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SPATIO-TEMPORAL CORRELATION OF THE MAXIMUM OBSERVABLE FREQUENCY ON MIDLATITUDE RADIO LINES

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We present the results of studying the spatial and temporal correlation of the maximum observable frequency on two midlatitude paths, Inskip (England)–Rostov-on-Don and Cyprus–Rostov-on-Don. Dynamics of variation in the maximum observable frequency on these paths as a function of the time of the day and geophysical conditions is explored. The presence of a high spatial correlation (up to 93.5%) between the studied maximum observable frequencies allowed the values of the maximum observable frequency on the Cyprus–Rostov-on-Don path to be retrieved from the data on the Inskip–Rostov-on-Don path by the method of artificial neural networks with a training efficiency of up to 97%.

1. INTRODUCTION

In the last two decades, there has been a notable increase in interest in short-wave (SW) radio communication. This interest is in many respects due to the rapid development of microelectronics, computer engineering, and digital signal processing. Merits and dimerits of SW radio communication are well known. Among the merits, one should include long range, high survivability, and low cost compared with other types of communication (satellite, radio-relay, etc.). The main deficiency of SW radio communication is that the ionospheric channel is nonstationary. The current ionospheric environment is subjected to diurnal and seasonal variations. Moreover, geomagnetic activity, which is stipulated by solar flares and the action of the shock waves of solar wind on the Earth's magnetosphere, is a factor that has a significant effect on propagation of radio waves. As a result of the magnetosphere-ionosphere interaction, charged particles precipitate into the Earth's atmosphere and electric fields and currents in the ionosphere increase. All this, together with the wind and electrodynamic effects, leads to variations in the spatio-temporal distribution of the electron number density and variations in the radio-wave propagation conditions.

For effective work of different-purpose radioelectronic systems (SW radio communication, over-the-horizon radio detection, radio navigation, and radio bearing) under conditions of a dynamically varied ionospheric environment, they should be adapted to the current state of the ionosphere by using the results of on-line diagnostics of the ionospheric channel. The use of modern techniques for monitoring of the ionospheric channel permits one to increase the reliability of SW communication systems up to 97–99%, i.e., to the level of reliability of satellite communication [1, 2]. One of the effective methods of the ionospheric-channel diagnostics is chirp sounding. A chirp sounder has a high noise immunity, which is reached by frequency compression of a chirp signal, a small radiated power (about 10–100 W), and a good electromagnetic compatibility with the radioelectronic equipment. However, the absence of an extensive network of

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chirp sounders makes topical the problem of spatio-temporal prediction of key parameters of the ionospheric channel for extrapolation of the sounding results to paths not equipped with diagnostic tools.

Study of spatial and temporal correlations between the parameters of the oblique-sounding paths [3, 4] is also important from the viewpoint of electromagnetic compatibility. Channel sounding should interfere radioelectronic systems as little as possible and should therefore take the minimum time and be maximum rare.

It should be mentioned that despite the significance of this topic, the issues of the ionospheric-channel prediction have not been paid due attention. This to a certain extent is due to the complexity of organization and fulfillment of systematic observations for obtaining representative data. Hence, investigations of spatio-temporal correlation of the ionospheric-channel parameters on paths of different length and orientation under different geophysical conditions are, in our opinion, of undoudtful interest and can be used both for studying the physics of the ionospheric processes and during planning of SW radio communication.

In this paper, we present the results of studying the spatio-temporal correlation of the maximum observable frequency, which is a key parameter of the ionospheric channel, on two paths, Inskip (England)–Rostov-on-Don (of length $D \sim 3000$ km) and Cyprus–Rostov-on-Don ($D \sim 1400$ km). Series of values of the maximum observable frequency on the Cyprus–Rostov-on-Don path are retrieved from the data on the Inskip–Rostov-on-Don path by the method of artificial neural networks.

2. STUDYING TEMPORAL VARIATIONS IN THE MAXIMUM OBSERVABLE FREQUENCY

For analysis of spatio-temporal correlation of the maximum observable frequency, we used the data obtained on oblique-sounding paths Inskip–Rostov-on-Don and Cyprus–Rostov-on-Don. Chirp transmitters in Inskip and on Cyprus operate twenty four hours, and the sounding is performed at 5-min intervals. The transmitters in Inskip and on Cyprus operated in frequency ranges 4.2–30 MHz and 8–30 MHz, respectively, and the frequency variation rate was 100 kHz/s. In Rostov-on-Don, the signals of these stations have been observed on a regular basis since 2004. For a detailed study, intervals from December 2 to 7 and from December 26 to 31, 2006 were chosen, since the gaps in data are minimum in these periods. The absence of data on the maximum observable frequency on both paths is due mainly to technical constraints on the least radiated frequency of the transmitter, as well as failures of the transmitting and receiving stations. A continuous sequence of maximum observable frequencies on each studied path was obtained by the method of mathematical interpolation of data by a cubic function. Within the limits of the studied interval, the oblique sounding path Cyprus–Rostov-on-Don contains a considerable gap in data on the maximum observable frequency, which is related to a technical failure. It will be shown in what follows that this gap can be filled using the method of artificial neural networks in the presence of a high spatial correlation between the maximum observable frequencies on the paths explored.

The state and dynamics of the midlatitude ionosphere and, therefore, variations in the maximum observable frequency are to a considerable degree determined by the diurnal motion of the Earth. In the period from December 2 to 5, 2006, the geomagnetic environment was quiet and the values of the total magnetic index $\sum K_{\mathrm{p}}$ varied within the limits of 4–9, while in December 6 and 7, a slight geomagnetic perturbation took place, and the $\sum K_{\mathrm{p}}$ values amounted to 36 and 26, respectively. In the period from December 26 to 31, the $\sum K_{\mathrm{p}}$ values ranged from 0 to 1.

For a study of the diurnal dependence of variations in the maximum observable frequency on both paths, the total daily interval was divided conditionally into three parts: morning, daytime, and nighttime. They were 04:00–07:00 UT, 07:00–16:00 UT, and 16:00–04:00 UT, respectively, for the Inskip–Rostov-on-Don path and 03:00–06:00 UT, 06:00–15:00 UT, and 15:00–03:00 UT, respectively, for the Cyprus–Rostov-on-Don path. In the winter months, a specific feature of the morning interval is rapid variation of the ionosphere. This time of the day is characterized by the abrupt appearance of a signal and rapid variation in the maximum observable frequency. Under these conditions, the signal was subjected to interpolation most of all, and this interval was therefore excluded from consideration when temporal and spatial correlations were sought.

Within the limits of daytime and nighttime intervals, the temporal correlations of the maximum observable frequency on each path were sought for all considered days, and the time delay amounted to from 5 to 180 min. According to obtained data, the temporal correlation radius of the maximum observable frequency was $R_{0.5} \sim 60$–70 min on the Inskip–Rostov-on-Don path and 35–45 min on the Cyprus–Rostov-on-Don path both in the daytime and nighttime hours under quiet conditions. It was found that correlation sign reversal takes place on both paths. Sign reversal occurs when the temporal shift ΔT is equal to 110–120 min for the Inskip–Rostov-on-Don path and 60–70 min for the Cyprus–Rostov-on-Don path. We assume that this effect is due to the influence of quisiperiodic traveling ionospheric disturbances. According to [5], wave disturbances with 20–90-min periods are almost constantly present on the studied paths. During a small geomagnetic perturbation in December 6, both the temporal correlation radius of the maximum observable frequency and the temporal shift ΔT, accompanied by the polarization sign reversal, decreased. This effect was more pronounced on the Inskip–Rostov-on-Don path in the daytime hours. For example, in December 6 on the Inskip–Rostov-on-Don path in the daytime hours, the temporal correlation radius $R_{0.5}$ amounted to about 40 min, and $\Delta T \sim 70$ min. Such an effect is possibly related to the passage of traveling ionospheric disturbances arising during a magnetospheric substorm as a result of the auroral electrojet enhancement.

3. STUDY OF THE SPATIAL CORRELATION OF THE MAXIMUM OBSERVABLE FREQUENCY

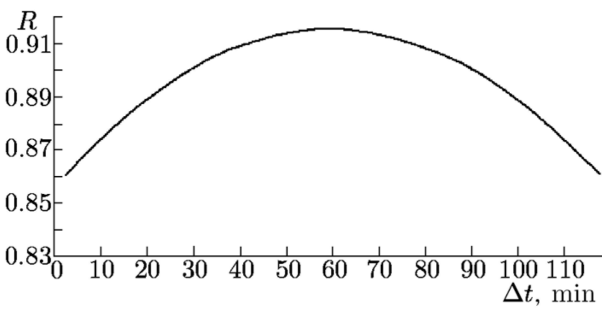

Fig. 1. Coefficient of spatial correlation between the maximum observable frequencies on the Inskip–Rostov-on-Don and Cyprus–Rostov-on-Don paths as a function of the delay time Δt.

TABLE 1. Maximum correlation coefficients R of the maximum observable frequency on the Inskip–Rostov-on-Don and Cyprus–Rostov-on-Don paths with alllowance for the temporal shift Δt for different observation days in December 2006.

Date	R
02.12.2006	0.90
03.12.2006	0.93
04–05.12.2006	0.94
06.12.2006	0.93
07.12.2006	0.88
26.12.2006	0.84
27.12.2006	0.88
28.12.2006	0.79
29.12.2006	0.84
30.12.2006	0.88
31.12.2006	0.94

The difference in the geographic position of the reflection points on the Inskip–Rostov-on-Don and Cyprus–Rostov-on-Don paths leads to the occurrence of a temporal shift Δt between the maximum observable frequencies on these paths. For determining the value of the shift Δt, linear correlations between the maximum observable frequencies on the studied path were sought. The values of the maximum observable frequencies on the Inskip–Rostov-on-Don path were shifted with respect to the Cyprus–Rostov-on-Don path with 5-min step. Spatial correlation coefficient as a function of the delay time is plotted in Fig. 1. Thus, the temporal delay Δt, for which the correlation between the maximum observable frequencies on two paths is maximum, amounts to about 60 min.

Later, the linear and nonlinear couplings between the maximum observable frequencies were sought with allowance for the specified time Δt.

The linear coupling between the maximum observable frequencies on the oblique-sounding paths Inskip–Rostov-on-Don and Cyprus–Rostov-on-Don was established by seeking linear correlations for each day of the studied interval. Spatial linear correlation coefficients are presented in Table 1. From the data in Table 1 it can be inferred that the correlation of the maximum observable frequencies on the studied paths is high in all the considered days, and the correlation level is only slightly varied throughout the entire interval.

Analysis of the geophysical environment in the studied days shows that in December 6, 2006 the solar radiation flux drastically increased at a wavelength of 10.7 cm, the geostationary satellite GOES-11 recorded an increase in the flux density of energetic particles, and increased amplitudes of the components of the interplanetary magnetic field were detected by the ACE space vehicle. Thus, the constant level of linear correlation between the maximum observable frequencies on the Inskip–Rostov-on-Don and Cyprus–Rostov-on-Don paths can indicate that variations in the spatial distribution of the electron number density in the meridian and latitude directions on scales of the order of 1600 km (the distance between the reflection of two paths) are synchronous in the midlatitude ionosphere, both for a small total level of perturbation ($D_{\mathrm{st}} \sim -50$ nT) and in unperturbed periods.

4. RETRIEVAL OF THE VALUES OF THE MAXIMUM OBSERVABLE FREQUENCY ON THE CYPRUS–ROSTOV-ON-DON PATH

It was mentioned above that the array of data on the maximum observed frequency on the Cyprus–Rostov-on-Don path has a gap related to the technical failure at the reception station. The presence of a high spatial correlation of data on the maximum observable frequency on the studied paths makes it possible to retrieve series of data on the Cyprus–Rostov-on-Don path from the values of the maximum observable frequency on the Inskip–Rostov-on-Don path.

The values of the maximum observable frequency on the Cyprus–Rostov-on-Don were retrieved by the method of artificial neural networks in several stages:

1) definition of the optimal architecture of a neural network, which includes choosing the architecture of artificial neural networks and the number of training cycles;

2) choosing additional parameters influencing the quality of training of an artificial neural network.

It is well known that Elman's artificial neural network with a backpropagation algorithm ensuring nonlinear memory of the process is the most widespread tool for effective prediction of geophysical and heliophysical parameters [6]. Hence, namely such a network was chosen for solving the problem of retrieval of the values of the maximum observable frequency on the Cyprus–Rostov-on-Don path from the data on the Inskip–Rostov-on-Don path. In the first stage, as the input data set for the neural-network training, a sequence of values of the maximum observable frequency on the Inskip–Rostov-on-Don path and the first-order derivative with respect to this frequency was chosen. During preparation of the input data set, the preset time Δt of shift of the values of the maximum observable frequencies on the mentioned paths with respect to each other, which amounts to 60 min, was taken into account. The peak efficiency PE of the neural-network training amounted to 93%. Here,

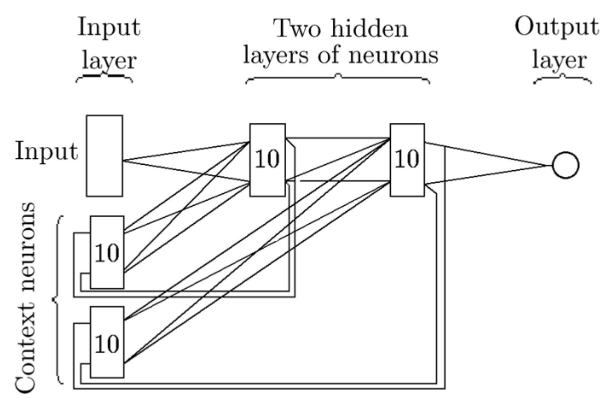

Fig. 2. Elman's network architecture which was used in this work. Each hidden and context layer comprises 10 neurons.

$$PE = \left(1 - \frac{\sum_i (T_i - A_i)^2}{\sum_i (T_i - \langle T \rangle)^2}\right) \cdot 100\%,$$

where T_i are the target values of a sequence of values of the maximum observable frequency, $\langle T \rangle$ is the ensemble-average value of the frequency T_i, and A_i is the response of the neural network.

Thus, the network architecture corresponding to the best efficiency of the network training was assumed the optimal one (Fig. 2).

In the second stage of the experiment, for increasing the efficiency of training of the chosen neural network and, as a consequence, increasing the quality of retrieval of data series to the standard input data set for an artificial neural network, which comprises a sequence of values of the maximum observable frequency and its first-order derivative, the values of the solar-zenith angle were added. This parameter is most effective in the daytime and makes it possible to improve the training quality [7]. The introduction

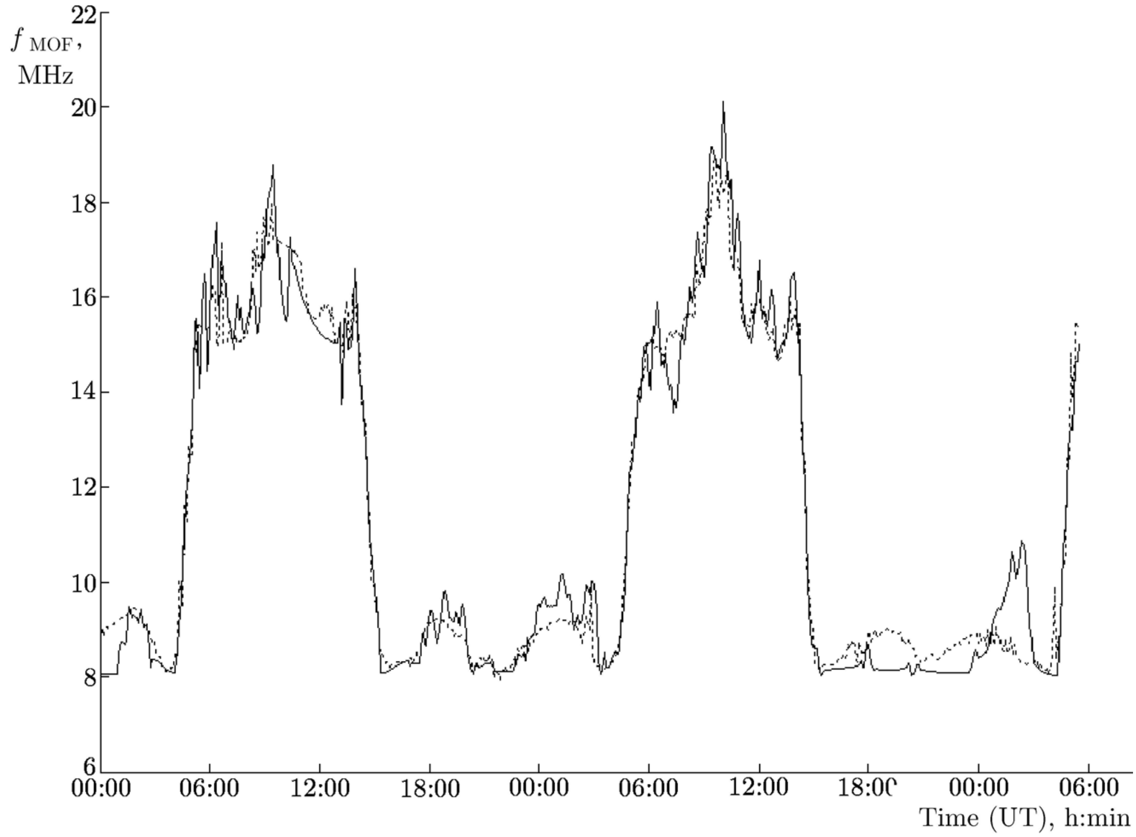

Fig. 3. Retrieval of the values of the maximum observable frequency f_{MOF} on the Cyprus–Rostov-on-Don path from the data on the Inskip–Rostov-on-Don path in December 2 and 3, 2006. The solid line is the actual values of the maximum observable frequency and the dotted line shows the values calculated by a neural network. The network training efficiency PE is 96.71%, and the coefficient R of linear correlation between the actual sequence and the sequence calculated using an artificial neural network is 0.983.

of the mentioned additional parameter allowed the quality of training of an artificial neural network to be increased up to 97% (Fig. 3). The introduction of other additional parameters, as well as the change of the architecture of an artificial neural network (addition of auxiliary hidden layers or varying the number of neurons in them) impairs dramatically the quality of the network training. Thus, it can be inferred that the chosen architecture of Elman's network, as well as the number and type of auxiliary parameters are the best for solution of the particular problem of retrieval of the values of the maximum observable frequency on the Cyprus–Rostov-on-Don path. The results of direct retrieval of the values of the maximum observable frequency on the Cyprus–Rostov-on-Don path from December 2 to 7, 2006 are presented in Fig. 4. Here, the black line represents the original data obtained by digitization of ionograms and the gray line shows a series of values retrieved with the use of an artificial neural network.

Thus, the presented method permits one to fill effectively the considerable gaps in the data on the maximum observable frequency in a quiet geophysical environment by using the minimum number of input parameters. However, such a method can be realized only if a high spatial correlation between the maximum observable frequencies on the studied paths takes place.

It should be mentioned that in the case of a high spatial correlation of the maximum observable frequency, the method of adaptation of the ionosphere model from the results of oblique sounding on the control path (where a complete set of data is available), followed by calculation of ionograms using the adapted model for the working path [2], can also be used.

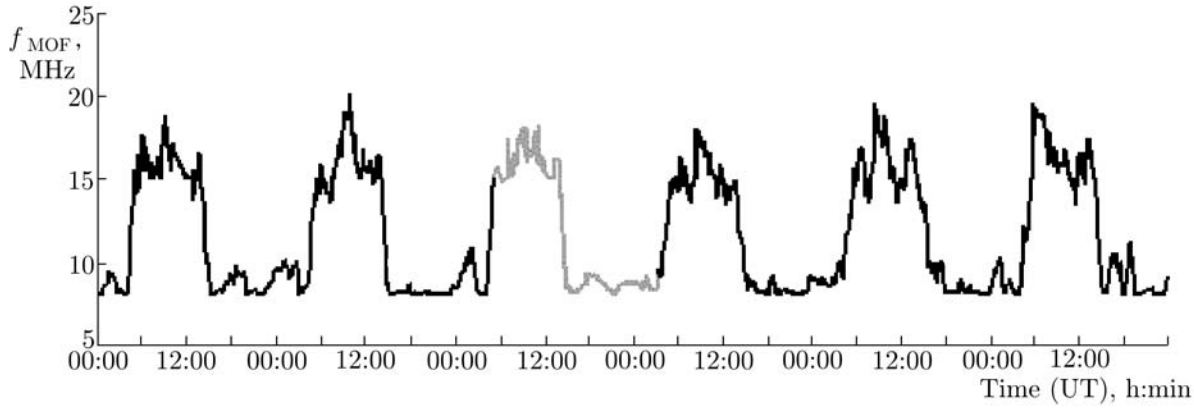

Fig. 4. Retrieval of the values of the maximum observable frequency using an artificial neural network (gray line).

5. CONCLUSIONS

It is established that at midlatitudes, the temporal correlation radius of the maximum observable frequency depends on the path length, time of the day, and geomagnetic disturbance. Under quiet conditions on the Inskip–Rostov-on-Don and Cyprus–Rostov-on-Don paths, the temporal correlation radius of the maximum observable frequency amounted to $R_{0.5} \sim 60$–70 and 35–45 min, respectively, both in the daytime and nighttime hours. It is found that the correlation sign reversal takes place on both paths when the temporal shift ΔT is equal to 110–120 min for the Inskip–Rostov-on-Don path and 60–70 min for the Cyprus–Rostov-on-Don path. We assume that this is related to the influence of traveling ionospheric disturbances. The correlation sign reversal effect was more obvious in December 6 when a geomagnetic disturbance took place. This is possibly due to the passage of a traveling ionospheric disturbance arising during a magnetospheric substorm as a result of the auroral electrojet enhancement.

High spatial correlation (the correlation coefficient $R \sim 0.8$–0.94) between the maximum observable frequencies takes place for different days of observation. This is evidence that the maximum observable frequency is synchronously varied on the meridian and latitudinal paths when the reflection points of radio waves for these paths lie within the limits of distances about 1600 km from each other.

A technology is developed for the retrieval of series of values of the maximum observable frequency on the oblique-sounding path Cyprus–Rostov-on-Don from the data on the Inskip–Rostov-on-Don path by the method of an artificial neural network. The use of the minimum number of input parameters (a sequence of the maximum observable frequency on the Inskip–Rostov-on-Don path, the first-order derivative of this frequency, and the values of the solar-zenith angle) permitted us to reach an efficiency of 97% for the neural-network training.

In conclusion, we note that the results of these studies can be used in applied problems for choosing sounding paths and their orientation for the optimal routing of the data flow through the ionospheric channel in the interests of effective functioning of different-purpose radioelectronic systems.

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