Telecommunications and Radio Engineering, **57**(10&11), 2002

APPLIED RADIO PHYSICS

Low Frequency Whistlers Generated in the Lower Ionosphere During Strong Thunderstorms

A. M. Gokov and O. F. Tyrnov

V. Karazin National University of Kharkov, 4, Svoboda Sq., Kharkov, 61077, Ukraine

Methods of determination whistler frequencies generated by the infrasound in E- and F- regions of the ionosphere near the strong thunderstorm epicentre in the Earth atmosphere are proposed. Experimentally, using methods of the vertical Doppler sounding and partial reflections, it has been confirmed the principle that the during a strong thunderstorm, near the epicentre, generating of infrasonic waves of $f_1 \approx 0.4\text{-}0.8$ Hz which spread up to the ionospheric F-region heights is possible. On the basis of both the infrasonic waves transformed in the ionosphere into the low frequency whistlers and the dispersion relations, the whistler frequencies were found to be $f_3 \approx 7\text{-}29$ kHz, which agrees closely with the theoretical calculations.

1. Introduction

It is well known, that in the period of an earthquake and at the time of preparation of it, under strong thunderstorms, explosions and other disturbances, the infrasonic waves are generated within frequencies 0,01 Hz $< f_1 <$ 20 Hz (see, e.g. Grigor'ev and Dokuchaev (1981); Al'perovich et al. (1983); Baker and Cotten (1971); Davis and Baker (1965); Rai and Kisabcth (1967); Barry et al. (1966)). Such waves spread rather easily up to the ionospheric E-region heights ($z \sim 100\text{-}160$ km) and higher than these up to the F-region heights, which leads to appearing additional currents and disturbation of the electric and magnetic fields, i.e. to generating or amplifying various waves. It is also known that whistlers (whistler modes) are electromagnetic waves propagating in weakly ionized plasma for which the following conditions are fulfilled: $\nu_{en} << \omega_{Be}, \nu_{in} >> \omega_{Bi}$, ($\omega_{Be}, \omega_{Bi}$ are the electron and ion gyro-frequencies, ν_{en}, ν_{in} are the frequencies of electrons and ions collision with neutrals). For such waves, the electrons taking part in a moving infrasonic wave are connected with magnetic field lines and drift in crossed fields; and the ions - due to their collisions with the neutrals - are not subjected to the magnetic field action and practically rest or move under the infrasonic wave control (if there is infrasound). These conditions are fulfilled at the ionospheric E-region heights and higher. The presence of such waves in the epicentral zone and at some distance from a disturbance source was found experimentally (see, for example, Mikhaylov et al. (1991); Mikhaylov et al. (1997); Sadovsky et al. (1979); Ralchovsky and Komarov (1989)).

The problems of the low frequency whistlers propagating in that height range were discussed rather fully in Mazur (1988). The problem of such waves generated by acoustic waves in the E -region was solved in Surkov (1989). It is shown in Gokov (2000) that the infrasonic waves excited in the atmosphere during disturbances of different natures, under their propagating in the Earth ionosphere, may

ISSN0040-2508

generate or amplify low frequency whistlers in the ionospheric E-region. Using the dispersion equation, a relation between the frequencies of infrasound and the whistler was obtained.

The frequency range, in which whistler generation is possible, was calculated on the basis of the experimental data about the frequency interval of infrasound generated in the atmosphere under disturbances of different natures.

In the presented paper, using the experimental measurements by means of the partial reflection methods (PR) and the vertical Doppler sounding (VDS), there is shown a possibility of generating a low frequency whistler by the infrasound in the lower middle-latitude ionosphere during a strong thunderstorm.

2. Formulation of the problem

The generation of the infrasonic waves in the atmosphere to the above-mentioned frequency range under the disturbances of various characters (both natural and artificial ones) was confirmed experimentally and theoretically (see the references in the introduction).

It is also known, that such atmospheric gas density fluctuations spread easily up to the ionospheric F-region heights: an approximate frequency range of the infrasound fluctuations reaching, for instance, 160 km is 0.05 Hz $\leq f_1 \leq$ 10 Hz (infrasonic waves of 15-20 Hz, as a rule, do not spread higher than about 120 km). The upper boundary of the range is limited by wave fading, the lower one is confined to the acoustic cutoff frequency, $f_a = \gamma g / 4\pi f_1$ (g being the acceleration of gravity, γ being the ratio of specific heats). Clearly that under high frequency sounding (for instance, within 2-10 MHz) of the ionosphere, radio waves will undergo diffraction by an infrasonic wave, which leads to a shift of the sounding frequency (satisfying Bregg's condition) by a magnitude equal to the infrasonic wave frequency, $f_d = f_1$, (Landsberg (1976)). Elsewhere there are a whole number of experiments concerning with the Doppler high-frequency sounding of the ionosphere (usually at 4-5 MHz) over the periods of recording low-frequency radiations during explosions and earthquakes (Al'perovich et al. (1983); Baker and Cotten (1971); Davis and Baker (1965); Gokhberg (1986); Afraymovich et al. (1984)). As a rule the Doppler frequency shift is of f_d = 0.2-2 Hz. Proceeding from this, using the Doppler frequency shift measurements under vertical sounding the ionosphere in the epicentre zone of the disturbance source (explosions, earthquakes, thunderstorm, etc.), one can find the frequency of the infrasonic waves to be $f_d = f_1$. Using the relation giving a connection between f_1 and the frequencies generated in this height range of the low-frequency whistlers, f_3, (Gokov (2000)),

$$f_3 = \frac{c^2}{\upsilon_1^2} \frac{f_1^2 f_{Be}}{f_p^2} \cos\theta \cos^2\theta_1, \tag{1}$$

one may obtain numerical values of these frequencies and, using the known relation, find their wavelength, $\lambda_1 = \upsilon_1 / f_1$. Here θ_1 is the angle between the vertical and the infrasonic wave propagation direction, the angle $\bar{k}\bar{B} = \theta$, $\bar{k}$ is the wave vector, $\bar{B}$ is the magnetic induction vector, c is the light velocity, υ_1 is the infrasound velocity, f_{Be} is the gyrofrequency of electrons, and f_p is the electron plasma frequency.

Note that the low frequency whistlers will seem to be experimentally recorded near the disturbance source epicentre since, as shown in Mazur (1988), the presence of rather a powerful layer with the considerable Pedersen conductivity leads to impossibility for a low frequency whistlers to propagate along the Earth surface (in the ionospheric region considered) over long distances (more than hundreds of kilometers). Nevertheless, they may essentially increase as the ionosphere may be a good resonator with the quality factor, $Q_n = \pi n(2\sigma_H / \sigma_P)^{1/2}(\cos\theta)^{1/2}(1+\cos\theta)^{-1}$ for the low frequency whistlers (Mazur (1988)). For harmonics with n ~ 3-5 and the calculated $\sigma_H / \sigma_P \approx 2$ (Volker and Carpenter (1975)) (σ_H, σ_P are the Hall and Pedersen conductivities), it may reach $Q_n \approx$ 20-30. Such fluctuations may be recorded, for instance, in natural radio noise spectra.

3. Equipment and investigation methods

Our experimental investigations, using the scheme given above, were conducted during several strong thunderstorms by means of the equipment complex (Tyrnov et al. 1994) with the help of the PR and VDS methods near the city of Kharkiv at the Radiophysical Observatory of Kharkiv V. Karazin National University (see Table 1).

Table 1.

Coordinates of Kharkiv V. Karazin National University Radiophysical Observatory

	Geographic		Geomagnetic				
Elevation (m)	Latitude (N)	Longitude (E)	Latitude (N)	Longitude (E)	Inclination	Declination (W)	L
156	49° 38'	36° 20'	45.37°	118.7°	66° 36.8'	6° 19.6'	~2.0

Main parameters of a complex of a method of partial reflections at realization of experiments are following: the operating frequency, f = 2.31 MHz, the duration of sounding pulses, τ = 25 μsec with the repetition frequency of F = 1-5 Hz, the radiated pulse power, P = 150 kW, the gain of antenna being G = 40. The amplitudes of signal plus noise of the ordinary and extraordinary polarizations, $A_{s,o}(z,t)$, $A_{s,x}(z,t)$, respectively (their height-time variations; z is the height in km over the Earth surface, τ is the time), were digitized at a rate of one per second and recorded on a magnetic tape. In order to determine the signal amplitudes $A_{o,x}(z,t)$ two samples of noise amplitudes $A_{no,x}(t)$ were acquired within each interpulse interval. The measurements of $A_{s,x}(z,t)$ and $A_{no,x}(t)$ were made within a height range of 45 – 126 km by a 3-km step. The measurements were conducted uninterruptedly over observation periods of 1-10 hours before, during and after the thunderstorms. Estimating of the variation periods of $A_{so,x}(z,t)$ and $A_{no,x}(t)$ was carried out by means of a quick Fourier transform over 30 min time intervals. Besides, the time series was made of every second values of $A_{no,x}(z,t)$, $A_{o,x}(z,t)$ and $A_{no,x}(t)$.

From the Doppler radar measurements, the dynamic Doppler spectra (DS) were estimated using 512 countings over a time interval of 51.2 seconds. At the same time, the frequency resolution was 0.02 Hz. Information on the Doppler spectra was recorded every minute. To estimate periods of rather slow variations of the Doppler frequency shift, $f_d(t)$, corresponding to the centre of the DS, f_{dm}, the quick Fourier transformation over the time intervals of 64 and 128 min was used. In addition, the time series was made of every minute values of f_{dm}. Two operation frequencies were used: 2.8 MHz and 3.5 MHz.

The comparison was made with the data obtained by the same equipment under similar heliogeomagnetic conditions without any thunderstorm activity in the observation region (on the control days).

An ionosonde controlled a state of the ionosphere.

The total number of simultaneous observation cycles by means of the PR and VDS methods is 4. The experimental information is given in Table 2.

Three problems were solved:

1) to find the infrasonic waves as $f_1 = f_d$ by means of the Doppler frequency shift measurements while vertical sounding the ionosphere in the epicentre thunderstorm zone;

2) to try to obtain an experimental confirmation of possible generation of infrasonic waves in the atmosphere during a thunderstorm using the PR technique measurements of the amplitudes of the partially reflected radio signals, $A_{o,x}(z,t)$, and the amplitudes of the radio noise, $A_{no,x}(t)$. To find the infrasonic wave frequency, f_1, by means of spectrum processing of the height-time records of $A_{no,x}(z,t)$, $A_{o,x}(z,t)$, and $A_{no,x}(t)$;

3) to compare the infrasonic wave frequency, f_1, for the simultaneous measurements obtained by the PR and VDS techniques, and then using relation (1) to calculate frequencies of the low frequency whistlers generated in this height range, f_3.

Table 2.

Experimental information

Date	Observation Time (LT)		Thunderstorm time (LT)
	PR-technique	VDS-method	
01.07.1997	18:37:00 – 24:00:00	21:10:00 – 24:00:00	22:20 – 23:00
07.07.1998	17:44:00 – 00:10:00	19:06:00 – 22:58:00	20:50 – 21:35
08.09.2001	15:30:00 – 19:32:00	15:20:00 – 21:25:00	19:20 – 19:50
25.09.2001	02:28:00 – 10:02:00	02:00:00 – 08:30:00	04:18 – 04:55 07:25 – 08:10

4. Experimental results and discussion

Earlier when analyzing the experimental data on $A_{no,x}(z,t)$, we discovered some differences in $A_{no,x}(z,t)$ behaviour during the thunderstorm, before and after it (Gokov and Tyrnov (1998); Gokov and Tyrnov (1999)). For instance, in the experiment of 15.07.1981 during the thunderstorm there were found some peculiarities in the $A_{no,x}(z,t)$ behaviour (when the sounding facility with F = 5 Hz was operating). It was not observed before the thunderstorm. Fig. 1 shows the height-time $< A_{s,o}^2(z,t) >$-profiles, each was obtained by averaging over 15 realizations (during 3 sec). Here one can clearly see the shift of the maximum value of $< A_{s,o}^2(z,t) >$ by about 10 km with regard to the height with the time (during 30 sec). A similar picture takes place for $< A_{s,x}^2(z,t) >$) as well. The vertical velocity of such a shift is V = 300 m/sec. (The measurements by the VDS method were not made in this period).

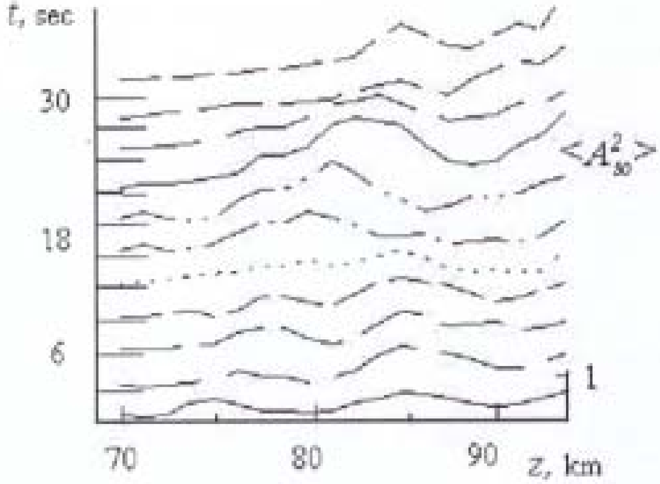

Fig. 1. Height-time $< A_{s,x}^2 >$ profiles, obtained by averaging over 15 realizations (over 3 sec) in the experiment 15.07.1981.

Under spectrum processing of the $< A_{s,x}^2(z,t) >$ dependences (at z = 78, 81 and 85 km) the energy increase in the spectrum component at f = 0.5 Hz was discovered. It corresponds to the infrasonic range. We may assume that such $A_{so,x}(z,t)$ behavior during the thunderstorm is possibly caused by appearing infrasonic acoustic waves which propagate from the source with small losses in an atmosphere.

Let us consider the results obtained in the experiments conducted simultaneously by the PR and VDS techniques.

In the experiment of 01.07.1997, there were measured $A_{so,x}(z,t)$ and $A_{no,x}(t)$ at f = 2.31 MHz within 18:37 – 24:00 LT in the height range of z = 45- 96 km, f_d being measured at 3.5 MHz and 2.8 MHz within 21:10 – 24:00 LT. In the first place a choice of operating frequencies was determined by the available radio noise. The thunderstorm was visually observed some kilometers away (the distance being $R_1 \approx$ 3-8 km) from the Radiophysical Observatory within 22:20 – 23:00 LT.

The dynamic Doppler spectra is obtained in the given experiment, as exemplified in Fig.2. (As was to be expected, the DS variations at the two close frequencies were similar to one another. Therefore we further describe the observations results at 2.8 MHz). After 22:40 LT, in the figure one can clearly trace at first the growth of f_d up to $f_{dm} \approx$ 0.5 Hz (f_{dm} is a maximum value of f_d) with the following decrease down to about $f_d \approx$ - 0.4 Hz over 35 min. Then, after the thunderstorm, one can see $f_d \approx$ 0-0.1 over about 25 min, as it took place before the thunderstorm. Such a change in f_d seems to be connected with infrasonic waves generated during the thunderstorm since, under spectrum processing of the $A_{so,x}(z,t)$ records obtained by the PR technique, there was noticed an increase in the whole height range of the spectrum component intensity, G, at $f \approx$ 0.5 Hz (an example of the dependences is shown in Fig. 3). It should be noted here that in the background measurements made on the control day of 07.07.1997 (the measurements were conducted by the PR technique 16:14-17:18 LT and by the VDS method 13:51-17:40 LT) there were observed no changes (as for a number of other experiments carried out under undisturbed conditions).

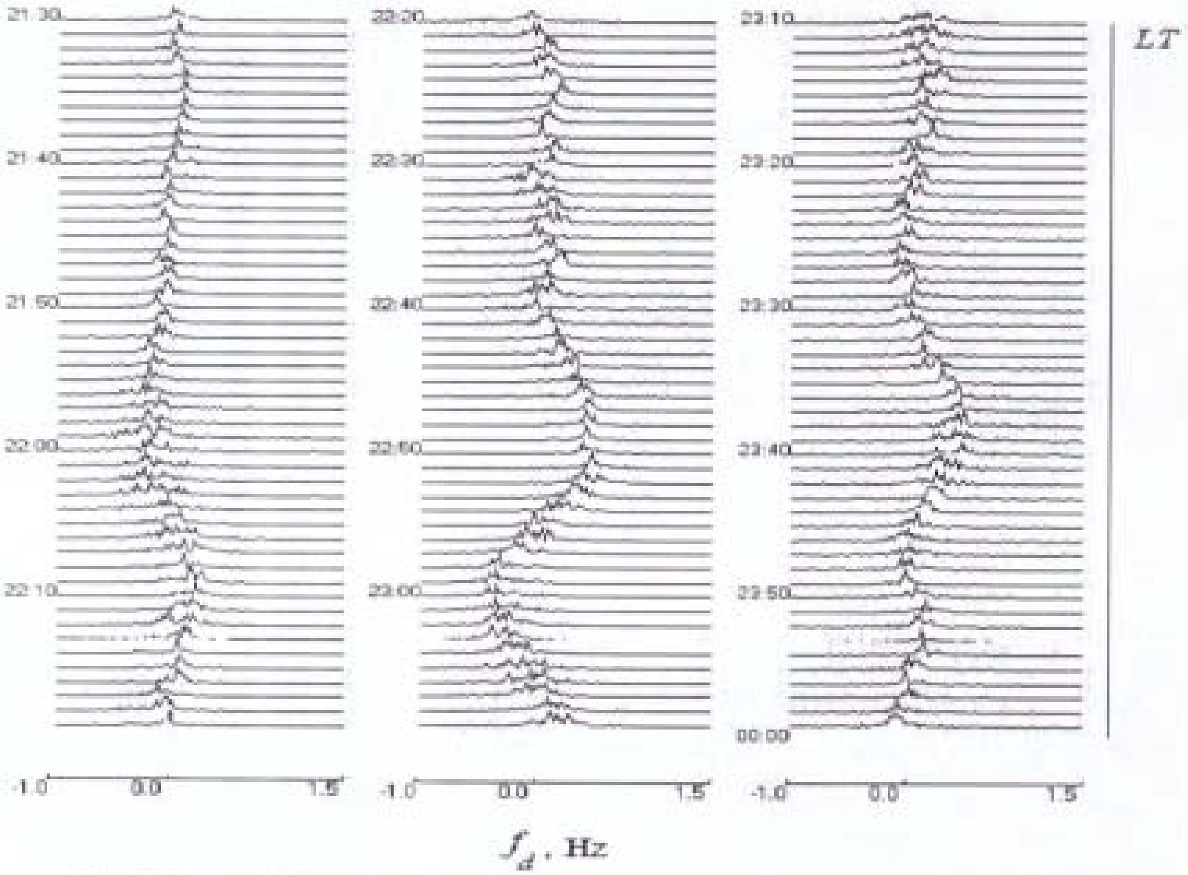

Fig. 2. Dynamic Doppler spectra obtained in the experiment of 01.07.1997 during the thunderstorm.

In another experiment made on 25.09.2001., the thunderstorm was observed at a short distance (04:18. – 04:55. LT, $R_1 \approx$ 3-6 km), and at some distance away (07:25. – 08:10. LT, $R_1 \approx$ 10-15 km) from the Radiophysical Observatory. The $A_{m,x}(z,t)$ and $A_{no,x}(t)$ measurements at f = 2.31 MHz were conducted within z = 60-126 km, the f_d values being measured at 3.5 MHz and 2.8 MHz. Fig. 4 shows an example of the dynamic Doppler spectra obtained in this experiment. Within 04:23–04:59 LT it is clearly seen that the positive Doppler frequency shift (~ 0.2 Hz) which began at 03:40 (i.e. about 40 min before the thunder commencement in the observation region) is superimposed by the DS "strewing" (its width changing from 0.5 to 1 Hz) which coincided with the thunderstorm period. The Doppler frequency change (shift) may be caused by changing of the middle ionosphere electron density, including that in the vicinity of the radio wave reflection region, and by the displacement of this region as well. This may be brought about by both the thunderstorm activity and other causes. Investigation of them is not within the framework of the paper presented here.

The DS "strewing" is caused by the presence of the small-scale random irregularities in the vicinity of the radio wave reflection region and lower. The main mechanism of generating irregularities having scale of $l \approx 10 - 10^3$ m in the E and F-regions, are instabilities in the magnetically active ionospheric plasma (Gershman (1974); Gel'berg (1986)). For their rise, the following conditions should be met: overstepping of the arising instability threshold, rather large values of the instability increment, etc. Violations of these conditions leads to suppressing instabilities and hence to irregular structures at the height discussed (besides, the one-mode DS structure is restored as a "regularization effect" of the DS).

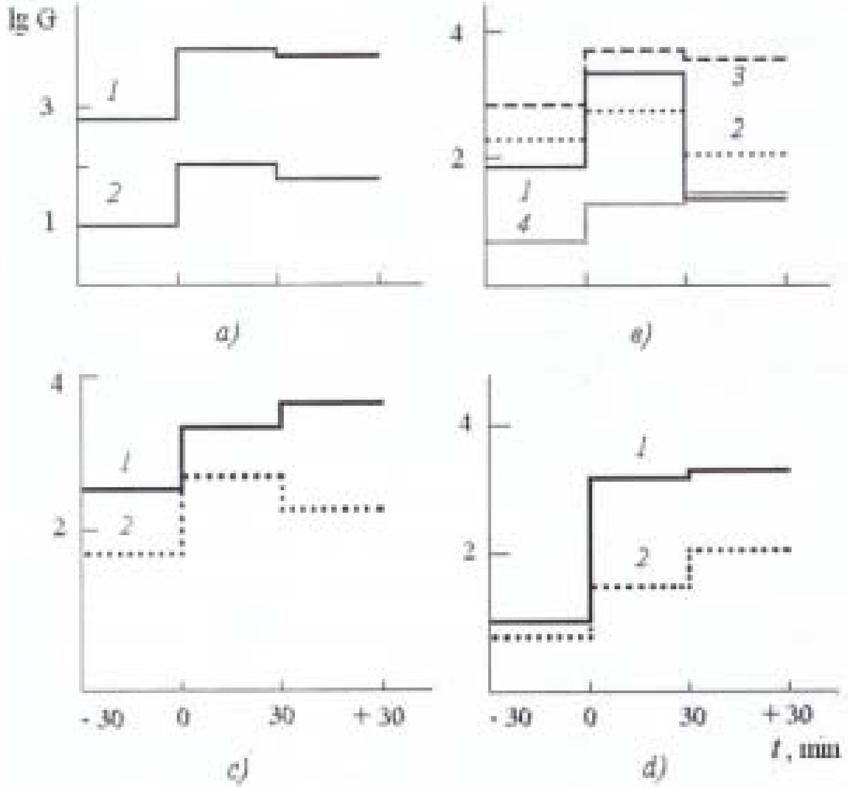

Fig. 3. The time dependences of the spectrum intensity G of $A_{sm}(t)$, obtained by the partial reflection technique during the thunderstorms (calculations are made for time intervals of 30 min):

a) 01.07.1997, curves: 1- z=60 km; 2- z=93 km (f_d=0.48 Hz);

b) 25.09.2001, curves: 1- z=69 km; 2- z=120 km (f_d= 0.48Hz);

3- z=63 km; 4 - z=117 km (f_d=0.92 Hz);

c) 07.07.1998, curves: 1- z=63 km; 2- z=96 km (f_d= 0.48Hz);

d) 08.09.2001, curves: 1- z=63 km; 2- z=96 km (f_d= 0.48Hz);

Sectoring on the time axis is as follows: "-30 - 0" is to 30 min before the thunderstorm; "0 - 30" for 30 min during the thunderstorm; "30 - +30» for 30 min after the thunderstorm.

It seems likely that over this lapse, the infrasonic waves were not generated or perhaps their intensity was low to be observed as in the PR technique measurements there were not observed clear changes either in the $A_{m,s}(z,t)$ and $A_{mo,s}(t)$ components.

During the second thunderstorm of 25.09.2001 (within 07:25 – 08:10 LT) there were observed clear changes in f_d up to $f_{dm} \approx 0.8$ Hz with lowering down to about $f_d \approx -0.4$ Hz over 40 min. These changes coincided with the thunderstorm period (the delay being about 8 min). Under spectrum processing of the $A_{m,x}(z,t)$ records obtained by the PR technique, there was observed over the whole height range an increase in the spectrum components intensity, G, at $f \approx 0.5, 0.9$ Hz (Shown in Fig. 3 is an example of the $G(t)$ dependences).

Fig. 4-6 show examples of the dynamic Doppler spectra obtained in the experiments of 07.07.1998, 08.09.2001, and 25.09.2001, respectively. The thunderstorm was observed near the Observatory ($R \approx$ 3-6 km). The $A_{m,x}(z,t)$ and $A_{m,x}(t)$ measurements at $f = 2.31$ MHz were conducted within z = 60 - 126 km. As in the examples considered above, in these experiments there are clearly observed changes in $f_d \approx \pm 0.4$-0.5 Hz during the thunderstorm. Under spectrum processing of the $A_{m,x}(z,t)$ records, there was observed over the whole height range an increase in the spectrum component intensity, G, at $f \approx 0.5$ Hz (an example of the $G(t)$ dependences is presented in Fig. 3).

The relation, obtained in Gokov (2002) (see (1)), between the frequencies of the infrasonic waves, f_1, generated under various disturbances in the atmosphere on the surface and under the Earth, measured experimentally, allows to calculate the frequencies of low frequency whistlers, f_3, which (as shown in Gokov (2000)) may be generated or enhanced at the same time in the E and F- regions of the ionosphere.

In order for calculation to be made, we assume that $c = 3 \cdot 10^8$ m/sec, υ_1 = 500 m/sec, $\omega_{Be} = 8 \cdot 10^6$ sec^{-1}. The estimation of the reflection height , h, and ω_p was obtained using vertical sounding ionograms obtained by means of the ionosode (Tymov et al. (1994)). The calculations were carried out assuming that the whistler propagates along the direction of the geomagnetic field ($\theta = 0°$); the infrasonic wave propagates vertically upward and $\theta_1 = 30°$, which corresponds to the magnetic inclination of ~ 60° in the middle latitudes.

Table 3 presents the calculation results.

Table 3.

Calculation results of low frequency whistler frequencies

Date	h, км	f_1, Hz	f_3, kHz
01.07.1997	160	0.5	11.3
07.07.1998	150	0.5	11.3
08.09.2001	150	0.5	11.3
25.09.2001	160	0.4	7.2
	150	0.8	28.9

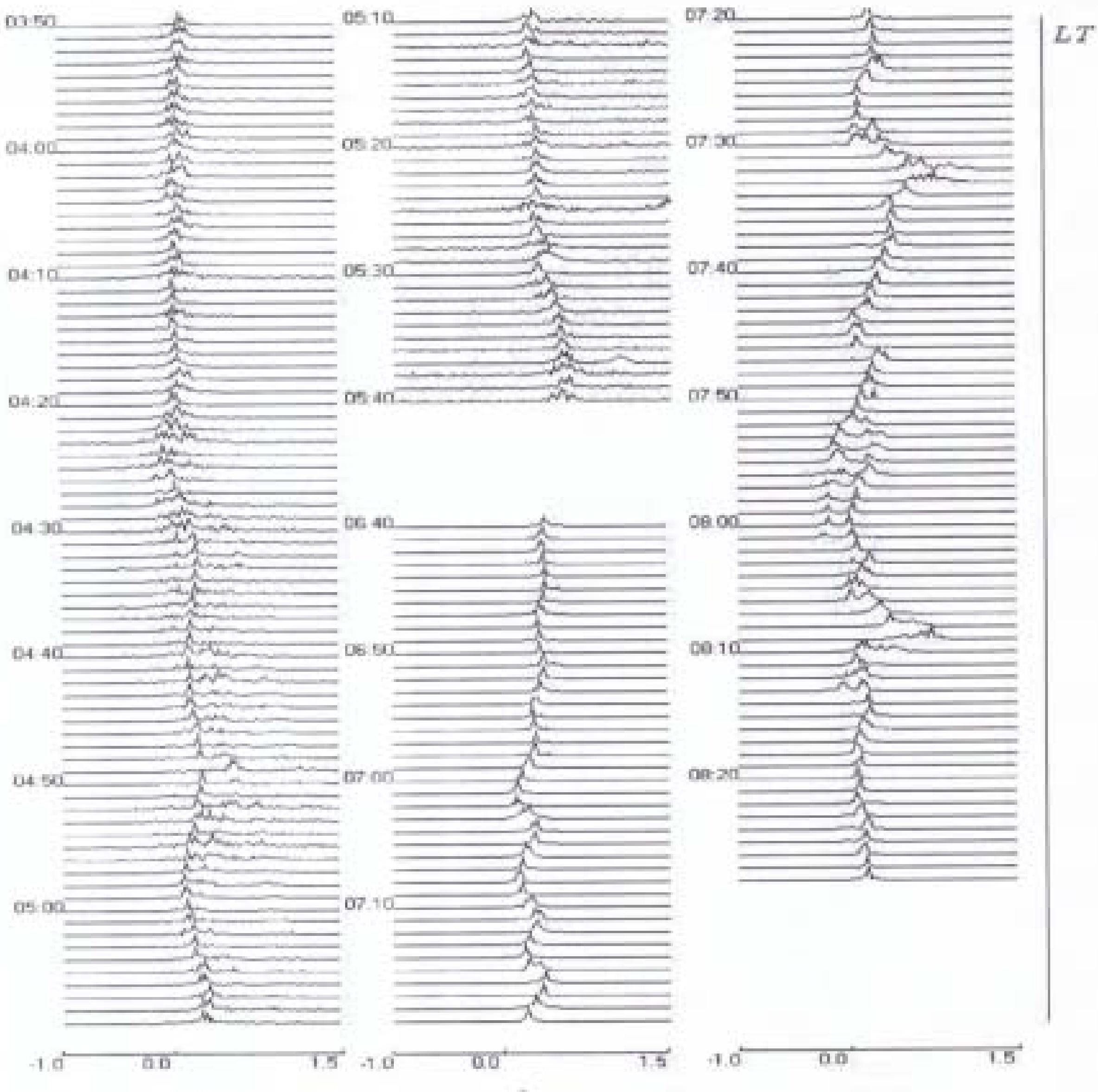

Fig. 4. Dynamic Doppler spectra obtained in experiment during the thunderstorm of 25.09.2001.

Note that the experimental values obtained for the infrasound frequencies, f_3, are well agreed with the theoretical calculations (Gokov (2000)).

Note also that the infrasonic acoustic waves similar to those obtained by us during the thunderstorms, had been early observed in the atmosphere and the ionosphere due to strong wind currents in the hilly country, volcano eruptions, heavy seas, and due to supersonic motion of the auroral arcs (Schlegel et al. (1980); Bertel et al. (1978)) as well. Characteristics (periods, propagation velocities) of such infra sonic acoustic waves turned out to be similar as to their order of the magnitude. Note also that as earlier as (Hines (1960)) there was suggested an interaction mechanism of the sounding electromagnetic waves and atmospheric ones in order to explain partial reflecting and back scattering of the waves from the ionospheric D-region irregularities.

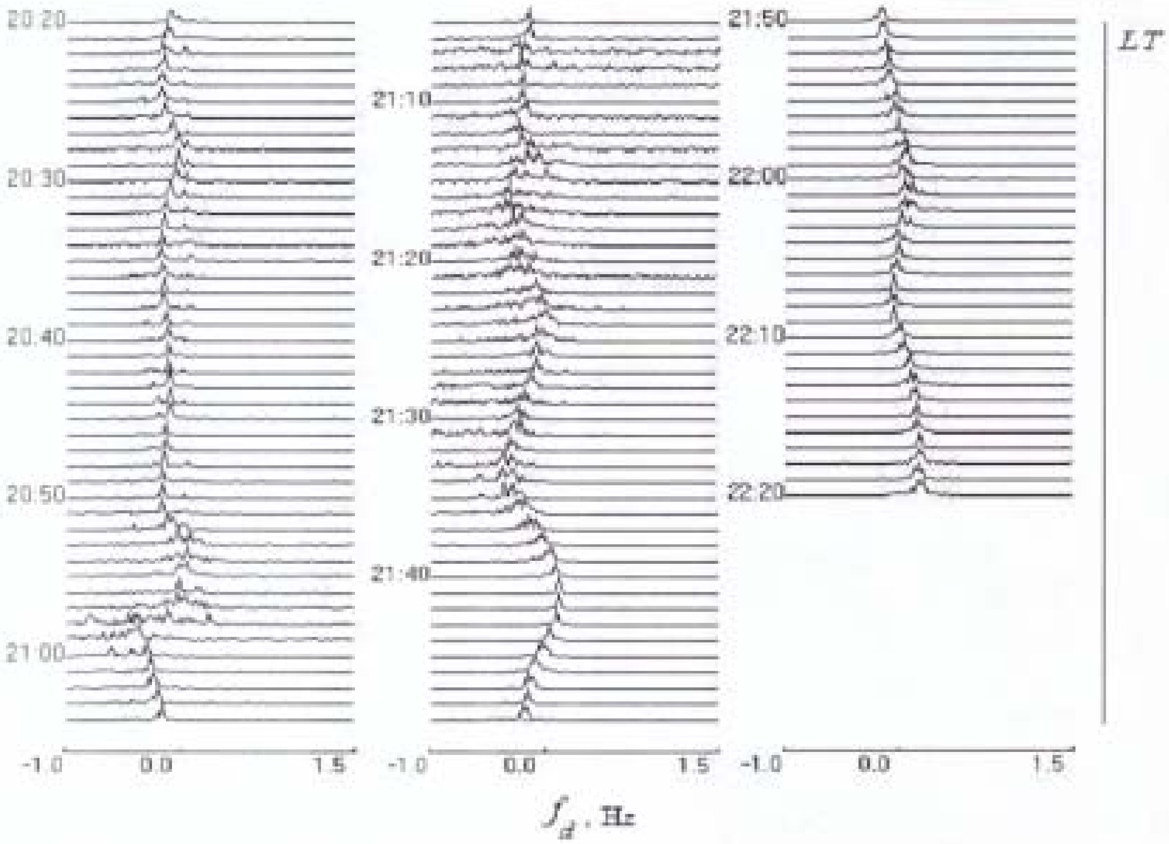

Fig. 5. Dynamic Doppler spectra obtained in experiment during the thunderstorm of 07.07.1998.

It should be noted that the methods considered are applicable to investigate the possible low frequency whistlers generated near the epicentre of other disturbances of different natures: earthquakes, explosions, rocket launches, etc..

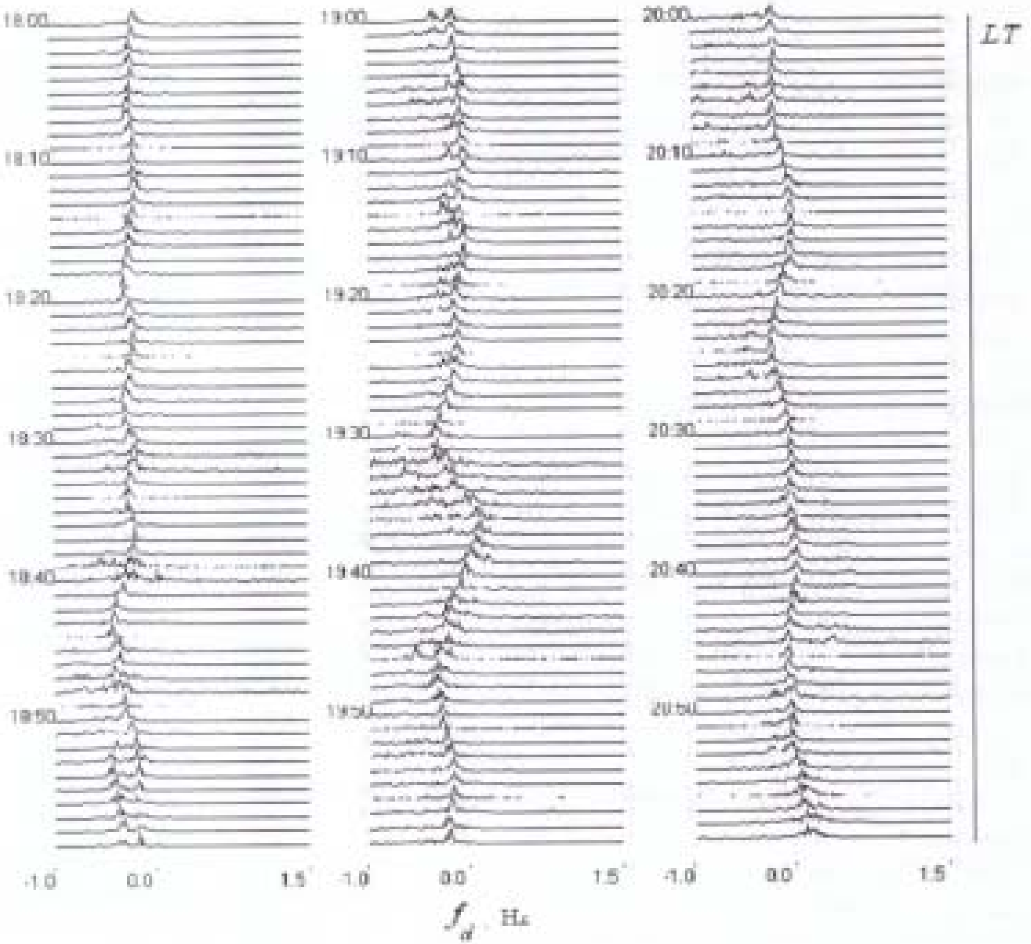

Fig. 6. Dynamic Doppler spectra obtained in experiment during the thunderstorm of 08.09.2001.

5. Conclusion

1. Methods for determining low frequency whistler frequencies generated by infrasound in the ionospheric E-region near the epicentre of a strong thunderstorm in the Earth atmosphere are suggested.

2. By means of the vertical Doppler sounding and partial reflection techniques, it is confirmed that during a strong thunderstorm near the epicentre there is possible generation of infrasonic waves with frequencies $f_1 \approx 0.4\text{-}0.8$ Hz, which spread up to the ionospheric E-region heights ($z \approx 100\text{-}170$ km.).

3. On the basis of the mechanism of infrasonic waves transformation in the ionospheric E-region into low frequency whistlers and on the basis of a dispersion relation, there were found whistler frequencies, $f_3 \approx 7\text{-}29$ kHz, which are well-agreed with the theoretical calculations.

Acknowledgment.

The authors are gratefull to Gritchin A.I., Chulakov S.G. and Shaptala S.N. for their help in the experimental investigations.

The work was fulfilled under supporting of the Science and Technology Centre in Ukraine (STCU), project agreements No1772, 1773.

References

1. Афраймович Э.Л., Варшавский И.И., Вугмейстер Б.О. и др. Влияние наземных промышленных взрывов на доплеровские и угловые характеристики отраженного от ионосферы радиосигнала (Effect of land industrial explosions on the Doppler and angular characteristics reflected from an ionosphere radio signal) // Геомагнетизм и аэрономия. – 1984. – Т. 24. – №2. - С. 322-324.
2. Альперович А.С., Вугмейстер Б.О., Гохберг М.Б. и др. Об опыте моделирования магнитосферно-ионосферных эффектов при сейсмических явлениях (On experimental modelling of magnetospheric - ionospheric effects under seismic phenomena) // Доклады АН СССР.-1983.-Т. 269.- №3.-С. 573-578.
3. Baker, D. M. and D. E. Cotten, Interpretation of high frequency doppler observations of waves from nuclear and natural sources, J. Geophys. Res., 76, 1803-1810, 1971.
4. Barry G.H., Griffiths L.J., Taenzer J.C. HF measurements of High-altitude acoustic waves from a ground-level explosion, J. Geophys. Res., 71, 4173-4182, 1966.
5. Bertel L., Bertin F., Vestud V. et. al., Evaluation of the vertical flux of energy into the thermosphere from medium scale gravity waves generated by the jet stream, J. Atmos. Terr. Phys., –Vol. 40, 691-696, 1978.
6. Davies, K. and D. M. Baker, Ionospheric effects observed around the time of the Alaskan earthquake of March, 28, 1964, J. Geophys. Res., –Vol. 70, 2251-2253, 1965.
7. Гельберг М.Г. Неоднородности высокоширотной ионосферы. (The irregularities of a highlatitude ionosphere) Новосибирск, Наука, 1986. 194 с.
8. Гершман Б.Н. Динамика ионосферной плазмы. (Dynamics of the ionospheric plasma) Москва, Наука, 1974. 256 с.
9. Гоков А.М.,Тырнов О.Ф.Экспериментальные исследования влияния сильных гроз на параметры среднеширотной D-области ионосферы. (Experimental investigations of strong thunderstorms effect on parameters of midlatitude ionospheric D-region) Геомагнетизм и аэрономия. 1998. Т.32.№ 2. С. 184-188.
10. Gokov A.M., Tyrnov O. F. Experimental investigations of strong thunderstorms having effects on the middle latitude ionospheric D-region parameters, Telecommunications and Radio Engineering, –Vol. 53, 6-12, 1999.
11. Gokov A.M., Low frequency whistlers generated by infrasonic waves in the ionospheric E-region during disturbances of different nature, J. Atmos. Electricity, –Vol. 20, 1-6, 2000.
12. Гохберг М.Б. Электромгнитные эффекты в ионосфере при сейсмо-акустических воздействиях (Electromagnetic effects in the ionosphere at seismic-acoustic effects) // Электромагнитная совместимость. – Вроцлав, 1986. – Т. 1. С. 15-24.
13. Григорьев Г.И., Докучаев В.П. Инфразвук и внутренние гравитационные волны при грозовых разрядах в атмосфере (Dokuchayev, Infrasonic and inner gravitational waves under thunderstorm charges in the atmosphere) // Известия АН СССР. Физика Атмосферы и океана.-1981. -Т.17.-№7.-С. 690-697.
14. Hines C.O., Internal atmospheric gravity waves at ionospheric heights, Can. J. Phys., –Vol. 38, 1441-1481, 1960.
15. Ландсберг Г.С. Оптика. (Optics) – М.: Наука. – 1976. 926 с.
16. Михайлова Г.А., Голявин А.М., Михайлов Ю.М. Динамические спектры ОНЧ-излучений во внешней ионосфере, связанные с Иранским землетрясением 21 июня 1990 г. ("Интеркосмос-24") (Dynamic spectra of VLF-electromagnetic background in the outer ionosphere observed around the time of the Iran earthquake of June 21, 1990 (satellite «Intercosmos-24»)) // Геомагнетизм и аэрономия. 1991. Т. 31. № 5. С. 801-809.

17. Михайлов Ю.М., Михайлова А.Г., Капустина О.В. КНЧ и ОНЧ - электромагнитный фон во внешней ионосфере над сейсмоактивными районами (ИСЗ «Интеркосмос-24») (ELF and VLF-electromagnetic background in the outer ionosphere over seismic active region (satellite «Intercosmos -24»)) // Геомагнетизм и аэрономия.-1997.-Т. 37.-№ 4.-С. 78-85.
18. Мазур В.А. О распространении низкочастотного вистлера в ионосфере (On propagation of a low frequency whistler in the ionosphere) // Известия вузов. Радиофизика.-1988.-Т. 31.-№12.-С. 1423-1430.
19. Rai, D.B. and G. L. Kisabeth, Ionospherric irregularities caused by acoustic waves, Nature, 216, 568-569, 1967.
20. Ralchovsky Tz. M., L.N. Komarov, Strong eartquakes on the Balkan peninsula and the Earth's electromagnetic activity, Bolgarsko geophys.spisanie, –Vol. XI, 60-65, 1989.
21. Садовский М.А., Соболев Г.А., Мигунов Н.И. Изменение естественного излучения радиоволн при сильном землетрясении в Карпатах (Change of natural radiation of radio waves at strong earquake in Carpathians) // ДАН СССР. 1979. Т.244. № 2. С.
22. Schlegel K., Thrane E.V., Brekke A., Partial reflection results in the auroral D-region explained in terms of acoustic waves, J. Atmos. Terr. Phys., –Vol. 42, 809-814, 1980.
23. Сурков В.А. Возбуждение низкочастотных электромагнитных возмущений ионосферы акустическими волнами (Low frequency electromagnetic ionospheric disturbances caused by acoustic wave) // М.: Препринт МИФИ №041-89.-1989.-24 с.
24. Tyrnov, O.F., Garmash, K.P., Gokov, A.M., Gritchin, A.I., Dorohov, V.L., Kontsevaya, L.G., Kostrov, L.S., Leus, S.G., Martynenko, S.I., Misura, V.A., Podnos, V.A., Pokhilko, S.N., Rozumenko, V.T., Somov, V.G., Tsymbal, A.I., Chernogor, L.F., and Shemet, A.S., The radiophysical observatory for remote sounding of the ionosphere, Turkish J. of Physics, –Vol. 18, 1260-1265, 1994.
25. Volker, W.J., H. Kirchhoff and L.A. Carpenter, Calculation on conductivities and currents in the ionosphere, Scientific Report №439. Classification Numbers 1.5.2, 1.5.3, 1.9.4. Ionospheric Research Laboratory, The Pennsilvania State University. Nov. 28, 46 pp., 1975.