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Studying of the spatial–temporal structure of wavelike ionospheric disturbances on the base of Irkutsk incoherent scatter radar and Digisonde data

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A B S T R A C T

In this paper the spatio-temporal structure of traveling ionospheric disturbances characteristics is studied on the base of the electron density profiles measured by two beams of the Irkutsk incoherent scatter radar and the Irkutsk Digisonde. The technique for determination of spatial–temporal structure of wavelike ionospheric disturbances was developed using cross-correlation and spectrum analysis of electron density. The automated method for extracting ionospheric disturbances including both long-period day-to-day variability and short-period variations has been developed. Full analyses of January 15–February 17, 2011 data, including total velocity vector, was carry out for 1–6 h ionospheric disturbances, corresponding to internal gravitational waves. The propagation characteristics agree with those obtained from the known studies of the wavelike ionospheric disturbances. An automated method of ionospheric disturbances analysis was created on the basis of regular continuous measurements with the Irkutsk Digisonde. The statistical analysis of electron density disturbances was carried out for 2004–2009 period.

1. Introduction

The study of wave disturbances (in particular internal gravity waves (IGW)) in the Earth's upper atmosphere is an important and actual problem of the modern solar-terrestrial physics. Now, researchers have understood that wave phenomena contribute greatly to the general circulation of the atmosphere, the formation of its global structure and dynamics (Holton, 1983; Fritts and Alexander, 2003; Alexander et al., 2008), carry out an efficient transfer of energy and momentum in the vertical direction (Drobyazko and Gavrilov, 2001; Pancheva et al., 2002; Lastovicka, 2006), provide connection between the lower, middle and upper atmospheres. Various factors (e.g. temperature stratification, vertical gradients of the background winds, and dissipative phenomena) determining the wave propagation conditions in the upper atmosphere are not investigated enough. The level of current experimental researches requires not only a wide spatial coverage and high temporal resolution but also height structure of disturbances characteristics. Only the observation of three-dimensional pattern and the determination of the horizontal and vertical wavelengths allows estimating the contribution of IGWs in the atmospheric dynamics and determining IGW energy and momentum flux (Alexander et al., 2008). The ionospheric responses to IGW are traveling ionospheric disturbances (TID), which have been studied for many years (Francis, 1975; Hunsucker, 1982; Williams et al., 1993; Hocke and Schlegel, 1996). Such characteristics of the TID as quasi-periods, wavelengths and amplitudes of virtual height h'F2 and critical frequency foF2 variations were obtained using vertical and oblique ionosondes. The dependences of these characteristics on solar and magnetic activity, season, and local time have been studied for different regions of the Earth. The numerical models were used to study the TID propagation features (Akhmedov and Kunitsyn, 2004) and the relation between the IGW and TID characteristics (Kirchengast et al., 1995). However, many problems are still of current interest. The key problems are the following: (1) identification of IGW sources, (2) transformation of large-scale IGW into small-scale waves, (3) wave–wave and wave–wind interaction mechanisms, and (4) effect of IGW on the development of ionospheric plasma instabilities and generation of plasma irregularities. These problems can be studied using new methods, which are able to measure TID complex spatial–temporal structure.

There are very few tools and systems, which can provide this data. Incoherent scatter radars (ISR) give the most complete information about the TID height structure (Oliver et al., 1988; Ma et al., 1998; Vadas and Nicolls, 2008). It is necessary to measure the TID parameters along three directions outside one plane in order to determine the full vector of the TID velocity. Large fully rotatable antenna systems of available radars require much time for changing the direction of sounding and, consequently, do not

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give high enough time resolution. ISR using electronic scanning have a restricted scan sector and, correspondingly, an insufficient spatial base for similar studies. A joint analysis of the data from several tools can considerably improve the situation. We designed the technique for determination of spatial–temporal structure of wavelike ionospheric disturbances using the Irkutsk incoherent scatter radar (IISR) (52.9N, 103.3E) and the Irkutsk Digisonde (DPS-4) located ~100 km of the radar (Ratovsky et al., 2008, Medvedev et al., 2009).

2. Method for determining TID propagation characteristics

The initial data are the electron density (Ne) profiles measured with two beams of IISR (Potekhin et al., 2008) and DPS-4. Two approaches were used depending on the disturbance character.

The cross-correlation approach is more universal and consists in determining delays between TID at spaced points using a correlation analysis. The shift corresponding to the cross-correlation function maximum is considered as a delay. We assume that Ne-TID have the form of planar wave:

$$\Delta \mathrm{Ne}(\vec{R},t)=\Delta N_0(z)A(t-\tau(\vec{R})) \quad (1)$$

where $\Delta N_0(z)$ is height profile of TID, $A(t)$ is its temporal form

$$\tau(\vec{R})=(\vec{e}\,\vec{R})/V \quad (2)$$

$\vec{R}=\{R_x,R_y,R_z\}$ is radius-vector of observation point, $\vec{e}=\{e_x,e_y,e_z\}$ is unit vector specifying the wave propagation direction, V is wave velocity. As a coordinate system we chose the Cartesian system with the origin in ISR location, where the z-axis is upward, the x-axis is northward, y-axis is eastward. In this system the $\vec{e}$ vector has the coordinates {cosθcosψ, cosθsinψ, sinθ}, where θ is the elevation angle over the horizon with upward wave propagation direction as a positive, ψ is azimuth angle with respect to north, taking clockwise as a positive.

The delay (or time difference) between the Ne-TIDs observed at the points with radius-vectors $\vec{R}_1$ and $\vec{R}_2$ is

$$\Delta\tau(\vec{R}_1,\vec{R}_2)=(\vec{q}(\vec{R}_1-\vec{R}_2)) \quad (3)$$

where

$$\vec{q}=\vec{e}/V \quad (4)$$

Using the mutual delays between the Ne-TIDs observed by two beams of ISR and DPS-4 at the same heights we obtain the linear system of equations for determination of q_x and q_y

$$\begin{cases} q_x(x_1-x_2)+q_y(y_1-y_2)=\Delta\tau_{12} \\ q_x(x_2-x_3)+q_y(y_2-y_3)=\Delta\tau_{23} \\ q_x(x_3-x_1)+q_y(y_3-y_1)=\Delta\tau_{31} \end{cases} \quad (5)$$

where (x_1, y_1), (x_2, y_2) and (x_3, y_3) are the observing points coordinates in xy-plain for two beams of ISR and DPS-4, respectively. Set of Eq. (5) is redundant and can produce three sets for determining q_x and q_y. This redundancy was used to decrease the error of measurements by averaging the results. Using the delays $\Delta\tau_z$ between the Ne-TIDs observed by DPS-4 at different heights we can determinate q_z

$$q_z=\Delta\tau_z/\Delta z \quad (6)$$

The phase difference approach for determining TID motion parameters can be used to extract one dominant harmonic from the entire TID spectrum. This method consists in determining the harmonic phase difference observed at different spatial points. Phase differences can be used to calculate the full wave vector $\vec{k}$ from the expressions similar to (5) and (6):

$$\begin{cases} k_x(x_1-x_2)+k_y(y_1-y_2)=\Delta\varphi_{12} \\ k_x(x_2-x_3)+k_y(y_2-y_3)=\Delta\varphi_{23} \\ k_x(x_3-x_1)+k_y(y_3-y_1)=\Delta\varphi_{31} \end{cases} \quad (7)$$

$$k_z=\Delta\varphi_z/\Delta z \quad (8)$$

We should mention one important circumstance: $V_h=\sqrt{1/(q_x^2+q_y^2)}$ and $V_z=1/q_z$ values can also be determined by both methods for measuring the TID velocity full vector. It is clear that these values are not velocity projections onto the corresponding axis or plane, and these velocities are always larger or equal to V, being related to the velocity magnitude by the following expressions:

$$V_z=V/\sin\theta \quad (9)$$

and

$$V_h=V/\cos\theta \quad (10)$$

3. Statistical analysis of the characteristics of TID based on data of ISR and ionosonde DPS-4

Continuous simultaneous observations of electron density with the IISR and DPS-4 were made during the winter stratospheric warming from January 15 to February 17, 2011. Full analyses of the data, including total velocity vector, was carried out for most pronounced ionospheric disturbances with the periods from 1 to 6 h, corresponding to IGW.

The automated method is based on selecting the dominant harmonic from all spectrum of a wave disturbance. The data from all beams were reduced to one point of time in 15 min increments by interpolation. The spectral analysis was carried out for each beam and at each height in the running 12-hour window. To reduce the effect of sidelobes the 12 h Blackman window was used. The coincidence of spectral maxima at three neighbor heights as a minimum for each tool (DPS-4, and two IISR beams) was a criterion for the presence of a wave-like disturbance. The measurement time was assigned to the middle of the current 12-hour window. Prolonged disturbances occurring in several neighbor windows are taken into account several times in the overall statistics.

The DPS-4 ionosonde Ne-profiles were constructed from the ionogram traces using the Reinisch and Huang method (Reinisch and Huang, 1983) with the extrapolation above a peak height (Reinisch and Huang, 2001). Only the heights below the peak height at middle of the current 12-hour window were included in the spectral analysis. The lower limit of the analyzed height range was 170 km due to IISR clutter obscures below this height.

Fig. 1 demonstrates an example of the 12-h window spectral analysis. Left column shows Ne variations at three tools, the black line indicates the peak height variations. Spectra presented in middle column show two local maxima satisfying the above criterion at ~0.33 h^{-1} and ~0.73 h^{-1} frequencies. Results of calculations of TIDs propagation characteristics are displayed in right column (solid for 0.33 h^{-1} and dotted for 0.73 h^{-1} frequencies). Five disturbances were included in the statistical analysis from the demonstrated case: three at ~0.33 h^{-1} frequency (200, 210, and 220 km heights) and two at ~0.73 h^{-1} frequency (210 and 220 km heights).

The processing of all data set revealed 2579 cases of TID corresponding to the criterion. Preliminary analysis showed that the number of detectable disturbances is noticeably higher at nighttime than at daytime which agrees with theoretical estimation (Ivanov and Tolstikov, 2003). It is known that day- and