

Using Partial Reflection to Determine the Temperature of the Mesosphere

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Abstract—A radiophysical technique is proposed for calculating mesospheric temperatures using experimental measurements of the frequencies of resonant atmospheric oscillations (the acoustic cutoff frequency and the Brunt–Väisälä frequency). The partial reflection method is used to measure temperatures at sunset and an altitude of 75 km for days when the planetary index of geomagnetic storms was $K_p \leq 1$. These temperatures are in good agreement with data from other researchers.

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INTRODUCTION

The temperature in the mesosphere (usually at altitudes of 50 to 90 km) is one of the most important characteristics of the atmosphere that determine its dynamic and photochemical processes. Experimental studies and theoretical analyses of the temperature distribution in the mesosphere have so far been performed to a lesser extent than for the underlying regions of the atmosphere. It is therefore important to monitor the composition and temperature of the mesosphere, especially when different atmospheric waves pass through it.

Developing remote atmospheric sounding techniques based on measuring and interpreting the characteristics of electromagnetic radiation after it interacts with a given medium is of considerable interest. Laser (lidar) sounding is the latest and most reliable active technique of atmospheric sounding. Lidar sounding uses its own monochromatic pulsed light source, allowing us to make long-term continuous observations with a high spatial and temporal resolution of the data obtained in arbitrary directions of the laser beam at different altitudes [1, 2].

A large volume of information about the temperature in the atmosphere, including the mesosphere, has been obtained via remote sounding by artificial Earth satellites. A global temperature database has now been obtained using, e.g., the ten-channel SABER (Sounding of the Atmosphere Using Broadband Emission Radiometry) infrared radiometer on board the TIMED (Thermosphere Ionosphere Mesosphere Energetics and Dynamics) satellite [3]; the high-resolution HIRDLS (High-Resolution Dynamics Limb Sounder) infrared radiometer on board the Aura EOS (Earth Observing System) satellite [4]; and the IASI

infrared atmospheric sounding interferometer on board the MetOP (ESA) satellite [5, 6].

Satellite and rocket techniques have major disadvantages. They make episodic measurements, cannot track minor variations in space and time, and are very expensive. Radiophysical ways of obtaining information on the parameters of the mesosphere can be used in any weather, in contrast to measurements made with optical ground facilities, which are largely limited by the transparency of the atmosphere's surface layer.

In this work, we propose a way of calculating the temperature of neutrals in the mesosphere based on the measuring the amplitude of partial reflections of radar signals reflected from the *D*-region.

MEASURING TEMPERATURE IN THE ATMOSPHERE ACCORDING TO RESONANCE FREQUENCIES

The theory of acoustic gravity waves (AGWs) in the atmosphere allows us to describe many wave-like oscillations in the atmosphere [7]. According to the theory of acoustic gravity waves, if the atmosphere is one-dimensional and isothermal, there are two intervals of frequencies in the atmosphere in which atmospheric waves can propagate as acoustic and gravity waves. These intervals are limited by the resonance frequencies of the atmosphere: acoustic cutoff frequency ω_{ac} (or period τ_{ac}) and Brunt–Väisälä frequency ω_{bv} (or period τ_{bv}). The acoustic cutoff frequency is defined as

$$\omega_{ac} = \gamma g / 2c,$$

where γ is the adiabatic exponent, g is the acceleration of gravity, and c is the speed of sound. The Brunt–

Väisälä frequency is defined as the buoyancy frequency at which a vertically displaced volume of air fluctuates near its equilibrium state in a statically constant environment (the state of hydrostatic equilibrium). The reciprocal force is in this case not just the compression, as in the case of acoustic waves, but the Archimedean force (the difference between the force of gravity and the pressure gradient) [8]. This frequency can be written as

$$\omega_{bv}^2 = (\gamma - 1)g^2/c^2.$$

The range of possible frequencies of atmospheric resonances under different heliogeophysical conditions can be determined using formulas of resonance frequencies from AGW theory and the values of atmospheric parameters in the empirical NRLMSISE-00 model of a neutral atmosphere.

Spectral analysis of time series of the experimental values of any parameter of the atmosphere at a given altitude yields the real spectrum of variations of this parameter for the selected range of frequencies. After identifying the resonances, the temperature at this altitude is calculated using the expressions for oscillations corresponding to periods of the atmospheric resonance of the acoustic cutoff and Brunt–Väisälä frequencies:

$$\tau_{ac} = 2\pi\sqrt{\frac{4kT}{\gamma M m_H g^2}}, \quad \tau_{bv} = 2\pi\sqrt{\frac{\gamma k T}{(\gamma - 1) M m_H g^2}},$$

where $\gamma = C_p/C_v$ is the ratio of the heat capacities at constant pressure and volume; k is the Boltzmann constant; and T is the neutral temperature.

$M = \frac{m}{\sum(m_i/M_i)}$, where m is the mass of the air mixture; m_i is the mass of the i th component; and M_i is the ratio of the mass of the i th component to the atomic unit of mass; m_H is the mass of a hydrogen atom; and g is gravitational acceleration.

A specific feature of the partial reflection method is the possibility of determining the resonant spectral components of an acoustic gravity wave at the altitudes where a radar wave is reflected and modulated. The partial reflection method thus allows us to calculate neutral temperature profiles at the sounding altitudes. An advantage of this technique is that data can be obtained regardless of weather conditions and the time of day.

THE PARTIAL REFLECTION METHOD AND THE FACILITY AT THE POLAR GEOPHYSICAL INSTITUTE

In the 1950s, Gardner and Pawsey proposed an effective way of studying the D -region of the ionosphere [9]. This technique was developed further in subsequent works [10, 11]. It is based on radar sounding of the lower ionosphere in the medium-wave

range. It is relatively simple to use and allows us to obtain information on the electron density and parameters of irregularities in the lower ionosphere.

The partial reflection method is based on the emission of two wave modes (ordinary and extraordinary) in the form of alternating pulses or linearly polarized waves at frequencies of 2 to 8 MHz and the backscattering of radio waves by plasma inhomogeneities [12]. In the first case, signals partially scattered by ionospheric irregularities are detected separately, and their amplitude is measured as a function of the delay time, which determines the height of reflection. In the second, there are two orthogonal linear polarizations that form the signals of two circular components by adding them with a phase shift of $\pm 90^\circ$. The ratio of the measured amplitudes, the difference between absorption during the propagation of ordinary and extraordinary radio waves (differential absorption), and direct or indirect phase measurements (differential phase and correlation) can all be used to determine the electron density. Phase measurements are usually more complex than those of amplitude, so differential absorption is most widely used in practice. We can therefore detect variations in partially reflected radio signals at selected heights and identify in them oscillations of the medium caused by different sources of natural and artificial origin.

The partial reflection facility of the Polar Geophysical Institute for the study of the lower ionosphere consists of a transmitter, a receiver, a tranceiver phased antenna, and an automated data acquisition system. The facility is located on the territory of the observatory Tumanny (69.0° N, 35.7° E). Its main parameters and signal processing technique were described in [13]. The radar operates at frequencies of 2.60–2.72 MHz; the power of a pulse from the transmitter is around 60 kW; the duration of a pulse is 15 μ s; and the sounding frequency is 2 Hz. The amplitude of a partially reflected ordinary wave is measured in millivolts. The antenna array consists of 38 pairs of crossed dipoles. It covers an area of 10^5 m² and has a half-power beamwidth of around 20°. Two circular polarizations are received in turn and amplified by a tuned radio-frequency receiver with an amplification band of 40 kHz. The survey range of heights is 30–240 km. The height step is $h = 0.5 \cdot n$ km, where $n = 1, 2, 3, \dots$

RESULTS AND DISCUSSION

The possibility of selecting a partially reflected signal of the resonant frequencies in the atmosphere from the oscillation spectrum depends on the wave activity above the ground. We used radar data when the solar terminator passed through the zenith of the station, in order to have the best probability of generating (or amplifying) oscillations in the investigated interval of altitudes during measurements.

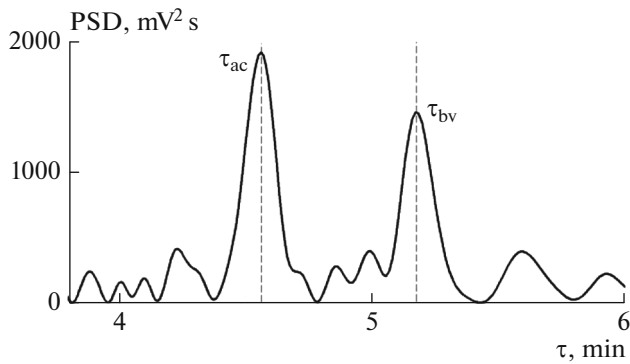


Fig. 1. Power spectral density of a partially reflected ordinary wave at an altitude of 75 km during sunset at 16:17:48 UT on February 27, 2015.

The idea that a moving solar terminator generates wave processes was formulated by Beer [14]. He suggested there are many similarities between processes that develop during the supersonic movement of the Moon's shadow during a solar eclipse and that of the solar terminator. The first experimental confirmation of this was published in [15, 16]. The theoretical foundations of this phenomenon were considered by Somikov in [17]. The solar terminator is thus a regular source of natural wave-like disturbances in the atmosphere that can amplify the natural frequencies in it (the acoustic cutoff frequency and the Brunt–Väisälä frequency).

We used data from measuring the amplitude of a partially reflected ordinary wave, from which the power spectral density of amplitude variations was calculated. Since the periods of atmospheric resonances in the *D*-region of the ionosphere approximately 4 to 6 min [18], the digital band-pass elliptical (Cauer) filter of the MathLab software package with a bandwidth of 2 to 8 min was used to treat variations in amplitude.

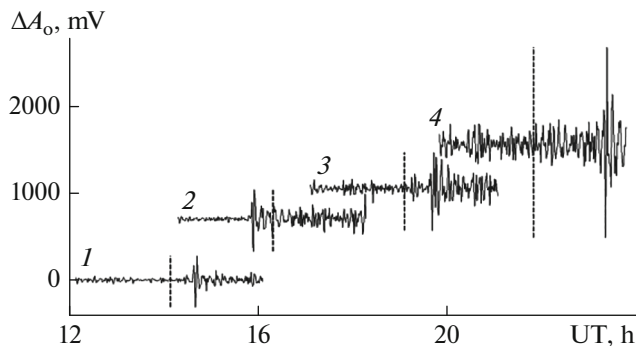


Fig. 2. Dependence of variations in the filtered amplitude of a partially reflected ordinary wave ΔA_o at an altitude of 75 km during sunset in winter and spring on (1) January 20, 2015; (2) February 27, 2015; (3) April 7, 2015; and (4) April 26, 2015.

This elliptical filter features a sharp reduction in amplitude response, allowing more efficient separation of frequencies than other line filters.

To study spectral characteristics and calculate the neutral temperature at different altitudes, we used the time series of amplitudes of a partially reflected ordinary wave in the altitude interval of 60 to 90 km as the solar terminator passed at sunset. The amplitude spectra were analyzed on geomagnetically quiet days, when the 3-h planetary index of geomagnetic storm K_p was less than or equal to unity and there were no other disturbances in the atmosphere.

To calculate the spectra, we used second data on a 2-h interval of the amplitude of a partially reflected ordinary wave—1 h before and 1 h after the solar terminator passes over the observatory during sunset. Spectra of temporal variations in the amplitude are calculated using the time series of the amplitude of a partially reflected ordinary wave at an altitude of 75 km. The spectral components corresponding to atmospheric resonances were identified from the experimental amplitude spectra using the AGW theory and the empirical NRLMSISE-00 model of the atmosphere, and the neutral temperature at the mesospheric altitudes was calculated.

Figure 1 shows an example of the dependence of the power spectral density (PSD) of variations in the amplitude of a partially reflected ordinary wave at an altitude of 75 km during sunset on February 27, 2015, at 16:17:48 UT on period τ of oscillation. The 2-h period from 15:17 to 17:17 UT was chosen for the calculation. For other days, a 2-h period was used with the time of sunset at an altitude of 75 km taken as the middle of the period. Spectral maxima with periods $\tau < \tau_{ac}$ and $\tau > \tau_{bv}$ can belong to acoustic (infrasound) or gravity modes, respectively.

Figures 2 and 3 show examples of filtered amplitude variation ΔA_o of a reflected ordinary wave at an

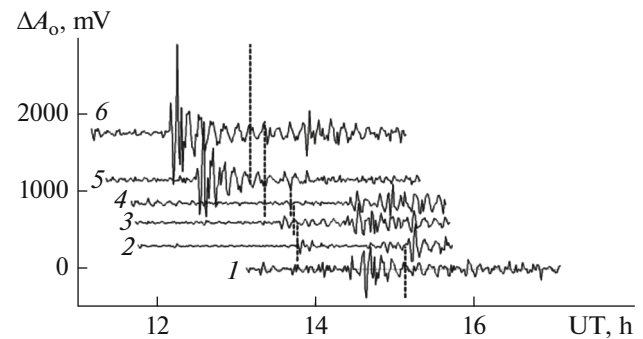


Fig. 3. Dependence of variations in the filtered amplitude of a partially reflected ordinary wave ΔA_o at an altitude of 75 km during sunset in autumn and winter on (1) October 26, 2015; (2) November 21, 2015; (3) November 22, 2015; (4) November 23, 2015; (5) December 3, 2015; and (6) December 16, 2015.

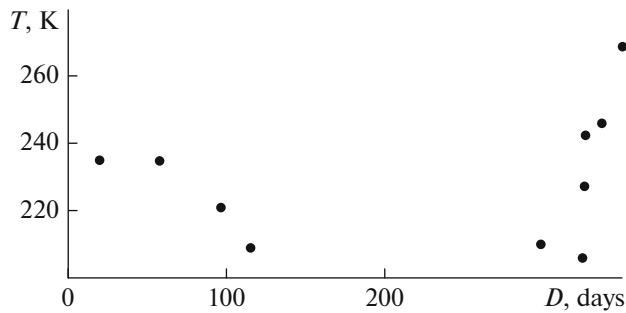


Fig. 4. Temperature at an altitude of 75 km for different seasons of 2015, depending on day D of the year.

altitude of 75 km when the solar terminator passed during sunset. The vertical dashed lines mark the time of sunset at an altitude of 75 km. The mean value of the variations in the filtered amplitude of a partially reflected ordinary wave is zero for all considered cases. However, the graphs of amplitude variations were shifted vertically relative to one another, in order to compare the behavior of these variations at different times and on different dates. It can be seen from Figs. 2 and 3 that wave activity emerges at an altitude of 75 km when the solar terminator passes, which can increase the resonant frequencies.

Figure 4 shows a graph of the values of neutral temperature at an altitude of 75 km calculated using the experimental data of τ_{ac} and τ_{bv} by formulas (1) for the days of the year D , which are shown in Figs. 2 and 3. The calculation is based on standard values typical for a neutral atmosphere. The seasonal behavior of temperature at an altitude of 75 km is obvious. It fell from 235 K in January to 210 K in April and rose from 210 K in October to 270 K in December.

CONCLUSIONS

The results from our analysis of partial reflection data demonstrate the possibility of using the power density spectra of a partially reflected ordinary wave to identify and determine the resonance periods of waves in the atmosphere at mesospheric altitudes, and of calculating the neutral temperature in the D -region of the ionosphere using these data. A seasonal change in the neutral temperature at an altitude of 75 km was obtained for the site of observation (69.0° N, 35.7° E). The neutral temperature fell from ~ 235 K in January to ~ 210 K in April and rose from ~ 210 K in October to ~ 270 K in December.

Our way of measuring the temperature of neutrals can in principle be used to analyze any experimental data in the form of time series that contain information on variations in atmospheric parameters.

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