Radiophysics and Quantum Electronics, Vol. 42, No. 1, 1999

ACOUSTIC–GRAVITY WAVES IN THE EARTH'S ATMOSPHERE (REVIEW)

G. I. Grigor'ev

UDC 551.511.3

We present the modern theory of small-amplitude acoustic-gravity waves (AGWs) in the Earth's atmosphere. Main attention is paid to the propagation and radiation of AGWs by different sources. We also consider problems of their dissipation, stability, and interaction with the ionospheric plasma. Basic methods of detecting the wave processes in the upper atmosphere in the AGW frequency range are briefly discussed. Experimental data on atmospheric inhomogeneities are compared with theoretical findings.

1. INTRODUCTION

This review deals mainly with problems of theoretical investigations of acoustic-gravity waves (AGWs) in the Earth's atmosphere. The first publications devoted to the influence of the stratification and the gravity force on wave motions in the atmosphere and the ocean appeared at the end of the previous century (see Lamb's book [1]). However, it is only in the second half of the XXth century that the interest in these problems increased drastically, and the number of publications started growing explosively. Martyn [2] and Hines [3] were the first to point out the important role of AGWs for many physical processes in the atmosphere.

At present, the basic AGW characteristics are thoroughly studied and presented in detail in a series of books [4–9] and reviews [10–24].

However, the interest in this problem is still very high. Traditional methods for observing the atmosphere state get improved, new measurement complexes including equipment and techniques are developed, the models of the medium, used for theoretical calculations of wave characteristics, become more complicated, better algorithms and programs for numerical calculations are worked out, unsolved questions are considered, and new problems related to the nonlinear effects in AGW radiation and propagation are formulated.

At present, the significant influence of AGWs on the electromagnetic wave propagation in the atmosphere in a broad frequency range, from HF–UHF bands down to VLF band (variations of the wave amplitude, phase, and the arrival angle of the signal, Doppler shift of the frequency, etc.) [16, 25, 26], is reliably settled. Another reason for the importance of AGW studies, related to their practical usage, is that the energy and momentum fluxes transferred by AGWs from the lower to the upper regions of the atmosphere are comparable to (and maybe sometimes greater than) those coming from the solar wind or the other sources [13, 27–30]. In this relation, it is necessary to take AGWs into account either in calculations of general atmospheric circulation or while determining the local dynamics (in particular, in weather forecasts).

This review contains five sections. In the first three of them, we present basic results of theoretical studies of AGWs in the atmosphere. In the other two sections, the diagnostic methods are briefly discussed and the AGW characteristics obtained experimentally are compared with the calculated ones.

The author admits that not all relevant papers can be represented in this review. There are two reasons for this. The first is that the material is too large (see bibliographies [31, 32]). The second is

Radiophysical Research Institute, Nizhny Novgorod, Russia. Translated from Izvestiya Vysshikh Uchebnykh Zavedenii, Radiofizika, Vol. 42, No. 1, pp. 3–25, January, 1999. Original article submitted January 15, 1998.

that some papers, especially those published during the last years, were inaccessible to the author since many journals and books had not been received by the libraries of the Institute of Applied Physics and the Radiophysical Research Institute.

2. BASIC EQUATIONS AND BOUNDARY CONDITIONS

The basic set of equations for the analysis of propagation conditions and generation mechanisms of AGWs is the magnetohydrodynamic one with sources of the mass (Q), momentum ($\vec{f}$), and energy (q') [24]:

$$\rho\frac{d\vec{u}}{dt} + \nabla p - \rho\vec{g} = \vec{f}, \tag{1}$$

$$\frac{d\rho}{dt} + \rho \operatorname{div}\vec{u} = Q, \tag{2}$$

$$\frac{dp}{dt} - c^2\frac{d\rho}{dt} = (\gamma - 1)q' = q, \tag{3}$$

where ρ is the density, p is the pressure, $\vec{u}$ is the velocity, $\frac{d}{dt} = \frac{\partial}{\partial t} + (\vec{u}\nabla)$, $c^2 = \gamma p/\rho$ is the square of the adiabatic sound velocity, γ is the adiabatic index, and $\vec{g}$ is the gravitational acceleration. When the deviations of the system parameters from their equilibrium values are small ($\rho = \rho_0 + \rho'$, $p = p_0 + p'$, $p' \ll p_0$, $\rho' \ll \rho_0$, etc.), and the regular wind $\vec{u} = \vec{u}_0$ is absent, Eqs. (1)–(3) may be linearized and written in the form

$$\rho_0\frac{\partial\vec{u}}{\partial t} + \nabla p' + \rho'\vec{g} = \vec{f}, \tag{4}$$

$$\frac{\partial\rho'}{\partial t} + (\vec{u}\nabla)\rho_0 + \rho_0 \operatorname{div}\vec{u} = Q, \tag{5}$$

$$\frac{\partial p'}{\partial t} + (\vec{u}\nabla)p_0 - c^2\left[\frac{\partial\rho'}{\partial t} + (\vec{u}\nabla)\rho_0\right] = q. \tag{6}$$

Based on Eqs. (4)–(6), the energy conservation law in the linear problems of hydrodynamics can be represented as [33]

$$\frac{\partial}{\partial t}\int\limits_V\left[\frac{\rho_0 u^2}{2} + \frac{p'^2}{2\rho_0 c^2} + \frac{(p' - c^2\rho')^2}{2(\gamma-1)\rho_0 c^2}\right]d^3\vec{r} + \oint\limits_S(p'\vec{u})dS = \int\limits_V\left[(\vec{f}\vec{u}) + \frac{pQ}{\rho_0} + \frac{(\gamma p' - c^2\rho')q}{\rho_0 c^2}\right]d^3\vec{r}. \tag{7}$$

The intergation volume V in Eq. (7) is bounded by the surface S.

The equilibrium pressure $p_0(z)$ and density $\rho_0(z)$ are determined first of all by the temperature distribution $T_0(z)$, and if $T_0(z) = \text{const}$, the simple formulas ($p_0(z)$, $\rho_0(z) \sim \exp(-z/H)$) are valid, where $H = æT_0/mg$ is the homogeneous atmosphere height (æ is the Boltzmann constant, m is the particle mass). If the temperature T_0 varies with height z, then $p_0(z)$ and $\rho_0(z)$ are given by the following relations:

$$p_0(z) = p_s\exp\left(-\int\limits_0^z\frac{dz}{H}\right), \qquad \rho_0(z) = \frac{\rho_s T_s}{T_0(z)}\exp\left(-\int\limits_0^z\frac{dz}{H}\right),$$

where p_s, ρ_s, and T_s are the pressure, density, and temperature at the level $z = 0$, respectively.

For the analysis, system (4)–(6) is usually reduced to a single equation for any of the unknown values. For example, if $\vec{f} = 0$, then we have for the vertical velocity component w in the cartesian coordinate system (x, y, z)

$$\frac{\partial^4 w}{\partial t^4}+\gamma g\frac{\partial^3 w}{\partial t^2 dz}-c^2\Delta\frac{\partial^2 W}{\partial t^2}-c^2\omega_g^2\Delta_\perp w=\frac{1}{\rho_0}\left(gQ-\frac{\partial^3 F}{\partial t^2\partial z}-g\Delta_\perp F\right), \tag{8}$$

where $F=q+c^2Q$, $\Delta=\dfrac{\partial^2}{\partial z^2}+\Delta_\perp$, $\Delta_\perp=\dfrac{\partial^2}{\partial x^2}+\dfrac{\partial^2}{\partial y^2}$, and $\omega_g=(\gamma-1)^{1/2}g/c$ is the Brunt-Väisälä frequency. It is significant that the left-hand side of Eq. (8) contains the term with the first-order derivative over the coordinate z. From this it follows that the solutions of Eq. (8) depend exponentially on the vertical coordinate z: $w\simeq\exp[z/(2H)]$. Similar equations for the pressure p and the density ρ [24] include $\dfrac{\partial^3 p}{\partial t^2\partial z}$ and $\dfrac{\partial^3\rho}{\partial t^2\partial z}$, respectively, with the opposite sign, hence p, $\rho\sim\exp[-z/(2H)]$.

If the solution of Eq.(8) is obtained, then other physical characteristics of the fields can be derived from the polarization relations which for $w\sim\exp(-i\omega t+ik_x x+ik_y y)$ are written in the form [15, 34]

$$\begin{gathered}
u=\frac{k_x(c^2\,dw/dz-gw)}{i(\omega^2-c^2k^2)},\\
v=\frac{k_y(c^2\,dw/dz-gw)}{i(\omega^2-c^2k^2)},\quad k^2=k_x^2+k_y^2,\\
p=\frac{\omega\rho_0(c^2\,dw/dz-gw)}{i(\omega^2-c^2k^2)},\\
\rho=\frac{\omega\rho_0\,dw/dz}{i(\omega^2-c^2k^2)}+\frac{w\,d\rho_0}{i\omega\,dz}-\frac{gk^2\rho_0 w}{i\omega(\omega^2-c^2k^2)}.
\end{gathered}\tag{9}$$

To analyze conditions of AGW excitation and propagation in the presence of bounding surfaces or boundaries between different media, it is necessary to supply basic equations (4)–(6) with the boundary conditions. * Dynamical and kinematical conditions on impermeable boundaries are reduced to the continuity of the total pressure $p-\rho_0 g\zeta$ and the vertical displacement ζ [37]:

$$p_1-\rho_{01}g\zeta_1=p_2-\rho_{02}g\zeta_2,\quad \zeta_1=\zeta_2, \tag{10}$$

combined with the equality of the frequencies, $\omega_1=\omega_2$, and the horizontal components of the wavevectors, $k_{x1}=k_{x2}$. If any of the boundaries is fixed and hard (for example, this can be the Earth's surface), then the normal components of the displacement ζ_n and the velocity u_n have to be zero at this boundary.

Dispersion relations [3, 12]. The equation for the potential $\psi=p\exp[z/(2H)]$, which follows from Eqs. (1)–(3) under the assumption $T_0(z)=\text{const}$, is given in [24]:

$$\begin{gathered}
\frac{1}{c^2}\cdot\frac{\partial^4\psi}{\partial t^4}-\left(\Delta-\frac{1}{4H^2}\right)\frac{\partial^2\psi}{\partial t^2}-\omega_g^2\Delta_\perp\psi=F_1,\\
F_1=\exp\left(-\frac{z}{2H}\right)\left[\left(\frac{\partial^2}{\partial t^2}+\omega_g^2\right)\left(\frac{\partial Q}{\partial t}-\operatorname{div}\vec{f}\right)+\omega_g^2\left(\frac{\partial}{\partial z}-\frac{1}{g}\frac{\partial^2}{\partial t^2}\right)f_z+\left(\frac{\partial^2}{\partial t^2}-g\frac{\partial}{\partial z}\right)\frac{\partial q}{\partial t}\right].
\end{gathered}\tag{11}$$

In an isothermal unbounded medium, we can use the Fourier transform to obtain from Eq. (11) the following integral representation:

$$\begin{gathered}
\psi=\int\frac{F_1(\vec{k},\omega)}{D(\vec{k},\omega)}\exp(i\vec{k}\vec{R}-i\omega t)\,d\vec{k}\,d\omega,\\
F_1(\vec{k},\omega)=(2\pi)^{-4}\int F_1(\vec{R},t)\exp(i\omega t-i\vec{k}\vec{R})\,dt\,d\vec{R}.
\end{gathered}\tag{12}$$

*Boundary conditions are also used for the numerical analysis of AGW propagation when the real medium is represented by a number of layers with constant or linearly varying temperature [35, 36].

From Eqs. (11), (12) it follows that sources of mass, momentum, and energy give comparable contributions to the radiation fields. Thus it is possible to consider for simplicity only one of those sources when analyzing the radiation fields.

The integrand in Eq. (12) contains the AGW dispersion relation

$$D(\vec{k},\omega) = \frac{\omega^4}{c^2} - \omega^2(k^2 + k_1^2) + \omega_g^2(k_x^2 + k_y^2), \tag{13}$$

where $k_1^2 = 1/(4H^2)$. Equation (13), resolved with respect to the frequency ω, gives two values of ω^2, one of them characterizing the fast acoustic waves at $\omega \geq \omega_{\rm A} = ck_1$, and the other describing the internal gravity waves (IGWs) at $\omega \leq \omega_g$. If $kH \gg 1$, then the roots of Eq. (13) are

$$\begin{aligned} \omega_1^2 &\simeq c^2(k_x^2 + k_y^2 + k_z^2 + k_1^2), \\ \omega_2^2 &\simeq \omega_g^2(k_x^2 + k_y^2)(k_x^2 + k_y^2 + k_z^2 + k_1^2)^{-1}. \end{aligned} \tag{14}$$

A thorough analysis of the AGW dispersion characteristics was made in papers [3, 8, 10, 12, 38, 39].

At large distances from localized sources, $k_s R \gg 1$ (the definition of k_s is given below, see Eq. (17)), the properties of the radiation fields are to a large extent determined by the dispersive properties of the medium, and some of them can be obtained from an analysis of the kinematic relations based on Eq. (13).

Using the definition of the group velocity $\vec{v}_{\rm g} = d\omega/d\vec{k}$ and introducing the angles ϑ and φ by the relations

$$\begin{aligned} v_{{\rm g}x} &= v_{\rm g} \sin\vartheta \cos\varphi, \\ v_{{\rm g}y} &= v_{\rm g} \sin\vartheta \sin\varphi, \\ v_{{\rm g}z} &= v_{\rm g} \cos\vartheta, \end{aligned} \tag{15}$$

we find from the dispersion equation (13)

$$\begin{aligned} v_{{\rm g}x} &= 2c^2 k_x(\omega^2 - \omega_g^2)\left(\frac{\partial D}{\partial \omega}\right)^{-1}, \\ v_{{\rm g}y} &= 2c^2 k_y(\omega - \omega_g^2)\left(\frac{\partial D}{\partial \omega}\right)^{-1}, \\ v_{{\rm g}z} &= 2c^2 k_z \omega^2\left(\frac{\partial D}{\partial \omega}\right)^{-1}. \end{aligned} \tag{16}$$

Using Eqs. (15)–(16), one can represent the components of the wave vector $\vec{k}$ in terms of the frequency ω and the angles ϑ, φ:

$$\begin{aligned} ck_{sx} &= \omega^2\left[\frac{\omega^2 - \omega_{\rm A}^2}{(\omega^2 - \omega_g^2)(\omega^2 - \omega_c^2)}\right]^{1/2} \sin\vartheta\cos\varphi, \\ ck_{sy} &= \omega^2\left[\frac{\omega^2 - \omega_{\rm A}^2}{(\omega^2 - \omega_g^2)(\omega^2 - \omega_c^2)}\right]^{1/2} \sin\vartheta\sin\varphi, \\ ck_{sz} &= \mathrm{sign}(\omega - \omega_g)\left[\frac{(\omega^2 - \omega_{\rm A}^2)(\omega^2 - \omega_g^2)}{\omega^2 - \omega_c^2}\right]^{1/2} \cos\vartheta. \end{aligned} \tag{17}$$

The wavelength $\lambda = 2\pi/k$, the phase velocity $v_{\rm ph} = \omega/k$, and the group velocity, according to Eqs. (14)–(15), are given by the relations

$$\frac{\lambda}{2\pi} = \frac{v_{\text{ph}}}{\omega} = c\left\{\frac{(\omega^2-\omega_g^2)(\omega^2-\omega_c^2)}{(\omega^2-\omega_{\text{A}}^2)[\omega^4\sin^2\vartheta+(\omega^2-\omega_g^2)^2\cos^2\vartheta]}\right\}^{1/2}, \tag{18}$$

$$v_g = \frac{c}{\omega}\frac{[(\omega^2-\omega_{\text{A}}^2)(\omega^2-\omega_g^2)^3(\omega^2-\omega_c^2)]^{1/2}}{(\omega^2-\omega_g^2)^2+\omega_g^2(\omega_{\text{A}}^2-\omega_g^2)\sin^2\vartheta}, \tag{19}$$

where $\omega_c = \omega_g\cos\vartheta$, $\omega_{\text{A}} = ck_1 = c/(2H)$, and $\omega_g = (\gamma-1)^{1/2}g/c$. In Figs. 1–4, we show the frequency dependences of $\lambda_z(\omega) = 2\pi/k_z$, $\lambda_\perp = 2\pi/k_\perp = 2\pi(k_x^2+k_y^2)^{-1/2}$, $\lambda(\omega) = 2\pi/k$, $v_g(\omega)$, $v_{\text{ph}}(\omega)$, and the refraction index $n = ck/\omega$ for different angles ϑ. As the unit length λ_0 we chose $\lambda_0 = 2\pi c/\omega_g$.

The anisotropy of the AGW propagation is more pronounced at low frequencies. While at $\omega > \omega_{\text{A}}$, wave propagation from an isotropic emitter is possible in all directions, the radiation at $\omega < \omega_g$ is bounded within the angular range $\vartheta_0 \leq \vartheta \leq \pi - \vartheta_0$. The limiting angle ϑ_0 decreases with frequency increase. This follows also from the analysis of the surfaces of wave normals which are determined by the function $k_z = k_z(k_\perp)$, following for $\omega = \text{const}$ from the equation

$$\frac{k_z^2}{a^2}+\frac{k_\perp^2}{b^2} = 1, \tag{20}$$

where $a^2 = \dfrac{\omega^2-\omega_{\text{A}}^2}{c^2}$, $b^2 = \dfrac{\omega^2}{c^2}\dfrac{\omega^2-\omega_{\text{A}}^2}{\omega^2-\omega_g^2}$. Equation (20) determines a family of ellipsoids at $\omega_g < \omega_{\text{A}} < \omega$ and a family of hyperboloids at $\omega < \omega_g$. At large k_z, $k_\perp$, the hyperboloid generation lines asymptotically approach the straight lines $k_z = k_\perp(\omega_g^2/\omega^2-1)^{1/2}$.

A particular case of wavelike motions obeying the dispersion equation (13) is the Lamb surface waves [1, 3, 40]. They propagate in the horizontal direction with the sound velocity c and without dispersion: $\omega = ck_\perp = c(k_x^2+k_y^2)^{1/2}$.

Analysis of the AGW dispersion properties was based on macroscopic equations of the hydrodynamics which can be violated at large heights in the Earth's atmosphere because of a significant increase in the particle free path l_{f}. In [41], the kinetic equation method was adapted for the inhomogeneous medium and applied for deriving the AGW dispersion relation and calculating their damping due to viscosity and heat conduction.

Returning to the integral formulas (12), we note that at large distances from the sources: $k_sR \gg 1$, integration of Eq. (12) over k_x, k_y k_z provides the spectral distribution $\psi(\omega)$

$$\psi = \frac{2\pi^2F(\vec{k}_s\omega)}{R[(\omega^2-\omega_g^2)(\omega-\omega_c^2)]^{1/2}}\exp\left\{i\frac{R}{c}\text{sign}\omega\left[\frac{(\omega_{\text{A}}-\omega)^2(\omega^2-\omega_c^2)}{\omega_g^2-\omega^2}\right]^{1/2}\right\}, \tag{21}$$

where the wave vector $\vec{k} = \vec{k}_s$, determined when integrating Eq. (12) over $\vec{k}$ by the stationary phase method, is specified by relations (17), obtained above by the kinematical approach. Particular examples of calculating the radiation fields of given sources are presented below.

3. PROBLEMS OF STABILITY AND DISSIPATION OF ACOUSTIC-GRAVITY WAVES

The important aspects of AGW propagation in the Earth's atmosphere are those of their dissipation and stability. Calculations of AGW damping rates due to viscosity and heat conduction were made by G. S. Golitsyn [42], under the assumption of height independence of the kinematic viscosity $\nu = \eta/\rho$, and in [43, 44], assuming the height independence of the dynamic viscosity $\eta = \nu\rho_0$. The damping of AGWs due to collisional interactions of neutral particles with a plasma in the magnetic field was considered in [45, 46]. The influence of the plasma component on the AGW propagation in a conducting medium can be taken into account by inclusion of the ponderomotive force $\frac{1}{c}[\vec{j}\vec{H}_0]$ into Eq. (1) for the motion of the medium; here, $\vec{j}$ is

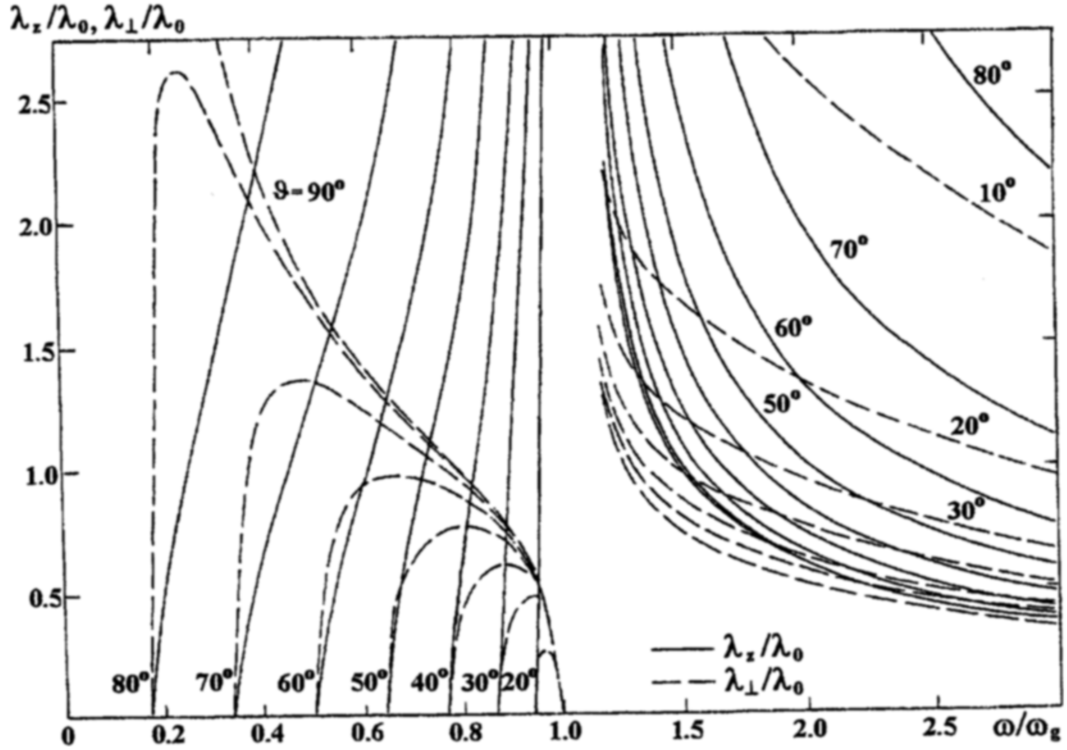

λz/λ0, λ⊥/λ0
2.5
2.0
1.5
1.0
0.5
ϑ=90°
80°
70°
60°
50°
40°
30°
20°
10°
λz/λ0
λ⊥/λ0
0
0.2
0.4
0.6
0.8
1.0
1.5
2.0
2.5
ω/ωg

Fig. 1.

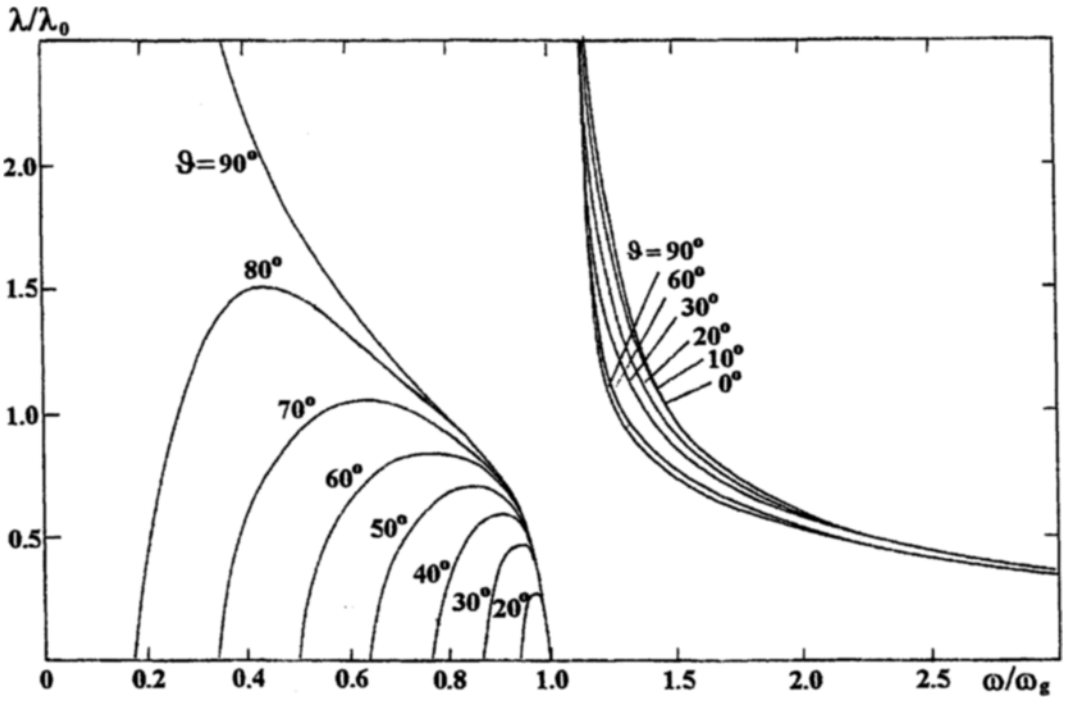
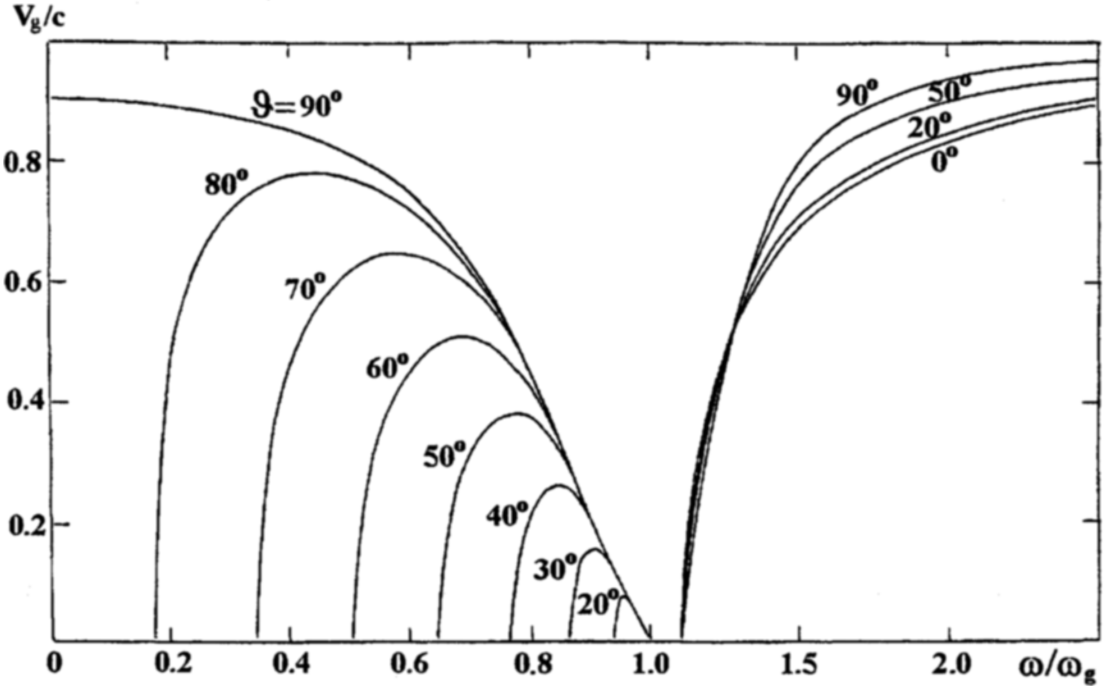
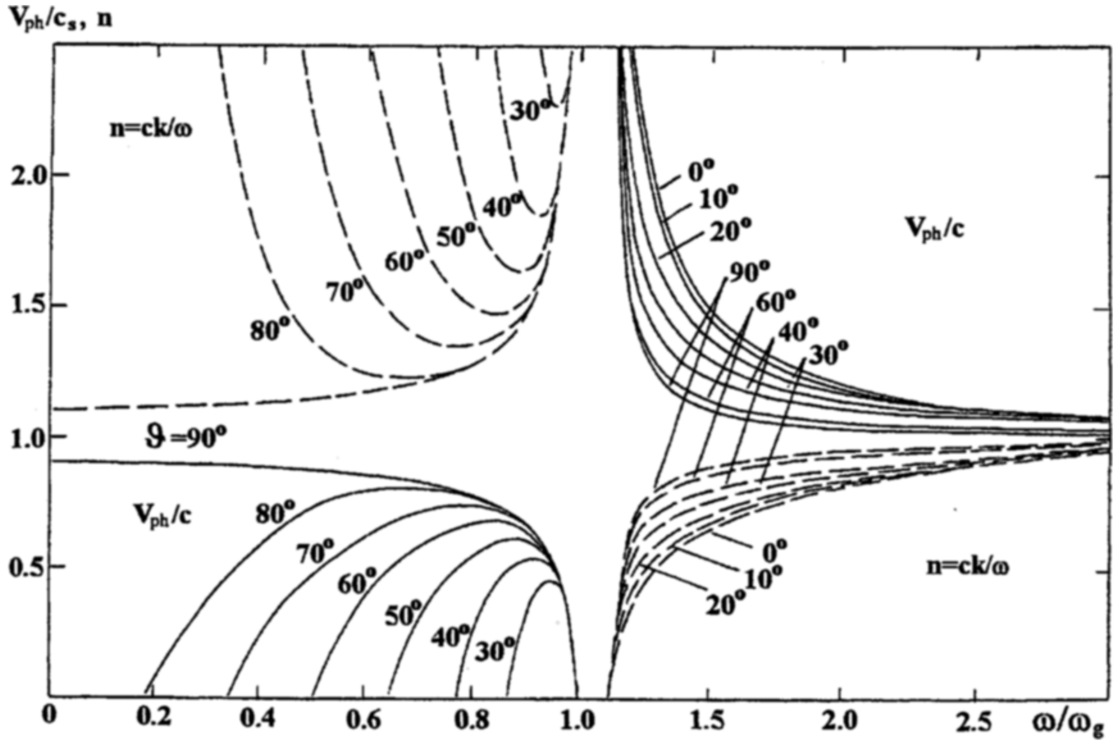

λ/λ0
2.0
1.5
1.0
0.5
ϑ=90°
80°
70°
60°
50°
40°
30°
20°
10°
0°
0
0.2
0.4
0.6
0.8
1.0
1.5
2.0
2.5
ω/ωg

Fig. 2.



V_g/c
$\vartheta=90^\circ$
80°
70°
60°
50°
40°
30°
20°
90°
50°
20°
0°
0.8
0.6
0.4
0.2
0
0.2
0.4
0.6
0.8
1.0
1.5
2.0
ω/ω_g

Fig. 3.



V_{ph}/c_s, n
n=ck/ω
30°
40°
50°
60°
70°
80°
0°
10°
20°
90°
60°
40°
30°
V_{ph}/c
$\vartheta=90^\circ$
V_{ph}/c
80°
70°
60°
50°
40°
30°
0°
10°
20°
n=ck/ω
2.0
1.5
1.0
0.5
0
0.2
0.4
0.6
0.8
1.0
1.5
2.0
2.5
ω/ω_g

Fig. 4.

the current density, and $\vec{H}_0$ is the Earth's magnetic field strength. If $\vec{j}$ is the current produced by the AGW propagation, then including such term into Eq. (1) leads to wave dissipation. However, if $\vec{j}$ is generated by external sources, then the force $\frac{1}{c}[\vec{j}_{\text{ext}}\vec{H}_0]$ † serves as the AGW source. If there is also a constant current $\vec{j}_0$ in the medium, then AGW dissipation can, under certain conditions, be changed by their growth [47]. The energy damping rate æ is defined by the relation

$$\text{æ} = \frac{Q_1}{|\vec{v}_{\text{g}}|E}, \tag{22}$$

where Q_1 is the energy dissipating per unit time in a unit volume, and E is the wave energy density [48]. The analysis showed that the magnetohydrodynamic AGW damping is anisotropic.

It was shown in [45–49] that at ionospheric heights a significant Joule dissipation of AGWs takes place due to the presence of the plasma and the geomagnetic field. However, this finding has to be corrected if regular currents $\vec{j}_0$ of sufficiently large intensity are present. We note that the strongest current systems are located in the E-layer, the maximum currents occurring in the auroral and equatorial electrojets.

The basic set of equations for analysis of Joule dissipation of AGWs is set (1)–(3) supplied with collision terms $m_e\nu_eN_{e0}(\vec{u}_e - \vec{u})$ and $M_i\nu_iN_{i0}(\vec{u}_i - \vec{u})$ and equations for electrons ($j = e$) and ions ($j = i$):

$$\frac{\partial\vec{u}_j}{\partial t} + (\vec{u}_{j0}\nabla)\vec{u}_j = -\frac{\nabla p_j}{m_jN_{j0}} + \frac{e_j\vec{E}}{m_j} - \nu_j(\vec{u}_j - \vec{u}) + \omega_{Hj}[\vec{u}_j\vec{\tau}], \tag{23}$$

$$\frac{\partial N_j}{\partial t} + (\vec{u}_{j0}\nabla)N_j + N_{j0}\text{div}\vec{u}_j = 0, \tag{24}$$

where $\vec{E}$ is the internal electric field strength, ω_{Hj} is the gyrofrequency of electrons and ions, $\vec{\tau}$ is the unit vector parallel to the geomagnetic field $\vec{H}_0$, N_j is the particle number density, and m_j is their mass. Assuming the influence of the plasma component to be weak (due to the small ionization degree in the ionosphere), one can use the perturbation technique to obtain a correction to the AGW frequency, $\omega = \omega_1 + i\Gamma$, related with collisions and the regular motion of charged particles. The equation for the damping rate Γ and its detailed analysis for various limiting cases is given in [47]. It is also shown there that, in the presence of current $\vec{j}_0$, wave dissipation under some circumstances is replaced by their growth (current instability of AGWs).

Close to the one just considered is the beam, or flow, instability of AGWs caused by collisional interactions of the moving component of the gas with the background medium. To describe an example of such a system with sound waves [50], we chose the five-momentum approximation, used for solving the kinetic equation without account of the viscosity and the heat conduction. The instability of the waves in a medium with a beam has two possible causes, namely, the motion of the beam particles and the high temperature of the beam.

The instability of the tangential discontinuity in the isothermal atmosphere is studied in [37]. As a basic one, we chose an equation for the pressure in two horizontally moving media which are denoted by the indices $i = 1, 2$

$$\frac{1}{c_i^2}\frac{d^4p_i}{dt^4} - \frac{d^2}{dt^2}\Delta p_i - \frac{1}{H_i}\frac{d^2}{dt^2}\frac{\partial p_i}{\partial z} - \omega_{g_i}^2\Delta_\perp p_i = 0. \tag{25}$$

The vertical displacement ζ_i is related with p_i by the formula

$$\rho_{0_i}\left(\frac{d^2}{dt^2} + \omega_{g_i}^2\right)\zeta_i = -\left(\frac{\partial}{\partial z} + \frac{g}{c_i^2}\right)p_i\,. \tag{26}$$

†See below concerning the Getmantsev effect.

Boundary conditions (10) are satisfied at the discontinuity in the plane (x, y) (at $z = 0$). Assuming the dependences of all the displacements on the time and the horizontal coordinates to have the forms of the plane wave, $\exp(i\omega t - ik_x x - ik_y y)$, we obtain the dispersion equation with the roots ($H_1 = H_2$, $c_1 = c_2 = c$, $\rho_{0_1} = \rho_{0_2}$, $v_0 = 0$)

$$\frac{\omega_{1-4}}{kc} = \frac{1}{2}M\cos\vartheta \pm \left[1 + \frac{1}{4}M^2\cos^2\vartheta + i\alpha k_1 \pm \left(1 + M^2\cos^2\vartheta - \frac{k_1^2}{k^2} + 2i\alpha k_1\right)^{1/2}\right]^{1/2},$$

$$\frac{\omega_{5-8}}{kc} = \frac{1}{2}M\cos\vartheta \pm \left[1 + \frac{1}{4}M^2\cos^2\vartheta - i\alpha k_1 \pm \left(1 + M^2\cos^2\vartheta - \frac{k_1^2}{k^2} - 2i\alpha k_1\right)^{1/2}\right]^{1/2}, \tag{27}$$

where $M = v_0/c$ is the Mach number, $\alpha^2 = 1 - \omega_g^2/\omega_A^2$, and ϑ is the angle between $\vec{k}$ and $\vec{v}_0$. If $kH \to \infty$ ($\omega_g^2 \to 0$, $g \to 0$), one obtains the formulas for the tangential discontinuity in a compressible medium without the gravity force, derived earlier by S. I. Syrovatsky [51]. The limit $c \to \infty$ (incompressible medium) gives, in the short-wave approximation ($kH \gg 1$),

$$2\omega = kv_0\cos\vartheta \pm (2\omega_g^2 - k^2v_0^2\cos^2\vartheta)^{1/2}. \tag{28}$$

From Eq. (28) it follows that a tangential discontinuity is stable in the range of wavelengths $1 \ll kH < (\sqrt{2gH}/v_0)\cos\vartheta$. If the stratification is neglected, ($\omega_g^2 \to 0$), the stability region vanishes, and $2\omega = kv_0(1 \pm i)\cos\vartheta$.

Wind profiles, measured in the Earth's atmosphere by rockets, sometimes show the reversal of direction from the East-West to the opposite one in the height range of several kilometers [52]. Therefore, for atmospheric waves with vertical scales exceeding 10 km, the flow boundaries can be regarded as tangential discontinuities. Disturbances arising due to the instability of the boundaries leave the generation region in the form of AGWs. The linear theory does not provide an estimate of the amplitudes of these waves and the radiation power. However, this approximation does provide the wave excitation conditions and characteristic time scales of the instability.

The interaction of AGWs with a tangential discontinuity was considered in [53, 54] where reflection and transmission coefficients of the waves (R and T, respectively) were obtained, and the possibility of the superreflection ($R \to \infty$) from the tangential discontinuity was shown.

4. GENERATION MECHANISMS OF ACOUSTIC-GRAVITY WAVES

Theoretical and experimental studies showed that AGW sources in the atmosphere are earthquakes and volcanic eruptions, tornadoes, thunderstorms, solar eclipses, terminator, jet flows, polar and equatorial electrojets, meteors, strong explosions, and powerful rockets launched [8, 55–61]. The efficiency of different AGW generation mechanisms is estimated from the solution of the corresponding gas-dynamic equations including sources of mass Q, energy q, and momentum $\vec{f}$ (see Eqs. (1)–(3)). When analyzing atmospheric disturbances caused by Rayleigh surface waves or waves at the ocean surface due to earthquakes and underground explosions [62–66], the sources can be provided also by external motions of the boundary. AGWs in the atmosphere may be also excited by the air flows along the irregularities of the Earth's surface [67].

As a rule, the problem of AGW excitation by some source is reduced to an analysis of the integral formulas similar to Eq. (12). For example, for an elementary monochromatic mass source in the unbounded medium

$$Q_1(\vec{r}, t) = Q_0\exp(-i\omega_0 t)\delta(z)\delta(r)/2\pi r \tag{29}$$

we have [68]

$$p=\frac{\omega_0 Q_0}{8\pi}\exp\left(-i\omega_0 t-\frac{z}{2H}\right)\int\limits_{-\infty}^{\infty}\exp(-iæz)H_0^{(1)}\left\{r\left[\frac{\omega_0^2}{\omega_g^2-\omega_0^2}\left(æ^2+\frac{\omega_A^2-\omega_0^2}{c^2}\right)\right]^{1/2}\right\}dæ. \quad (30)$$

For integration over the radial wavenumber k, the radiation condition was used to choose the sign of the argument of the Hankel function $H_0^{(1)}$. From Eq. (30) it follows that the disturbances are wavelike if this argument is real, i.e., at $\omega_0<\omega_g$ and $\omega_0>\omega_A$. After integrating Eq. (30) over æ, we have

$$p=\frac{\omega_0 Q_0}{4\pi}\left(\frac{\omega_0^2 r^2}{\omega_g^2-\omega_0^2}-z^2\right)^{-1}\exp\left\{-\frac{z}{2H}-i\omega_0 t+\frac{i}{c}\left[(\omega_A^2-\omega_0^2)\left(\frac{\omega_0^2 r^2}{\omega_g^2-\omega_0^2}-z^2\right)\right]^{1/2}\right\}. \quad (31)$$

As seen from Eq. (31), the phase fronts do not coincide with the surfaces of equal amplitudes. For the fast waves ($\omega>\omega_A$), the phase fronts are ellipsoids, while for the slow waves ($\omega<\omega_g$), they are hyperboloids of rotation. The radiation intensity I is defined as the energy flux through the side surface of a cylinder with the radius r and the axis directed along z:

$$I=2\pi r\cdot\frac{1}{4}\int\limits_{-\infty}^{\infty}(pu_r^*+p^*u_r)\,dz, \quad (32)$$

where $u_r=\dfrac{1}{i\omega_0\rho_0}\dfrac{\partial p}{\partial r}$ and the the asterisk $*$ denotes complex conjugation. Calculations of I provide the following result:

$$I=\begin{cases}\dfrac{\omega_0 Q_0^2}{8\pi\rho_{0_0}}\displaystyle\int\limits_0^{\infty}dæ, & \omega_0<\omega_g\,,\\[2ex] \dfrac{\omega_0 Q_0^2}{8\pi\rho_{0_0}c}\left(1-\dfrac{\omega_A^2}{\omega_0^2}\right)^{1/2}, & \omega_0>\omega_A\,.\end{cases} \quad (33)$$

The IGW radiation intensity I of an elementary source at frequencies $\omega_0<\omega_g$ diverges at large æ corresponding to small wavelenghts. This divergence is removed by taking into account either the final size of the emitter or the dissipation (due to, e.g., viscosity and heat conduction). It is easily seen that at low frequencies $\omega_0<\omega_g$ the amplitude of the disturbance grows resonantly along the directions $z=r\omega_0(\omega_g^2-\omega_0^2)^{-1/2}$. The influence of the final emitter size on the properties of the generated disturbances was estimated in [68–70].

For analysis of AGW generation by modulated auroral currents, the source was chosen as the radial force * [71]

$$f_{\text{ext}}=B\frac{\delta(z)\delta(r-r_0)}{2\pi\tilde{c}r}\exp(-i\omega_0 t), \quad (34)$$

where $\delta(z)$ is the Dirac function. In that case, we obtain the formula for the pressure p

$$p=\frac{\alpha^2\beta J_1[\alpha^2\beta r_0(\alpha^2-\cot^2\vartheta)^{1/2}]}{4\pi\tilde{c}R(\alpha^2-\cot^2\vartheta)\sin\vartheta}\exp\left(-\frac{R}{2H}\cos\vartheta\right)\exp\left\{i\beta R(\alpha^2\sin^2\vartheta-\cos^2\vartheta)^{1/2}-i\omega_0 t-\frac{i\pi}{2}\right\}, \quad (35)$$

where $\alpha^2=\omega_0^2(\omega_g^2-\omega_0^2)^{-1}$, $\beta^2=k_1^2-\omega_0^2/c^2$, $\tilde{c}$ is the light velocity, J_1 is the Bessel function, $B=I_0(\omega_0)H_0$, $I_0/(2\pi r_0)$ is the curent flowing through the cross-section of the ring, and H_0 is the magnetic field strength.

Disturbances from a pulsed source of mass

$$Q=Q_0\,\delta(t)\,\delta(z)\,\delta(r)/(2\pi r), \quad (36)$$

*An alternative way is choosing the energy source [72–74].

can be derived from the solution to the problem of AGW excitation by the corresponding monochromatic source by integration of the formulas obtained over the frequency. In the low-frequency limit ($\omega \ll \omega_g$) and for the incompressible medium, we obtained for the pressure p [75]:

$$p = -\frac{\omega_g Q_0 \omega_c t \exp[-z/(2H)]}{4\pi R (t^2 - t_0^2)^{1/2}} J_1(\omega_c \sqrt{t^2 - t_0^2})\, h(t - t_0), \tag{37}$$

where $\omega_c = \omega_g z/R = \omega_g \cos\vartheta$, $R^2 = z^2 + r^2$, $t_0 = R/(2\sqrt{gH})$, and $h(t - t_0)$ is a step function equal to 1 at $t > t_0$ and to 0 at $t \leq t_0$. As follows from the solution shown, oscillations of p with a characteristic frequency $\omega = \omega_c$ and the amplitude decreasing in time are set up at an observation point after the passage of the pulse front.

In [70, 76], disturbances in the Earth's atmosphere generated by lightning discharges and burning meteors were analyzed. Due to the short duration as compared to the AGW periods, these wave sources are of pulsed type. Meteors with large initial masses and velocities efficiently generate AGWs due to the large release of energy E_0 during their burning out. The burning meteor almost instantly creates a trace of length L and radius a. The region of this trace serves as an energy source with the density of the energy release $q = E_0 D(t, r, z)$,

$$D(t, r, z) = \frac{\delta(t)}{\pi^{3/2} a^2 L} \exp\left(-\frac{r^2}{a^2} - \frac{z^2}{L^2}\right). \tag{38}$$

The point r=0, z=0 in Eq. (38) was placed at the point of maximum evaporation of the meteor. In calculations of disturbances from thunderstorm regions, the pulsed energy source was chosen as [70]

$$q = \frac{W_0}{\pi a^2 L} f(t)\, h(z, L) \exp(-r^2/a^2). \tag{39}$$

The small-scale function $f(t)$ describes the temporal variation of the energy release, $W_0 = E_0/\tau$ is the power, $h(z, L) = 1$ at $z \leq L$, and $h = 0$ at $z > L$. For both sources defined by Eqs. (38), (39), asymptotic formulas for the disturbance fields at large distances were obtained, numerical estimates of the disturbance amplitudes were given, and the spectral distribution of the wave energy was found.

The Čerenkov mechanism of AGW generation was considered by many authors (see, for example, [33, 68, 77–80] and references therein). In [81], we obtained the spectral representation of the radiation fields created by a mass source moving uniformly at an angle α to the vertical direction, and also a formula for the frequency spectrum of the AGW power radiated by such a source. In problems of wave radiation by moving sources in the unbounded medium, the Čerenkov resonance condition may be written as

$$\cos\vartheta_0 = v_{\mathrm{ph}}/v_0\,, \tag{40}$$

where ϑ_0 is the angle between the wave vector $\vec{k}$ and the source velocity $\vec{v}_0$. For a source moving at an angle α to the vertical direction, $\cos\vartheta_0 = \cos\vartheta_k \cos\alpha + \sin\vartheta_k \sin\varphi_k \sin\alpha$, where the angles ϑ_k and φ_k determine the projections of $\vec{k}$ onto the cartesian coordinate axes $k_z = k\cos\vartheta_k$, $k_x = k\sin\vartheta_k\cos\varphi_k$, $k_y = k\sin\vartheta_k\sin\varphi_k$, and Eq. (40) takes the form

$$M = \frac{v_0}{c} = \left(\frac{\omega^2 - \omega_g^2 \sin^2\vartheta_k}{\omega^2 - \omega_{\mathrm{A}}^2}\right)^{1/2} (\cos\vartheta_k \cos\alpha + \sin\vartheta_k \cos\varphi_k \sin\alpha). \tag{41}$$

Thus, if the source velocity is fixed, then a certain direction of radiation corresponds to the wave of a certain frequency. For example, if all the values depend only on x and z ($\varphi_k = 0$), the internal waves are not radiated at $v_0 > c\omega_g/\omega_{\mathrm{A}}$. If the source moves at a constant velocity $\vec{v}_0(v_{0_x}, 0, v_{0_z})$, then the phase fronts of the generated waves, $\phi_1 = \vec{k}\vec{R}_1 = \mathrm{const}$, in the source reference frame ($x_1 = x - v_{0_x}t$, $y_1 = y$, $z_1 = z - v_{0_z}t$) are determined parametrically (through the parameter ζ):

$$
\begin{aligned}
x_1 &= 2Ha_1^2\phi_1 \frac{-\xi\zeta^2 + [\xi\cos\alpha + \zeta\sin\alpha/(a_1M)]\cos\alpha}{\zeta^2(b_1\zeta^2 - \eta^2 - a_1^2\xi^2)}, \\
y_1 &= 2Ha_1^2\phi_1 \frac{\eta(1-\zeta^2)}{\zeta^2(b_1\zeta^2 - \eta^2 - a_1^2\xi^2)}, \\
z_1 &= 2Ha_1^2M\phi_1 \frac{2b_1\zeta^3 - \zeta[\eta^2 + a_1^2(\xi^2+1)]}{\zeta^2(b_1\zeta^2 - \eta^2 - a_1^2\xi^2)} + \frac{a_1\xi\cos\alpha + \zeta\sin\alpha/M)\sin\alpha/M}{\zeta^2(b_1\zeta^2 - \eta^2 - a_1^2\xi^2)}, \\
&\eta^2 = (\zeta^2-1)^{-1}[b_1\zeta^4 - a_1^2\zeta^2(\xi^2+1) + (a_1\xi\cos\alpha + \zeta\sin\alpha/M)],
\end{aligned}
\tag{42}
$$

where $a_1 = \omega_{\mathrm{A}}/\omega_g$, $b_1 = 1 - M^{-2}$.

For a source moving in the horizontal plane ($\alpha = \pi/2$) [79, 80], phase isolines in the cross-sections $x = 0$, $y = 0$ are easily obtained from Eqs. (42):

$$
\begin{aligned}
&z_1^2 = (M^2-1)\left(x_1^2 + \frac{a_1^2M^2\phi_1^2}{a_1^2M^2-1}\right), && y = 0, \\
&\left.\begin{aligned}
y_1 &= -a_1\phi_1\frac{(\zeta^2-1)^{3/2}(b_1\zeta^2 - a_1^2 + M^{-2})^{1/2}}{(a_1^2-1)\zeta^3} \\
z_1 &= a_1M\phi_1\frac{a_1^2 + b_1\zeta^4 - 2b_1\zeta^2 - M^{-2}}{(a_1^2-1)\zeta^3},
\end{aligned}\right\} && x = 0.
\end{aligned}
\tag{43}
$$

Approximate expressions for the pressure p_{A} of the fast (sound) and slow (internal) waves for this case are given in [80]:

$$
p_{\mathrm{A}} = \begin{cases} -\dfrac{v_0Q}{2\pi}\dfrac{\partial}{\partial x}\dfrac{\cos[k_{\mathrm{A}}^*((x-v_0t)^2 - (M^2-1)r^2)^{1/2}]}{[(x-v_0t)^2 - (M^2-1)r^2]^{1/2}}, & v_0t - x > r\sqrt{M^2-1}, \\ 0, & v_0t - x < r\sqrt{M^2-1}, \end{cases}
\tag{44}
$$

where $r = (x^2+z^2)^{1/2}$, $k_{\mathrm{A}}^* = k_1(M^2-1)^{-1/2}$, $k_1 = 1/(2H)$. We note that in [40, 55, 68, 82, 83] the case of the vertically moving source is considered, and in [77, 84, 85] horizontal movement is analyzed.

In reports [86], we reviewed theoretical work and observation data on the analysis of generation and propagation mechanisms of atmospheric and ionospheric AGWs caused by eartquakes and volcano eruptions. During sufficiently strong earthquakes (with magnitudes above five) long-period surface waves arise. Surface displacements lead to the generation of AGWs with the spectrum determined by the frequency spectrum of the Earth's surface during the earthquake and the spatial scale of the propagating seismic waves.

In [40, 87], we studied the transition radiation of AGWs and the excitation of Lamb waves above the solid surface of the Earth by moving and stationary sources. For a source of mass

$$
Q = Q_0\exp[-z/(2H)]\,\delta(x)\,\delta(z - vt)\,h(t),
\tag{45}
$$

where $h(t)$ is the Heaviside step function, the volume disturbance far behind the signal front ($d = \omega_{\mathrm{A}} \times \sqrt{t^2 - R^2/c^2} \gg 1$) is represented by the sum $\psi = \psi_1 + \psi_2$ of the stationary field ψ_1 of the moving source and the transition radiation field ψ_2:

$$
\psi_1 = \frac{Q_0}{2\pi\sqrt{1-M^2}}\frac{\partial}{\partial t}K_0(\omega_{\mathrm{A}}\beta\sqrt{1-M^2}),
\tag{46}
$$

$$\psi_2 = \frac{Q_0}{\pi\sqrt{1-M^2}} \frac{\partial}{\partial t} \frac{\sin d}{[d^2 + \omega_A^2 \beta^2 (1-M^2)]^{1/2}}, \tag{47}$$

where $\beta = \dfrac{1}{c(1-M^2)}[(z-vt)^2 + x^2(1-M^2)]^{1/2}$, $M = v/c$, and K_0 is the MacDonald function. Near the signal front ($d \ll 1$), the Lamb wave structure is described by the relation

$$\psi_\Lambda = \frac{\omega_A Q_0 t\sqrt{t^2 - R^2/c^2}}{\pi(t^2 - x^2/c^2)(R + Mz)} \left[z + \frac{1}{3}\omega_A c \left(1 + \frac{z}{4H}\right)\left(t^2 - \frac{R^2}{c^2}\right)\right]. \tag{48}$$

The energy radiated by the source (45) into the surface waves is equal to $E = Q_0^2/2M\rho_s$, where ρ_s is the density at $z = 0$.

5. METHODS OF DETECTION OF ACOUSTIC-GRAVITY WAVES

The AGW propagation in the Earth's atmosphere changes its parameters such as density, pressure, gas velocity, temperature, sound velocity, etc. AGW detection methods can be schematically divided into two groups. One of them is based on *in situ* measurement of any of the listed parameters of the medium or several of them; this is presented in detail in review [23]. The other group is related to recording the physical processes or the parameters of the medium which are changed due to the AGW propagation. We discuss this group of methods in greater detail.

The degree of ionization in the Earth's atmosphere is small up to heights $z \simeq 500$ km. Therefore, the charged component can be considered as a passive addition. Thus, one can obtain certain information on the background medium from observations of the ionized component. At low altitudes, where the influence of the magnetic field on the plasma movement is weak (i.e., from the Earth's surface up to the ionospheric D- and E-layers), the charged and neutral components move almost together, $\vec{u}_p \simeq \vec{u}_n$ [6]. In the F-layer and above, it is impossible to neglect the influence of the magnetic field. However, when this influence is known and taken into account, one can achieve certain conclusions on parameters of the neutral component in this height range too, using the characteristics of plasma disturbances [8, 10, 48, 88]. Therefore, it is possible to use different radio methods for diagnosing the state of the atmosphere and AGWs propagating there.

The frequency band of electromagnetic waves, which is now used for these purposes, is very wide, ranging from the optical to VLF frequencies.

Ionosondes with frequencies from several Hz up to 10–15 MHz and power W of tens of watts became widely used for getting height-frequency characteristics and profiles of electron density $N(h)$, measuring maximum values $N_{\max}$ in different ionosphere regions, determining the corresponding heights $h_{\max}$, and also for the observations of electron density inhomogeneities (sporadic layers, traveling ionospheric disturbances, drift and wave motions of the plasma, etc.). Ionosondes installed on satellites [89] provide the data on the electron density distribution at heights from the F-layer maximum to the satellite location.

The substantial increase of the power of the HF transmitters made it possible to significantly increase the limits of their usage. Now, powerful radio transmitters are used for probing the inhomogeneities in different ionosphere regions, such as the mesosphere, stratosphere, and thermosphere (MST and ST radars) [90]. For example, in [91] a method and results are presented for measurements of the wind and AGW velocities in the height range from 80 to 105 km by radio sounding of meteors at a continuous radiation station with frequency $f = 29.8$ MHz and the transmitter power $W = 4$ kW. Clear sky radars are based on radiowave scattering at inhomogeneities of the refractive index n caused by wavelike and turbulent fluctuations of the air temperature and humidity. For the HF range, according to the Debye empirical formula, we have [92]

$$n = 1 + 10^{-6}\frac{79}{T}\left(p + 4800\frac{e}{T}\right), \tag{49}$$

where T is the absolute temperature in degrees, p is the pressure in millibars, and e is the pressure of the water vapor in millibars. Radiowaves scattered by the refractive index inhomogeneities provide information on the processes leading to variations of the temperature, pressure, and humidity. Review [93], devoted to the radiolocation remote sensing of the clear sky, presents a historical reference, technical parameters of different facilities, and analysis of opportunities for atmosphere monitoring and the results achieved.

The same effect is used in the method of the radioacoustic sounding (RAS) of the atmosphere, employing the partial wave reflection from a periodic structure of the refractive index n created by propagating sound waves [94]. The RAS technique has been developed and improved for more than 30 years, and the possibilities and drawbacks of this method are discussed in detail in the monography [94].

A periodic structure of artificial inhmogeneities can be created not only by the infrasound but also by powerful radiowave beams. For these purposes, special facilities for ionosphere heating by vertical beams of high-frequency (HF) radiation were created [95]. The power of HF transmitters is $W \simeq 100$–1000 kW, and the equivalent power W_{eq}, taking into account the antenna gain, reaches 300 MW.

The theory of radiowave propagation in the ionosphere with account of nonlinear effects is now well developed and may be found in [96].

Using the heating facilities, researchers studied different types of plasma instabilities, artificial radioemission of the ionosphere (Getmantsev effect), quasiperiodic ionospheric lattices, etc. For diagnosing the effects which accompany the influence of powerful radiowaves on the ionosphere, people use all the modern radiophysical methods, such as ionosondes with linear frequency modulation (LFM-sounding), the probing wave method for measuring the amplitude, phase, and spectral characteristics of the reflected signals, and the method based on recording scintillations of the radiosignals from satellites and discrete radiosources in the range 100–300 MHz, passing through the disturbed regions of the ionosphere.

Papers [97–99] present a detailed description of the technique of measuring the IGW parameters and some results obtained for the lower ionosphere heights during the observations near Nizhny Novgorod in 1990–1991.

The Getmantsev effect is the basis for a new method of AGW diagnostics at heights of 70–90 km. The method uses the generation of low frequency radiation by ionospheric current systems under the influence of powerful HF radiation. The physical basis of this method and the results obtained are presented in [100–103].

Large-scale complex studies of the upper atmosphere at heights 80–110 km are performed with optical devices such as interferometers, lidars, spectrometers, photometers, and all-sky cameras, which are installed on the ground, airplanes, and satellites [104–109]. Most often, such observations are related to the night-time and dusk-time atmospheric airglow in the range of wavelengths corresponding to hydroxyl OH, oxygen, and sodium [110–112].

6. COMPARISON OF EXPERIMENTAL DATA AND THEORETICAL CALCULATIONS

The atmosphere stratification and the influence of the gravity force are most important at low frequencies, $\omega < \omega_g$. In the isothermal atmosphere, the Brunt-Väisälä frequency ω_g is determined by the relation $\omega_g = \sqrt{\gamma - 1}\, g/c$. This frequency corresponds to the free oscillations of an elementary volume of air displaced from the equilibrium position. If the parameters determining ω_g have the values $\gamma = 1.4$, $g = 10^3$ cm·s^{-2}, $c = 3 \cdot 10^4$ cm·s^{-1}, we get $\omega_g \simeq 2 \cdot 10^{-2}$ s^{-1}, and the corresponding period is $T_g = 2\pi/\omega_g \simeq 5$ min. The frequency ω_g varies with height because the Earth's atmosphere is nonisothermal. The height dependence $\omega_g(z)$ from the Earth's surface to $z = 130$ km is given in the monography [8].

Some peculiarities of atmospheric wave motions with periods from several minutes up to several hours are roughly explained by the properties of the internal gravity waves (IGWs) obtained for the simplest atmosphere models. These are the temporal and spatial scales, the amplitude variation with height, the characteristic velocities, etc. To our knowledge, such a comparison was made for the first time after detecting the traveling ionospheric disturbances by vertical probing ionosondes [3, 113].

More thorough testing of the theory required more realistic models of the propagation medium, taking into account altitude variations of the temperature $T_0(z)$, the wind $u_0(z)$, and also various dissipative processes. Numerous calculations of the wave properties in the framework of such models were made both analytically, using the WKB approximation [114], and with computers [115–122]. According to [123], a numerical code for calculating the atmosphere response to external IGW sources was developed.

The most complete data set was obtained for traveling ionospheric disturbances (TIDs) which are of a wavelike nature and often propagate to large distances as compared to the wavelength λ (see reviews [13, 24]). TIDs are divided into large-scale ones, with $\lambda \simeq 10^3$ km, and middle-scale ones, with wavelengths ranging from tens to hundreds of kilometers. The former have large periods ($\tau \gtrsim 1$ hour) and horizontal propagation velocities from 300 to 1000 m s^{-1}. They typically appear after strong magnetic storms and move towards the equator as a wide front without significant changes of the amplitude and the waveform.

Middle-scale TIDs with periods $\tau \simeq$ 10–30 min have smaller velocities, $v \simeq$ 100–250 m s^{-1}. Their dominating direction of propagation is also the meridional one, but the East-West velocity component is often detected too. The deviation of the electron number density N in TIDs from its equilibrium value N_0 varies in a wide range ($N/N_0 \simeq 10^{-3}$–10^{-1}).

It is commonly accepted that TIDs are related to IGW passages through the ionosphere. In the low frequency limit, $\omega \ll \omega_g$, and at $4k^2H^2 \gg 1$, we obtain from the AGW dispersion relation (13):

$$\omega^2 = \omega_g^2 k_\perp^2 (k_\perp^2 + k_z^2)^{-1}. \tag{50}$$

If we take into account that the horizontal scales of TIDs are typically much larger than the vertical ones, Eq. (50) is simplified,

$$\omega = \omega_g k_\perp / k_z. \tag{51}$$

Under these conditions, the wave period is $\tau = T_g \lambda h/\lambda_z \ll T_g$, the polarization becomes linear $u_x/u_z \simeq -\lambda_x/\lambda_z$, and the propagation velocities are expressed as [10]

$$\begin{aligned} v_{\mathrm{g}x} &= \omega_g/k_z\,, \quad v_{\mathrm{g}z} = -\omega_g k_x/k_z^2\,, \\ v_{\mathrm{ph}x} &= \omega_g k_x^2/k_z^3\,, \quad v_{\mathrm{ph}z} = \omega_g k_x/k_z^2\,. \end{aligned} \tag{52}$$

These formulas show the strong spatial dispersion: the phase velocity is directed almost vertically while the group velocity is almost horizontal. In comparing the data on TIDs with any model calculations one should bear in mind that the wave properties depend not only on the medium dispersion but also on the nature of the sources. Equations (50)–(52) are valid for quasimonochromatic signals, and the case of pulse-like sources was discussed in detail in several papers (see, for example, [39, 75, 125]).

Satellite measurements of the atmospheric density showed that in 10% of the satellite passes, wavelike distrubances of the density ρ were detected. Their mean relative amplitude was $\Delta\rho \simeq$ 0.1–0.2 of the undisturbed value ρ_0. Such disturbances dominated at high latitudes and most often were recorded in the early morning and late evening.

Spectral analysis of IGWs revealed a power-law decrease of their intensity with increasing frequency, with the spectral index $p = 2$ [8, 97, 98].

For a more detailed study of atmospheric AGWs, several scientific campaigns were organized, such as WAGS-85 [126–128], AIDA-89 [129], and MASSA [130]. Many data on AGWs were obtained in large-scale complex experiments on noctilucent clouds (ANLC-93) and the airglow of different atmospheric layers (ALOHA-93), when not only ground-based but also satellite and airplane devices were used [107–109].

Extensive experimental material reliably confirms the permanent presence of AGWs in the atmosphere. These waves, according to calculations [131, 132] and measurements [133–138], play an important role in the energy and momentum transfer between different regions of the atmosphere.

A large number of publications contain data on atmospheric disturbances recorded after strong explosions such as nuclear and volcanic ones or the Tunguska event [139–142]. During such explosions, the entire atmosphere becomes disturbed. Shock waves arising at some distance from the source are transformed into linear AGWs propagating as far as to tens of thousands of kilometers [13].

Infrasound disturbances caused by nuclear explosions were detected at a large network of stations. Depending on the explosion power and the distance, the oscillation amplitudes at the ground varied in the range from units to several hundreds of dyn/cm^2 [139]. At ionospheric heights, large variations of the $F2$-layer critical frequencies f_0 and the height of the F-layer maximum were detected, and an almost linear increase of quasiperiods of the electron density oscillations with the distance from the explosion point was recorded [125]. Studies of explosions in the atmosphere are reviewed in [142].

The observed linear increase of the AGW period with distance from a pulse-like source can be explained theoretically. From Eq. (37) for the Green function it follows that the wave frequency ω approaches the value $\omega_c = \omega_g z/r$ after the signal reaches an observation point (r, z) at a large horizontal distance from the source ($r \gg z$). If the observation height is fixed (z = const), the oscillation period is expressed as $\tau = 2\pi/\omega = 2\pi r/\omega_g z$. This fact is also easily explained on the basis of kinematical relations for AGWs (see Eqs. (20), (52)). In the low frequency band $\omega \ll \omega_g$, the waves propagate in a cone with a generatrix making the angle $\vartheta = \mathrm{arctg}\, \omega/\omega_g$ with horizontal direction. Thus, a wave with period $\tau = 2\pi/\omega$ reaches the F-layer maximum, located at height $z \simeq 250$–300 km, at the horizontal distance $r = z\tau\omega_g/2\pi$ from the source.

For a more detailed comparison of the recorded waveforms with the calculated ones, many authors performed numerical modeling of the AGW propagation in the Earth's atmosphere for both plane and spherical waveguides. The results obtained are analyzed in review [13].

Nonlinear propagation regimes of AGWs were analyzed in several papers [143–148].

In summary, based on the material presented above, we find that theoretical results are in satisfactory and sometimes even in good argeement with the experimental data on AGW propagation and excitation. This agreement made it possible to formulate and solve the inverse problem, namely, to obtain AGW parameters from the recorded characteristics of TIDs [149–150].

7. CONCLUSION

AGW properties are studied in fair detail for the simplest atmosphere models such as an isothermal atmosphere without wind or with the wind independent of height. This serves as a basis for a further analysis of the peculiarities of AGW propagation and excitation under conditions closer to real ones. The basic features of the waveguide propagation of AGWs are also clarified and successfully used for the interpretation of experimental data. However, as correctly noted in review [15], despite extensive studies, there are many unsolved problems related to the description of AGW generation and propagation and to their influence on the Earth's atmosphere. We point to several of them.

For the analysis of nonlinear effects (see, e.g., [152, 153]), the perturbation method, when all the physical values are expanded in a series with respect to a small parameter, is used as a rule. However, even in the linear approximation for AGWs, amplitudes of different values (for example, the velocity $\vec{v}$ and the pressure p) change oppositely with height z. As V. I. Karpman suggested more than 20 years ago, it would be better to derive an exact nonlinear equation for at least one unknown value and then construct its approximate solutions. That would make it possible to estimate the validity and accuracy of the widely used approximate methods for calculating the nonlinear effects under AGW propagation in an inhomogeneous atmosphere. Apparently, the same goal can be achieved by the numerical analysis of the basic nonlinear equations for AGWs, using modern supercomputers.

Another direction of studies which seems to be underestimated by researchers is development and application of the kinetic equation method for describing the AGW propagation. Besides the paper [41] cited above, the author knows only several articles published by the research group of S. B. Leble from Kaliningrad University.

Among the problems whose studies are not complete to date, we mention those of AGW stability (though much was done in this respect), and several generation mechanisms (for example, at atmospheric fronts, thunderstorm clouds, convection zones, etc.). The influence of the horizontal inhomogeneity of the medium on AGW propagation is not yet clear, etc.; some other problems are still unsolved.

The author wishes to thank the Russian Foundation for Basic Research for financial support of this work under grants 95–02–05001 and 96–02–18632.

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