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Angular Dependencies of the Ionospheric Scintillation Parameters Based on Observations of the Cosmic Radio Sources in the Decameter Radio Wave Range

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Abstract

Passing through the Earth's ionosphere the radio wave from cosmic source crosses the layer with electron concentration irregularities which cause random phase fluctuations of the radio wave that leads to intensity fluctuations. Due to movement of the irregularities along the line of sight the intensity fluctuations at the receiving point, are observed as the temporary fluctuations of radio signal known as ionospheric scintillations. This effect is most pronounced in decameter radio wave range. Its intensity is determined by the heterogeneous structure of ionosphere, and, among other things, depends on the geometry of the radio signal propagation which is associated with the manifestations of the angular dependencies of the ionospheric scintillation parameters. Such dependencies reflect the heterogeneous structure of ionosphere and can serve as a research tool. According to long-term observations of the power cosmic radio sources in the decameter radio wave range the estimations of the ionospheric scintillation parameters – index, period and spectral index, were obtained. The dependencies of these values on the zenith angle and on the angle between source direction and geomagnetic field line were analyzed. It is shown, that the scintillation index and period are related to each other in inverse proportion and show the dependencies on angle between source direction and geomagnetic field line. At the same time, the spectral index demonstrates the well expressed dependence on the radio source zenith angle.

Key words: Cosmic radio sources; Ionospheric scintillations; Angular dependencies.

Introduction

Passing through the Earth`s ionosphere, the radio wave from cosmic source intersects a layer with irregularities of electron concentration which cause random phase fluctuations, resulting in intensity fluctuations. Due to the movement of irregularities along the line of sight, intensity fluctuations at the receiving point are observed as temporary fluctuations of the radio signal known as *ionospheric scintillation* [Aarons, 1982]. This effect depends on the wavelength and is most pronounced in the decameter radio wave range.

The intensity of the ionospheric scintillation is determined by the inhomogeneous structure of the ionosphere and, among other things, depends on the geometry of radio signal propagation, which is associated with the manifestations of the angular dependences of the ionospheric scintillation parameters [Vasylyev et al., 2022]. Such dependencies reflect the inhomogeneous structure of the ionosphere and can serve as a tool for its study.

The main geometric factors influencing the scintillation intensity are the dependence on the zenith angle θ due to the changes in thickness of the scattering layer and dependence on the angle β between direction to the source (the line of sight) and the geomagnetic field line due to elongation of irregularities along field lines. Figure 1 shows the geometry of signal propagation from a radio source to the observer with taking into account the passage through ionospheric layer with irregularities of electron concentration; direction of the geomagnetic vector is also shown. Symbols used in the Figure 1: D – magnetic declination; I – magnetic inclination; **H** – geomagnetic vector; $\delta_m = I - (90^o - \Phi)$ – angle between the vector **H** and the equatorial plane; Φ – latitude; S – line of sight of the source; θ – zenith angle of the source; δ – angle between the line of sight and the equatorial plane; β – angle between the vector **H** and the line of sight.

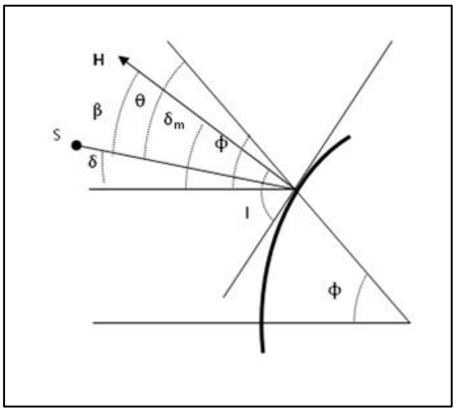

Figure 1. *Geometry of the radio wave propagation from a source to the observer crossing of ionospheric layer*

The purpose of the work is to study the angular dependencies of the ionospheric scintillation parameters based on long-term observations of the cosmic radio sources in the decameter radio wave range.

Observations and processing method

Observations, the analysis of which is presented in this studying, were obtained on the radio telescope (RT) URAN-4 on the frequencies 20 and 25 MHz. From 1987 to present the observations of the power cosmic radio sources 3C 144, 3C 274, 3C 405, 3C 461 were carried out on the RT URAN-4 in monitoring regime. All observed radio sources scintillate on irregularities of the electron concentration of ionosphere. The measurements consist in the fact that during the day the several passages of each radio source through RT direction pattern are recorded for discrete values of the hour angle near culmination moment [Derevyagin et al., 2005]. Separate record of the radio source is used for processing data. To decrease the influence of the RT direction pattern the fluctuating row was separated in the central part of record. This row was used to determine the scintillation parameters [Panishko and Lytvynenko, 2023].

The scintillation index SI was estimated on the fluctuating row as

$$\mathrm{SI} = \sqrt{\langle (\mathrm{I(t)} - \langle \mathrm{I} \rangle)^2 \rangle / \langle \mathrm{I} \rangle^2}\ . \tag{1}$$

Scintillation period ST (in seconds) was calculated as a value of the time shift when the auto correlation function of the fluctuating row first reaches zero. Spectral index SP was defined as the slope of the spectrum which was obtained by the Fourier transformation of the fluctuating row. The scheme for obtaining scintillation data is shown in the Figure 2.

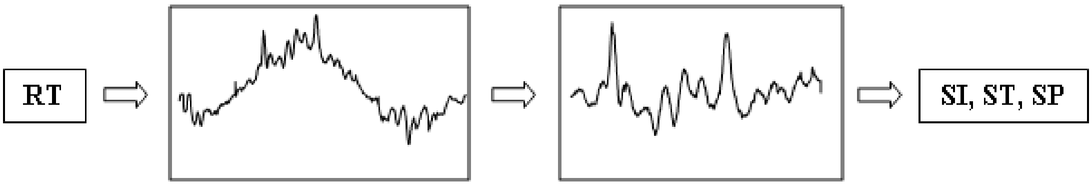

Figure 2. *The scheme for obtaining the scintillation data*

Given that for RT URAN-4 is D = 2°, I = 63.73°, δ_m = 20.127°, the angles β_0 were calculated by coordinate transformation for culmination moment of each radio source on the ionospheric latitudes at the observation point. Data is presented in the Table 1. The quantities of the zenith angles for culmination moment and type of observed radio sources are also placed here (SNR – supernova remnant; RG – radio galaxy).

Table 1. *Angular characteristics of the radio sources*

Source	Source type	θ_0°	β_0°
3C 144	SNR	24.4	1.84
3C 274	RG	34.0	-7.36
3C 405	RG	05.7	20.54
3C 461	SNR	-12.4	38.52

The Figure 3 shows how the zenith angle of the radio sources changes during observations at different hour angles. It is clear from the Figure 3 that radio sources 3C 405 and 3C 461 are observed near zenith, while 3C 144 and 3C 274 are lower altitudes.

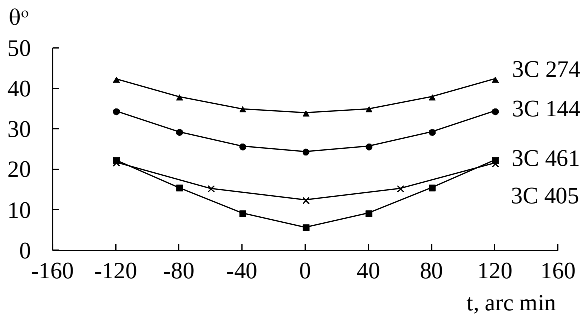

Figure 3. *Change of zenith angle on the dependence of the hour angle of radio source during observations*

Results and their analysis

During 1987–1990 analog observations were carried out on RT URAN-4. These measurements were used for estimations of the scintillation index and periods. Insufficient data was received on the 20 MHz due to the radio interference. Average values were calculated for all estimations of each radio sources on the frequency 25 MHz, that showed there was the inversely proportional relationship between the index and period (Figure 4, on the left) [Lytvynenko and Panishko, 2000]. Further digital measurements which carried out during 1998–2000 confirmed this relationship at two frequencies (Figure 4, on the right).

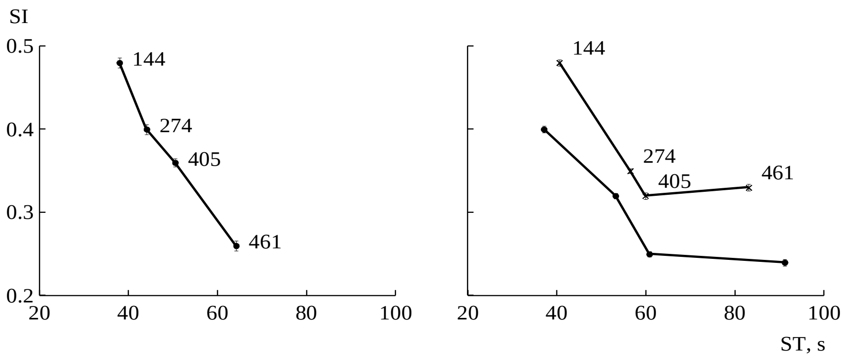

Figure 4. *The dependence index–period for average values of each radio source. On the left – data from 1987-1990, 25 MHz; on the right – data from 1998-2007, 20 (crests) and 25 (dots) MHz*

As can be seen from Table 2, the values of ionospheric scintillation parameters on the two frequencies are significantly correlated with each other, so the data on the 25 MHz is used in further analysis.

Table 2. *Correlation coefficients of the scintillation parameters on the 20 and 25 MHz*

NS	R(SI)	R(ST)	R(SP)
3C 144	0.94	0.93	0.90
3C 274	0.90	0.84	0.52
3C 405	0.87	0.46	0.54
3C 461	0.90	0.64	0.73

The dependence considered above allows us to assume the presence of geometric factor due to influence of the geomagnetic field. The dependence of the average periods for each radio source on the angle β_0 is shown in the Figure 5. From graph we can approximately estimate the coefficient of elongation of irregularities along the geomagnetic field lines in relation to the transverse size as 1:2.6.

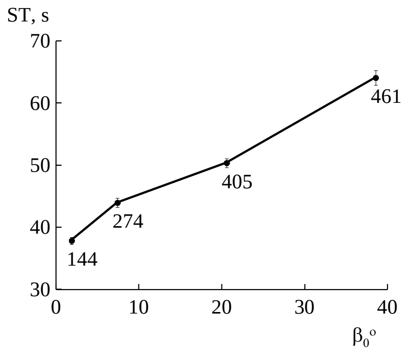

Figure 5. *The dependence of the scintillation period on the angle between the radio source line of sight and the geomagnetic vector on the ionospheric altitudes*

Since 1998, digital registration of the observation data has been used and estimations of spectral index have been added to the index and period already measured. The dependence of the scintillation parameters on the radio source zenith angle which was calculated for culmination moment is shown in the Figure 6.

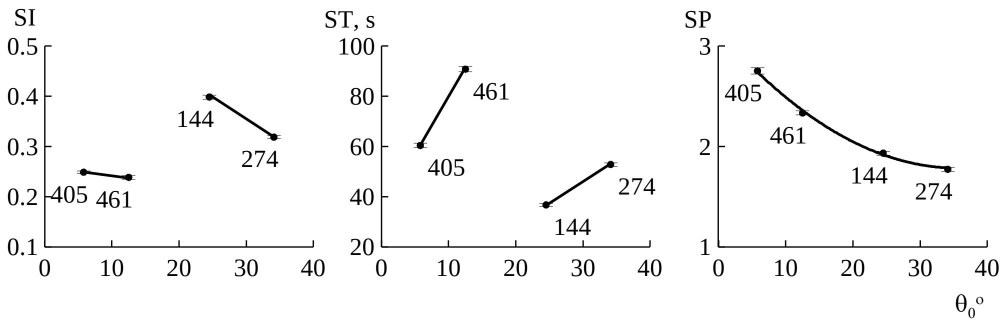

Figure 6. *The dependence of the average index, period and spectral index on the zenith angle*

The dependence of scintillation parameters on the angle between line of sight and geomagnetic field line is shown in the Figure 7.

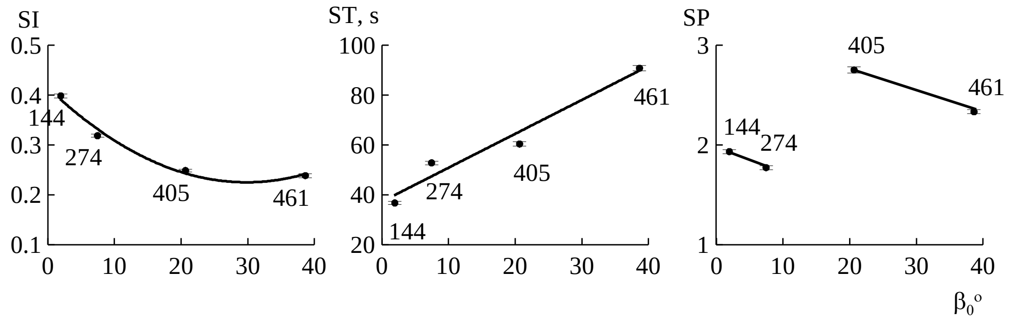

Figure 7. *The dependence of the index, period and spectral index on the angle between line of sight and geomagnetic field line*

As mentioned above (Figure 3), the graphs show that the observed radio sources can be divided into two groups: «high» and «low» with similar characteristics within groups. Further dependencies for each scintillation parameters on the angles θ and β are considered in more detail.

There is a dependence on the angle β for the scintillation index, which is emphasized by the second-degree polynomial. Dependence on the angle θ is observed within groups of the radio sources. In general, the index decreases with both an increasing in angle β and an increasing in angle θ. Due to the inversely proportional relationship between the index and the period, the period increases with angle β almost linearly and increases with increasing angle θ within groups. The spectral index has a clearly expressed dependence on the angle θ, which is emphasized by the second-degree polynomial, and decreases with its growth, within groups – decreases with the growth of the angle β.

Thus, the obtained results allow us to state that the nature of the angular dependencies of the ionospheric scintillation parameters is influenced by both the change in the thickness of the scattering layer and the elongation along the lines of force of the geomagnetic field of the irregularities responsible for the occurrence of scintillations.

Conclusions

Based on the long-term observations of the cosmic radio sources 3C 144, 3C 274, 3C 405 and 3C 461 in decameter range wave, estimations of the scintillation parameters (index SI, period ST and spectral index SP) were obtained. Dependences of SI, ST and SP on the zenith angle θ and on the angle β between line of sight and geomagnetic field line were analyzed. It was found:

1. By the nature of angular dependencies of the ionospheric scintillation parameters the radio sources can be divided into two groups: with smaller zenith angles (3C 405, 3C 461) and larger zenith angles (3C 144, 3C 274).
2. The index and period of the ionospheric scintillations are inversely related and show dependence on the angle β, with the index decreasing and the period increasing with increasing angle β. The obtained data made it possible to estimate the coefficient of elongation along the lines of force of geomagnetic field of the irregularities causing scintillations in relation to the transverse size as 1:2.6. The dependence on the angle θ is manifested within groups: the index decreases and the period increases with increasing angle θ.
3. The spectral index has a clear dependence on the angle θ, decreasing with its growth. Within groups spectral index decreases with increasing angle β.
4. Analysis of these results allows us to conclude that the angular dependencies of the ionospheric scintillation parameters contain a contribution from both angle θ and angle β, which must be taken into account when interpreting the observation data.

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