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Results of comparison of fast variations of geomagnetic field and ionospheric scintillations of 3C 144 radio source in the area of Odessa geomagnetic anomaly

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From November 2017 to May 2019 at the Astronomical Observatory of Odessa I.I. Mechnikov National University, the variational component of the geomagnetic field was monitored to study short-periodic geomagnetic variations in the central part of the Odessa regional magnetic anomaly. The measurements were carried out using a LEMI-008 precision fluxgate magnetometer with a sampling rate of 1 Hz. The aim of this work is to compare the manifestation of short-periodic geomagnetic oscillations (which in some cases coincided with periods of geomagnetic pulsations) and ionospheric scintillations of the 3C 144 radio source (Taurus A) according to the data of URAN-4 low-frequency phased antenna array at frequencies of 20 and 25 MHz. The data obtained were processed on a daily basis using the method of continuous wavelet transform, as well as band-pass filtering based on Fourier transform, to select individual frequency bands containing irregular and quasi-harmonic variations in the geomagnetic field and radio flux density. The analysis of results of the observations, during geomagnetic disturbances, storms and in calm conditions, is carried out. The data from long-term monitoring of variational component of the geomagnetic field in the most interesting, central part of the Odessa magnetic anomaly, where such studies have not been conducted before, have been obtained. Observations of various manifestations of ionospheric scintillations were carried out both during magnetic storms and during a calm geomagnetic field. It is shown that during storms, main scintillation time scale of the 3C 144 radio source is 1–3 minutes. Ionospheric scintillations occasionally show a quasiperiodic structure.

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1 Introduction

Currently, an important scientific task in the study of terrestrial magnetism is the study of geomagnetic pulsations in areas of magnetic anomalies (areas of the Earth's surface, where the geomagnetic field differs significantly from its normal values). This makes it possible to describe and determine the features and effects of Solar activity due to the influence of the magnetic anomaly. In the southwestern part of the territory of Ukraine, there is a large and intense Odessa regional magnetic anomaly [1], which was discovered and investigated back in 1892 [2]. Regional magnetic anomalies are associated with presence of magnetized rocks throughout an entire section of the Earth's crust, and possibly in the upper mantle. The abnormal magnetic field in the Odessa region varies from –400 nT (eastern part) to 1200 nT (central part). Modulus

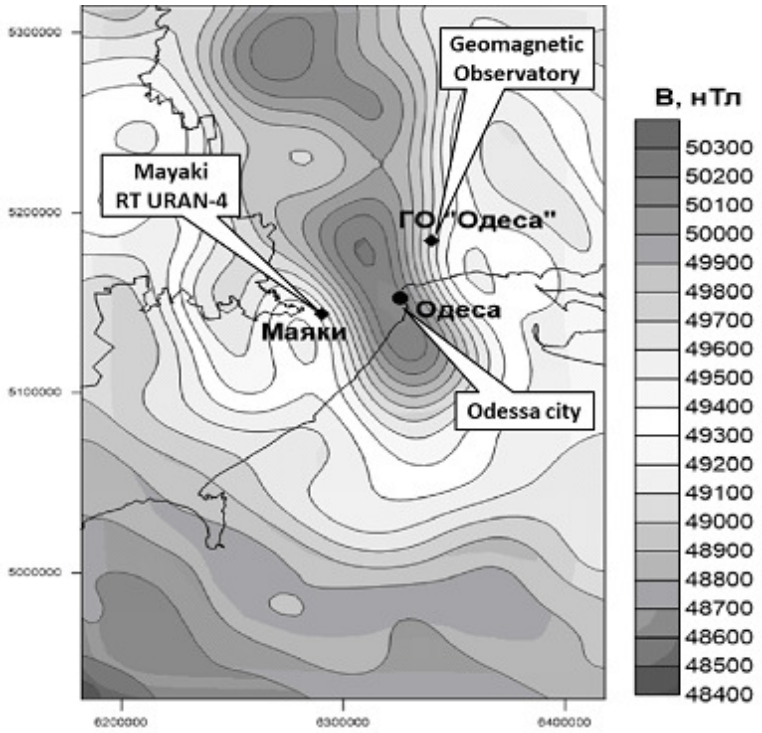


Figure 1 Map of induction module of the geomagnetic field in the area of Odessa for epoch 2015, developed on the basis of analytical model [3]. The flags on the map indicate locations of the "Odessa" magnetic observatory in the Stepanovka village, and the Odessa city, where also there is a magnetometer on territory of the Odessa Astronomical Observatory.

of induction of the geomagnetic field (sum of anomalous and normal magnetic fields) also varies within 48600–50400 nT (shown in Figure 1).

The detailed study of the spatial structure of geomagnetic field, carried out by employees of the Institute of Geophysics of the National Academy of Sciences of Ukraine, showed that magnetic sources are located in the upper and lower parts of the Earth's crust, at depths from 7 to 40–45 km [4]. According to calculations, at the heights of formation of ionospheric and magnetospheric sources of geomagnetic variations, some differences in the intensity of the field, both normal and anomalous, remain [5, 6]. Thus, the Odessa regional anomaly can affect the processes in the Earth's ionosphere and the associated variations in geomagnetic field, under the influence of Solar activity. Since the state of the ionosphere strongly influences the conditions of the observations of powerful space radio sources at the Odessa radio observatory "URAN-4" (decameter range 10–30 MHz), direct measurement of the disturbance of the geomagnetic field in the central part of the magnetic anomaly will clarify the physical reasons for the regularly observed effects in changing flux density of space radio sources [7]. In this regard, in November 2017, by a joint agreement of the Radio Astronomy Institute of the NAS of Ukraine with the Institute of Geophysics of the NAS of Ukraine, on the territory of the Astronomical Observatory of the Odessa I.I. Mechnikov National University, in the park named after T.G. Shevchenko, a precision fluxgate magnetometer LEMI-008 was installed. The location of that device approximately corresponds to the central area of Odessa magnetic anomaly. Thus, the aim of this work is to study features and properties of short-periodic geomagnetic variations and ionospheric scintillations (according to data from URAN-4 low-frequency antenna), as well as the features of their digital spectral "stamps" during magnetic storms, disturbances, and geomagnetically quiet days.

2 Tools and Methods

2.1 Geomagnetical measurements

The LEMI-008 precision three-dimensional fluxgate magnetometer is designed and manufactured by the Lviv Center of Space Research Institute of the NAS of Ukraine. It is designed for high-precision measurement of variations in the geomagnetic field in observatory and field conditions. Detailed technical characteristics of the device used were discussed in [8].

Continuous registration is provided by a software and hardware complex, consisting of a three-coordinate magnetic sensor in a waterproof case, an electronics unit with a GPS receiver, a backup battery and a netbook. The data obtained from the magnetometer are continuously recorded into text files. Data blocks are formed on a daily basis, each file contains 86400 samples (number of seconds in a day) of variations in the induction of geomagnetic field for each coordinate X, Y, Z in nanoteslas. In this work were analyzed variations of the northern Bx-component of the geomagnetic field induction vector. To protect against external interference, the magnetometer was located in a cellar laboratory of the Odessa Astronomical Observatory, which is located in the T.G. Shevchenko park, quite away from sources of powerful man-made interference.

2.2 Radio astronomical measurements on the URAN-4 antenna array

For observations of ionospheric scintillations of powerful cosmic radio sources, the URAN-4 radio telescope located in the Mayaki village in Odessa region, Ukraine, was used. The antenna array is shown in Figure 2.



Figure 2 Low-frequency radio telescope URAN-4 for decameter wavelength range (frequency range 10–30 MHz).

This is a multi-element phased antenna array, consisting from 128 antenna vibrators placed in four rows of 32 vibrators, which are oriented along the parallel. Antenna size is 238 × 28 meters with a geometric area of approximately 7000 square meters. Antenna beamwidth at half power level at 25 MHz is 2.7 × 22 degrees, when operating as part of the URAN interferometer, the angular resolution is approximately $2''$. Control of the antenna beam is electric along the angular coordinates U and V. Position of the antenna beam in space is changed using synchronous remote switching of delay lines in time-type phase shifters with a fixed phase center. When pointing at the radiosource, signals from the vibrators are first phased in the North-South direction, and then the West–East direction is phased. At the same time, 128 beam positions are provided along the U (West–East) coordinate, and 16 beam positions are provided along the V coordinate (North–South direction). At present, the main frequencies for monitoring observations are 20 and 25 MHz in two linear polarizations A and B (receiving of which is provided by two mutually orthogonal broadband horizontal vibrators on each column of the antenna array). The radio telescope operates both as part of the URAN low-frequency interferometer of the Radio Astronomy Institute of the National Academy of Sciences of Ukraine, and in single station mode. Since 1998, the radio telescope has been fully automated and operates according to predetermined programs. Long-term monitoring of scintillating cosmic radio sources 3C 144 (Crab Nebula), 3C 405 (Cygnus A), 3C 196 (quasar), 3C 461 (Cassiopeia A), 3C 274 (Virgo A) is performed in the single mode of operation.

The observation of these sources allowed us to accumulate unique long-term observational material for different cycles of Solar activity, which makes it possible to

study the seasonal dependences of variations in the ionospheric scintillation index, as well as the ionospheric scintillations themselves due to space weather disturbances caused by active events on the Sun. The unique location of the URAN-4 antenna in the region of a large regional magnetic anomaly makes it very important to study the interrelation and differences between ionospheric scintillations and geomagnetic pulsations as a response to space weather variations. In more detail, the equipment and parameters of the URAN-4 radio telescope are described in [9], [10].

2.3 Data analysis methods

Time-frequency spectra of geomagnetic variations and ionospheric scintillations were constructed using a continuous wavelet transform based on the Gauss derivative analyzing function. A fast version of the calculation of wavelet spectra through FFT (Fast Fourier Transform) was applied [11] which made it possible to significantly speed up the processing of a large number of observations. Previously, the average value of geomagnetic induction was subtracted from the data in order to avoid suppression of the high-frequency part of the spectrum by frequencies close to zero. In addition, STFT spectrograms (time-frequency spectra based on windowed FFT) with Bartlett or Hamming spectral windows were used to analyze the scintillation from radio-data. Fourier filtering was used to remove the sinusoidal trend of the beam pattern of the URAN-4 antenna and to identify fast variations in the fluxes of radio sources [12].

The records of radio sources obtained by the URAN-4 antenna often contain radio-interference in the form of groups of outliers points (usually 2–5 times bigger than average value of the recorded radio source flux), as well as episodic radio-interference that expands the noise level. Outliers points were removed manually from each individual record, and two methods were used to isolate the signal against the background of noise and simultaneously interpolate – cubic spline smoothing [13] and Loess–type (locally weighted least squares) sliding window smoothing procedure using Tricube weighting function [14]. The smoothing cubic spline was used when the records of radio sources contained moderate noise and interference, Loess-smoothing was used in cases where the noise and interference were quite large. Sometimes, at the beginning of the observation session, powerful noise and interference appeared, completely distorting the record of the passage radio source through the antenna pattern, in which case the section of the record with noise was removed, and the part of the record that was not distorted by interference was used.

Daily data of geomagnetic variations show a very wide spectrum, on time scales from several hours to tens of seconds. Often there are overlaps of different types of pulsations, so it is convenient to isolate the bands of periods containing the pulsations of interest from the total spectrum and analyze them separately. For this, band-pass filtering based on the Fourier transform was also used. To reduce the edge effects that distort the wavelet spectra, the addition of zeros to the time series, at its beginning and end, by the size of the time series itself, was used. For more details on the calculation of confidence levels for wavelet spectra, there is information in [15]. To smooth out high-frequency noise and sharp spikes in geomagnetic induction records, the popular Savitsky–Golay method was used [16], which is based on polynomial calculation in a sliding window by the least squares method and is efficient for large sets of uniform noisy data.

3 Short-periodic geomagnetic variations at the Odessa Astronomical Observatory

We consider, for example, several records of geomagnetic variations on the days of magnetic storms. Figure 3 shows plots of variations in the northern Bx component of the geomagnetic field (initial data and smoothed data) for a magnetically quiet day on January 8, 2019. It can be seen that, despite the location of the magnetometer far from sources of artificial interference (such sources as industrial production, railway lines, large shopping centers and residential areas), there is high-frequency noise typical of a big city in the records, which increases from 4 am and decreases from 9 pm, local time. This is especially noticeable in variations of the Bz component, which, according to [17], is the most sensitive to technogenic interference. Horizontal components were found to be less prone to technogenic interference. The data were smoothed with a Savitsky–Golay filter with a window half-width of 120 points, a polynomial degree of 4, and a number of passes of 3. Amplitude of the noise is usually 10–15 nT but rarely, on some especially "noisy" days it can increase to 20–30 nT. In [18], a comparison was made of the records of geomagnetic field variations at the Odessa Astronomical Observatory and the Odessa Geomagnetic Station, located in the sparsely populated village Stepanovka, where magnetometers are located in deep cellars and are well

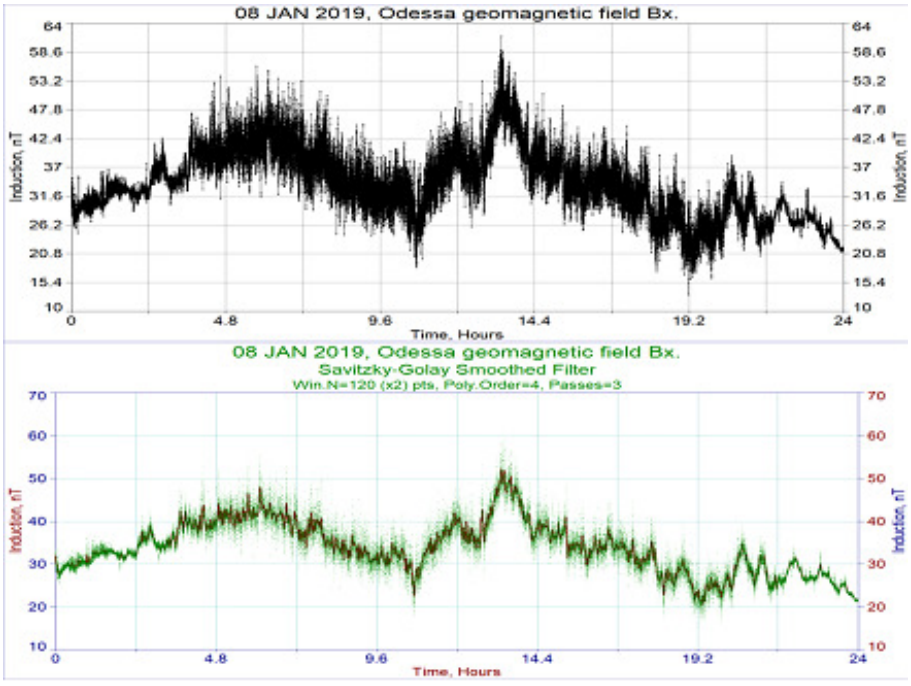


Figure 3 The original, unsmoothed plot of variations in the Bx (northern) component of the geomagnetic field (upper figure), and the smoothed plot (lower figure) for a quiet magnetic field on January 8, 2019. On the plots, along the X-axis – time in hours, along the Y-axis – induction in nT (nanotesla).

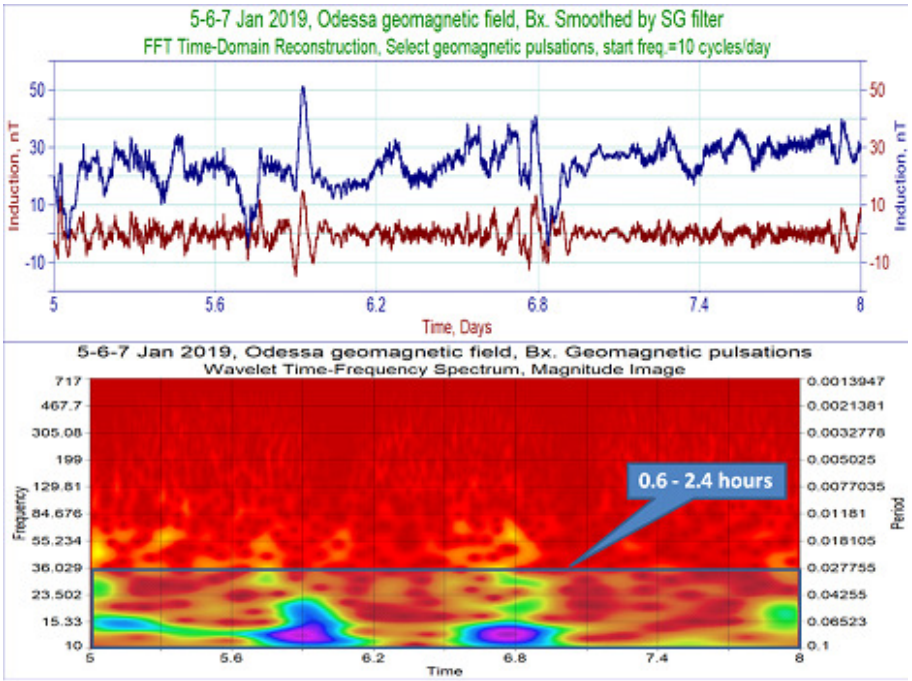


Figure 4 Smoothed data and fast variations of the Bx component of the geomagnetic field highlighted by FFT filtering on January 5, 6, 7, 2019 (top). Wavelet spectrum of a time series of short-period geomagnetic variations, the flag indicates area of the most powerful variations in the band of periods from 0.6 to 2.4 hours (below). On the X-axis – time in fractions of a day, on the Y-axis – frequency (cycles per day) and period (in fractions of a day), on the Z-axis – amplitude in the form $Z = \sqrt{R^2 + I^2}$, where R and I – real and imaginary parts of the wavelet transform.

protected from artificial industrial interference and noise. The comparison showed a good identity of the data smoothed by the Savitsky–Golay filter with the reference data from the Odessa geomagnetic station.

We also consider, for example, a time series of days January 5–7, 2019. January 6 was a geomagnetic storm, January 5 was an increased geomagnetic activity, January 7 was a magnetically calm day. Figure 4 shows an example of a smoothed Bx component of the geomagnetic field, as well as a wavelet spectrum of geomagnetic field variations during the transition from a magnetic storm to a calm magnetic field. In geomagnetic data, in addition to fast pulsations with characteristic times from several tens to several minutes, digital spectra also usually show fragments of harmonics of solar-diurnal oscillations of the geomagnetic field, which, due to their significant amplitude, often suppress short-period variations, reducing their significance. The lower part of Figure 4 shows the wavelet spectrum after the highlight by bandpass Fourier filtering of the data fragment, corresponding to the band of periods on the spectrum from 0.6 to 2.4 hours (36–144 minutes). A quasi-period of about 1.5 hours (with a slight increase over time) is clearly visible throughout almost all of January 5th. Also, there were high-amplitude bursts with a characteristic time of about 2 hours. However,

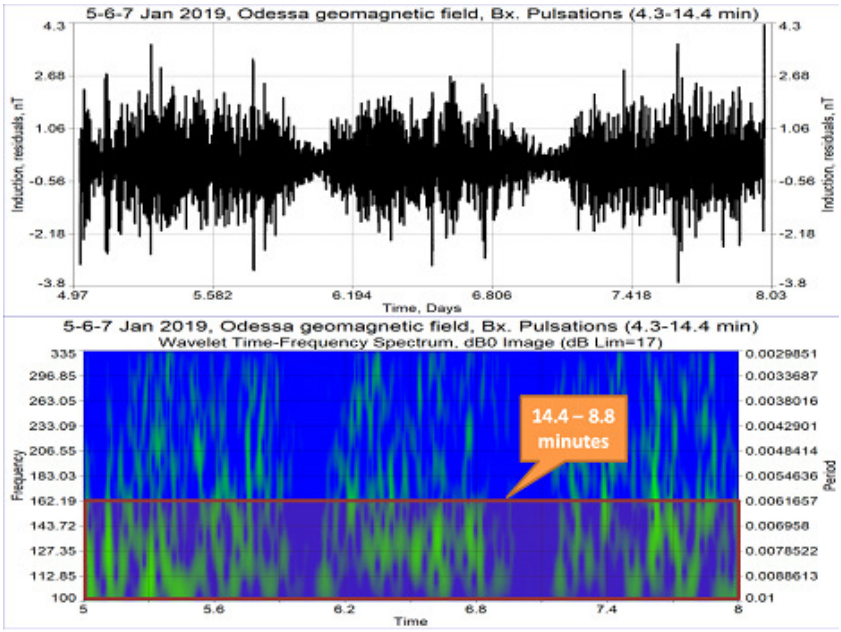


Figure 5 Geomagnetic scintillation region identified, and selected by FFT filtering in the band of periods from 4.3 to 14.4 minutes for January 5, 6, 7, 2019 (top). The wavelet spectrum (bottom) of these geomagnetic pulsations, the flag indicates the area of quasi-periodic variations with a very fast change in period and amplitude, in that band from 8.8 to 14.4 minutes. In the region of periods less than 8.8 minutes, the noise variations of the Bx component of the geomagnetic field dominate. Here, on the wavelet spectrum, the Z-axis is in decibels $Z = 10 \cdot \log_{10}(R^2 + I^2)$, where R and I – real and imaginary parts of the wavelet transform, normalized to zero for the convenience of determining the areas with the highest power on the spectrum; X-axis is time in fractions of days, Y-axis (left) is frequency in cycles per day, Y-axis (right) is period in fractions of a day.

geomagnetic variations of low amplitude (with a fast period change) are suppressed by longer variations and are obscured in the wavelet spectrum. Irregular bursts also appear on a time scale of about 8 minutes or less.

We consider the spectrum of geomagnetic pulsations for January 5–7, 2019 (Figure 5). For this purpose, a region on the FFT-spectrum in the band of periods from 4.3 to 14.4 minutes was selected using band-pass Fourier filtering and reconstruction. This example is interesting in that quasi-periodic pulsations with a rapid change in periods appeared on these days, mainly in the period band from 8.8 to 14.4 minutes. For periods less than 8 minutes, noise-like variations, clearly localized in time, prevailed. Usually, during magnetic storms, according to the measurements, the addition of irregular, as well as short-term quasi-periodic fluctuations in geomagnetic induction, are more often observed, usually with changes in the values of the periods with time, however, records with quite stable quasi-periodic fluctuations of induction are rare, as shown in the example.

The next step is to consider the manifestations of geomagnetic storms on January 25 and 26, 2019. They are distinguished by the presence of quasi-regular variations,

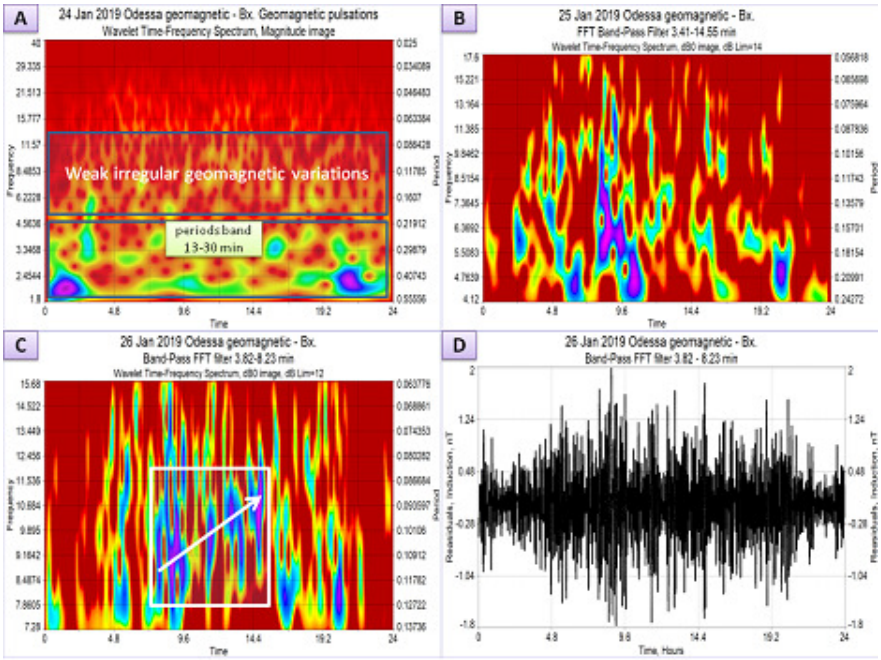


Figure 6 A) Wavelet spectrum for the geomagnetic storm of January 24, 2019, the rectangle marks the area of spectrum for relatively long-term variations in geomagnetic induction in the period band of 13–30 min, the second rectangle marks the region of spectrum with irregular, higher-frequency variations with a small amplitude. B) The wavelet spectrum for the geomagnetic storm on January 25, 2019 in the period band of 3.4–14.5 minutes shows superposition of noise and quasi-regular induction variations, quite clearly localized in time. C) The wavelet spectrum for the geomagnetic storm on January 26, 2019 in the period band of 3.8–8.2 minutes shows the presence of pronounced high-frequency variations in induction on this day, and from approximately 7 am local time to 4 pm local time (indicated by a rectangle) there is a general decrease in the characteristic time of variations (shown by the arrow) from approximately 7 minutes to 5 minutes. On the X-axis – time in hours, on the Y-axis – frequencies in cycles per hour (left) and periods in fractions of hour (right). D) Example of the selected variations in geomagnetic induction in the period band of 3.8–8.2 minutes for the geomagnetic storm on January 26, 2019.

in the period band about 3.8–8.2 minutes (January 26) and about 3.4–14.5 minutes (January 25). The storm on January 26 is characterized by a weak trend towards a decrease in the characteristic time of induction variations. The magnetic storm that occurred on January 24 differed from other storms in January by the predominance of the long-periodic part with quasi-regular variations in the band of periods from 13 to 30 minutes, throughout almost the entire daily recording interval. In the area of the wavelet spectrum with periods shorter than 13 minutes, mostly irregular variations with low amplitude dominated, barely noticeable against the noise background. Examples are shown in Figure 6.

Thus, on geomagnetically quiet and slightly disturbed days, in addition to Solar-diurnal periodic variations, quasi-periodic geomagnetic induction fluctuations with

periods in the range of about 15–30 minutes and irregular, short-term fluctuations with shorter characteristic times, are often observed. During geomagnetic storms, the characteristic time of short-periodic variations of induction is usually in the range of about 4–15 minutes. This is a manifestation of both noisy flares occurring over short time intervals, and quasi-periodic variations with rapidly changing periods. A quite strong noise component does not allow one to reliably record geomagnetic pulsations with characteristic times less than 3–4 minutes on geomagnetically quiet and slightly disturbed days. Only during strong magnetic storms does the amplitude of pulsations with periods less than 4 minutes become high enough to show up in the wavelet spectrum. For the observation point at the Odessa Astronomical Observatory, this rarely happens. At the same time, at night, when the noise of the city is negligible, it is possible to investigate nightly short-period pulsations of the geomagnetic field, which will be the topic of further research.

4 Geomagnetic variations in Dymer, Kiev region

To confirm the special nature of the appearance and propagation in time of geomagnetic variations in the zone of the Odessa regional geomagnetic anomaly, comparisons were made with geomagnetic variations, according to the data of the magnetic observatory located in the town Dymer, Kiev region, where the geomagnetic field is close to normal. For that task, we used data of variations of the northern component of the geomagnetic field Bx, with a sampling frequency of 1 Hz, as for the Odessa geomagnetic data. Examples of wavelet spectrograms of pulsations extracted by FFT filtering and reconstruction from the original records are shown in Figure 7 for three days of magnetic storms and one day of a calm field. It can be seen that, unlike geomagnetic pulsations in the area of Odessa anomaly, in Dymer, high-frequency variations of the geomagnetic field during magnetic storm days are more chaotic, without certain clear quasi-periods. The main energy of short-period oscillations is in the range of periods from 12–30 minutes, and in this range, they are sometimes having quasi-periodic structure. In the range of wavelet spectra less than 12 minutes, irregular variations mainly appear. A special example of the complex structure of quasi-periodic variations was seen on January 25, in the range of periods from 20 minutes to 5 minutes (from 1 am to 10 am local time) (Figure 7). Complicated transitions of the regions of quasi-periods form a kind of "grid". In geomagnetic records for Dymer, this happens quite rarely. Also, an interesting example for the day of quiet magnetic field on January 1st. It can be seen clearly localized in time quasi-periodic bursts in the range of periods 30–13 minutes, with a structure of faster irregular pulsations in the range of periods 8–2 minutes. There are no quasi-periodic variations with periods less than 13 minutes in this example. Summarizing the results of digital spectral analysis for the whole of January 2019, we can say that for the records of geomagnetic field in Dymer (Kiev region), during geomagnetic storms, there are significantly fewer quasi-periodic high-frequency variations than in the Odessa magnetic anomaly. In general, the short periodic part of the geomagnetic variations is more chaotic in comparison with the Odessa data. On days of a quiet geomagnetic field in Dymer, rapid irregular variations are often observed, on a time scale of several minutes, while at the same time there are fewer quasi-periodic variations than in the Odessa data.

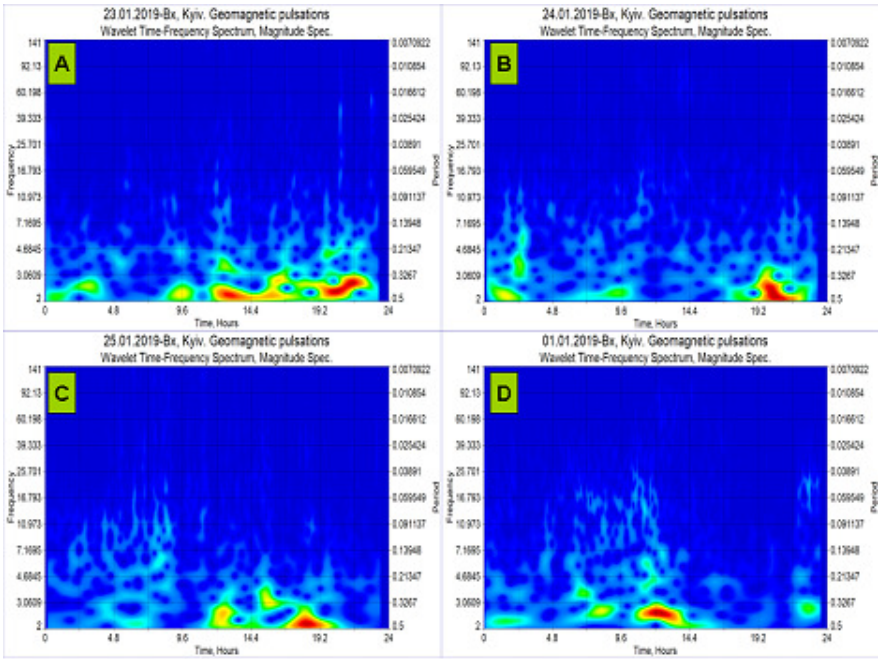


Figure 7 Examples of wavelet spectrograms of geomagnetic pulsations for Dymer, Kiev region (January 2019). A) Magnetic storm on January 23; B) Magnetic storm on January 24; C) Magnetic storm on January 25; D) Geomagnetically quiet day on January 1. On the horizontal axis on the plots – time in hours, on the vertical axis, on the left – the frequency, showing number of cycles per hour, on the right – the period in fractions of hour.

Now we consider longer variations of the geomagnetic field (on a time scale of several hours) in Dymer, and compare them with those in Odessa. Examples are shown in Figure 8. On the FFT spectra on January 26, Dymer has the following quasi-periods: 6.0, 4.0, 2.1 hours; and in Odessa – 6.0 hours is the predominant quasi-period, and then a slightly different picture is visible, 2.4, 1.9, 1.6 hours. Quasi-periods, with values close to 2, 4, 6 hours, are harmonics of a 24-hour daily period, the so-called solar-diurnal variations of the geomagnetic field. In the Odessa data, in this example, the quasi-period of 4.0 hours is "erased", however, the 2-hour quasi-period has a split into several close harmonics, which potentially indicates its change over time. Thus, solar-diurnal variations during some magnetic storms also little differ in the region of magnetic anomaly (Odessa) and the region of normal field (Dymer).

Analysis of the full spectrum of geomagnetic field variations in Dymer for January 2019 (Figure 9) shows a normally significant predominance of the daily period harmonics. At the same time, a complex structure of variations, individual "bursts" of variability are visible. To see the presence of variations, with characteristic times greater than 52 hours, an FFT spectrum was built, on which the harmonic of 161 hours was clearly manifested. This quasi-period (with a value about 7 days) was previously found in the variation of total electron density (TEC) of the ionosphere. In turn, variability with a quasi-period close to 7 days was found in variations in pa-

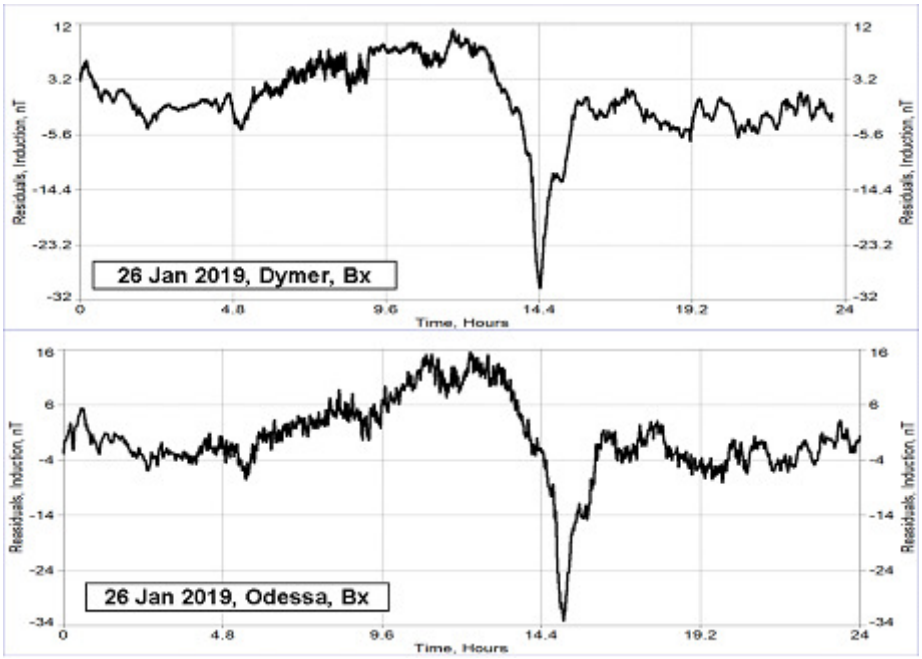


Figure 8 Plots of the initial data of changes in the geomagnetic induction Bx component for Dymer (upper plot) and Odessa (lower plot). On the X-axis, local time in hours; on the Y-axis, induction in nT (average values were subtracted). It can be seen that despite the similarities that seem likely at first glance, the plots have, albeit small, but obvious differences (especially in fast variations). For example, the main minimum of magnetic induction in Dymer came a little earlier than in Odessa. Which indicates a similar, but slightly different, development of geomagnetic variations over time in a region with a magnetic anomaly, and in a region without an anomaly.

rameters of the high-speed solar wind. In addition, some authors found 9- and 7-days periods in the analysis of data on changes in the areas of coronal holes (more details about one of fundamental periods in geomagnetic and solar activity are described, for example, in the work [19]). These 7-days fluctuations in the F-layer of the ionosphere can also be caused by planetary waves, which, for example, were observed in China [20]. Therefore, a logical continuation of this work should be analysis of the time-frequency distribution of long-term geomagnetic variations throughout 2019.

Thus, it can be seen that the solar 160 hours quasi-period is clearly reflected in the data of geomagnetic field variations in Dymer (normal magnetic field) during January 2019. A characteristic feature of the January 26 magnetic storm, according to Dymer, is a burst of very fast irregular variability, with a characteristic time of about 40 seconds from 5 to 9 am local time. It is interesting that on other days of both geomagnetically disturbed and quiet days, according to Dymer's records, in January 2019, such high-frequency variations were not observed at all. This period is much shorter than the minimum significant characteristic time according to Odessa data (about 4 minutes). In general, the comparison showed that on the days of

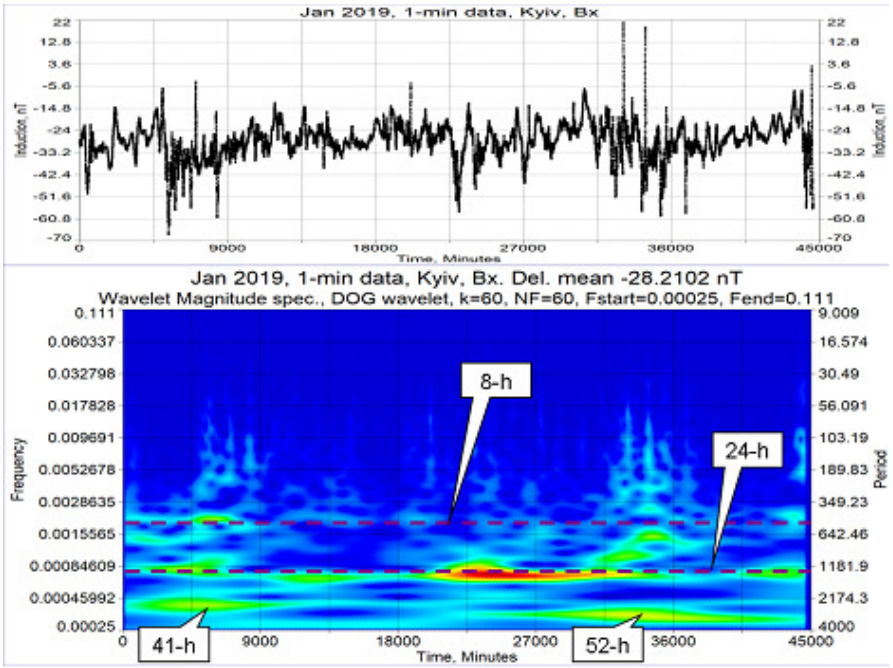


Figure 9 The upper figure is the initial data of the Bx component variations in Dymer, for the whole of January 2019, the lower figure is the wavelet spectrum of variations (X-axis is time in minutes, Y-axis is frequency in cycles per minute (left) and period in minutes (right)). Some of the most powerful quasi-periods are marked by flags. It can be seen that the 24-hour period and its 8-hour harmonics dominate throughout the month, but their periods vary slightly over time. A part of the spectrum, with periods less than 8 hours, is filled with close to irregular low-amplitude variations; areas of "bursts" of variability are also visible, and those oscillations with different time scales superimposed on each other. Quasi-periods with values of 41 hours and 52 hours have the largest amplitude of variations at the beginning and in the second half of the data, respectively.

geomagnetic disturbances, in the Dymer data series, the time scale of geomagnetic variations is larger than according to the Odessa data (that is, the characteristic times of variations in the area of the geomagnetic anomaly are shorter than those in the area of the normal geomagnetic field).

5 Ionospheric scintillations of the 3C 144 radio source

The supernova remnant Taurus A (3C 144) is traditionally one of the most popular radio sources for studying both the ionosphere and interplanetary space using the scintillation method. 3C 144 is a very powerful source of radio emission at wavelengths from decameter and meter to centimeter and millimeter radio bands (for example, article [21]). Its "fortunate" location near the ecliptic makes it the most important object for studying the structure of the Solar wind in a wide range of radio wavelengths. In the decameter radio range 10 – 30 MHz, ionospheric scintillations make

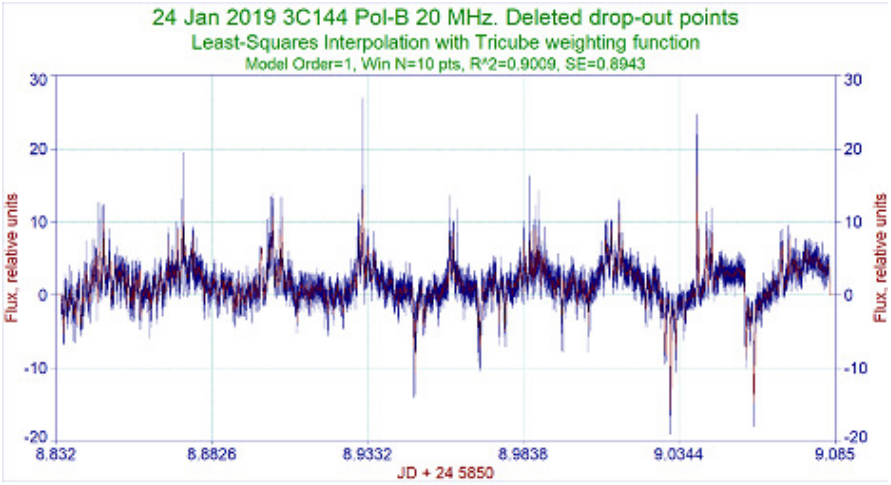


Figure 10 Recording of the radio source 3C 144 (Taurus A) as it passes through the beam pattern of the URAN-4 antenna array, January 24, 2019, at a frequency 20 MHz (linear polarization B). On the X-axis – fractions of the Julian date. The original data and the overlaid Loess-smoothed data series are shown. Flux density in relative units is measured relative to the calibration step of the high-stable noise generator.

the main contribution to the observed rapid variability of the 3C 144 flux density and occur on moving plasma irregularities in the ionosphere. The URAN-4 antenna array is the only one of the elements of the URAN low-frequency interferometer located in region of the large regional Odessa magnetic anomaly, which makes the study of the relationship between geomagnetic pulsations and ionospheric scintillations, particularly interesting.

An example of recording the flux density at a frequency 20 MHz (linear polarization B) is shown in Figure 10. The passage of the 3C 144 radio source through the URAN-4 beam pattern is 40 minutes, after which the antenna beam switches to the position in front of the radio source, and it passes again. Thus, a series of records of many passages of the source through antenna beam pattern is obtained. Near minima are the side lobes of the beam pattern. Receiving is carried out in the modulation mode, when the signals from the two halves of the antenna are multiplied. This allows us to effectively suppress the background radio emission and noise, which is quite strong in the decameter radio range.

To isolate and highlight the fast variations of the 3C 144 flux density, against the background of a sine-like trend associated with passing through the beam pattern, this trend was removed using Fourier filtering. After extracting the fast fluctuations of the flux density from smoothed data with removed noise and outliers points, time-frequency spectra were constructed. Usually, in the study of ionospheric scintillations, the method of calculating frequency-time spectra based on the Fourier transform in a sliding window (Short Time Fourier Transform) is traditionally used. However, this classical method is not always convenient, since it depends on the width of the spectral window, its type, and the amount of overlap of the spectral windows, which leads to the need to correct the parameters for different records of 3C 144 radio emission,

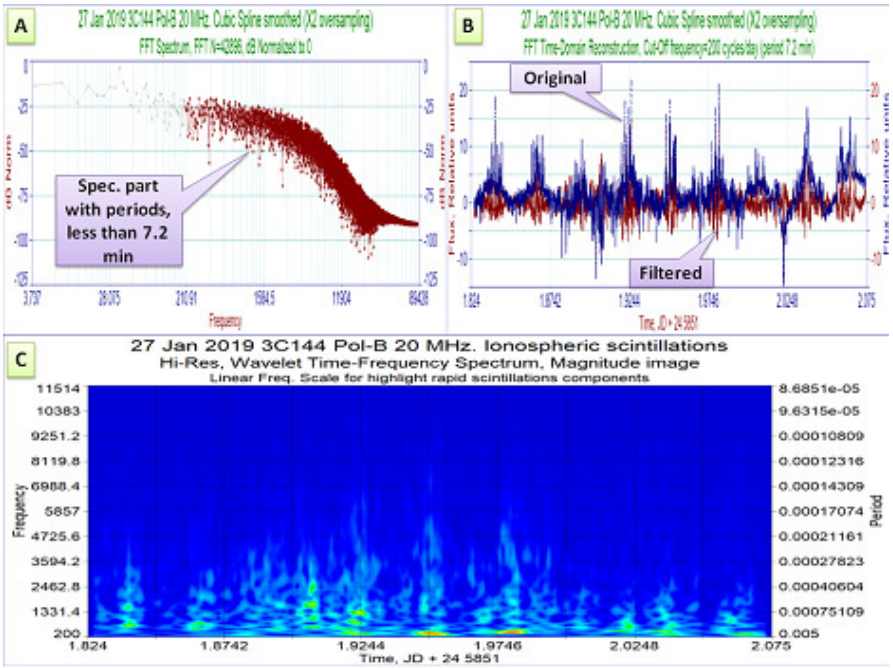


Figure 11 An example of magnetic storm in January 27, 2019 A) FFT spectrum of a smoothed, cleared of interference and cubic-spline interpolated data series, a part of the spectrum is taken for reconstruction, with a period scale of less than 7.2 minutes (sinusoidal trend of passage the 3C 144 source through the antenna diagram is removed). C) Initial data series of 3C 144 scans in the form of a sinusoidal trend and the highlighted fast fluctuations of flux density (ionospheric scintillations). C) Wavelet spectrum of scintillations in a linear frequency scale to emphasize fast fluctuations in the flux with a characteristic time of several minutes. On the X-axis – time in fractions of the Julian date, on the Y-axis – frequencies in cycles per day and periods in fractions of a day.

for example, on calm days and days of strong geomagnetic storms. Therefore, the fast method of continuous wavelet analysis was used in the work, with the complex analyzing function Gauss Derivative (derivative of the Gauss function) with the wave number k=60 (in this case, for optimal balance between time and frequency resolution) and length of FFT 65536 points. However, for individual scans, the STFT method of constructing spectrograms was used for compatibility with previous calculations. An example of the wavelet spectrum of ionospheric scintillations in the Odessa region is shown in Figure 11.

Figure 12 shows an example of wavelet spectra of ionospheric scintillations for a magnetically quiet day January 1, 2019 and a magnetic storm on January 5, 2019. For magnetically quiet days, ionospheric scintillations of the 3C 144 flux density are usually noise-like short bursts of low-amplitude flux density, although there are scans with high amplitude noise-like scintillations. Quite rarely, quasi-harmonic variations of the 3C 144 flux with quasi-periods in the range of 2–3 minutes are noted. During the days of magnetic storms, many short-term bursts of high amplitude appear in the

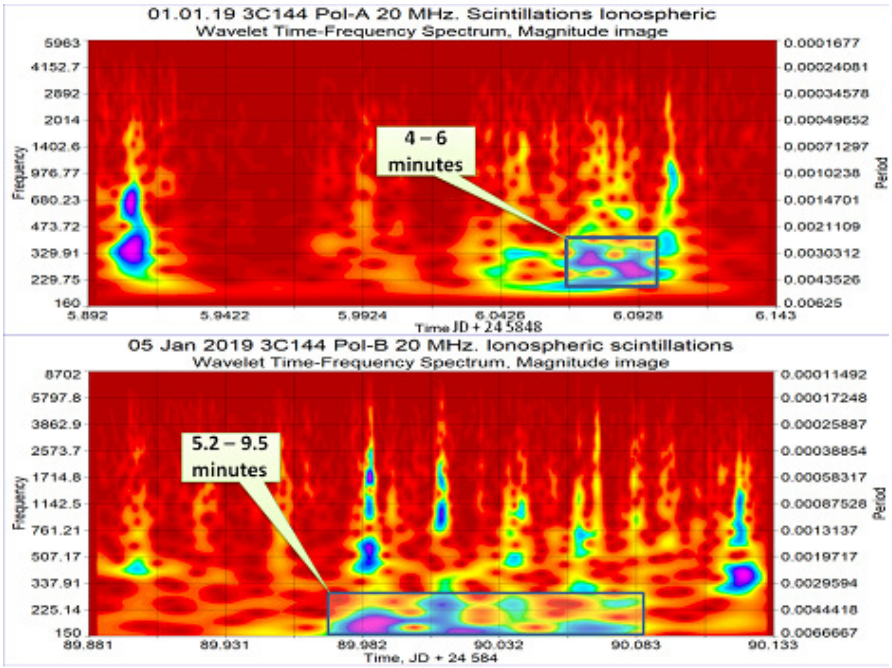


Figure 12 On geomagnetically quiet days, ionospheric scintillations of the 3C 144 radio source are most often noisy with rare quasi-periodic flux variations (upper figure, January 1, 2019). During magnetic storms, the amplitude of scintillations most often increases, and their characteristic time decreases to a minute or less, while maintaining the noise-like type of variations, at the same time, relatively long quasi-periodic flux variations with characteristic times of 5–10 minutes may appear (example at lower figure, January 5, 2019).

interval of periods 0.5–4 minutes. They are usually irregular, but analysis of individual 3C 144 scans shows that there are quasi-periodic flux variations with characteristic times of 1–2 minutes. Fourier analysis of power spectra, with Tukey spectral window (Tapered–Cosine) (window shape parameter k=0.4) showed that on the days of magnetic storms, the main spectral power of fast flux variations is often concentrated in the interval of periods of 1–3 minutes, with characteristic times of about 1 minute predominating. On geomagnetically quiet days, the Fourier spectrum predominantly has many maxima without concentration in certain frequency ranges, which indicates the presence of predominantly irregular scintillations. In addition, during the days of magnetic storms, quite long and atypical for scintillation variations of the flux with characteristic times of 5–10 minutes can appear.

An interesting property of scintillations of the radio source 3C 144 was discovered on some days of magnetic storms (January 24, 25, 26, 31) and on a quiet field day on January 2, in 2019. These days, FFT spectra showed a maximum of very fast, "narrow-band", low-amplitude and irregular variations of radio emission, with a characteristic time of 8–12 seconds. These fluctuations are at the limit of resolution, and their reliability of selection is questionable, however, it can be said that most likely these are real fluctuations. This conclusion can be drawn, since the work [22] where

ionospheric waves with periods of about 10 seconds or less are described.

It should also be noted that the method of continuous wavelet analysis with analyzing DOG function used in this work is much more efficient in the analysis of ionospheric scintillation data than the traditionally used method of the Fourier transform in a sliding window (STFT-method of constructing spectrograms). In the future, it is planned to use this approach to analyze ionospheric scintillations and other radio sources (Cygnus A, Cas A) observed on the URAN-4 phased low-frequency antenna array, in the area of Odessa regional magnetic anomaly.

6 Discussion

A huge number of works have been devoted to the study of geomagnetic variations and pulsations (for example, [23]) according to the data of many geomagnetic observatories at different latitudes. However, on the territory of Ukraine, the study of geomagnetic variations is mainly represented by works on the properties of solar-diurnal variations (basic periods 6–24 hours) in different regions of the country (for example, [24]), and the possible influence of intense regional magnetic anomalies on the appearance of short-periodic oscillations of the geomagnetic field during magnetic storms and their absence has not been practically studied. Directly within the Odessa magnetic anomaly, long-term measurements with a second time resolution, near the central region of the highest field induction, are carried out for the first time. The difficulty for research lies in the fact that the central part of the anomaly with the highest induction is located on the territory of the city of Odessa, which gives significant interference and makes it difficult to choose a location for the magnetometer. After processing the entire array of received data, it is planned to compare the properties of geomagnetic variations with the data obtained at the Odessa and Dymer magnetic stations, which are located in the region of the normal geomagnetic field.

Currently, many different types of geomagnetic variations are known, which differ in their frequency composition, change over time, different distribution over the latitude of the Earth's surface, appearance during a calm and disturbed field, seasonal features, and so on. Usually, long-term quasi-periodic variations are associated with large-scale changes in the structure of the magnetosphere and resonant oscillations of the geomagnetic field lines, while irregular short-period variations most often correspond to the times of development of geomagnetic disturbances. Oscillations are generated in localized regions of the magnetosphere. More complete reviews of the types of geomagnetic pulsations and the reasons for their appearance are presented in [25], [26]. The Odessa regional magnetic anomaly is characterized by the presence of a secular increase in magnetic induction [27]. In this regard, it is a perspective and important scientific task to study the development of geomagnetic pulsations in such special conditions.

A unique opportunity to research the response of ionospheric processes in the region of regional magnetic anomaly is provided by the presence in this region of the low-frequency phased antenna array URAN-4 of the Odessa Radio Observatory of the Radio Astronomy Institute of the National Academy of Sciences of Ukraine. Since geomagnetic variations and ionospheric scintillations of cosmic radio sources are formed in the Earth's ionosphere as a result of various physical processes, the

study of the interrelations between these phenomena and their response to Solar activity makes it possible to reveal the "stamp" of the magnetic anomaly on them. Despite the presence of works by other authors devoted to the interrelations between geomagnetic pulsations and ionospheric scintillations during magnetic storms, such studies were very episodic, and this topic is largely understudied and perspective. This is especially true for areas of an anomalous geomagnetic field, where often there is simply no equipment for observing ionospheric scintillations of cosmic radio sources or satellite signals. As a result of the work done on the study of geomagnetic variations and ionospheric scintillations of the radio source 3C 144 (Taurus A) (in January 2019), the following is shown. The time-frequency distribution of geomagnetic variations for Odessa and Dymer is significantly different. In the region of Odessa geomagnetic anomaly, variations of geomagnetic induction with a characteristic time of several minutes predominate, which are quasi-harmonic more often than the geomagnetic variations in Dymer, where the geomagnetic field is almost normal. In Dymer, longer variations prevail with characteristic times in the range of periods of about 30–10 minutes, which are quite often quasi-periodic, while shorter variations, especially on days of geomagnetic disturbances, have an amplitude less than that according to the data in Odessa, and are often chaotic, without clear quasi-periods. However, for a number of magnetic storms, according to Dymer's data, wavelet spectrograms show structures from superposition of several quasi-periodic and irregular variations in the form of a characteristic "grid" on the spectrograms. Sometimes, structures similar to this can also be seen on geomagnetically quiet days. Note that in Odessa, geomagnetic variations are more often quasi-periodic compared to those in Dymer. In observations at both geomagnetic observatories, fluctuations in the interval of periods of 40 – 30 minutes and 20–15 minutes have the largest amplitude. In the Odessa and Dymer data, the quasi-periods of Solar-diurnal variations are sometimes quite distorted. The ionospheric scintillations of the radio source 3C 144, observed at frequencies 20 and 25 MHz, on a phased antenna array URAN-4, have much shorter characteristic times than geomagnetic variations on days of a quiet magnetic field. The most significant in the observed data series are the variations in the 3C 144 flux with characteristic times in the range of 1–3 minutes. However, on the days of some magnetic storms, much faster noise-like variations appear, with characteristic times in the range from 8 to 12 seconds. This requires some additional verification, because the time series of observations are sampled at a frequency of 1 Hz (one sample per second), which does not allow one to reliably distinguish the time distribution of these fast scintillations. On the days of magnetic storms, the characteristic times of geomagnetic variations often decrease to 4–8 minutes and partially overlap with the characteristic times of the long-term part of the scintillation spectra of the radio source 3C 144. The period range of 1–3 minutes, for geomagnetic measurements in Odessa, turned out to be inaccessible due to high-frequency noise of technogenic origin. In continuation of this perspective work, observational data from the Odessa geomagnetic observatory, located in the Stepanovka village, will be used, where the measuring instruments are located in deep cellars (several meters below ground level) and are practically not affected by interference.

As is known, ionospheric scintillations of cosmic radio sources are usually noise-like, without significant cyclicity. Meanwhile, on some geomagnetically quiet days, and more often on days of magnetic storms, close to quasi-periodic variations in the

radio flux of the 3C 144 source are sometimes observed. Quasi-periodic ionospheric scintillations of 3C 144 were observed earlier, as reported in the paper [28]. Our study shows that quasi-periodic variations in the 3C 144 source flux (in decameter radio range) have a rapidly changing period and amplitude over time.

7 Conclusions

1. The cycle of measurements of geomagnetic field variations in the center of the Odessa Regional Magnetic Anomaly demonstrated the perspective of such research for elucidating features of the ionospheric component of flux variations of cosmic sources in the decameter radio range (10 – 30 MHz).
2. Comparison of geomagnetic variations in the Odessa regional magnetic anomaly and in the region of normal geomagnetic field, the Dymer village, Kiev region, was made. It is shown that during magnetic storms there is often overlapping of quasi-periodic and irregular variations with a wide spectrum, usually from 4 to 30 minutes, with the highest amplitude in the periods band 10 – 30 minutes. Irregular geomagnetic variations are often observed in the form of many separate short-term bursts on different time scales. In this regard, it is planned to compare the types of observed variations with types of magnetic storms during which they are observed. During some magnetic storms, quasi-harmonic pulsations appear even in periods range from 4 to 10 minutes. In the area of Odessa magnetic anomaly, the time scale of geomagnetic variations is shorter than in Dymer, and quasi-periodic variations are more often observed here. In Dymer, a typical type of geomagnetic pulsation is chaotic and irregular. In Odessa, there are also quasi-periodic variations on a time scale of less than 10 minutes. However, in Dymer, sometimes there are clear overlaps and transitions of quasi-harmonic variations, which looks like a "grid", and this appears less frequently in Odessa.
3. Observations of ionospheric scintillations of the galactic radio source 3C 144 at frequencies 20 and 25 MHz showed the following properties. In the range of periods 4–7 minutes, scintillations usually predominate on days of a calm geomagnetic field. During the days of magnetic storms, periods of ionospheric scintillations are usually concentrated in the range of 1–2 or 1–3 minutes, sometimes up to 30 seconds. The amplitude of these variations increases significantly. Mostly these are irregular variations, but less often there are also quasi-periodic ones, usually on a time scale less than 3 minutes. During magnetic storms on January 24, 25, 26, 31 2019 and on January 2 when the magnetic field was calm, variations were presumably recorded on a time scale 8–12 seconds. During magnetic storms, when the characteristic time of geomagnetic variations in Odessa decreases to 4 minutes or less, the time scales of ionospheric scintillations 3C 144 and geomagnetic variations have intersected. During several "scans" of the 3C 144 source, the characteristic times of scintillation can remain quite close, forming "chains" along the time axis on wavelet spectrograms.
4. The work that we completed showed that, according to measurements at the Odessa Observatory and Dymer (located in region of normal geomagnetic field) the properties of geomagnetic variations are different. This indicates that large regional geomagnetic anomalies, whose field dome reaches ionospheric heights, can influence the formation of geomagnetic variations.

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