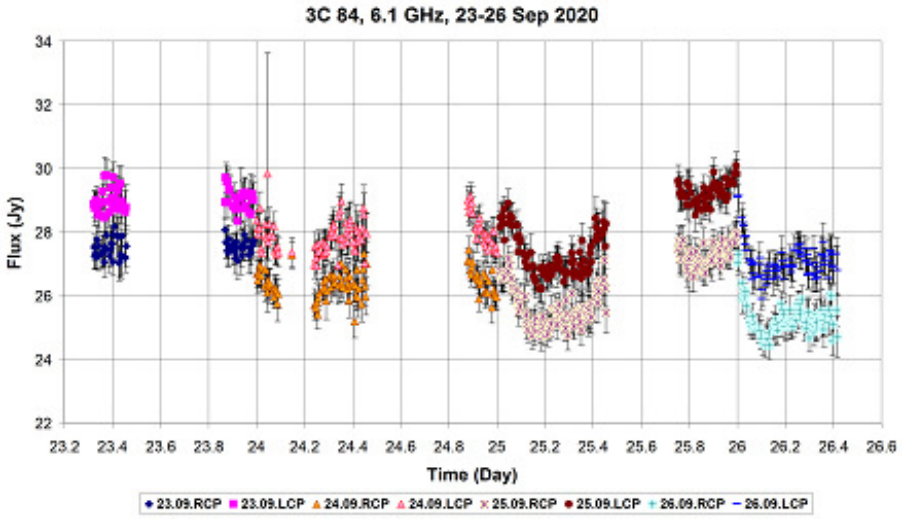


Figure 7 Recording of the flux density (in Jy) of the radio source 3C 84, obtained at VIRAC, Latvia, at a frequency of 6.1 GHz, from September 23 to 26, 2020 in two circular polarizations. One can see some change in the flux density against the background of a noise component.

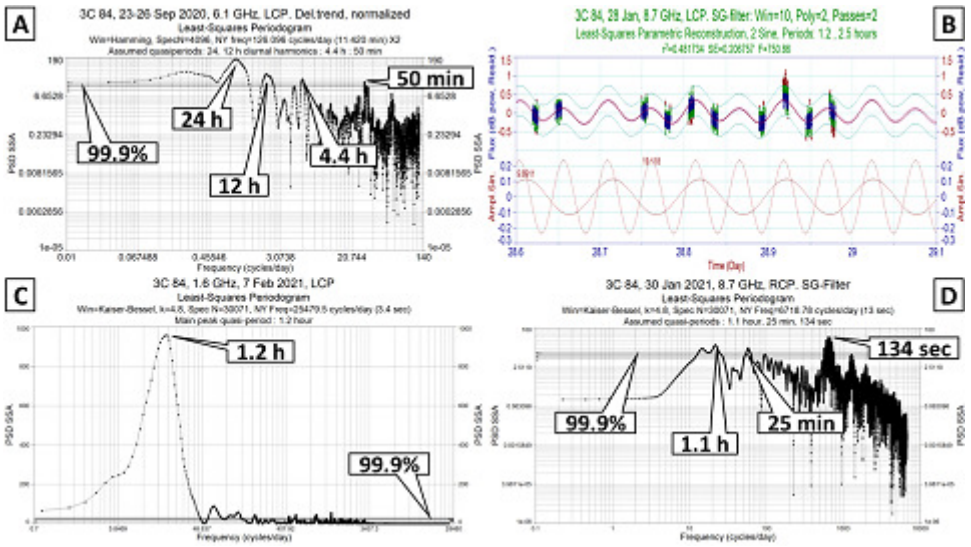


Figure 8 Examples of analysis of the curves of flux variations of the 3C 84 source, according to observation data on the radio telescopes VIRAC, Latvia. Panels of the figure show the following plots: A) Lomb–Scargle spectrum, for non-uniform time series, recorded for September 23–26, 2020, at a frequency of 6.1 GHz. In the plot, flags show the quasi-periods of flux density variations for that observation time interval. B) This example shows a trigonometric polynomial fit (with least-squares optimization) for observations of source 3C 84, which were obtained on January 28, 2021 at a frequency of 8.7 GHz. Periods of sinusoids that were used for approximation are 1.2 and 2.5 hours, the main estimated quasi-period is 1.2 hours. C) This figure shows Lomb–Scargle spectrum of the 3C 84 7 flux density recording from February 2021, at a frequency of 1.6 GHz. It can be seen that a clear quasi-period of 1.2 hours also appears here. D) In this example, Lomb–Scargle spectrum of the flux density recording of 3C 84, taken on January 30, 2021 at 8.7 GHz, also shows a main quasi-period of 1.1 hours, as well as maxima corresponding to faster flux density variations with quasi-periods of 25 minutes and 2.2 minutes.

8.7 GHz. Corresponding examples are shown in Figure 8. In general, it can be said that the characteristic times of intra-day variability of 3C 84 are very close to those observed on the RT-32 Zolochiv antenna, in Ukraine. Unfortunately, publications describing a detailed study of intra-day radio variability (radio IDV) for the 3C 84 source are practically absent, however, an analysis of the manifestation of radio IDV for other, relatively well-studied radio sources, shows a similar picture. For example, smooth decreases and increases in the flux density at the source OV 236 (BL Lac object) at a frequency of 90 GHz were found for 2–3 days according to observations with the Kitt Peak telescope in Arizona, USA. In addition, similar fluctuations were detected for the source OJ 287 at a wavelength of 3.5 mm in May 1971 with some weak correlation with optical brightness fluctuations. In February 1972, the variability of OJ 287 was noted on a time scale of several hours at a wavelength of 3.5 mm over several days, as detailed in [28]. For quasar 3C 454.3 was also found to have intra-day radio variability with characteristic times from two to ten hours in the centimeter

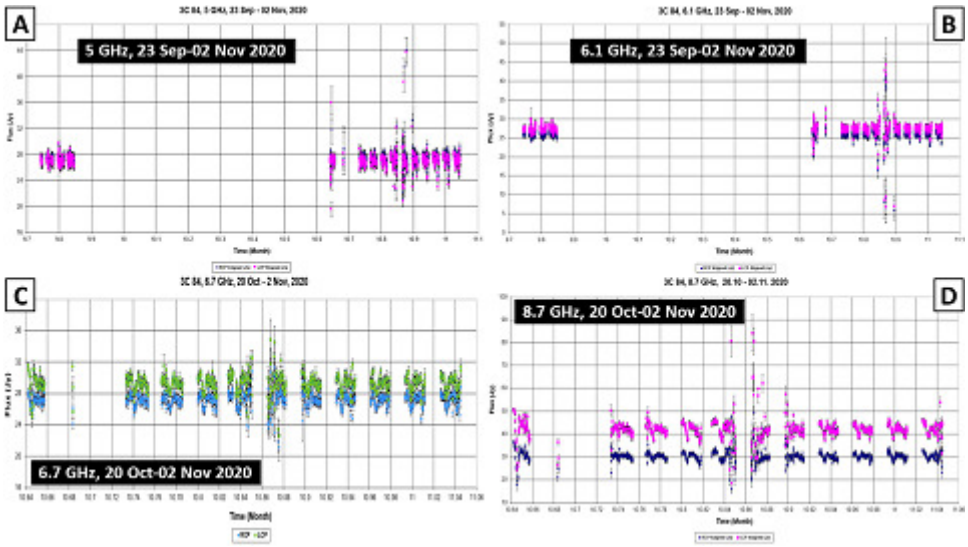


Figure 9 Records of the flux density of the radio source 3C 84, which were obtained in VIRAC, Latvia (measurement mode in Jy) from October 20 to November 02, and also from September 23 to November 02, at frequencies of 5, 6.1, 6.7, 8.7 GHz.

radio range [29]. Thus, the observed characteristic IDV times for the 3C 84 source generally correspond to those observed earlier for other radio sources. At the same time, an interesting property of the 3C 84 source is the episodic occurrence of IDV and the presence of "calm" conditions, when regular variability is completely absent.

It can be seen that, in addition to the maxima at 24 and 12 hours, that is, the daily and semidiurnal harmonics (which are associated with the "gaps" of observational data), in Figure 8, there are two more maxima exceeding the critical level of 99.9%, with quasi-periods of 4.4 hours and 50 minutes. Thus, in different observation sessions, and at different frequencies, consistent results were obtained for the appearance of regular variability of the 3C 84 radio source on time scales from several hours to approximately one hour or even less. The following example is shown in Figure 9, for longer consecutive observations of the 3C 84 source.

Figure 9 shows the original data cleaned from noise, but without removing outliers points. It can be seen that during the observation time interval, there was no slow change in the flux density, that is, the average value of flux density between observation sessions remained practically unchanged. However, there were fast flux density variations in the data with a characteristic time of several hours, as seen in the following example at Figure 10.

Analysis of successive, more than a week, observations of the source 3C 84 at the 16-m radio telescope VIRAC showed that at frequencies of 5, 6.7, 8.7 GHz, the quasi-period of 8 hours was predominant, however, at a frequency of 6.1 GHz, that quasi-period was about 6 hours. This can be explained by the fact that there were several "gaps" in the data set at 6.1 GHz and a different average time between measurements, which led to finding a time-shifted sinusoidal time series model. In itself, the presence

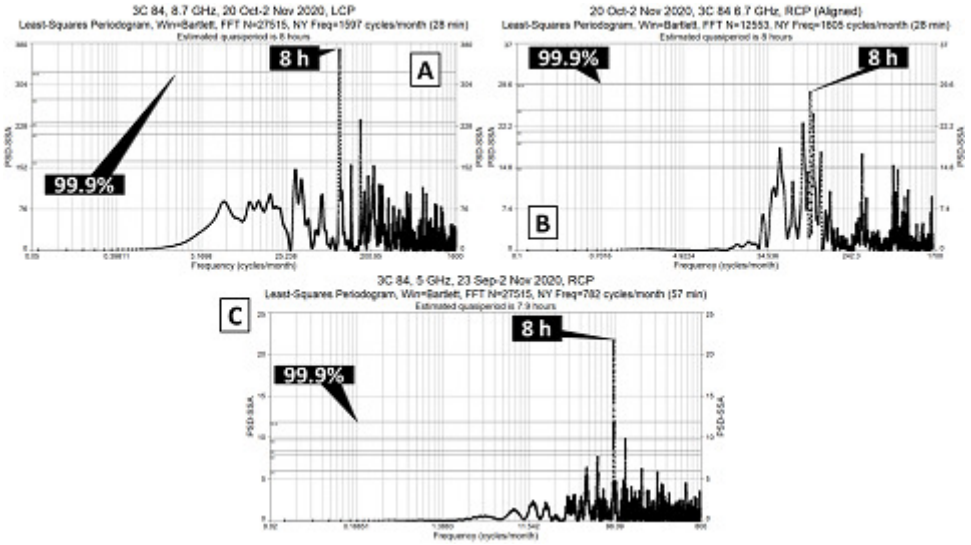


Figure 10 Example of Lomb–Scargle spectra for "cleaned" records of the flux density of the radio source 3C 84. Panels of the figure show the following plots: A) LS spectrum, for recording at a frequency of 8.7 GHz, obtained in the time interval 20 Oct – 2 Nov 2020, in left circular polarization (LCP); B) LS spectrum, for recording at a frequency of 6.7 GHz, obtained in the time interval 20 Oct – 2 Nov 2020, in right circular polarization (RCP); C) LS spectrum, for recording at a frequency of 5 GHz, obtained on the time interval 23 Sep – 2 Nov 2020, in right circular polarization (RCP). Flags indicate the main maximum in LS spectra, corresponding to a quasi-period of 8 hours, in this example. Those plots also indicate the critical level of 99.9% confidence in detection of quasi-period, and as can be seen in graphs A) and C) the main peak is higher, and in graph B) it is slightly lower than the critical level, which indicates actual presence in the observational data of the radio source 3C 84, variations flux density with a characteristic time of about 8 hours.

of such fluctuations in the 3C 84 flux density is very interesting. It should be noted that in the observational data of standard stable radio sources Cassiopeia A and Cygnus A, no quasi-periodic flux density variations with characteristic times of several hours were recorded at all.

8 Possible explanation of the observed fast variability of the 3C 84 by ionospheric effects

Of particular interest are quite unusual, often close to quasi-periodic, variations in flux density of the 3C 84 source, with characteristic times from 20–40 minutes to 1.5–2 hours. These variations were observed quite often (usually several times a week) on all available radio frequencies, from 1.6 to 8.8 GHz, both in Zolochiv and Irbene radio telescopes. These ulta-fast fluctuations of the flux density were registered especially clearly according to the data of a high-precision and noise-resistant radiometer of RT-32 Zolochiv antenna, simultaneously at two radio frequencies, 5 and 6.2 GHz. It

should be noted that similar flux variations with characteristic times of about 1 hour or slightly less were also observed from the 3C 273 radio source at the Chinese Urumqi Observatory at a frequency of 5 GHz [30]. The nature of such very fast change in the flux density is still unknown, and is a debatable topic of astrophysics, since in this case the spatial region of emission should have a size of the order $1.08 \cdot 10^9$ kilometers (size of the Solar system is about $1.6 \cdot 10^{10}$ kilometers, which corresponds to a light path time of about 15 hours), and a light path to Pluto, for example, is about 5 hours, with a distance of about $5.3 \cdot 10^9$ kilometers. This means that such variations in radio flux density are possible only in central region of the accretion disk, where the base of the relativistic jet is formed and collimated. At the same time, reliable registration of these variations in Irbene (VIRAC), in radio range of 1.3–1.7 GHz, which is most affected by radio wave propagation medium, suggests that these variations can be caused by ionospheric processes.

It is known that the amplitude of ionospheric scintillations decreases with increasing frequency, and at radio frequencies in the centimeter radio range, in our case in the range of 5–8 GHz, ionospheric scintillations should not significantly affect the variability of radio emission from extragalactic sources. However, acoustic-gravity waves often form in the lower atmosphere. These waves lead to time-variations in the spatial distribution of electrons at ionospheric heights. The source of such waves can be a terminator (boundary separating illuminated and night parts of the Earth's surface), earthquakes, volcanic emissions, and atmospheric vortices. They can even be caused by powerful lightning discharges that cause propagation of acoustic-gravity waves from the troposphere to the ionospheric region (detailed, for example, in [31]). Periods of mid-latitude acoustic-gravity ionospheric waves are often in the range from 30 minutes to two hours [32]. The high sensitivity of the 32-m Zolochiv and VIRAC radio telescopes is sufficient to detect ionospheric scintillations. In favor of the ionospheric nature of the fast variability of the 3C 84 radio source, with characteristic times of about 1 hour or less, is the fact, that manifestations of quasi-periodic variations in data sets of the 3C 84 radio flux, are often limited in time. Examples are shown in the wavelet spectrograms in Figures 11 and 12. The time-limited appearance of close to quasi-periodic variations in the radio flux density of radio sources translucent to the ionosphere is typical for acoustic-gravity waves, which have a limited lifetime of several hours, which is seen in the examples of spectrograms.

It is worth noting, that from some other extragalactic radio sources, very fast variability in the radio range were also reliably detected, with characteristic times less than one hour, the so-called intra-hour variability (for example in [33]). The authors of the cited paper report the detection, using the Apertif system, of extreme ($\sim$50%) and quick changes in flux of the radio source J1402+5347 on a time scale of only 6.5 minutes in the decimeter range of 1.4 GHz. Intra-hour variability refers to quasi-random modulation of radio signal intensity of extragalactic radio sources, which is similar to interstellar scintillations, but on much shorter timescales, also characteristic for the Earth's ionosphere. The nature of plasma clouds causing that very fast variability is still unclear. This is generally thought to be caused by nearby (about 10 parsecs away) turbulent plasma. Since the effect of plasma scattering of radio emission is weaker if the plasma clouds are at short distances, plasma densities obtained from intra-hour variability observations are orders of magnitude higher than in the surrounding ionized interstellar gas. The formation and stability over time of

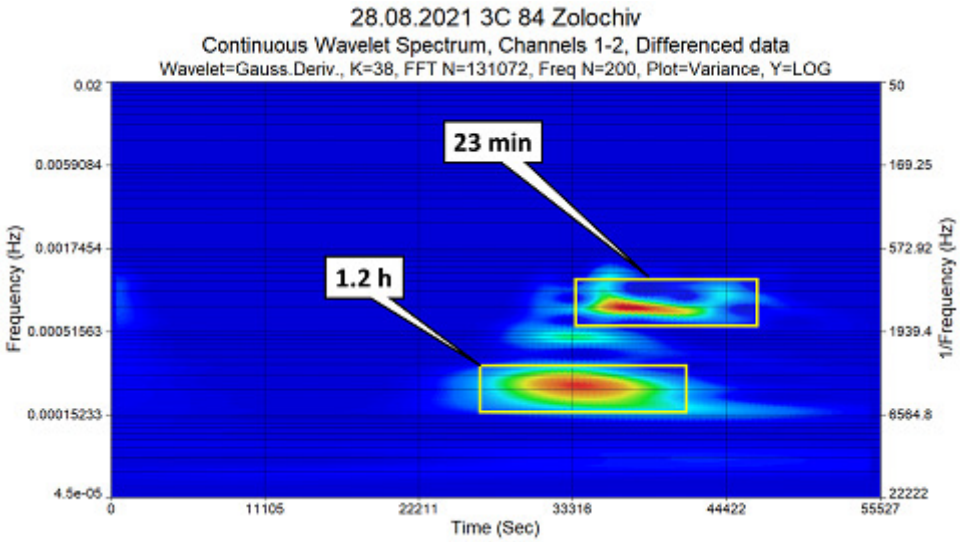


Figure 11 Example of a wavelet spectrogram for the source 3C 84, obtained at a frequency of 6 GHz on August 28, 2021. Significant spectral components with periods of about 1.2 hours and 23 minutes are clearly visible, which appeared from the middle of time series in the form of quite well localized "spots". Main spectral power of the signal is concentrated on a segment of time lasting 19232 seconds or 5.3 hours. The period of 1.2 hours fits into this time interval 4.4 times. On the vertical Y-axis – frequency in hertz (left) and period in seconds (right). On the horizontal X-axis – time in seconds. Here, the spectral power is normalized to the variance of data set.

such clouds with a relatively high density is currently very poorly understood and is not reliably known [34]. In the case of 3C 84 variability, caused by scattering of radio emission from this radio galaxy by dense inhomogeneities of the galactic medium, variations in flux density close to irregular should be observed, which can be constantly present in the signal records during different observation sessions. But, in the case of 3C 84 source, according to our observations, variability with characteristic times of about 1 hour and several tens of minutes is clearly localized in separate time intervals and manifests itself episodically. This is more consistent with disturbances of ionospheric turbulence with the help of acoustic-gravity waves.

Observations carried out over several months show that fluctuations with a quasi-periods of about 1 hour are real, and appear in the data at all available observation frequencies from 1.6 to 8.8 GHz. These fluctuations are not related to radio-interference and weather conditions. At the same time, it is difficult to assume that these flux density variations are related to the 3C 84 radio source itself (internal variability). Although it is possible to assume, that among all episodes of registration variability with quasi-periods of about 1 hour, there were also appearance of the internal variability of 3C 84, however, without proof by registering these variations simultaneously on two antennas, located at quite big distances apart, it is premature to talk about this. But it was possible to check the ionospheric nature of the appearance of fast near-hour fluctuations in the flux density of the 3C 84 source, and a separate article

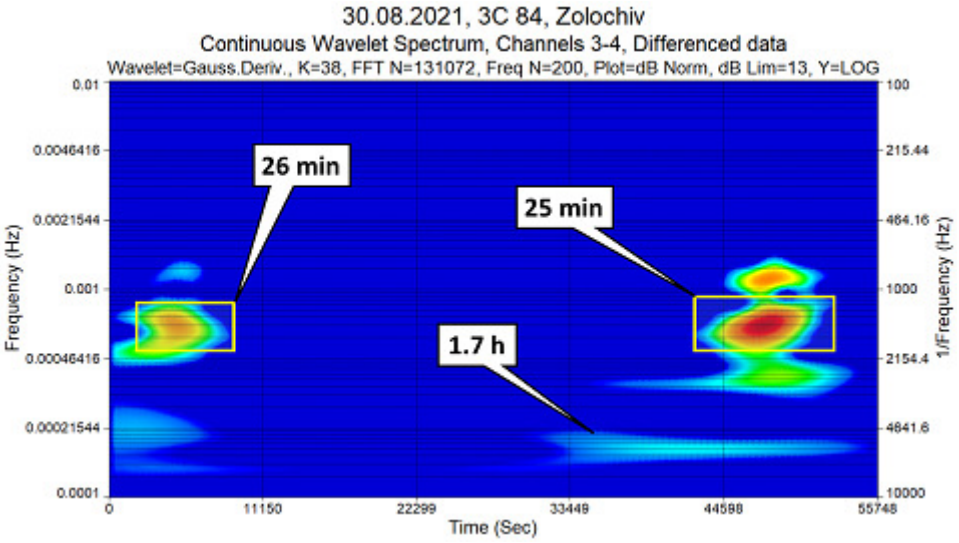


Figure 12 Wavelet spectrogram for the 3C 84 source, obtained at a frequency of 6 GHz on August 30, 2021. Here, the quasi-period of about 1.7 hours is less in amplitude than variations with characteristic times of about 25–26 minutes, which also have a clear time-localization. The duration of oscillation with a period of 25 minutes is about 145 minutes, or almost 6 cycles with a period of 25 minutes. The duration of an almost two-hour cycle (1.7 h) is about 360 minutes or 6 hours, which is 3.5 cycles with a period of 1.7 hours. Recording length 15 hours. In this example, intensity of the wavelet transform coefficients is normalized to zero decibels – $10 \cdot log_{10}\left(\Re^2 + \Im^2\right)$.

is being prepared on the basis of that experiment, dedicated to this topic. The fact is that mid-latitude acoustic-gravity waves often have characteristic periods of variations also in the range of 30 minutes – 1.5 hours and a little more. The influence of these waves on radio astronomical observations in the centimeter radio range is almost not considered in available publications and is currently little studied. The high time resolution and high sensitivity of the 32-m radio telescopes in Zolochev and Irbene are sufficient to detect such very weak variations in the 3C 84 flux density caused by ionospheric waves.

9 Discussion

The fast intra-day variability of radio emission from extragalactic radio sources is currently a very popular topic for research at many large observatories in the world, as a result of which many remarkable results have been obtained. According to the works [35], [36], scintillations of radio galaxies and quasars, caused by passage of radio emission through inhomogeneities of interstellar medium, located on the line of sight, are the main cause of observed changes in radio sources flux density over several hours. The strongest argument in favor of scintillations due to inhomogeneities in distribution of electrons in interstellar plasma as reason of intra-day variability is the lack of

correlation between intensity variations in the radio, infrared, and optical ranges. Sometimes, the correlation is low or absent even at different observation frequencies of the same source in radio range. Also, during interstellar scintillations, variability should be chaotic, without any periodicity, or in the case of quasi-periods, they must be unstable and change strongly over time or disappear altogether. In favor of real internal variability due to physical processes in the radio source itself, is stability of quasi-periods over time, as well as the interrelation (observed correlation) of radio and infrared, optical, rarely X-ray, intra-day variability. Revealing contribution of internal variability of radio sources against background of external component associated with scintillations due to inhomogeneities in distribution of electrons in the interstellar medium and ionospheric effects is an important task. The external variability of radio sources with characteristic intra-day time scales is indicated by a weak correlation between several radio frequencies of observations, as well as irregular variability in the flux density without clear quasi-periods, or quick changing in values of quasi-periods over time and abrupt transitions between them.

Earlier, a cross-correlation between radio and optical data for 3C 84 has not yet been reliably found. In our work, cross-spectral analysis, in some sessions of quasi-simultaneous observations on the RT-32 Zolochiv and RT-32 VIRAC antennas, showed the presumed presence of variations with a characteristic time of about 6 hours in the signal records on two antennas. But the series of observations were not long enough to accurately interpret this phenomenon. The occurrence of a quasi-period of about 1 hour, over a time interval of about 2 days, was supposedly recorded from observations in Irbene, Latvia. For example, on March 15 and 16, 2021, at a frequency of 6.2 GHz, the cross-amplitude FFT spectrum had a maximum corresponding to the characteristic time of flux density variations of about 1.2 hours. The maximum on the plot of cross-amplitude versus frequency or period, shows that there are variations in the two time series with the same characteristic time. This provides some confirmation that observed rapid fluctuations in flux density of the 3C 84 source on a time scale from 1 hour to several hours are real, since there is information about their registration at two observatories in Ukraine and Latvia, on the same days. Examples of cross-amplitude FFT spectra are shown in Figure 13. More details about the method used in data analysis for calculating the mutual Fourier transform for two time series can be found in [37].

As a result of intensive observations of the radio source 3C 84 from the end of 2020 until the autumn of 2021 from the radio telescopes in Latvia and Ukraine, it was found that the radio source 3C 84 really has intra-day variability in the centimeter range, with characteristic times from 3 to 8 hours. This is confirmed by observations from two 32-meter radio telescopes in Ukraine and Latvia, and 16-meter radio telescope in Latvia. Moreover, the Latvian radio telescopes are located at a distance of about 1000 kilometers from the Ukrainian one, and the agreed results were obtained by different mathematical methods for data-processing the recorded signals. Unfortunately, technical problems prevented the planned simultaneous observations at Zolochiv–Irbene from being carried out in full, but where the observation sessions were overlapped, the characteristic times of variability according to records in the Zolochiv and Irbene were quite close. The detected flux variations of the 3C 84 source can be both external in nature (interstellar scintillations, for example) and internal. In the future, to confirm the internal nature of intra-day variability, observations from two radio telescopes are

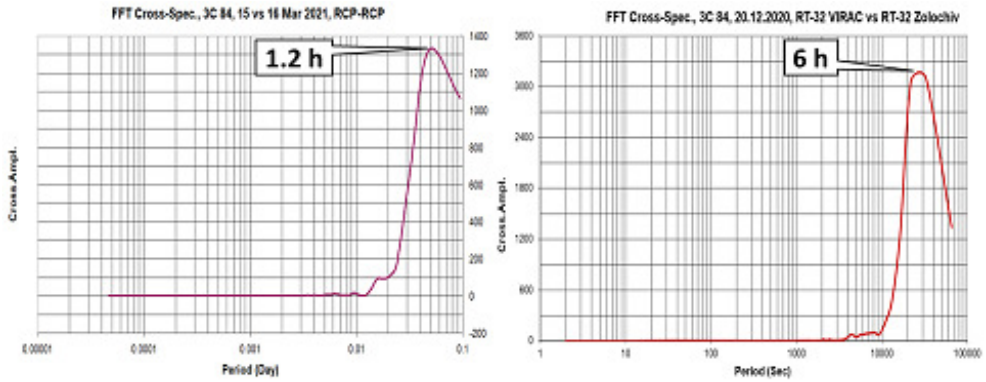


Figure 13 Cross-amplitude plots for data series of the 3C 84 radio source. On the right is the cross-amplitude plot obtained for simultaneous recordings on the 32-m Zolochiv and VIRAC antennas on December 20, 2020 at a frequency of 5 GHz. It can be seen that maximum on the plot corresponds to a quasi-period of 6 hours. On the left is a cross-amplitude plot obtained for records on the 16-m antenna of VIRAC on March 15 and 16, 2021, in right circular polarizations. It can be seen that maximum on the plot is corresponds to a quasi-period of 1.2 hours, which was visible in the data for two days.

required, in the phase interferometer mode, or many consecutive quasi-simultaneous observation sessions from two radio telescopes, with followed calculation of amplitude and phase cross-spectra, square of coherence and gain, to confirm that fluctuations in the flux density are actually detected on two antennas simultaneously and the characteristic times of these variations coincide.

A more reliable answer about the nature (internal or external) of observed variability of the 3C 84 source can be given by interferometric observations on a short-baseline interferometer between the 16-m and 32-m antennas of VIRAC, Latvia, which has recently begun work in test mode. The flux density recorded in this mode is practically devoid of uncorrelated noise and radio-interference. Also in the future, a test interferometric recording of the 3C 84 flux density between the antennas in Zolochiv and Irbene will be possible. If in this case the flux variability of the 3C 84, with characteristic times of several hours is also observed, this will be a quite strong argument in favor of internal variability of the source itself.

To control the correctness of measurements, many sessions of observations of calibration (standard) radio sources were carried out and data obtained about the effect of weather conditions (cloudness, fog, haze) on measurements and only the best records of the 3C 84 source flux density, made in good weather, were selected for analysis. Thus, the influence of weather conditions on the results of measurements and data analysis is minimized. Figure 14 shows an example of an unsmoothed recording of the flux density of the 3C 295 calibration radio source, in good weather and in the presence of clouds.

It can be seen that haze and cloudiness significantly expand the noise track of received signal from the radio source. Also, the error of measurements and scatter of points increase several times during rapidly changing dense clouds. In general, a series of observations of calibration sources showed that their data did not have any

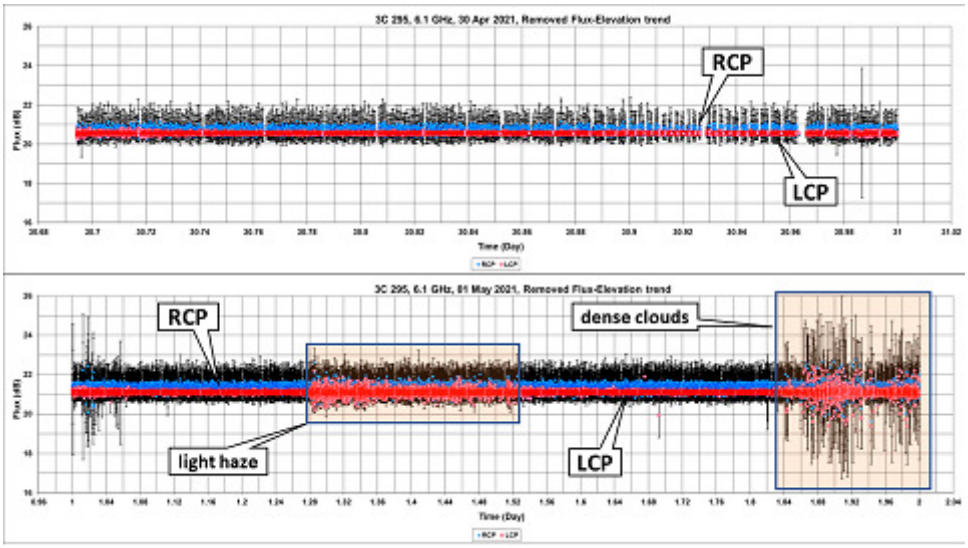


Figure 14 Example of a "raw" unsmoothed recording of the 3C 295 calibration source made in Irbene (VIRAC) at a frequency of 6.1 GHz in right (RCP) and left (LCP) circular polarization. The observations were made on April 30 and May 1, 2021. The upper plot is the 3C 295 record obtained in good weather with a clear sky, when width of noise track of unsmoothed data is about 0.5 dB. The lower plot is the record 3C 295 obtained in conditions of light haze and further, with variable dense clouds. The influence of weather is clearly visible in form of a sharp increase in the noise track and scatter of points, when measurement error also increases. Thus, for a more reliable study of the intra-day variability of extragalactic objects, it is desirable to conduct observations in a clear sky (although with episodic flux density measurements 1–5 times per day with large averaging, the effect of cloudiness is not so critical).

variability on time scales that was found in the 3C 84 source, which means that there were no recurring hardware problems and long-term periodic noise that could distort the results obtained in the work.

10 Conclusions

As a result of observations of the radio galaxy NGC 1275 (3C 84) at the radio telescopes of Ukraine (RT-32 Zolochiv) and Latvia (RT-32, RT-16 VIRAC) in the time interval from the end of 2020 to autumn 2021, the following results were obtained:

Numerous appearances of intra-day variability were recorded for the 3C 84 radio source, according to observations both in Ukraine and Latvia, at frequencies of 5 and 6 GHz (RT-32 Zolochiv) and at frequencies of 5, 6.1, 6.7, 8–8.8 GHz (RT-32, RT-16 VIRAC), as well as additional observations at a frequency of 1.6 GHz (RT-32 VIRAC).

The characteristic times of this variability differed quite significantly from session to session of observations, and usually were in the range of 3–5–8 hours. In addition

to "activity phases" with fast fluctuations in the flux density, the 3C 84 radio source also exhibited "calm phases" when there was no significant cyclic variability. It is possible that the activity phases are manifestations of interstellar scintillations, as has already been established for some other extragalactic radio sources.

At the same time, there is evidence in the form of peaks in cross-amplitude spectra that flux density variations with characteristic times of about 6 hours were observed simultaneously at two 32-m radio telescopes in Ukraine and Latvia. But for unambiguous confirmation of the internal nature of fast variations of radio intensity of 3C 84, an insufficient number of simultaneous observations were carried out. For further study of this fast variability of the 3C 84, longer series of simultaneous interferometric observations should be used.

Acknowledgements

The contributions of all authors were supported by the Latvian Council of Science project "Joint Latvian–Ukrainian study of peculiar radio galaxy "Perseus A" in radio and optical bands". Nr: lzp-2020 /2-0121". Project is being implemented in Ventspils University of Applied Sciences.

References

[1] A.C. Fabian, J.S. Sanders, S.W. Allen, C.S. Crawford, K. Iwasawa, R.M. Johnstone, R.W. Schmidt, G.B. Taylor. A deep Chandra observation of the Perseus cluster: shocks and ripples. Monthly Notices of the Royal Astronomical Society, 2003, Vol. 344, Issue 3, P. L43–L47

[2] Edge A.C., Stewart G.C., Fabian A.C. Properties of cooling flows in a flux-limited sample of clusters of galaxies. Monthly Notices of the Royal Astronomical Society, 1992, Vol. 258, P. 177-188

[3] D.C. Homan, J. F. C. Wardle. High Levels of Circularly Polarized Emission from the Radio Jet in NGC 1275 (3C 84). The Astrophysical Journal,2004, Vol. 602, No. 1, P. L13

[4] Gallagher John S. III, Lee M., Canning R., Fabian A., O'Connell R.W., Sanders J., Zweibel E. Dusty Gas and New Stars: Disruption of the High Velocity Intruder Galaxy Falling Towards NGC 1275. American Astronomical Society, 2010, AAS Meeting #215, id.363.08; Bulletin of the American Astronomical Society, Vol. 42, P. 552

[5] Silke Britzen, Christian Fendt, Michal Zajacek, Frederic Jaron, Ilya Pashchenko, Margo F. Aller, Hugh D. Aller. 3C 84: Observational Evidence for Precession and a Possible Relation to TeV Emission. Galaxies, 2019, Vol. 7, Issue 3, P. 72

[6] S. Ansoldi, L.A. Antonelli, C. Arcaro, D. Baack et al. Gamma-ray flaring activity of NGC 1275 in 2016-2017 measured by MAGIC. Astronomy&Astrophysics, 2018, Vol. 617, Article Number A91

[7] Yuhai Yuan, J.H. Fan, H.J. Pan, Z.Y. Peng, Y. Liu, H.B. Xiao. Optical monitoring and spectral analysis of the Seyfert galaxy NGC1275. Astrophysics and Space Science, 2015, Vol. 360, Article number: 9

[8] Pronik I.I., Merkulova N.I., Metik L.P. Characteristics of the variability of the nucleus of NGC 1275 in the optical in 1982-1994. Astronomy and Astrophysics, 1999, Vol.351, P. 21-30

[9] Pengfei Zhang, Zhongxiang Wang, Mark Gurwell, Paul J. Wiita. A double-period oscillation signal in millimeter emission of the radio galaxy NGC 1275. 2021, arXiv:2112.03544v1

[10] A.L. Sukharev, V.V. Bezrukovs, M.Y. Bleiders, A.A. Orbidans, M.I. Riabov. About program and preliminary results of investigations of intraday and interdiurnal flux variability of extragalactic radio sources on telescopes of Ventspils International Radio Astronomy Center (VIRAC). Radio Physics and Radio Astronomy, 2017, Vol. 22, No. 4, P. 256-269

[11] A. Sukharev, M. Ryabov, V. Bezrukovs, A. Orbidans, M. Bleiders, S. Udovichenko, L. Keir, I. Eglitits, P. Dubovsky. Study of Rapid Variability of the Blazar OJ 287 in the Radio and Optical Ranges. Astrophysics, 2020, Vol. 63, P. 32-44

[12] Artem Sukharev, Michail Ryabov, Vladislavs Bezrukovs, Arturs Orbidans, Marcis Bleiders, Sergei Udovichenko, Leonid Keir, Ilgmars Eglitis, Igor Kudsey, Pavol Dubovsky. Program and Results of Investigations Rapid Variability of the BL Lac Object 3C 371 in Radio and Optical Ranges. Galaxies, 2020, Vol. 8, No. 3, P. 69

[13] A.L. Sukharev, M.I. Ryabov, V.V. Bezrukovs. Property Study of OJ 287 and BL Lac Variability in Optical and Radio Ranges. Radio Physics and Radio Astronomy, 2019, Vol. 24, No. 4, P. 254

[14] Jacob T. VanderPlas. Understanding the Lomb–Scargle Periodogram. Astrophysical Journal Supplement Series, Vol. 236, No 1, P. 16

[15] Mark K. Transtrum, James P. Sethna. Improvements to the Levenberg-Marquardt algorithm for nonlinear least-squares minimization. 2012, arXiv:1201.5885v1 [physics.data-an]

[16] E. Ostertagova, O. Ostertag. Methodology and application of Savitzky-Golay moving average polynomial smoother. Global Journal of Pure and Applied Mathematics, 2016, Vol. 12, No. 4, P. 3201-3210

[17] H.A. Gaberson. Applying the inverse FFT for filtering, transient details and resampling. Sound & Vibration, 2005, Vol. 39, Issue 8, P. 18-23

[18] Dariusz Komorowski, Stanislaw Pietraszek. The Use of Continuous Wavelet Transform Based on the Fast Fourier Transform in the Analysis of Multi-channel Electrogastrography Recordings. J. Med. Syst., 2016, Vol. 40, P. 10

[19] Torrence C., G.P. Compo. A Practical Guide to Wavelet Analysis. Bull. Am. Meteorol. Soc., 1998, Vol. 79, P. 61–78

[20] M. Bleiders, Vl. Bezrukovs, A. Orbidans. Performance Evaluation of Irbene RT-16 Radio Telescope Receiving System. Latvian Journal of Physics and Technical Sciences, 2017, Vol. 54, No. 6, P. 42

[21] K. Skirmante, Vl. Bezrukovs, N. Jekabsons, I. Shmeld. Preparation of the VIRAC Radio Telescope RT-32 for e-VLBI Observations. Baltic Astronomy, 2013, Vol. 22, P. 329-340

[22] O.M. Ulyanov, A.M. Reznichenko, V.V. Zakharenko, A.V. Antyufeev, A.M. Korolev, A.N. Patoka, V.I. Prisyazhniy et al. Creation of the RT-32 radio telescope based on the MARK-4B antenna system. 1. Modernization project and first results. Radio Physics and Radio Astronomy, 2019, Vol. 24, No. 2, P. 87-116

[23] A.V. Antyufeev, A.M. Korolev, A.N. Patoka, V.M. Shulga, O.M. Ulyanov et al. Creation of the RT-32 radio telescope based on the MARK-4B.2 antenna system. Assessment of the possibility of conducting spectral observations of radio astronomical objects. Radio Physics and Radio Astronomy, 2019, Vol. 24, No. 3, P. 163-183

[24] Dent W.A. Variation in the radio emission from the Seyfert galaxy NGC 1275. Astrophysical Journal, 1966, Vol. 144, P. 843

[25] Aller Hugh D., Aller Margo F., Plotkin Richard M. Circular Polarization Variability in Extragalactic Sources on Time Scales of Months to Decades. Astrophysics and Space Science, 2003, Vol. 288 (1-2), P. 17-28

[26] Craven P., Wahba G. Smoothing noisy data with spline functions: Estimating the correct degree of smoothing by the method of generalized cross-validation. Numerische Mathematik, 1979, Vol. 31, P. 377-403

[27] E. Cadenas, R. Campos-Amezcua, W. Rivera, M. Antonio Espinosa-Medina, A. Rosa Mendez-Gordillo, E. Rangel, J. Tena. Wind speed variability study based on the Hurst coefficient and fractal dimensional analysis. Energy Science & Engineering, 2019, Vol .7, Issue 2, P. 361-378

[28] Epstein E.E., Landau R., Rather J.D.G. Extragalactic radio sources - Rapid variability at 90 GHz. Astronomical Journal. - 1980. - Vol. 85. - P. 1427 - 1433

[29] A.G. Gorshkov, A.V. Ipatov, I.A. Ipatova, V.K. Konnikova, V.V. Mardyshkin, M.G. Mingaliev, M.A. Kharinov. Long-Term and Rapid Radio Variability of the Blazar 3C 454.3 in 2010–2017. Astronomy Reports, 2018, Vol. 62, P. 183-199

[30] A.G. Gorshkov, A.V. Ipatov, I.A. Ipatova, V.K. Konnikova, V.V. Mardyshkin, M.G. Mingaliev, M.A. Kharinov. Long-Term and Rapid Radio Variability of the Blazar 3C 454.3 in 2010–2017. Astronomy Reports, 2018, Vol. 62, P. 183-199

[31] Tong Liu, Zhibin Yu, Zonghua Ding, Wenfeng Nie, Guochang Xu. Observation of Ionospheric Gravity Waves Introduced by Thunderstorms in Low Latitudes China by GNSS. Remote Sens., 2021, Vol. 13, P. 4131

[32] Barabash Vladimir, Chernogor Leonid, Panasenko Sergii, Domnin Igor. Ionospheric manifestations of acoustic-gravity waves under quiet and disturbed conditions. EGU General Assembly 2014, held 27 April - 2 May, 2014 in Vienna, Austria, id.6162

[33] T.A. Oosterloo, H.K. Vedantham1, A.M. Kutkin, E.A.K. Adams et al. Extreme intra-hour variability of the radio source J1402+5347 discovered with Apertif. Astronomy&Astrophysics, 2020, Vol. 641, Article No. L4

[34] H.E. Bignall, D.L. Jauncey, J.E.J. Lovell, A.K. Tzioumis, J.-P. Macquart, L. Kedziora-Chudczer. Observations of intrahour variable quasars: scattering in our Galactic neighbourhood. Astronomical & Astrophysical Transactions, 2007, Vol. 26, Issue 6, P. 567-573

[35] X. Liu, P.P. Yang, J. Liu, B.R. Liu et al. Radio and optical intra-day variability observations of five blazars. MNRAS, 2017, Vol. 469, No. 2, P. 2457–2463

[36] T.P. Krichbaum, A. Kraus, L. Fuhrmann, G. Cimo and A. Witzel. Intraday Variability in Northern Hemisphere Radio Sources. Publ. Astron. Soc. Aust., 2002, Vol. 19, P. 14-18

[37] Daniel J. Hancock, Douglas N. Yarger. Cross-Spectral Analysis of Sunspots and Monthly Mean Temperature and Precipitation for the Contiguous United States. Journal of the Atmospheric Sciences, 1979, Vol. 36, Issue 4, P. 746-753