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# Oscillations of a vertically stratified dissipative atmosphere. II. Low frequency trapped modes

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ABSTRACT

Trapped atmosphere waves, such as IGW waveguide modes and Lamb modes, are described using dissipative solution above source (DSAS) (Dmitrienko and Rudenko, 2016). According to this description, the modes are disturbances penetrating without limit in the upper atmosphere and dissipating their energy throughout the atmosphere; leakage from a trapping region to the upper atmosphere is taken into consideration. The DSAS results are compared to those based on both accurate and WKB approximated dissipationless equations. It is shown that the spatial and frequency characteristics of modes in the upper atmosphere calculated by any of the methods are close to each other and are in good agreement with the observed characteristics of traveling ionospheric disturbances.



## 1. Introduction

This paper is devoted to describing atmospheric trapped modes extending to large heights. A description of these modes at higher altitudes, above all, is extremely important in terms of their experimental identification. The energy of the waveguide modes is mainly concentrated in low heights, into their trapping region. However, if the disturbance amplitude at these heights is very small compared with the background atmospheric parameters, then we have a possibility of indirect observation the disturbance in the upper atmosphere only, where, due to an increase of relative disturbance amplitude because of the atmospheric density drop, it can lead to significant changes in the charged component of the ionosphere. It is because of the "invisible" IGW propagation in the lower atmosphere we can observe such a phenomenon as the traveling ionospheric disturbances (TID) (Hines, 1960).

The problem of describing the atmospheric trapped modes can be solved, using a dissipative solution above source (DSAS) (Dmitrienko and Rudenko, 2016). Actually, any DSAS satisfies the upper boundary condition for trapped modes, that is, the absence of the flow of energy towards the Earth in the upper layers of the atmosphere, and, because there is no source, is applicable at all altitudes above the Earth's surface. Therefore, the problem of trapped mode finding reduces to the problem of selection of a DSAS that satisfies the lower boundary condition for trapped modes – the zero displacement on the Earth's surface. Thus, the condition of the equality to the zero of vertical velocity for DSAS on the Earth's surface is the dispersion equation for trapped mode. This dispersion equation can be regarded as an equation for a horizontal wavenumber at known frequency or vice versa. We consider IGW waveguide modes, which exist due to the temperature inhomogeneity of the lower atmosphere and Lamb modes. Given a real frequency, we find the complex horizontal wavenumber. The complexity of horizontal wavenumbers is a consequence of dissipation and presence of subbarrier leakage from the IGW waveguide. The horizontal wavenumber found, we can obtain a vertical structure of the mode, which gives relationships of the disturbance parameters in the lower atmosphere with its parameters in the upper isothermal atmosphere.

We organize our paper as follows. A model of the atmosphere applied for calculations is described in Section 2. Section 3 is devoted to construction and analysis of waveguide modes of the IGW spectral range. We compare the solutions of the waveguide problem, constructed from a DSAS, to solutions obtained in the frames of the dissipationless approximation by both the WKB method and numerical ones. Such comparisons aim at two things at once. First, they allow us to reach clarity in understanding of dissipation effect on the main characteristics of the waveguide propagation: the dispersion relations, the waveguide leakage, and the horizontal attenuation of the waveguide modes. Second, they serve as

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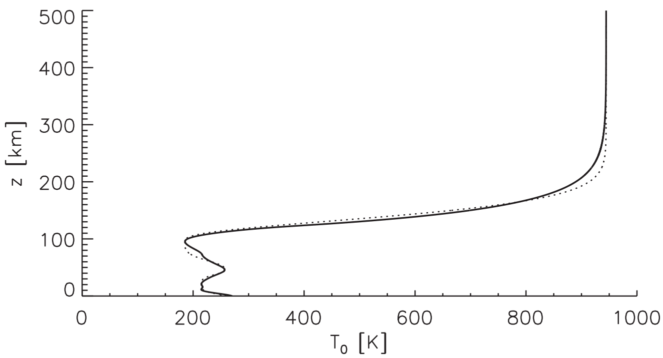


**Fig. 1.** The approximate temperature dependence on height (dotted line); the basic dependence (solid line).

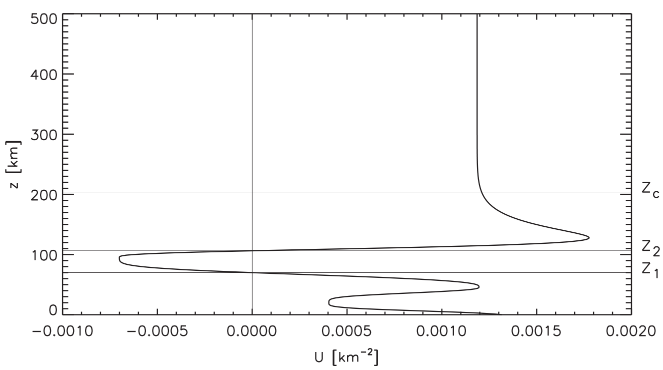


**Fig. 2.** The characteristic height distribution of *U*-function.

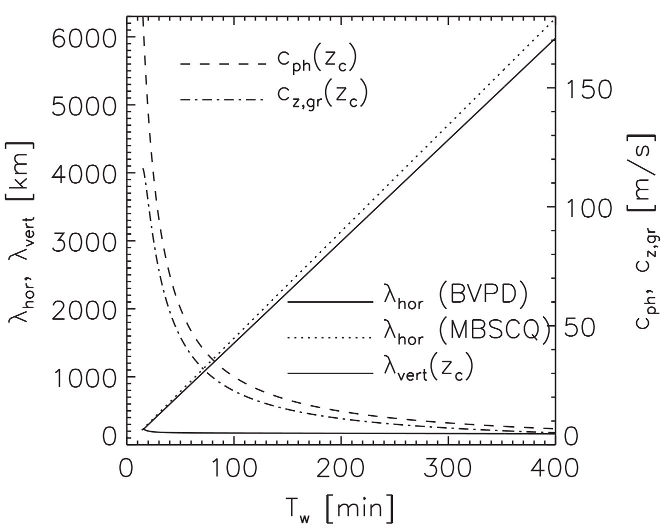


**Fig. 3.** The waveguide characteristics of 0-mode: horizontal wavelength from the BVPD=BVP (solid line); horizontal wavelength from the MBSCQ (dotted line); full phase velocity of the upward propagating wave (dashed line); vertical group velocity of the upward propagating wave (dash-dotted line); vertical length of the upward propagating wave (dash-dot-dotted line).

additional tests to the tests of Dmitrienko and Rudenko (2016), of both method for DSAS and corresponding codes. We obtain dispersive properties and a description of a height structure of all disturbance parameters. All special features of trapped IGWs are present in the obtained waveguide solution in the real atmosphere: localization due to the temperature stratification, the leakage through the opacity area, and qualitative changes of the wave structure related to dissipative nature of the disturbances in the upper atmosphere. We obtain complete information on all the height structure of waveguide modes, which can be directly used

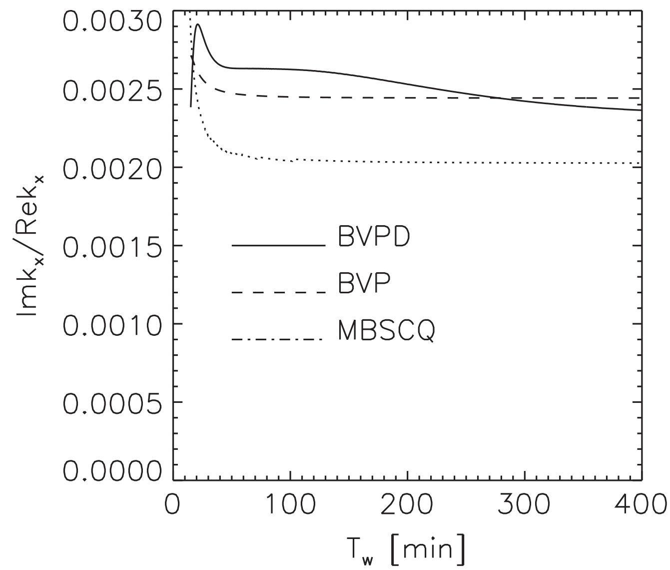


**Fig. 4.** The waveguide characteristics of 0-mode: horizontal attenuation characteristic from the BVPD (solid line); horizontal attenuation characteristic from the BVP (dashed line); horizontal attenuation characteristic from the MBSCQ (dotted line).

**Table 1**
The angular and velocity characteristics.

| | $T_w = 82$ min *Elevation* | $T_w = 182$ min *Elevation* | $T_w = 82$ min *Velocity* | $T_w = 182$ min *Velocity* |
|---|---|---|---|---|
| Medvedev et al. (2013) | [−78°, −71°] | [−86°, −73°] | [12, 28] (m/s) | [19.5,32] (m/s) |
| Our values | −82° | −86° | 35 m/s | 15.6 m/s |

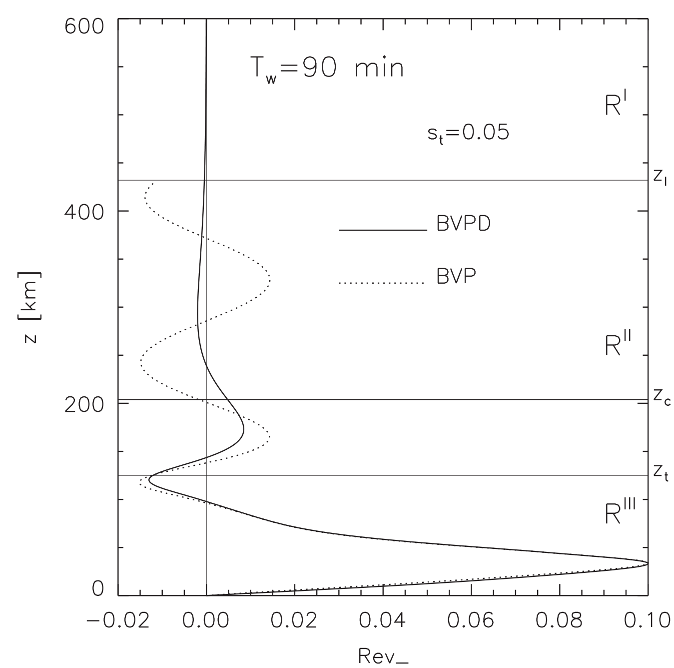


**Fig. 5.** The example of comparison of a BVPD and BVP solutions.

to reveal a quantitative compliance of IGW modes with TIDs. We show that the properties of the obtained waveguide solutions are in good agreement with the main characteristics of TIDs following from their observations: the periods to space scales ratios, the weak horizontal attenuation, the values of full phase velocity, and