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DETERMINATION OF TEMPERATURE IN THE MESOSPHERE USING PARTIAL REFLECTION METHOD

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Abstract. For quiet geomagnetic conditions during solar terminator passages results of observations of amplitude variations of the partial reflection radar signals (the observatory Tumanny of the Polar Geophysical Institute, 69.0N, 35.7E) at the heights of the D-region of the ionosphere are given. Temporary variations of signal amplitudes which were reflected at the height of 75 km and their spectra were analyzed. It was found that the components of the time spectrum of the variations which correspond to resonant frequencies of the atmosphere (the acoustic cut-off and the Brunt-Väisälä ones) in certain cases were intensified. On the basis of the theory of acoustic-gravity waves and the empirical model of neutral structure and temperature of the atmosphere NRLMSISE-00 identification of the experimental periods corresponding to the atmospheric resonances has been done and calculation of neutral temperature at the heights of the mesosphere have been carried out. The values of the calculated temperature from experimental data showed satisfactory consent with data of other independent observations.

Introduction

Temperature in the mesosphere is one of the most important characteristics of the atmosphere, determining the dynamic and photochemical processes in it. The processes occurring in the upper atmosphere are of particular scientific interest. Temperature is a key parameter of the atmosphere, affecting the dynamics and energy. Temperature analysis in the mesosphere region has so far been carried out in a much smaller volume than for the lower layers of the atmosphere. The composition and temperature regime of the mesosphere, the dynamic and chemical processes occurring in it, as well as the energy balance are intensively studied at the present time. The study of temperature is an important link in understanding of solar-terrestrial relations and the construction of empirical models of the upper atmosphere. The strong variability of the parameters of the upper layers of the atmosphere, the diversity and complexity of the processes occurring in them, the ambiguity of interpreting the results of observations, the lack of a uniform distribution of observation points on the surface of the globe - all this is the fact that a complete understanding of the processes in the mesosphere is still far from its complete resolution.

It is very difficult to conduct measurements in the mesosphere because it is too high for airplanes (maximal height is about 25 km) or for balloons (maximal height is about 45 km) and too low for satellites (minimal height is about 130 km). The most important means to conduct measurements in the mesosphere is launching of sounding rockets. During the launches built-in instruments conduct measurements during the rising and descending parts of the trajectory. One rocket can measure only one vertical profile on each flight and can only be used once. This is a very expensive experimental method that brings rather limited results.

The development of remote sensing techniques of the atmosphere, based on the measurement and interpretation of the characteristics of the electromagnetic field after its interaction with the medium under study, is of current interest. Remote measurements of atmospheric components and parameters are carried out by two groups of methods: passive and active. The first group includes spectrometric (radiometric) sensing methods based on measuring and analyzing the spectral composition of the solar radiation and thermal radiation of the atmosphere (absorption bands in the IR range and separate telluric lines in the microwave range, etc.) from the ground, balloons, aircraft or spacecraft. Of the active methods of studying the atmosphere, laser (lidar) sounding is the most progressive and relevant. The advantages of lidar sensing arising from the use of own monochromatic pulsed light source include the high spatial-temporal resolution of the data obtained, the possibility of conducting long-term continuous observations, the evaluation of the selected characteristic in an arbitrary direction of the laser beam and at different heights, etc.

A large amount of information about the temperature of the mesosphere is obtained on the basis of remote sensing from artificial earth satellites. Global temperature data are currently obtained from the satellite TIMED (Thermosphere, Ionosphere, Mesosphere, Energetics and Dynamics) with the instrument SABER (Sounding of the Atmosphere Using Broadband Emission Radiometry), from the satellite Aura EOS (Earth Observing System) with the instrument HIRDLS (High-Resolution Dynamics Limb Sounder), etc.

Satellite and rocket methods have several significant drawbacks: their episodic measurements, the impossibility of tracking small-scale space-time variations, relatively low accuracy and, finally, high cost of living. The use of radio physical methods for obtaining information on the temperature of the mesosphere can be useful in the case when measurements by optical ground-based means are impossible, for example, during heavy clouds and the like situations. In addition, it may be an additional source of information about temperature in the mesosphere.

The aim of the article is to show possibility to estimate temperature at different heights of the mesosphere by the partial reflection method.

1. Partial Reflection Method and Facility

One of the effective methods for studying the *D*-region of the ionosphere is the partial reflection method (PRM), proposed in the early 1950s by F. Gardner and J. Pawsey [*Gardner and Pawsey*, 1953]. This method was further developed in subsequent works [*Belrose and Burke*, 1964; *Coyne and Belrose*, 1972]. It is radar sounding of the lower ionosphere in the range of medium waves. The method is relatively simple to implement and allows obtaining information about the electron density and parameters of irregularities at the heights of the lower ionosphere.

The method of partial reflections is based on the emission of two wave modes (ordinary and extraordinary waves) in the form of alternating pulses or linearly polarized waves at frequencies in the range from 2 to 8 MHz and the back scattering of radio waves by plasma irregularities. In the first case, separate reception of signals, partially scattered by ionospheric irregularities, is carried out, and their amplitudes are measured depending on the delay time, which determines the height of reflection. In the second case, two orthogonal linear polarizations are received, and then by summing those with the phase shift of ± 90°, signals of two circular components are formed. To determine the parameters of the medium according to the PRM, one can use either amplitude measurements or the difference in absorption along the propagation paths of the ordinary and extraordinary radio waves (differential absorption method), or direct or indirect phase measurements (differential phase method and correlation method). Phase measurements are usually more difficult than amplitude measurements; therefore, in practice, the differential absorption method has received the widest application. To obtain the most complete and accurate information about the lower ionosphere, it is necessary to simultaneously measure the amplitude and phase of the scattered signals.

The partial reflection facility of the Polar Geophysical Institute (PGI) for the study of the lower ionosphere consists of a transmitter, a receiver, a receiving-transmitting phased array and an automated data acquisition system. It is located at the observatory Tumanny (69.0N, 35.7E). Technical characteristics of the radar: operating frequency 2.60-2.72 MHz; transmitter power per pulse of about 60 kW; pulse duration 15 μs; probing frequency 2 Hz. The antenna array consists of 38 pairs of crossed dipoles, covers an area of 10^5 m^2 and has the beam width at the half power level of about 20°. Two circular polarizations are received alternately, which are amplified by a direct gain receiver with the 40 kHz bandwidth. Signal amplitudes can be recorded in the altitude range from 30 km up to 150 km. The step of data recording in height is $h = 0.5 \cdot n$ km, where $n = 1, 2, 3, \ldots$.

Irregularities of electron density or collision frequency give rise to partial reflections of radio waves [*Belrose, and Burke*, 1964]. The ratio *Ax*/*Ao* of the amplitudes of the extraordinary *(x)* and ordinary (*o*) components of the weakly scattered signals is given by a simple formula with effective reflection coefficients *Rx*,*o* and absorption indexes *Kx*,*o*, which exponentially depend on height. The exponential term gives differential absorption of the magneto-ionic components scattered from a height h and depends on the electron density and collision frequency below this height. The coefficient *Rx*,*o* for very weak scattering is given by the Fresnel formula $Rx,o = \Delta n/2n$, where *n* is the complex refractive index of the medium, which is near unity. The ratio *Rx*,*o* is determined by the wave frequency, the gyrofrequency, and electron collision frequency, but is independent of the actual electron density. When *Ax*/*Ao* is observed, as a function of height, and collision frequency is known, the electron density may be determined.

2. Resonance frequencies of the atmosphere

Basic acoustic-gravity wave (AGW) theory in the atmosphere gives an opportunity to describe many of wave-like oscillations in the atmosphere [*Knížová and Mošna*, 2011; *Yeh and Liu*, 1974]. In case of the plane-stratified, isothermal atmosphere there are two frequency domains for atmospheric waves where they can propagate as acoustic and gravity waves. The domains can be described by two resonant frequencies of the atmosphere: the acoustic cut-off frequency ω_a (or the period τ_{ac}) and the Brunt-Väisälä frequency ω_g (the period τ_{bv}). For the heights of *D* region the resonant periods are less that 6 min [*Knížová and Mošna*, 2011]. The atmosphere is a compressible gas which, after being compressed then and then released, begins to oscillate near its equilibrium state.

In the early seventies Chimonas and Hines [*Chimonas, Hines*, 1970] have assumed that during a solar eclipse the atmospheric gravity waves caused by supersonic passing of the lunar shadow across the Earth's surface and cooling of the atmosphere due to reduction of sunlight in the passing shadow have to be observed. In the next years researchers have received confirmation of the existence of this effect [*Sauli et al.*, 2007].

The main idea of the wave generation by the moving solar terminator was formulated by Beer [*Beer*, 1973]. He suggested that there is an analogy between the processes arising from the supersonic movement of the lunar shadow during a solar eclipse and the supersonic movement of the solar terminator. One of the first experimental evidences of generation of waves at ionospheric altitudes during sunrises and sunsets can be found in [*Herron*, *Donn*, 1973; *Rees et al.*, 1972]. The theoretical foundations for these phenomena were considered in [*Somsikov*, 2011].

The solar terminator is a regular source of wave-like atmospheric disturbances. We can observe the events, as a rule, two times per day. It means that we have a natural source of wave disturbances and features of the disturbances we can research. During the passage of the solar terminator the atmosphere is influenced by the arising wave processes and the ones can generate different types of waves including two characteristic frequencies of the atmosphere: the acoustic cut-off frequency and the Brunt-Väisälä frequency [*Liu et al.*, 2009].

3. Experimental results

During the research we use amplitude measurements of the partially reflected ordinary and extraordinary waves above the observatory in Tumanny to register characteristic frequencies of the atmosphere during disturbances of different kinds in the atmosphere for to calculate temperature in the D region of the ionosphere. In our case we use the solar terminators as the source of the regular and well known process which causes disturbances in the atmosphere above the observation point.

For the study of the effect of the solar terminator passages on the ionosphere as the first approach we took the data for some quite geomagnetic days with Kp ≤ 1 and also when there were no any sources of strong disturbances in the atmosphere. Here we present some examples of variations of the ordinary wave amplitude for that days. For calculation of temperature we took the variations during two hour's time sector with the middle at the time of a sunset. In Fig. 1a, b variations of the ordinary wave amplitude for different seasons during solar terminator passages are shown. Vertical dashed lines mark the time of sunset at the height of 75 km.

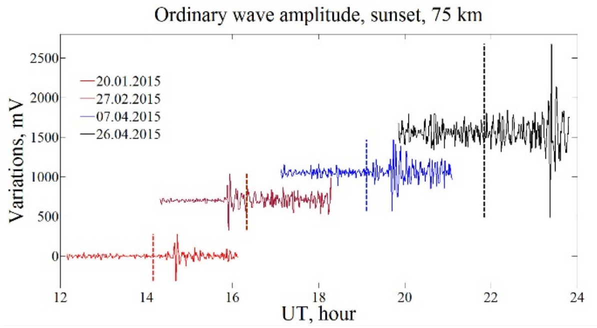

Figure 1a. Behaviour of ordinary wave amplitude in autumn and winter.

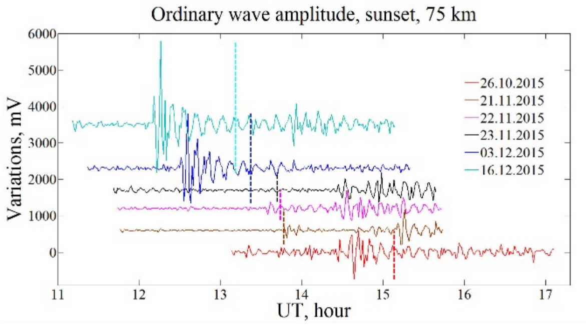

Figure 1b. Behavour of ordinary wave amplitude in winter and spring.

In Fig. 2 a sample of calculation of of spectral power density of ordinary wave variations at the height of 75 km is shown for the solar terminator pass on 27 February 2015 at 16:17:48 UT . For the calculation the period of time from 15:17 UT till 18:17 UT was taken. For other considered days periods of plus-minus one hour from the time of a sunset at the 75 km have been analysed. Symbols τ_{ac} and τ_{bv} denote the cut-off and Brunt-Väisälä periods, respectively. The power density spectrum in Fig. 2 exhibits two distinct peaks. As the result of the analyses of our experimental spectra on the basis of the theory of AGW and the empirical atmosphere model NRLMSISE-00 resonance atmosphere oscillations with the acoustic cut-off period and the Brunt-Väisälä period were identified [*Hines*, 1974]:

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

where $\gamma = Cp/Cv$ - heat capacity ratio, k - Boltzmann constant, T - temperature, M - molecular mass, m_H - mass of hydrogen atom, g - acceleration of gravity. Spectral maxima for which $\tau < \tau_{ac}$ belong to acoustic modes (infrasound) and maxima for $\tau > \tau_{bv}$ belong to gravity modes.

In Fig. 3 values of temperature calculated from the experimental data at the height of 75 km are presented (blue dots). As it can be seen, they show a seasonal behavior of the temperature decreases from ~ 235 K in January to ~ 210 K in April and increases from ~ 210 K in October to ~ 270 K in December. It is worth to mention that the received temperature is the mean temperature for the two hour's time period taken for calculation and we refer it to the middle of the period i.e. to the time of a sunset.

4. Concusion

The method for definition of temperature in the lower ionosphere is presented. It uses the theory of acoustic-gravity waves and the empirical model of composition and temperature of the atmosphere (NRLMSISE-00) as well as the experimental data of the partial reflection method for calculation of the resonance atmosphere periods of oscillations: the acoustic cut-off period and the Brunt-Väisälä period. It gives the opportunity to estimate the temperature at the heights of the D-region of the ionosphere or at the heights of the mesosphere and the lower thermosphere. The first results show season dependence of the calculated temperature. For the point of observations (69.0N, 35.7E) a seasonal change in neutral temperature at the height of 75 km was obtained: temperature decreases from ~ 235 K in January to ~ 210 K in April and increases from ~ 210 K in October to ~ 270 K in December.

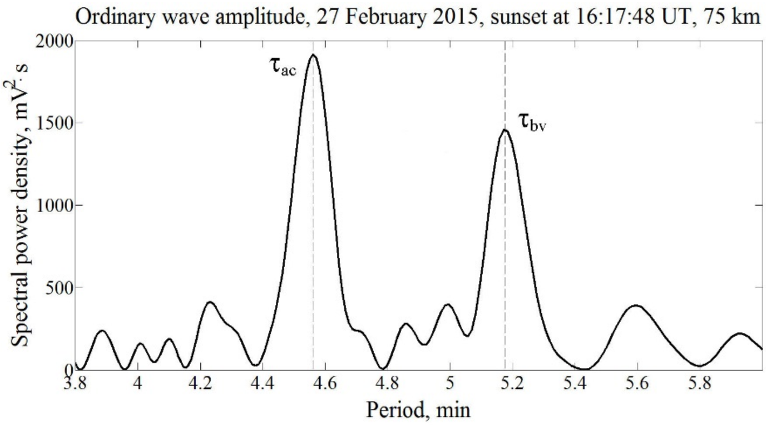

Figure 2. Spectral power density of the partially reflected ordinary wave at the height 75 km with the cut-off and the Brunt-Väisälä periods, filtered by the digital elliptical bandpass filter from the radio signal.

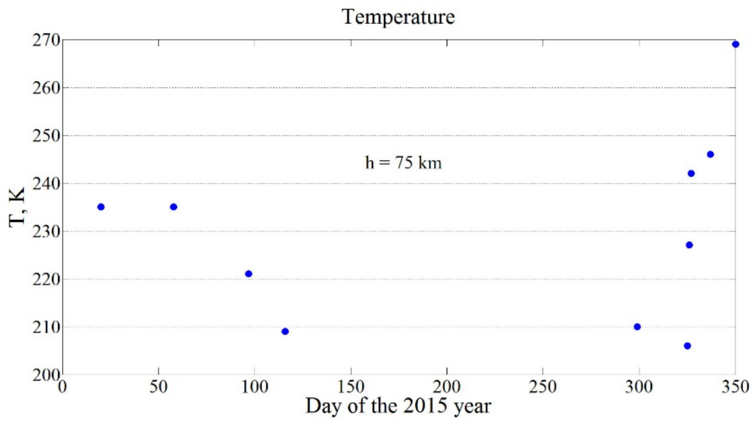

Figure 3. Temperature at the 75 km for different seasons of 2015.

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