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INVESTIGATION OF WAVE MOTIONS IN THE LOWER IONOSPHERE BY THE METHOD OF RESONANCE SCATTERING OF RADIO WAVES FROM ARTIFICIAL PERIODIC INHOMOGENEITIES

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We present the results of studies of wave motions at lower-ionosphere altitudes by a new method based on measurements of the velocity of vertical motion of plasma by the variation of the phase of the signal that is backscattered from artificial periodic inhomogeneities of electron density (ionospheric arrays). The method allows us to study processes with different time scales and periods of from several dozens of seconds to some hours or longer. In the course of long-term 1990-1991 observations conducted near Nizhny Novgorod we determined some dynamic and spectral characteristics of internal gravity waves.

1. INTRODUCTION

The study of internal gravity waves (IGW) as one of the most important components of atmosphere dynamics has a many-year history. These waves are constantly observed in the upper atmosphere and appear as irregular variations of ionospheric parameters such as the regional and meridional components of the velocity of the neutral wind [1, 2], in shape distortion of meteor trails and artificial chemical clouds [3, 4], atmospheric turbulence, electron density disturbances [5, 6], etc.

IGWs at mesosphere and lower-thermosphere altitudes have been studied by various methods in a great number of papers, many of which were prepared within the framework of international projects such as MAP, GLOBMET, DYANA, etc. [7–9]. We study the influence of IGWs on the thermal regime of the upper atmosphere and atmospheric turbulence, the conditions of propagation of these waves, the interaction of waves among themselves and with atmospheric streams, propagation velocity and direction, and the energy and spectral characteristics.

In recent years, among the relatively old methods for studying IGW such as the method of vertical HF sounding [2], detection and ranging of meteor trails [1], and observation of artificial clouds [5] an important role has been played by methods that use hydroxyl radiation for registration of waves near the mesopause [10], incoherent scattering radars [11], lidars [12], and MST-radars [13]. The latter have high space-time resolution and permit measurements over a great range of altitudes.

In this paper we present some results of IGW studies on the basis of measurements of the velocities V of the vertical motions of plasma using a new radiophysical method, which involves measurements of the phase of the signal that is backscattered from artificial periodic inhomogeneities (API) of electron density appearing in the ionosphere under the action of high-power standing radio waves in the HF spectrum.

In this paper we determine some IGW characteristics from measurements of V at altitudes of from 60 to 120 km carried out in the daytime hours from September 1990 to December 1991 at the laboratory of the Radiophysical Research Institute near Nizhny Novgorod (56.15°N, 44.3°E).

2. MEASUREMENT METHODS

The process of formation of artificial periodic inhomogeneities during ionospheric modification by

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high-power HF radio waves is comprehensively studied and described in review [14] and other papers. Measurement methods based on resonance scattering of test radio waves from APIs involve measurements of such parameters of the scattered signal as its amplitude and relaxation time after the heating is over, which, in particular, allows us to determine the atmospheric density and temperature, as well as the vertical component of the velocity of turbulent motions. In turn, the velocity of vertical plasma motions V is related to the variation of the backscattered signal phase by the relation [14]

$$V = \frac{\lambda}{4\pi}\frac{\Delta\phi}{\Delta t},$$

where λ is the length of the test wave and $\Delta\phi$ is the variation of its phase over time Δt.

The advantage of this method is its good time resolution, which is actually determined by the operation time of the heating transmitter and can be up to several seconds, which allows us to study processes with durations of from several seconds to hours or longer. In this measurement sequence the time resolution is 15 sec. The altitude resolution is determined by the sounding-pulse duration ($\Delta h = c\tau/2$) and does not exceed 1.5 km for sufficiently short pulses with durations of the order of 10 μsec, for example. In the experiments Δh was from 5 to 7 km.

To create APIs, we used a heating facility that emitted into the zenith radio waves at frequency $f = 5.545$ MHz with an effective power of 20 MW for 5 sec. In the subsequent 10 sec, as a sample signal during the API relaxation, we used the signal of the transmitter of the device of partial reflections with a pulse duration of 50 (25) μsec and a repetition frequency of 50 Hz. To record the phase of the backscattered signal, we used special receiving and recording equipment, which permitted us to record the signal phase and amplitude from six altitudes simultaneously. Most measurements were for altitudes of from 90 to120 km.

3. DYNAMIC AND SPECTRAL CHARACTERISTICS OF VERTICAL MOTION VELOCITY

The determined velocities of vertical motions are presented in detail in [15], where, in particular, we studied the seasonal and daily variations of V. The average monthly values of V during the day hours were about 1 m/sec at altitudes below 90 km and reached 5 m/sec as the altitude h increased up to 120 km. On the average, upward motions prevailed at altitudes above 90 km. As an example, Fig. 1 shows altitude profiles of vertical velocity for three 1991 fall months, which present the average character of variations in magnitude and direction of V with altitude (positive Vs denote downward motion). It is noteworthy [15] that downward motions with great scatter of V were prevailing only in November 1990 records.

On the whole, the character of seasonal and daily variations of V is rather complicated. Spectral analysis of V, results of which are given partially in [15, 16], shows that time variations of V on each observation day are due, mainly, to the existence of different-scale wave motions in the lower ionosphere. Let us discuss in more detail the dynamic and spectral characteristics of V on the days with the longest continuous measurements (from 6 to 7 h).

First, let us analyze the curves of daily variation of V. As an example, Fig. 2 shows time variations of V averaged over 1 min for two days of measurements: February 27, 1991 (for 6 altitudes), Fig. 2a, and March 15, 1991 (for 4 altitudes), Fig. 2b, which are smoothed out using the moving-average method for ruling out the fastest fluctuations. The plots demonstrate the main features of V behavior that are typical on the whole of the data array obtained, in particular, we clearly see wave-like variations of V with different periods at all altitudes. The large-scale wave motions become more pronounced with altitude. As a rule, the absolute value of V increases with altitude (see Fig. 2a). Variation of V is more complicated near local midday, or from 12 a.m. to 2 p.m., to be more exact. The curves of time variations of $V(t)$ seem to converge, and the difference between Vs at nearby frequencies drops significantly. Therefore, on February 27, 1991 this difference for altitudes of 117 and 97 km was ≈ 9 m/sec in the interval from 10 to 11 a.m., and the velocity direction varied with altitude from positive (downward direction) at lower altitudes to negative (upward) for all other altitudes; the vertical velocities at all altitudes were close to zero by 2 p.m. The same picture was observed almost always on other days of long-duration measurements on October 1, 1990, and March 15, 1991, excluding December 6, 1991, when motions with a several-hour period had a much smaller

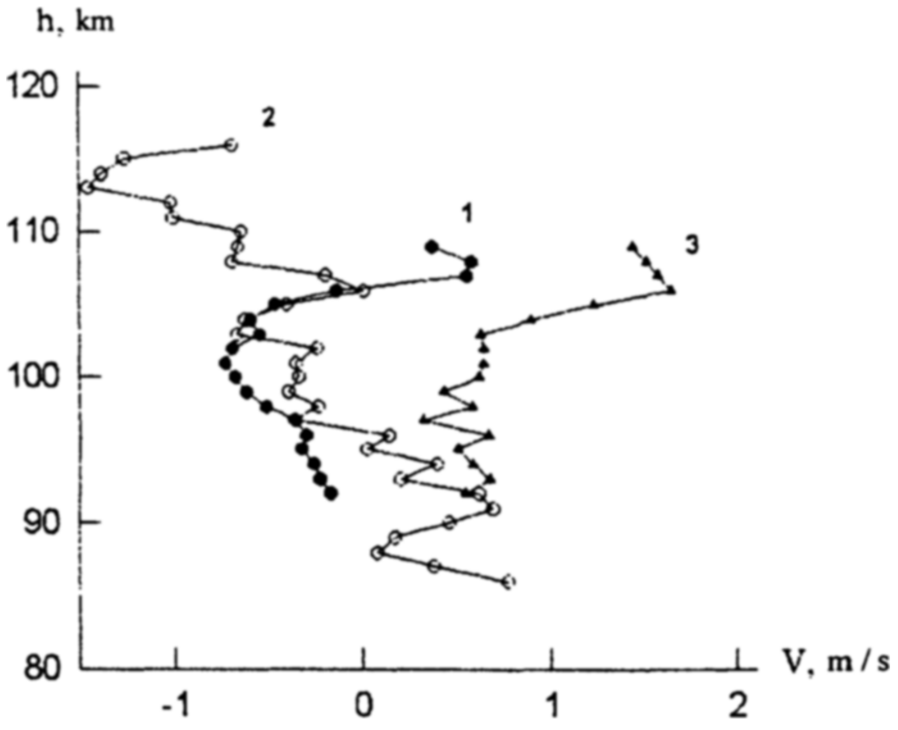

Fig. 1. Altitude profiles of vertical velocity for three 1991 months: curve 1 - September (12 days), curve 2 - October (15 (days), curve 3 - November (5 days). Averaging with weight factors that correspond to the number of measurements performed was used. The profiles are smoothed with respect to altitude with a smoothing interval of 3 km.

amplitude. After 2 p.m. the character of the altitude distribution of V recovers on the whole. Figure 2 shows the wave structure of time variations of V for all altitudes.

Therefore, on the whole, in the measurements the absolute value of vertical velocity increases with altitude with a prevailing upward direction at altitudes exceeding 90 km.

A more accurate spectral composition of oscillations contributing to the dynamics of V was obtained using spectral analysis. The spectral power density of V (or frequency spectrum) was calculated using the FFT method and the time realization $V(t)$ by the formula (Wiener-Khinchine theorem)

$$S_V(\nu) = \lim_{T\to\infty} \frac{1}{T}\left|\int_{-T}^{T} V(t)\exp(-j2\pi\nu)\,dt\right|^2,$$

where T is the duration of realization $V(t)$. The spectrum was smoothed out using Hahn's spectral window [17].

To determine the power spectrum index for the power dependence sections, the method of least squares was used. Examples of spectra calculated in this manner for 6 altitudes in the range of from 89 to 114 km on March 15, 1991, are shown in Fig. 3. The spectra of V calculated for other days have a similar form.

The power spectra of vertical velocity have the following features. As a rule, the spectrum $S_V(\nu)$ includes two sections such that in each section the spectral density can be approximated by the power law $S_V(\nu) \propto \nu^{-p}$ with the exponent $p_1 \approx 0.5$–1.0 from $\nu \approx 0$ to a certain frequency ν_* and exponent $p \approx 2.2$–4.7 for $\nu > \nu_*$. The period for frequency ν_* is shown in Fig. 3 by the vertical segment. Since the spectra in Fig. 3 are distributed vertically for convenience, the vertical axis is not shown.

The spectral analysis showed that time variations of V involve oscillations with different durations from the shortest, ones that last from 5 to 10 min, up to those with many-hour durations. On different days

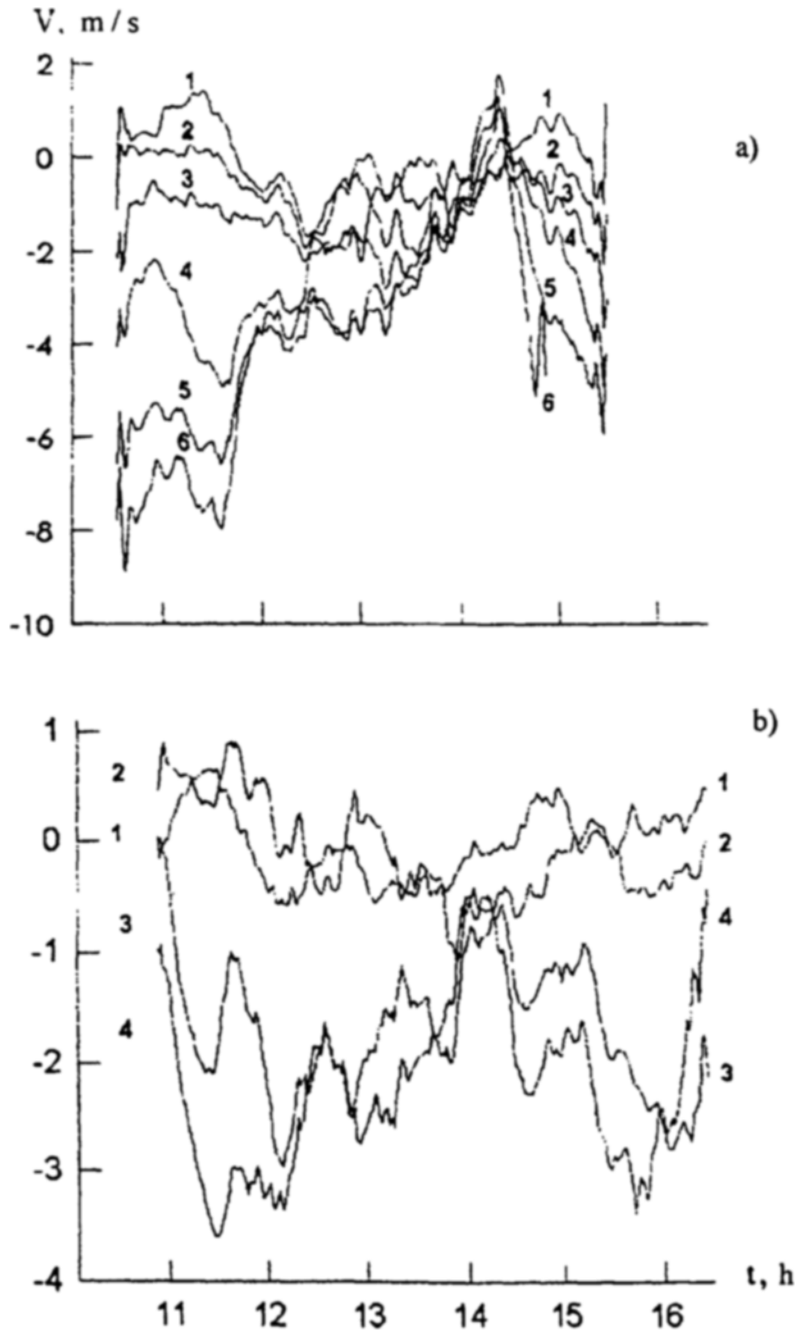

Fig. 2. The time dependence of vertical velocity for measurements on February 27, 1991, (a) and March 15, 1991, (b) for different altitudes. The curves in Fig. 2a have numbers from $h = 97$ km (curve 1) to $h = 117$ km (curve 6) with steps $\Delta h = 4$ km;curve 1 in Fig. 2b corresponds to $h = 89$ km, curve 2 corresponds to $h = 94$ km, curve 3 corresponds to $h = 109$ km, and curve 4 corresponds to $h = 114$ km.

we observed periods with durations of from 5 to 10, 15, 20, 30, 40, and 60 min with a certain reliability. In addition, intense wave motions with periods of 2, 2.5, 3.3, and 4.5 h were observed. Unfortunately, the rather short-term measurements prevented us from direct detection of still greater periods. The future use of special methods for spectral treatment of short-term records [18] will allow us to obtain more detailed information on vertical velocity spectra.

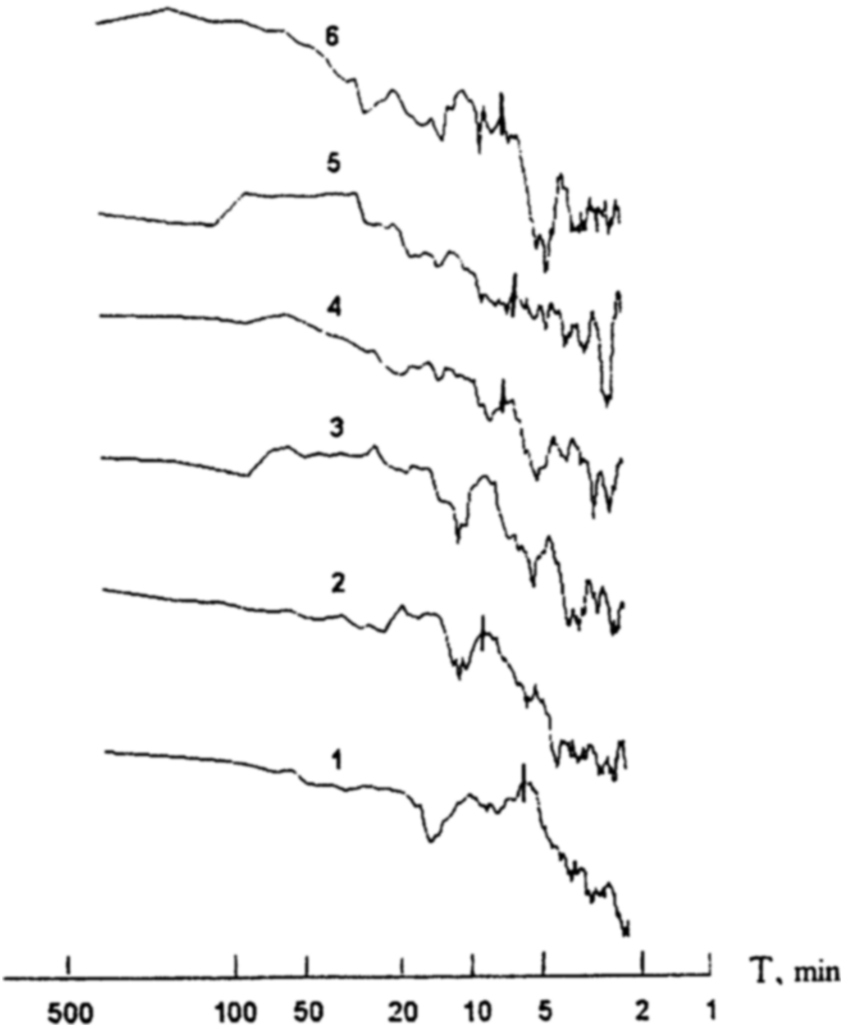

Fig. 3. Spectral power density of vertical velocity for six altitudes on March 15, 1991. The curves have numbers starting from altitude $h = 89$ km (curve 1) to $h = 114$ km (curve 6) with altitude steps $\Delta h = 5$ km. The vertical section denotes the value of period T_* at which the sharp spectrum cutoff occurs.

As was mentioned above, the feature of the spectra $S_V(\nu)$ is a sharp "cutoff" of spectral density at frequencies $\nu > \nu_*$, which is usually very pronounced practically at all altitudes. Often this spectrum cutoff is accompanied by a significant increase in $S_V(\nu)$ near frequency ν_* on the side of smaller values (curves 1, 2, and 3 in Fig. 3). Moreover, near ν_* a local minimum of $S_V(\nu)$ is observed (the same curves).

Practically always, in the time variations of V we clearly see a phase delay of wave oscillations at smaller altitudes (see Fig. 2), which corresponds to a downward directed vertical component of phase velocity of the order of from 60 to 100 m/sec during different observation sessions. Vertical wavelengths of oscillations that are present in the altitude profile of V vary from 3–5 to 30–40 km.

Figure 4 shows curves of polynomial smoothing of the time dependences $V(t)$ on different observation days for six altitudes. Such an approach allows us to concentrate our attention only on the large-period waves and follow the variation in the character of such motions with altitude. If we assume that the main contribution to variations of V is from wave motions, it can be concluded from Fig. 4 that wave amplitudes with relatively large periods grow significantly with altitude. For example, on February 27, 1991, (Fig. 4a) the amplitude of a wave with a period of about 6 h almost tripled as the altitude varied from 109 to 117 km. Moreover, Figs. 4b and 4c demonstrate, as it seems, wave transformation into the second harmonic as the altitude increases with a harmonic amplitude increase (on the average) with altitude.

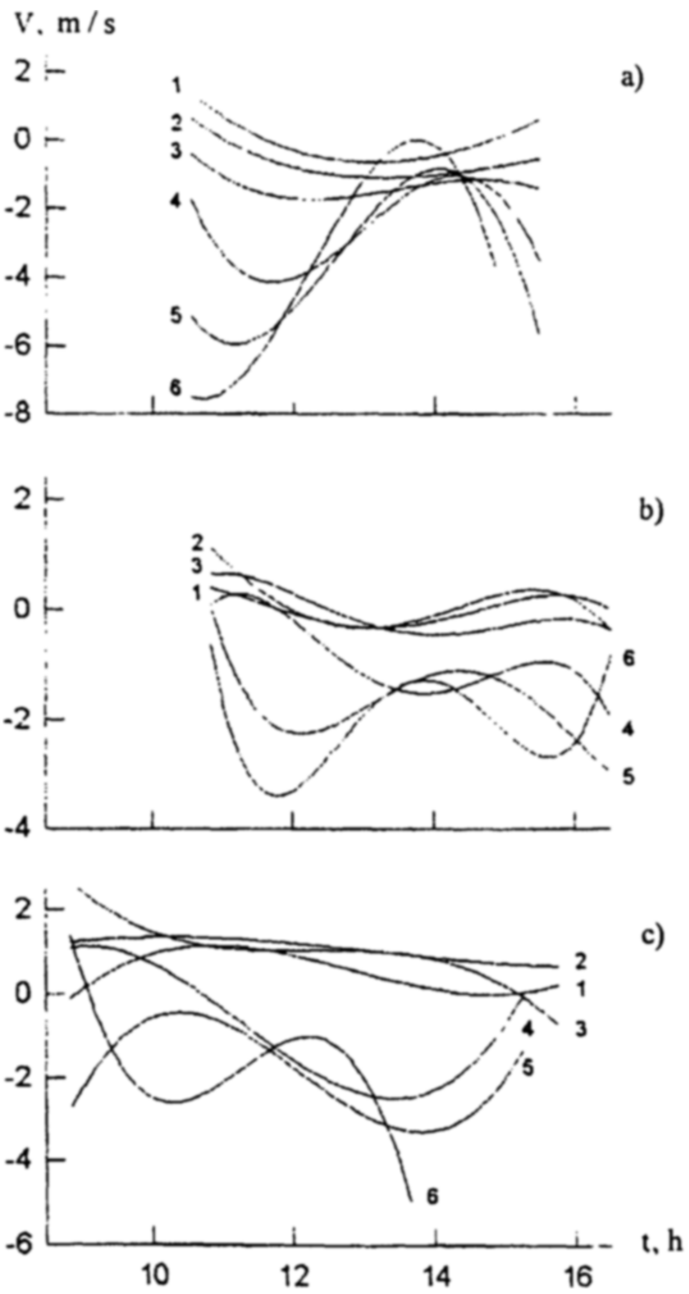

Fig. 4. The results of polynomial smoothing of minute values of $V(t)$: (a) - – on February 27, 1991, (b) — on March 15, 1991, (c) — on December 6, 1991, (minute points are not indicated). The curve numbers in Fig. 4a correspond to those in Fig. 2a, and the curves in Fig. 4b have numbers starting from altitude $h = 89$ km (curve 1) with steps $\Delta h = 5$ km, curve 1 in Fig. 4c is for $h = 89$ km with altitude steps $\Delta h = 5$ km.

4. DETERMINATION OF SOME PARAMETERS OF IGWs AND DISCUSSION OF RESULTS

The measurements of velocity of vertical plasma motions at altitudes of from 60 to 120 km carried out using the method of resonance scattering of radio waves by artificial periodic inhomogeneities of electron density are interpreted as follows. During the whole observation period, the oscillations of vertical velocity were recorded at any time for V varying in time over the entire altitude interval. The absolute value of V, as a rule, increases with altitude and velocities are directed mainly upwards at altitudes exceeding 90 km. In the dynamics and the spectra of vertical velocity we observe pronounced wave motions of different scales of from several minutes to several hours with the value and direction of phase velocity, which are typical of IGWs. Therefore, we assume that the above features of the dynamic and spectral properties of vertical velocity are due to the propagation of internal gravity waves. Let us analyze the results in the previous section from this viewpoint. As was mentioned, the wave periods obtained by spectral analysis of V correspond exactly to the periods of IGWs observed using different methods [7–9]. As far as the spectrum form is concerned, the results of measurements of frequency spectra of IGWs are few (see, for example, [19–21]). However, it must be noted that many of them are described by a power function of $\sim \nu^p$, but the exponent p varies. Therefore, from measurements of the spectra of the regional component of horizontal wind velocity the values in the interval from $\approx$ 0.47–0.82 were obtained in [19] for the waves with periods from 1 to 8 h at altitudes of from 90 to 100 km such that p decreased with altitude. The method of partial reflections was used in Saskatoon (52°N, 107°W; Canada) to investigate short-period IGWs ($T \approx 5-90$ min) by measurements of the meridional and regional components of neutral wind velocity [20] for altitudes of from 52 to 118 km. The spectra of both wind components are similar for slopes close to 1. Using the results of HF radar wind measurements in Adelaide (35°S, 139°E; Australia), we obtained total spectra of wind components for altitudes of from $\sim$ 70–80 km with power spectrum index $p < 2$ for the short-period part of the spectrum in the interval $T \approx$ 10–100 min [21]. Velocity spectra of vertical motions at altitudes of the lower ionosphere which are similar to those presented in this paper are given in [22]. And, finally, spectra of the parameters of artificial VLF signals measured using a method based on the Getmantsev effect [23, 24] and interpreted as IGW spectra for periods exceeding 2 h give a power dependence on frequency with exponent $p \approx 2$. Therefore, the obtained frequency spectra of vertical velocity agree with the currently available information on IGW spectra.

In the interval of periods that correspond to medium-scale IGWs ($T \approx$ 5 min – 2 h) we obtained the values of phase velocity $V_{\rm ph} \approx$ 60–100 m/sec, which are practically independent of the wave period (frequency). This result was also obtained in [5] by the method of polarization fading.

Another feature of V spectra is their "cutoff" at frequency ν_* (the corresponding period is T_*). Let us compare ν_* with the local maximum frequency of the IGW spectrum cutoff, which is the Brunt–Vaisala frequency

$$w_B^2 = \frac{1}{2\pi}\left(\frac{g}{C}\right)^2\left(\gamma - 1 - \gamma\frac{dH}{dz}\right),$$

where $H = \dfrac{kT}{mg}$ is the reduced altitude of the homogeneous atmosphere, C is the acoustic velocity, g is the free fall acceleration, and γ is the adiabatic exponent of an ideal gas [25].

The values of T_* and T_V are close in magnitude. Therefore, the value of T_* can be interpreted as a period that corresponds to the Brunt-Vaisala frequency in the IGW spectrum. It is known that IGWs with periods $T < T_V$ do not exist.

The spectrum cutoff period T_* coincides totally with T_V if we ignore the neutral wind velocity. Otherwise, they differ by $\Delta T = \dfrac{V_{\rm hor} - U}{V_{\rm hor}}$ [25], where $V_{\rm hor}$ is the horizontal velocity of IGWs in the propagation direction, U is the horizontal component of the wind, which is parallel to $V_{\rm hor}$. For $V_{\rm hor} = U$, $T_V = T_*$, and U or $V_{\rm hor}$ can be estimated from the difference between these times.

To determine other characteristics of waves, we use some relations resulting from the dispersion equation for IGWs, which is written for an isothermal incompressible atmosphere in the form [25]

$$k_z^2 = \left(\frac{\omega_B^2}{\omega^2} - 1\right)k^2 - \frac{1}{4H^2} + \frac{\omega^2}{C^2}, \tag{1}$$

where $k^2 = k_x^2 + k_y^2$. The IGW branch is determined by frequencies $w \ll w_B$. The simplest expressions are obtained from Eq. (1) for large-scale (long-period) IGWs when $|k| \gg 1/2H$. In this case

$$k_z^2 \approx \left(\frac{w}{w_B}\right)^2 k^2, \tag{2}$$

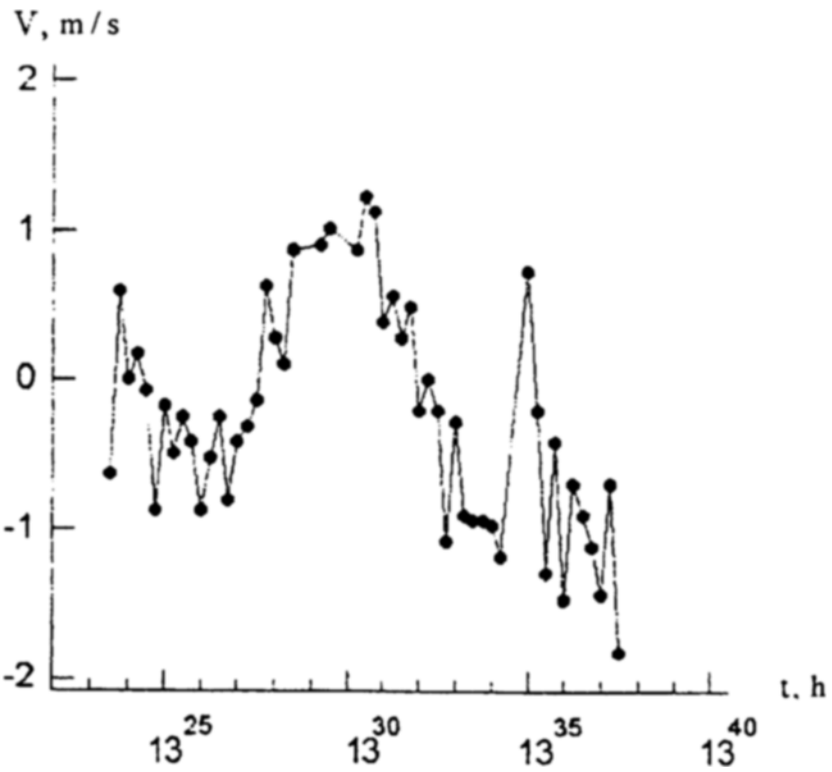

Fig. 5. Fragment record of $V(t)$ for the session from 13.23 to 13.38 on March 15, 1991, at an altitude of 89 km with a recording interval of 15 sec.

Table 1.
Altitude dependence of the spectrum cut-off period (T_*) and the Brunt–Vaisala period (T_V)

z, km	90	100	110	120
T_*, min	5.5	8	8.2	9
T_V, min	6.1	6.1	7.5	8.4

from which we easily obtain $\lambda = \lambda_z \frac{T}{T_V}$, where λ and λ_z are the horizontal and vertical wavelengths of IGWs. The value of λ_z is determined from either the altitude profile $V(h)$ or relationship $\lambda_z = V_{\rm phz} T$, where $V_{\rm phz}$ is the vertical component of the phase velocity. Assuming $V_z = 80$ m/sec, $T = 10$ min, and $T_V = 5$ min, we obtain $\lambda_z = 48$ km and $\lambda = 96$ km. It must be noted that although these estimates fit in the variation interval of λ for IGWs, the horizontal components of λ for the group and phase velocity must be determined by the method of diversity reception. Moreover, in Eq. (1) we assume that the average velocity of the wind is zero, but this is not actually true. If we allow for an average wind with velocity U, Eqs. (1) and (2) must involve the frequency $w' = w - \vec{U}\,\vec{k}$, which gives $w' = w - Uk$ for $U_z \ll U_{x,y}$ [25]. In this case the relation between the phase velocity of the wave and the velocity of an average wind is important. The largest-scale wave processes are observed for altitude profiles of V (see Fig. 1) averaged over long observation periods. The profiles of $V(h)$ for the 1990 fall months show oscillations with an altitude period of from 10 to 30 km, which could be due to the existence of tidal waves [25].

In this paper we omit the problem of fast fluctuations of vertical velocity of plasma at altitudes with a characteristic time scale below 1 min, which could be due to various atmospheric processes. As an example, in Fig. 5 we show a 15 min record of $V(t)$ for a session at 13^{23}–13^{38} h on March 15, 1991, and an altitude of 89 km obtained with a recording interval of 15 sec. In the figure we see very fast (with a 15-sec period) oscillations superimposed on an intense component with the period of about 5 min. Sometimes we observe almost monochromatic oscillations of V, which can be due to either the regime of the IGW source or other causes. More detailed experimental data and discussion of this problem will be presented in the future.

5. CONCLUSION

The method of resonance scattering of radio waves by artificial inhomogeneities of ionospheric plasma at altitudes of the lower ionosphere can be successfully used for studying dynamic processes in the atmosphere. With its high space-time resolution this method allows us to study processes with periods of from several seconds to hours and longer over a wide frequency spectrum.

The method is used for investigating the characteristics of wave motions in the lower ionosphere. The IGW characteristics obtained from measurements of the velocity of vertical motions at altitudes of from 90 to 120 km correspond generally to the existing concepts of IGW propagation. On the average, the amplitude of V increases with altitude, the value of the downward phase velocity is from 60 to 100 m/sec, and upward motions prevail.

The power spectra of the velocity of vertical motions at altitudes of from 90 to 120 km are studied, which have a power dependence on frequency with an exponent of less than unity and a spectrum cutoff frequency close to the Brunt-Vaisala frequency, which allows us to interpret them as IGW spectra. This method makes it possible to obtain the altitude dependence of the Brunt-Vaisala frequency and study the altitude variation and dynamics of the main IGW parameters.

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