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APPLIED RADIO PHYSICS: SPACE, ATMOSPHERE, AND EARTH'S SURFACE RESEARCH

STUDYING THE POSSIBILITY OF LOW-FREQUENCY WHISTLERS GENERATION BY INFRASOUND IN THE LOWER IONOSPHERE DURING THE PERIODS OF POWERFUL ATMOSPHERIC FRONT PASSAGE

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It is confirmed experimentally that in course of the powerful atmospheric front passage a generation of infrasonic waves with the frequencies $f_1 \approx 0.4-0.8$ *GHz penetrating up to the heights of the ionospheric E-region (* $z \approx 100-170$ *km) is possible. Based on the mechanism of the infrasonic waves transformation into the low-frequency whistlers in the ionospheric E-region and the obtained dispersion ratio there were experimentally determined the frequencies of the whistlers* $f_3 \approx 7-29$ *kHz forming a good match with theoretical calculations and data from the reference literature experimental results.*

KEY WORDS: *lower ionosphere disturbances, powerful atmospheric front, infrasonic waves, mid-latitude ionospheric D-region, low-frequency whistlers*

1. INTRODUCTION

Experimental research being performed during the recent years demonstrated that the ionospheric D-region conditions were often controlled to a great extent by powerful natural sources of tropospheric disturbances (heavy thunderstorms, cyclones and anticyclones, big fires, powerful atmospheric fronts etc.), world ocean disturbances (typhoons, tsunami etc.), and lithospheric disturbances (volcano eruptions, earthquakes), which, in addition, often occurred at the background of solar and geomagnetic variations including solar flares and geomagnetic storms. Natural disturbances in the lower ionosphere often exert a substantial influence upon the atmosphere and ionosphere of the Earth and thus represent a serious interest to understanding the physics of ionosphere and solving of quite a number of application problems of radio communication, radio navigation etc. To investigate the phenomena occurring in this case in the lower ionosphere the method of partial reflections (PR) has been used the most frequently during the recent decades.

It is known that the key part in dynamics and energetics of atmosphere and ionosphere is played by the atmospheric gravity waves (AGW): acoustic waves (AW) the periods of which are less than 5 minutes and the wavelengths are less than 100 km and the internal gravity waves (IGW) with the typical periods from 5 minutes to 3 hours and the wavelengths of more than 100 km. Penetrating to the heights of the ionosphere AGW reveal their properties in the form of moving ionospheric disturbances (MID). There are two types of MID present in the ionosphere (see, for example, [1]): 1) the medium-scale ones propagating with the velocity of 100…250 mps (less than the speed of sound in the lower atmosphere); their periods vary from 15 minutes to 1 hour and their horizontal length amounts to ~ 10…100 km, vertical lengths do not exceed ten kilometers; 2) the large-scale ones propagating with the velocity of 400…1 000 mps (comparable with the speed of sound at those altitudes); their periods vary from 30 minutes to 3 hours and their horizontal wavelength is more than 1 000 km. The sources of wave disturbances propagating from the lower to the upper atmosphere and ionosphere may include: tropospheric cyclones, frontal systems, stream currents, polar and equatorial current systems related to magnetic storms, solar terminator, hurricanes, thunderstorms, nuclear tests, earthquakes, volcano eruptions, supersonic rocket flights etc. The wave mechanism is one of the efficient mechanisms of interaction between the atmospheric layers and the influence from the part of the lower atmospheric layers.

Disturbances of the atmosphere excite a broad time and space spectrum of AW and IGW. These waves propagate from the source of disturbance to different directions with various velocities due to the dispersion and filtered at the extent of their propagation in the atmosphere. As it is shown by the investigations, AW are observed over the place of the disturbance; IGW [2] are observed, primarily, at large distances. For that reason in addition to control over the helio- and geomagnetic conditions while performing analysis of the effects of the wave disturbances revealed in the ionospheric parameters the meteorological situation in the area under investigation should be considered because passage of the atmospheric fronts can also be a source of IGW that is witnessed by the results provided in this section.

It is mentioned above that powerful atmospheric processes and phenomena (cyclones, stream currents, hurricanes, heavy thunderstorms etc.) are accompanied by generation of AGW and, in particular, infrasonic waves. Propagating not only in horizontal direction from the source but also upwards, the latter attain the altitudes of 170…200 km (and higher) and interact with the magnetoactive plasma that results in occurrence of additional currents and excitation of electric and magnetic fields, that is in generation or enhancement of different waves.

In [3–5] it is demonstrated the possibility of generation of the low-frequency whistler by the infrasound and it is developed the methodology of determining the frequencies of the low-frequency whistlers, which are generated by the infrasound in the mid-latitude lower ionosphere near the epicentrum of a heavy thunderstorm and at the passage of a powerful atmospheric front in the atmosphere of the Earth.

It is determined that the spectrum of those waves is defined as (it is used the linear approximation for the equations in the Gaussian system of coordinates selected as follows: the wave vector $\vec{k}$ matches with the axis *z*, the magnetic induction vector $\vec{B}$ lies in the plane *yz*, the angle $\vec{k}\vec{B} = \theta$):

$$\omega_3(k) = |\,\omega_{Be}\cos\theta\,|\,k^2c^2 / \omega_p^2, \tag{1}$$

where ω_3 are the frequencies of the whistlers; ω_{Be} is the gyrofrequency of the electrons; $\omega_p^2 = 4\pi q^2 N \,/\, m$ is the plasma frequency of the electrons.

The waves described by the dispersion ratio (1) are purely electronic and may propagate in the ionospheric plasma within the narrow cone of angles with the axis running along the entire magnetic field [6,7].

Eigen solution (1) allows determining the interrelation between the infrasonic frequencies f_1 ($\omega_1 = 2\pi f_1$) and the frequencies of the whistlers f_3 , which are generated in this region of the altitudes and to perform the calculations:

$$f_3 = \frac{c^2}{\upsilon_1^2}\frac{f_1^2 f_{Be}}{f_p^2}\cos\theta\cos\theta_1, \tag{2}$$

where θ_1 is the angle between the vertical and the direction of the infrasonic wave propagation; *c* is the velocity light; υ_1 is the infrasound velocity, and f_p is the plasma frequency.

2. SETTING OF THE PROBLEM

Generation of infrasonic waves in the above mentioned frequency bandwidth of the atmosphere in course of the periods of various kinds of disturbances (both natural and man-made) is confirmed both experimentally and theoretically (see references above). It is also known that such variations of the atmospheric gas density are rather freely attaining the heights of the ionospheric F-region: the approximate interval of frequencies of the infrasonic oscillations reaching, for example, the height of 160 km will be 0.05 Hz ≤ f_1 ≤ 10 Hz (the infrasonic waves with the frequencies 15…20 Hz are normally never attaining the heights of about 120 km and higher). The upper boundary of the interval is limited by fading of the waves, the lower one – by the acoustic cutoff frequency $f_a = \gamma g / 4\pi f_1$ (g is the free fall acceleration, γ is the ratio between the specific thermal capacities). It is natural to assume that at high-frequency sensing (for example, within the 2…10 MHz frequency bandwidth) of the ionosphere the radio waves would be subject to diffraction at the infrasonic wave that results in shifting of the sensing frequency (satisfying the Bragg condition) by the value equal to the value of the infrasonic wave frequency $f_d = f_1$ (the Doppler frequency shift). The reference literature contains description of a number of experiments related to the Doppler high-frequency sensing of the ionosphere (most often at the frequencies of 4…5 MHz) during the periods of recording low-frequency radiation at explosions and earthquakes (see, for example, [8-10]). As a rule, the Doppler frequency shift amounts to f_d = 0.2…2 Hz.

Based on the foregoing upon the measurements of the Doppler frequency shift it is possible to determine at the vertical sensing of the ionosphere in the epicentrum zone of the source of disturbances (explosions, earthquakes, thunderstorms etc.) the frequency of the infrasonic waves $f_d = f_1$. From the ratio (2) determining the interrelation between f_1 and the frequencies of the low-frequency whistlers f_3, which are generated in this region of altitudes, there can be obtained numerical values of those frequencies and their wavelength $\lambda_1 = v_1 / f_1$ can be determined based on the known ratio. It is mentioned above that experimentally the low-frequency whistlers would be recorded, apparently, in the vicinity of the epicentrum of the source of disturbances.

3. INVESTIGATION EQUIPMENT AND METHODS

Experimental investigations based on the scheme as suggested above were performed during the passage of a powerful atmospheric front with the help of the set of equipment [11] using the methods of partial reflections (PR) and the vertical Doppler sensing (VDS) at Radio Physical Observatory of V. Karazin Kharkiv National University near Kharkiv, Ukraine. The measurements were performed continuously with the session duration of 3…5 days before, during and after the passage of a powerful atmospheric front. Estimation of amplitude variation periods for PR-signals $A_{so,x}(z,t)$ and radio noises $A_{no,x}(t)$ (for two tape recorder components) was performed using the fast Fourier transform upon the 30-minute time intervals. At that, the temporal series is created from the values $A_{so,x}(z,t)$ and $A_{no,x}(t)$. Based on the results of measurements with the Doppler radar, the Doppler spectra (DS) were estimated upon 512 counts at the 51.2 s time interval. In this conditions the resolution upon frequency was 0.02 Hz. The information about the Doppler spectra was recorded every minute. For estimation of the periods of rather slow variations of the Doppler frequency shift $f_d(t)$ correspondent to the DS center f_{dm}, it was applied a fast Fourier transform upon the time intervals of 64 and 128 min. The temporal series was, at that, formed from the per-minute values of f_{dm}. Two frequencies – 2.8 MHz and 3.5 MHz – were applied. The comparison was performed with the data obtained at the same equipment under similar helio-magnetic conditions without any effect of thunderstorm activity in the area of observations and under the non-disturbed conditions before and after the passage of a powerful atmospheric front (on the reference days). Control over the ionospheric conditions was performed with the iono-probe. General number of cycles of simultaneous observations with the help of PR and VDS methods was 4. The experimental data are provided in Table 1. We note that results of the experiments performed during thunderstorms are provided in previous publications (see, for example, [5,12]).

Three problems were solved: 1) to determine based on measurements of the Doppler frequency shift at vertical sensing of the ionosphere (in the powerful atmospheric front passage area) the frequency of infrasonic waves as $f_1 = f_d$; 2) based on measurements of PR amplitudes of partially reflected radio signals $A_{so,x}(z,t)$ and radio noises $A_{no,x}(t)$ to try and obtain an experimental proof of a possible generation of the infrasonic waves in the atmosphere at the passage of a powerful AF. Using spectral processing of time and height records of $A_{so,x}(z,t)$ and $A_{no,x}(t)$ to determine the infrasonic wave frequency f_1; 3) to compare using the simultaneous measurements based on the PR and VDS methods the obtained values of the infrasonic frequencies f_1 and to calculate based on the ratio (2) the frequencies of the low-frequency whistlers f_3 generated in this region.

TABLE 1: Information about the experiments

Date	Time of measurements, (LT)		Time of the AF passage, (LT)
	PR method	VDS method	
27 – 30.10.2004	Continuously (several breaks for 1…3 hours)		29.10.2004: 11:00am–02:30pm
30.03 – 04.2004	continuously		02.04.2004: 09:00am – 02:00pm
07 – 09.02.2007	continuously		08.02.2007: 08:00am – 03:00pm
20 – 23.03.2007	continuously		22.03.2007: 11:30am–02:30pm

4. EXPERIMENTAL RESULTS

Subsequently, we consider basic experimental results obtained during the experiments performed simultaneously with the PR and VDS methods at propagation of a powerful

AF. Analysis of the experimental results proved that main particularities of time and height variations of $A_{so,x}(z,t)$ and $A_{no,x}(t)$ during all of the analyzed experiments are reduced to the following typical ones (see also [13]): 1) during the AF passage and 1…5 hours after (sometimes even longer but identification is difficult due to the effect of the solar terminator) non-stationarity of PR-signals and radio noises is noticeably higher than before the fronts passage periods; 2) in about a half of the considered cases there were revealed certain differences in behavior of $A_{so,x}(z,t)$ during the AF passage compared to the periods before and after: quasi-periodical changes of $A_{so,x}(z,t)$ are observed during tens of minutes; in doing so, motion of the process by height occurs. As it is shown by the analysis of primary recordings of the PR-signals, the estimated velocity of the process motion was ~ 350…340 mps. Figure 1 provides the example of the profiles $A_{so}(z,t)$, each of which is obtained during the experiment held on 29.10.2004 (01:10 p.m. LT) at the AF passage by averaging upon 50 realizations (for 5 s) (like in the experiment on 22.03.2007) [13]. There were determined the particularities that had not been observed before the AF passage. It is clearly seen the frequency shift by height with time (during 30 s) by approximately 12 km of the maximal value of $A_{so}(z,t)$ (a similar phenomenon is also typical for $A_{sx}(z,t)$), the estimated vertical motion velocity of the disturbance is $V \approx$ 350 mps. We note that the similar changes occurred also during the periods of heavy thunderstorms (see, for example, [5]).

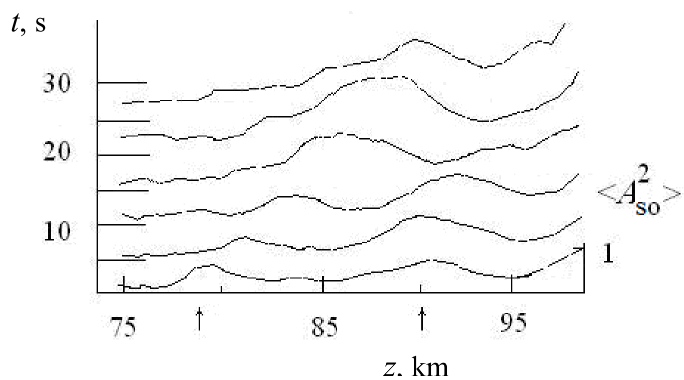

FIG. 1: Example of time and height profiles $< A_{so}(z,t) >$ obtained during the experiment on 29.10.2004 (01:10 p.m. LT) at the AF passage

At spectral processing of the dependences $A_{so,x}(z,t)$ (for z = 75, 78, 81, 84, 87, 90 and 93 km, see the example in Fig. 2) it is revealed a significant increase of the spectral component energy at the frequency of $f \approx$ 0.5 Hz that corresponds to the infrasonic band. It can be assumed, as before, that such behavior of $A_{so,x}(z,t)$ during the atmospheric front passage might be stipulated by occurrence of the infrasonic acoustic waves propagating with low losses from the source in the atmosphere.

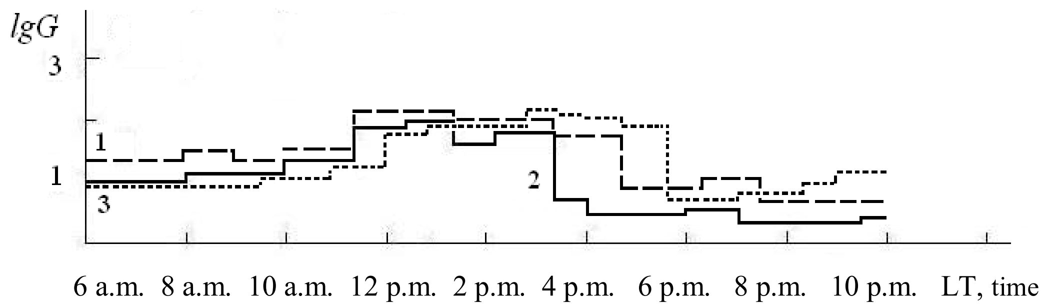

FIG. 2: Time dependences of the spectral density G for $A_{so}(t)$ obtained during the atmospheric front passage with the help of the PR method on 29.10.2004, curves: 1 – z = 75 km; 2 – z = 84 km; 3 – z = 93 km (f = 0.5 Hz)

Figure 3 provides the example of the Doppler spectra obtained during the experiment on 29.10.2004.

It is evident from Fig. 3 that approximately after 11:30 a.m. LT it is clearly traced, first, the increase of f_d to $f_{dm} \approx 0.3$ Hz (maximal value of f_d) with subsequent decreasing to about $f_d \approx$ -0.4 Hz during 15 minutes and further increases and decreases of the values of f_d within the limits $f_d \approx \pm 0.3 - 0.35$ Hz. After the atmospheric front passage, same as before it, $f_d \sim 0 \ldots 0.1$ during approximately 60 min. This variation of f_d is apparently related to generation of the infrasonic waves at the atmospheric front passage because, as it is mentioned above, at spectral processing of the records of $A_{so,x}(z,t)$ obtained with the help of the PR method, within the entire range of heights it is determined the increase of the spectral component G intensity at the frequency of $f \approx 0.5$ Hz (the example of such dependences is provided in Fig. 2, the calculations are performed for the time intervals of 30 min).

It is necessary to note that at the background measurements no similar variations were detected on the reference day 27.10.2004 (like in a number of other experiments held under the non-disturbed conditions). During other experiments, as it is mentioned above, it is observed, in general, a similar behavior of f_d and $A_{so,x}(z,t)$ as well as $A_{no,x}(t)$ (the values of f_d varied within the limits of $f_d \approx \pm 0.4 - 0.55$ Hz).

It is obtained (see the formula (2)) the relationship between the frequencies of the infrasonic waves f_1 generated at different disturbances in the atmosphere, on the Earth surface and under the ground and the experimentally measured ones that allows calculation of frequencies of the low-frequency whistlers f_3. As it is shown above and in the paper [4], it may be generated or amplified at that in the E- and F-regions of the ionosphere.

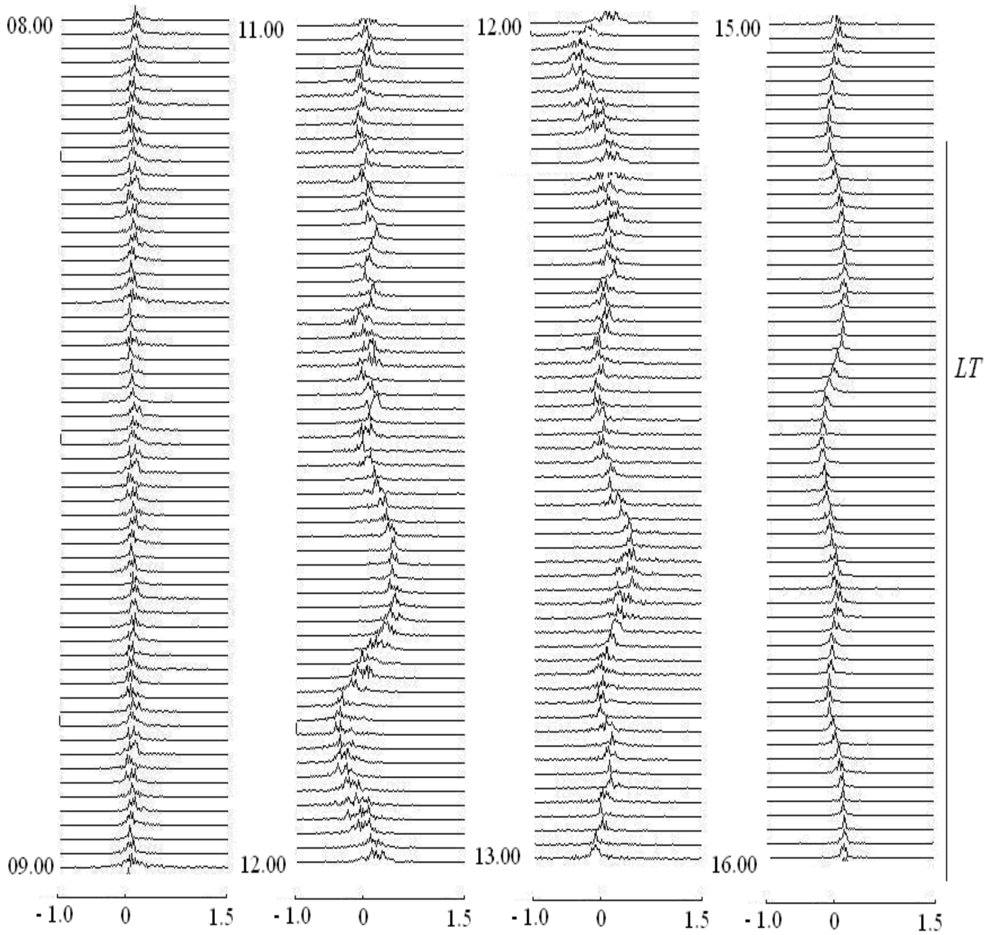

FIG. 3: Example of the Doppler spectra obtained during the experiment on 29.10.2004

We accept for the calculations that $c = 3\cdot10^8$ mps, υ_1 = 500 mps, ω_{Be} = $8\cdot10^6$ s^{-1}, ω_p = $17.6\cdot10^{-6}$ s^{-1}, the reflection height estimate h is taken from the ionograms of the vertical sensing obtained with the help of the ionoprobe [11]. The calculations are performed at the supposition that the whistler is propagating along the geomagnetic field θ = 0$^{\mathrm{o}}$ direction; the infrasonic wave is propagating vertically upwards and $\theta_1 = 30^0$ that corresponds to the magnetic inclination of ~ 60$^{\mathrm{o}}$ in the middle latitudes. The results of calculation are provided in Table 2.

It should be mentioned that the experimentally obtained values of infrasonic frequencies f_3 form a good match with theoretical calculations provided in [4]. We also note that the infrasonic acoustic waves similar to those obtained by us during thunderstorms [5] and at the passage of a powerful atmospheric front were observed previously in the atmosphere and ionosphere due to strong wind flows in mountainous areas, volcano eruptions, rough sea and due to supersonic motion of the auroral arcs (see, for example, [1,14–17]). Their characteristics (periods and propagation velocity of) turned out to be similar in terms of the order of values.

TABLE 2: Results of calculations of the frequencies of the low-frequency whistlers

Date	*h*, km	f_1, Hz	f_3, kHz
01.07.1997	170	0.5	11.3
07.07.1998	160	0.5	11.3
08.09.2001	160	0.5	11.3
25.09.2001	170 160	0.4 0.8	7.2 28.9
29.10.2004	170	0.4	7.2
02.04.2004	170	0.4	7.2
08.02.2007	160	0.5	11.3
22.03.2007	160	0.4	7.2

We also note that already in the paper [16] in order to explain the partial reflections and backscattering of radio waves from plasma inhomogeneities in the D-region of the ionosphere it is suggested the mechanism of interaction between the electromagnetic sensing waves and atmospheric waves. It is important that the considered techniques was applied for investigation of the possibility of generation of the low-frequency whistlers near the epicentrum and other disturbances of different nature – earthquakes, explosions, rocket launches etc.

5. CONCLUSIONS

Using the VDS and PR methods it is experimentally confirmed that at the passage of a powerful AF generation of infrasonic waves with the frequencies $f_1 \approx 0.4–0.8$ Hz penetrating up to the heights of the ionospheric E-region ($z \approx 100–170$ km) is possible.

Based on the mechanism of the infrasonic waves transformation into the low-frequency whistlers in the ionospheric E-region and the obtained dispersion ratio there were experimentally determined the frequencies of the whistlers $f_3 \approx$ 7–29 kHz forming a good match with theoretical calculations and data from the reference literature experimental results

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