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EXPERIMENTAL INVESTIGATIONS OF SPATIAL STRUCTURE OF TRAVELING IONOSPHERIC DISTURBANCES

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A methodology is proposed for the solution of the inverse problem associated with experimental investigation of traveling ionospheric disturbances on oblique-incidence radiosonde observation on the ground.

Experimental data on traveling ionospheric disturbances (TID) several kilometers in size on oblique-incidence observation are few and incomplete, although the potentialities of radiosonde ground equipment are rather high. The first suggestions on the evaluation of TID sizes and anisotropy were proposed in [1]. However, that publication carried only information on problem formulation.

The physical model of TID are spatially bounded disturbances of electron density of the ionosphere, whose properties are determined, due to their random nature, by the function of spatial correlation of electron density. The Earth's magnetic field and the regular gradient of electron concentration play a decisive role in the processes of ionospheric electrons diffusion, therefore the MID correlation function has a quadratic argument, and its level lines can be approximated by a prolate uniaxial ellipsoid of revolution, whose major axis lies in the plane of the geomagnetic meridian. Thus, the inverse problem consists in using radiosonde observation data for finding the parameters of this ellipsoid, namely, its elongation (the ratio of axes) e and the angle α between its major axis and the vertical. In this formulation, the inverse problem is a model one.

The scattering of radio waves in the ionosphere can be described by small-angle fluctuations of the direction of the beam unit vector

$$\mathbf{S} = \mathbf{S}_0 + \mathbf{S}_1,$$

where $\mathbf{S}_0$ is the unit vector coinciding with the direction of the undisturbed beam, and the vector $\mathbf{S}_1$ lies in the plane of the undisturbed wave front, satisfying $\mathbf{S}_1^2 \ll 1$ [2]. The fluctuations are described by a normal two-dimensional distribution law $W(S_{1x}, S_{1y})$ of the projections of $\mathbf{S}_1$ in the coordinate system associated with the undisturbed beam (the z-axis is directed along $\mathbf{S}_0$, the x-axis lies in the plane of undisturbed wave propagation). The cross section of this probability distribution defines the equation of the so-called characteristic ellipse in the plane of the undisturbed wave front

$$S_{1x}^2/\sigma_x^2 + S_{1y}^2/\sigma_y^2 + 2RS_{1x}S_{1y}/\sigma_x\sigma_y = \text{const}.$$

The equation involves the variances and the correlation coefficient of projections of $\mathbf{S}_1$,

$$\sigma_x^2 = \langle S_{1x}^2\rangle, \quad ,\sigma_y^2 = \langle S_{1y}^2\rangle, \quad ,R = \langle S_{1x}S_{1y}\rangle/\sigma_x\sigma_y.$$

The shape and orientation of the characteristic ellipse depend on two parameters

$$h = \sigma_x/\sigma_y \quad \text{and} \quad R, \tag{1}$$

which, in the case of arbitrary oblique-incidence sounding of the ionosphere, depend very intricately on the parameters e and α of the correlation ellipsoid which simulates TID, on the orientation of $\mathbf{S}_0$, and the properties of a regular ionospheric layer.

However, analysis of isotropic ionosphere shows that there exists an opportunity of selecting the most favorable conditions for the experiment, when the characteristics e and α of the correlation ellipsoid are relatively simply related to the parameters h and R. These conditions are, firstly, the use of a singly reflected radio path, perpendicular to the plane of the geomagnetic meridian and, secondly, the use of the frequency close to the maximum applicable frequency (MAF) of the f_{mu} layer.

Following [2], one can show that for such experimental conditions

$$e^2 = \frac{1 + h^2 + \sqrt{(1-h^2)^2 + 4h^2R^2}}{1 + h^2 - \sqrt{(1-h^2)^2 + 4h^2R^2}}, \quad \tan 2\alpha = \frac{2Rh}{h^2 - 1}, \tag{2}$$

and thus calculate both e and α.

The authors of [1] proposed a differential-phase method for the investigation of TID, using a rectangular horisontal antenna system with the legs (bases) $\Delta x'$ and $\Delta y'$. The primed system of coordinates x', y' is associated with the measurement bases, the z'-axis is directed vertically upwards. From the measured values of the fluctuations of the corresponding spatial phase differences $\Delta\varphi_{1x'}$ and $\Delta\varphi_{1y'}$ one can calculate the projections of the random vector $\mathbf{S}_1$

$$S_{1x'} \cong \frac{\Delta\varphi_{1x'}}{k\Delta x'}, \quad S_{1y'} \cong \frac{\Delta\varphi_{1y'}}{k\Delta y'},$$

where k is the wave number, and then the corresponding statistical characteristics

$$\sigma^2_{x'} \cong \frac{(<\Delta\varphi_{1x'}>)^2}{(k\Delta x')^2}, \quad \sigma^2_{y'} \cong \frac{(<\Delta\varphi_{1y'}>)^2}{(k\Delta y')^2}, \quad B_{x'y'} \cong \frac{<\Delta\varphi_{1x'}\Delta\varphi_{1y'}>}{k^2\Delta x'\Delta y'},$$

because $<\Delta\varphi_{1x'}> = 0$, $<\Delta\varphi_{1y'}> = 0$. This allows one to define expressions similar to (1)

$$h' = \sigma_{x'}/\sigma_{y'}, \quad R' = B_{x'y'}/\sigma_{x'}\sigma_{y'}. \tag{3}$$

The h' and R' obtained in this way define the characteristic ellipse in a horizontal plane. Therefore, the shape and orientation of this ellipse differ essentially from those of the characteristic ellipse in the plane of undisturbed wave front and depend strongly on the zenithal θ_0 and azimuthal φ_0 angles of the vector $\mathbf{S}_0$ (in the horizontal system of coordinates associated with the antenna measuring triangle).

Based on the aforesaid, at the last stage of solving the inverse model problem, in order to produce reliable information one has to transform the experimental values of h' and R' by passing from the measurement system of coordinates (x', y', z') to the system (x, y, z) related to the undisturbed beam. After appropriate calculations, the actual h and R can be represented as functions of h', R', θ_0, and φ_0

$$\begin{gathered} h^2 = \frac{1}{\cos\theta_0}\sqrt{\frac{h'^2 + \tan^2\varphi_0 + 2R'h'\tan\varphi_0}{1 + h'^2\tan^2\varphi_0 \cdot 2R'h'\tan\varphi_0}}, \\ R = \frac{(1-h'^2)\tan\varphi_0 + 2R'h'(1-\tan^2\varphi_0)}{\sqrt{(h'^2 + \tan^2\varphi_0 + 2R'h'\tan\varphi_0)(1 + h'^2\tan^2\varphi_0 \cdot 2R'h'\tan\varphi_0)}}. \end{gathered} \tag{4}$$

Having found h and R from (4), one can use (2) to determine the elongation e and the orientation α of the correlation ellipsoid, i.e., to determine the average spatial structure of ionospheric disturbances and hence to solve the inverse problem.

Let us dwell on the conditions of organizing the experiment. The main of them is the selection of the frequency f of radiosonde observation: the closer f to the MAF, the better (2) is satisfied. This fact can be explained as follows.

In oblique-incidence sounding, the beam is oriented differently at different points of the ionosphere relative to the correlation ellipsoid major axis due to regular diffraction. As the MAF is approached, the beams which pass through the reflection domain quasi-horizontally and (under optimum experimental conditions) perpendicularly to the magnetic meridian plane "examine" the irregularities at the desired angle, thus providing for the extraction of adequate information about the elongation e and orientation angle α.

Furthermore, when the sounding frequency tends to the MAF, the beam total horizontal displacement L, as it leaves the ionosphere, is mainly determined by the quasi-horizontal interval L_a of the propagation path. Thus, the main contribution to the experimentally determined fluctuation characteristics of S_1 comes from the irregularities located in the reflection domain. This is confirmed by the numerical calculations given below.

Applying the modified traveling-wave method [3] in the reflection domain, we can find total horizontal displacement of the MAF beam as it leaves the ionosphere parabolic layer

$$L = L_a + L_b.$$

The quasi-horizontal part L_a of the reflection domain is an element of the parabolic layer whose thickness is of the order of radius a of the spatial correlation of inhomogeneities. The other part of the beam total horizontal displacement, L_b, is determined by its upward and downward segments. For sufficiently thick layers H, i.e., for $k_{mu}H \gg 1$ (k_{mu} is the wave number for the MAF), and for not very large inhomogeneities, for which the wave parameter $D = H/k_{mu} > 1$, the asymptotic estimate holds

$$\frac{L_b}{L} \cong \frac{8}{\pi^2}\frac{\ln(H/a)}{\ln(40k_{mu}H)}.$$

Taking, for example, $D = 150$ km (the $F2$ layer), $a = 5$ km, $\theta_0 = 60°$, $\lambda_{mu} = 30$ m (the critical wavelength), we have $L_b/L = 0.2$. Consequently, the quasi-horizontal path length L_a amounts to 80% of the total horizontal displacement L, which proves the above assumption that the determining contribution to the fluctuations of S_1 is made by inhomogeneities in the reflection domain (in the layer where the beam is nearly horizontal).

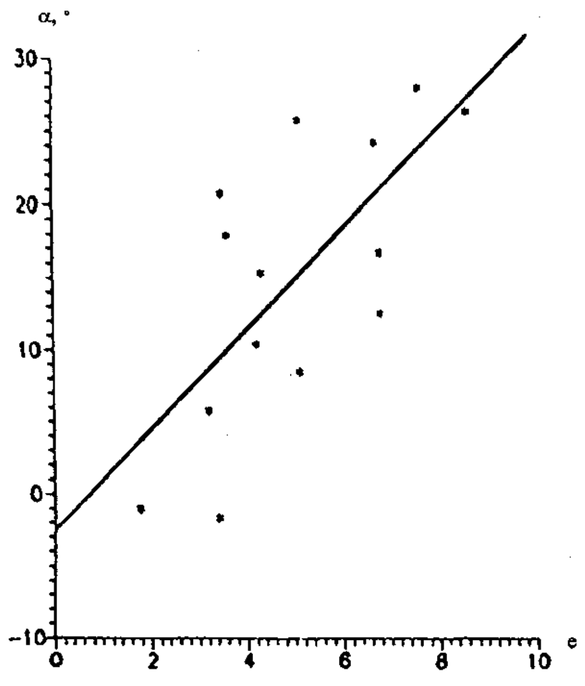

Fig. 1

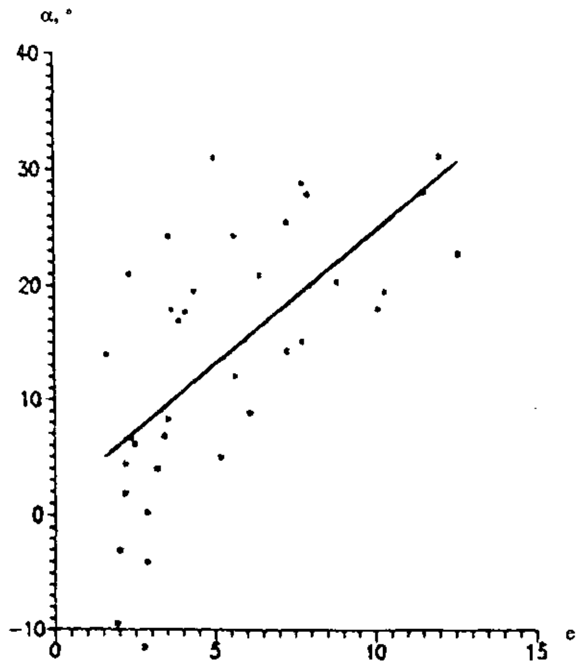

Fig. 2

The theoretical arguments described above were used in experimental studies carried out at the Moscow University Physics Faculty with the aid of an angle/Doppler meter [4]. The necessary conditions for the selection of the radio path and the sounding frequency were met. The BBC broadcasting station in London operating at the frequency $f = 17.8$ MHz was used as a transmitter. The zenithal angle of the incoming wave and the radio path azimuthal angle relative to the measuring system were $\theta_0 \cong 59°$ and $\varphi_0 \cong 39°$, respectively.

Twenty sessions, in which the time variations of the incoming radio wave direction $\mathbf{S}_1$ were observed, were selected from the array of experimental data. The duration of each session was 180 minutes. In order to suppress noise components in the experimental data, we used a procedure for eliminating linear trends caused by slower disturbances and tidal oscillations in the ionosphere. High frequencies were filtered by a moving average procedure [5] (with a typical averaging interval of 3 minutes for analyzing minute disturbances and, separately, a 5-second interval for studying rapid second variations). Then we determined the variances and the correlation coefficient of the variations, $\mathbf{S}_{1x'}$ and $\mathbf{S}_{1y'}$, and used formulas (3), (4), and (2) for calculating the elongation e of the correlation ellipsoid and the orientation angle α of its major axis relative to the vertical.

The experimental data are shown in Figs. 1 and 2, in which α is plotted as a function of e. Figure 1 refers to minute disturbances (according to the adopted moving average interval). Each point corresponds to an individual measurement session. Figure 2 refers to rapid second disturbances, each point corresponding to a five-minute interval in a typical three-hour session.

As is seen from Figs. 1, 2, the typical parameters of the model TIDs (in the case of slower disturbances) are $e \sim (2\text{–}8)$, $\alpha \cong (0\text{–}30)°$. More elongated formations are observed among second disturbances. In both cases, the reader's attention is drawn by the fact that more extended disturbances deviate from the vertical wider than less extended ones.

As a concluding remark, let us note that the direct use of h' and R' for evaluating e and α by formula (3) gives erroneous results, which indicates that it is absolutely necessary to transform h' and R' according to (4).

Thus, a particular algorithm has been proposed for experimental data processing. The algorithm takes into account the features of radio wave propagation in the ionosphere at the near-MUF sounding frequencies and allows one to obtain adequate data on ionospheric inhomogeneities. The experiment that has been conducted allowed us not only to validate the proposed technique but also to obtain objective characteristics of inhomogeneities modeled in the form of ellipsoids of revolution.

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