URSI GASS 2020, Rome, Italy, 29 August - 5 September 2020

Measurement of neutral wind velocity full vector using the combined Irkutsk Incoherent Scatter Radar and ionosonde data

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Abstract

The present study was performed on the basis of the analysis of 3-D characteristics of IGW propagation in the upper atmosphere of the Earth. Representative statistics of these characteristics was obtained using electron density profiles measured with the Irkutsk Incoherent Scatter Radar and DPS-4 ionosonde. The main result of this study is the development of the new method for determining the neutral wind velocity vector, based on IGW group velocity measurements. Testing the new method showed that it is in quantitative agreement with the Fabry-Pérot interferometer. Of particular interest are the results of measuring the vertical wind velocities. We have demonstrated that two independent methods give the presence of vertical wind velocities up to 20 m/s. The estimation of the vertical wind contribution to the plasma drift velocity has shown the importance of vertical wind measurements and the need to take them into account in physical and empirical models of the ionosphere and thermosphere.

1 Introduction

A unique network of radio instruments for ionospheric research has been developed in ISTP SB RAS. Ionosonde DPS-4 and two beams of the Irkutsk Incoherent Scatter Radar (IISR) [Medvedev and Potekhin] form a triangle with ~ 100 km side, convenient for investigating medium and large-scale traveling ionospheric disturbances (TIDs). Ionosonde DPS-4 is located directly in Irkutsk. The IISR is located 98 km to the north-west from Irkutsk. In the mode of detecting TIDs dynamic parameters, the radar measures vertical profiles of scattered signals at two frequencies. Accordingly, the instruments allow obtaining three electron density profiles measured independently at spaced sites. Methods for determining TID space-time structure and propagation parameters have been developed with using the cross-correlation and phase difference analysis of the IISR and DPS-4 ionosonde data [Ratovsky et al., 2008; Medvedev et al., 2009]. Further development of the technique for TID propagation parameter measurements allowed us to automatically process long series of electron density profiles and obtain representative statistics of parameters of wave disturbance propagating in the ionosphere (including the TID phase velocity and wave vectors). The automatic method of TID detection is based on assumption that dominant harmonic containing most of the energy can be isolated from the entire spectrum of a wave disturbance. If the assumption is valid, then, on each height covered by the wave we should observe a local maximum at the same frequency in the spectrum of electron density variations. Accordingly, the existence of local spectral maxima at the same frequencies for three adjacent heights (at least) for each instrument (ionosonde and two radar beams) indicated the presence of TID. The technique is described in detail [Medvedev et al., 2013]. TIDs are believed to be ionospheric manifestations of internal gravity waves (IGWs). Using the obtained statistics of TID parameters, we tested the Boussinesq and Hines dispersion relations for IGWs. It was shown that the observational data are in good consistence with theoretical concepts on IGW propagation in the upper atmosphere [Medvedev et al., 2015]. We found a strong anisotropy of TID azimuths. It was shown that the detected anisotropy can be explained by the neutral wind integral effect in the atmosphere on the path of wave propagation [Medvedev et al., 2017]. The probability of TID detection is higher for IGWs propagating against the neutral wind acting at the observation height. By contrast, IGW propagation is blocked in directions coincident with strong neutral wind (over 50 m/s) at any height that IGWs had passed before they reached the observation height. It was shown that depending on the wave front inclination angles, peculiarities of TID azimuth distribution can be easily explained by IGW wind filtering.

In linear approximation, IGW interaction with horizontal wind is limited to the Doppler frequency shift:

$$\omega' = \omega_{obs} - \vec{k} \cdot \vec{U} \qquad (1)$$

where ω' is the intrinsic wave frequency (a wave frequency in moving medium), ω_{obs} is the observed frequency, U is the wind velocity vector, and k is the wave vector. The IGW intrinsic frequency can be obtained from a dispersion relation. Using expression (1), one can obtain the wind velocity projection along the IGW propagation direction [Vadas and Nicolls, 2008]:

$$U_p = \frac{\omega_{obs} - \omega'}{|k|} \qquad (2)$$

In single measurements, this approach is not of high significance since the calculated wind velocities are highly dispersive. If we have sufficient statistics of the wind velocity projections, it is possible to determine monthly averages of zonal and meridional winds by minimizing functional [Medvedev et al., 2015]. The comparison of the obtained monthly average diurnal variations of zonal and meridional neutral winds with the HWM2007 model prediction and independent meridional wind measurements at the IISR [Sherbakov et al., 2015], showed satisfactory agreement of wind patterns obtained in various ways [Medvedev et al., 2015; Medvedev et al., 2017]. Especial significance of this result is that currently, there are very few methods of measuring zonal wind in the upper atmosphere. In this paper, we propose a new method for determining the neutral wind velocity vector, based on IGW group velocity measurements. In contrast to the previously developed method, it allows us to obtain not only a statistical pattern but also potentially instantaneous values of the neutral wind velocity. Another advantage of the new method is the ability to measure the vertical velocity of the neutral wind.

2 Method for determining neutral wind velocity full vector

As mentioned above, automatic method of TIDs detection 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 local 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. Phase differences observed at different spatial points can be used to calculate the full wave vector by solving line equations system[Medvedev et al., 2013]. 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. Using Hines dispersion relation, we can obtain the full vector of group velocity in a coordinate system moving with the neutral wind velocity.

$$\begin{aligned} G_x' &= \frac{\partial\omega'}{\partial k_x} = \frac{k_x\omega' C_0^2(\omega'^2-\Omega_B^2)}{(\omega'^4-(k_x^2+k_y^2)\Omega_B^2C_0^2)} \\ G_y' &= \frac{\partial\omega'}{\partial k_y} = \frac{k_y\omega' C_0^2(\omega'^2-\Omega_B^2)}{(\omega'^4-(k_x^2+k_y^2)\Omega_B^2C_0^2)} \\ G_z' &= \frac{\partial\omega'}{\partial k_z} = \frac{k_z C_0^2\omega'^3}{(\omega'^4-(k_x^2+k_y^2)\Omega_B^2C_0^2)} \end{aligned} \qquad (3)$$

The intrinsic period (frequency) can be found from the Hines equation.

From experimental data we can detect the group velocity in a fixed coordinate system. From dispersion relation one can obtain the exact expression:

$$d\omega = \frac{\partial\omega}{\partial k_x}dk_x + \frac{\partial\omega}{\partial k_y}dk_y + \frac{\partial\omega}{\partial k_z}dk_z = G_x dk_x + G_y dk_y + G_z dk_z \qquad (4)$$

or an approximate expression for finite differences:

$$\Delta\omega = G_x\Delta k_x + G_y\Delta k_y + G_z\Delta k_z \qquad (5)$$

To determine the group velocity full vector, one needs three equations similar to (5). So, besides frequency ω corresponding to local spectral maximum we need another three frequencies. Let assume that the disturbance covers a certain frequency band. For spectral neighbors (ω-3Δω, ω-2Δω, ω-Δω, ω+Δω, ω+2Δω, ω+3Δω), we calculate full wave vectors by using phase differences. Further we select three frequencies with the minimum azimuthal difference of wave vectors (assume these frequencies belong to the same disturbance). Assuming that group velocity varies slightly, we obtain liner equations system:

$$\begin{cases} \Delta\omega_1 = G_x\Delta k_{x1} + G_y\Delta k_{y1} + G_z\Delta k_{z1} \\ \Delta\omega_2 = G_x\Delta k_{x2} + G_y\Delta k_{y2} + G_z\Delta k_{z2} \\ \Delta\omega_3 = G_x\Delta k_{x3} + G_y\Delta k_{y3} + G_z\Delta k_{z3} \end{cases} \qquad (6)$$

Knowing group velocity in a coordinate system moving with the neutral wind velocity and in a fixed coordinate system, we can calculate the neutral wind velocity full vector.

$$\begin{cases} U_x = G_x - G_x' \\ U_y = G_y - G_y' \\ U_z = G_z - G_z' \end{cases} \qquad (7)$$

It should be noted, that determining intrinsic period (frequency) from the Hines equation we also determine wind along the IGW propagation direction (2). Therefore, system (7) should be added with equation:

$$\frac{k_x}{|k|}U_x + \frac{k_y}{|k|}U_y + \frac{k_z}{|k|}U_z = \frac{\omega-\omega'}{|\vec{k}|} \qquad (8)$$

In addition, when calculating group velocity in a fixed coordinate system we assumed that the dispersion relation was valid at least at three more frequencies (we call those *ω1, ω2, ω3*), hence, system (7) should be added with three more equations similar to (8). Final system is excessive, we will solve it with the midsquare method. Method is described in detail [Medvedev et al., 2019].

We compare neutral wind obtained by using measurements of IGWs group and phase velocities with the HWM2007 model, results of our previously developed method [Medvedev et al., 2015; Medvedev et al., 2017] and Fabry-Pérot interferometer data. Figure 1 shows the winter wind patterns obtained in various ways.

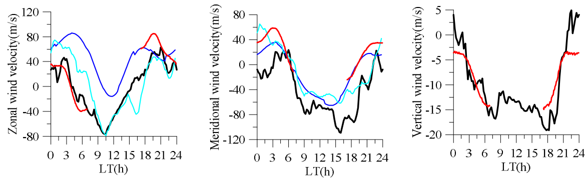

Figure 1. Wintertime diurnal variations in zonal (positive eastward, left panel), meridional (positive southward, central panel), and vertical (positive upward, right panel) winds obtained in various ways: new method based on IGW group velocity measurements (black), FPI (red), HWM2007 (blue), and previously developed method based on wind projection measurements (cyan).

The horizontal wind diurnal variations obtained in various ways are in qualitative agreement. All the ways show eastward and southward winds in the nighttime, as well as westward and northward winds in the daytime. The zonal wind obtained by the new method agrees with the Fabry-Pérot interferometer. Insofar as FPI and new method give similar results we consider that in this case HWM2007 does not describe the wind accurately. Of particular interest is the vertical wind measurement. The presence of large vertical wind velocities in the upper thermosphere causes controversy in the scientific community. Neither empirical nor physical models predict the presence of large vertical wind velocities. Large vertical velocities obtained with Fabry-Pérot interferometer are sometimes interpreted as apparent vertical velocities due to horizontal wind and scattering in the upper troposphere. Figure 1 shows that both the new method and Fabry-Pérot demonstrate the same diurnal trend in the vertical wind. Thus, two absolutely independent methods give the presence of vertical wind velocities. Vertical winds can have a significant effect on the wind induced vertical drift of the ionospheric plasma. The effect may be comparable with the meridional wind effect. To clarify this issue, we calculated the contributions of the meridional VEFFX and vertical VEFFZ winds to the plasma drift velocity as well as the total contribution VEFF:

$$V_{EFFX} = U_x \cos I \sin I,\ V_{EFFZ} = U_z \sin^2 I,\ V_{EFF} = V_{EFFX} + V_{EFFZ} \quad (9)$$

where I is the magnetic field inclination (~72°). The calculated contributions were compared with the peak heights (hmF2) from the Irkutsk ionosonde averaged over the same period, and the correlation coefficients were calculated (Figure 2).

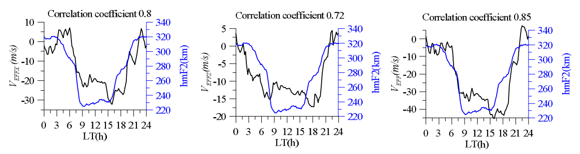

Figure 2. Comparison of meridional wind contribution (left, black), vertical wind contribution (central, black), and total contribution (right, black) to plasma drift velocity with peak height (blue) from the Irkutsk ionosonde.

Figure 2 demonstrates that the contributions of the meridional and vertical winds to the plasma drift velocity are really close to each other. The total contribution has the largest correlation coefficient with the height. These results clearly demonstrate the importance of vertical wind measurements and the need to take them into account in physical and empirical models of the ionosphere and thermosphere.

3 Conclusion

The new method for determining the neutral wind velocity vector was presented in this paper. The basis of the method is measurements of group velocities of internal gravity waves. We compare neutral wind obtained by new method with the HWM2007 model, results of our previously developed method and Fabry-Pérot interferometer data. The horizontal wind diurnal variations obtained in various ways are in qualitative agreement. All the ways show eastward and southward winds in the nighttime, as well as westward and northward winds in the daytime. The zonal wind obtained by the new method agrees with the Fabry-Pérot interferometer. Insofar as FPI and new method give similar results we consider that in this case HWM2007 does not describe the wind accurately. Of particular interest are the results of measuring the vertical wind velocities. We have demonstrated that two independent methods give the presence of vertical wind velocities up to 20 m/s. The estimation of the vertical wind contribution to the plasma drift velocity has shown the importance of vertical wind measurements and the need to take them into account in physical and empirical models of the ionosphere and thermosphere.

4 Acknowledgements

For the analysis, the methods obtained with budgetary funding of Basic Research program II.12 were used.

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