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VARIATIONS IN MESOSPHERIC TEMPERATURE DURING POLAR MESOSPHERIC SUMMER ECHOES

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Abstract. The behavior of the ordinary radio wave amplitude at the frequency of 2.66 MHz of the partial reflection radar of the Polar Geophysical Institute (Tumanny observatory, Murmansk region, 69.0N, 35.7E) during the appearance of the polar mesospheric summer echoes on August 15, 2015 was considered. Using of radio physical method from the spectra of the amplitude at different heights the mesospheric temperature profile was calculated for the considered data. Significant reduction of temperature values near the heights of the mesopause corresponded to sharp changes in the amplitude spectra of the ordinary wave.

Polar Mesospheric Summer Echoes (PMSE) is intense reflection of radio waves that occurs most often in the polar lower ionosphere in the summer at the height interval of 80–90 km near the mesopause [*Rapp and Lübken*, 2004]. This effect of intense reflection of radio waves in the VHF range at mesospheric heights was first detected in the late 70s on the SOUSY radar (53.5 MHz, Germany) [*Czechowsky et al.*, 1979], and then on the 50 MHz MST (mesosphere-stratosphere-troposphere) radar at Poker Flat (Alaska) [*Ecklund and Balsley*, 1981]. Subsequently, this effect in the polar region was also observed by other researchers [*Vlaskov and Bogolyubov*, 1998]. It was shown that during some periods the polar summer mesosphere intensely reflects radio waves. The most surprising thing was that such reflections should not have existed at all. The classical theory of scattering of radio waves from turbulent structures of electron density existing at that time could not explain this effect. So far, various hypotheses have been proposed, ranging from gravity waves and turbulence to aerosols, but the exact cause of PMSE is still unknown. Since at first this unusual phenomenon was more often observed only in summer, it was called the polar mesospheric summer echoes. Later, a similar effect was also observed in winter. By analogy with the summer echoes, the winter effect is called the Polar Mesospheric Winter Echoes (PMWE). Numerous studies in this direction have led to the understanding that this PMSE phenomenon is associated with increased turbulence, the existence of charged aerosols, and low temperatures in the mesosphere.

Temperature in the mesosphere is one of the most important characteristics of the atmosphere, determining the dynamic and photochemical processes in it. 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 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, but for many years this was the only way to obtain various and more or less reliable information about the mesosphere.

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. Active observations of the mesosphere from Earth became possible after the creation of powerful radar facilities and lidars. Among the radars that make it possible to explore this region of the atmosphere, it is necessary to note a) partial reflection radars (operating frequencies 2-6 MHz), b) mesosphere-stratospherictropospheric (MST) radars (operating frequencies about 50 MHz), c) incoherent scatter radars (operating frequencies above 150 MHz).

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* [1953]. 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. 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), The partial reflection facility of the Polar Geophysical Institute for the study of the lower ionosphere consists of a transmitter, a receiver, a receiving-transmitting phased array and an automated data acquisition system [*Tereshchenko et al.*, 2003]. It is located at the Tumanny observatory (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 160 km. The step of data recording in height is $h = 0.5 \cdot n$ km, where $n = 1, 2, 3, ...$.

Basic acoustic-gravity wave theory in the atmosphere gives an opportunity to describe many of wave-like oscillations in the atmosphere. 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 (period) and the Brunt-Väisälä frequency (period). 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 and the Brunt-Väisälä periods give the opportunity to estimate the temperature at the heights of the D-region of the ionosphere or at the heights of the mesosphere [*Cherniakov and Turyansky*, 2020].

In the literature, it is noted that PMSE occurs in the same seasons and at almost the same altitudes as Noctilucent clouds (NLCs): noctilucent clouds are usually located at heights of 80-85 km, and PMSE - at the heights of 80-90 km [*Rapp and Lübken*, 2004]. This led to the assumption that these are rather closely related phenomena occurring simultaneously. The first joint observations of PMSE and NLCs were described by *Nussbaumer et al.* [1996]. Of the total number of observations of NLCs and PMSE, their simultaneous occurrence was noted by these authors in 80% of registrations, while in most cases NLCs were located below the lower edge of the PMSE. This allowed the authors to conclude that low temperatures and ice particles play an important role in the appearance of radar echoes. The appearance and duration of observation of PMSE and NLCs are closely related to temperature, since the lower the temperature, the more likely the formation of charged aerosols, which reflect radio waves. Subsequently, a lot of works were devoted to joint observations of PMSE and NLCs [*Cho and Röttger*, 1997; *Roldugin et al.*, 2018]. The relationship between PMSE and NLCs, however, is ambiguous - there are NLCs without PMSE, and vice versa. An analysis of joint observations shows that these are still different phenomena. A large difference in the physics of both phenomena was pointed out in [*Kirkwood et al.*, 2002].

Special conditions for the formation of PMSE and NLCs arise at the altitudes of the polar summer mesopause. The mesopause is the upper boundary of the mesosphere, where the temperature has a minimum, then increases with height in the thermosphere. The mesopause region at high latitudes in summer is the coldest region of the earth's atmosphere. There is agreement between researchers of this region of the atmosphere that conditions for reflection of radio waves at low temperatures are formed in this region. NLCs, whose morphology is similar to that of PMSE, are composed of ice particles that condense at nucleation centers (such centers can be meteoric dust or cluster ions). Low temperatures are a prerequisite for ice formation, since the concentration of water at these altitudes is very low.

It is still very difficult to detect PMSE structures at frequencies of the order of 2-3 MHz. In fact, during PMSE periods, the partial reflection signal consists of two components: normal partial reflection and reflection related to PMSE. In principle, it is impossible to strictly separate these components. Various characteristics of the reflected signal at the HF frequencies are distinguished, which indicate the presence of PMSE, for example: at the heights where these PMSE appear, the amplitude of the scattered signal has sharp gradients; PMSE are observed throughout the considered range of heights (80-90 km), but with the greatest probability in the region of heights 84-87 km.

Currently, none of the PMSE researchers question the fact that low temperatures are a prerequisite for the onset of PMSE. In the work [*Inhester et al.*, 1994] data of temperature measurements during rocket launches during the periods when the MST radar recorded PMSE are given. The instruments on the rockets actually measured the temperature in the areas from which the PMSE was recorded. The main conclusion of this work: PMSE is recorded by radar at temperatures below 140 K.

On 15 August 2015 NLCs were observed over the Kola Peninsula [*Roldugin et al.*, 2019]. Weather conditions for optical observations were good, and NLCs were recorded by a camera from an observation point in the city of Apatity and an all-sky TV camera at the Apatity observatory, located 4 km from the city. Visually, NLCs were observed from about 20:30 UT, and at 22:08 UT visual and photographic observations were terminated. NLCs projections on the ground were built from television images, assuming their height is 80 km. At this time in the Tumanny observatory operated the partial reflection radar (RFR) at the frequency of 2.66 MHz, which recorded the amplitudes of ordinary and extraordinary waves at altitudes from 50 to 160 km with a time resolution of 1 s and with the height step of 0.5 km. According to visual observations, NLCs appeared above the radar at 20:40 UT, and the appearance of PMSE at heights of 83-87 km begins only at 21:15 UT, i.e. 35 minutes later. In fig. 1 a two-dimensional distribution of a partially reflected signal of an ordinary radio wave for 14 August 2015 (left figure) and 15 August 2015 (right figure) are shown. The day preceding the appearance of PMSE was geomagnetically quite (daily ∑Kp = 4) and can be considered as a control day. During the considered period of time on the control day of 14 August, the lower boundary of the radio wave reflections was relatively constant. On the other hand, on 15 August, at approximately 21:12 UT, it sharply dropped by about 6 km to 83-83 km, and this state lasted for more than 1 hour.

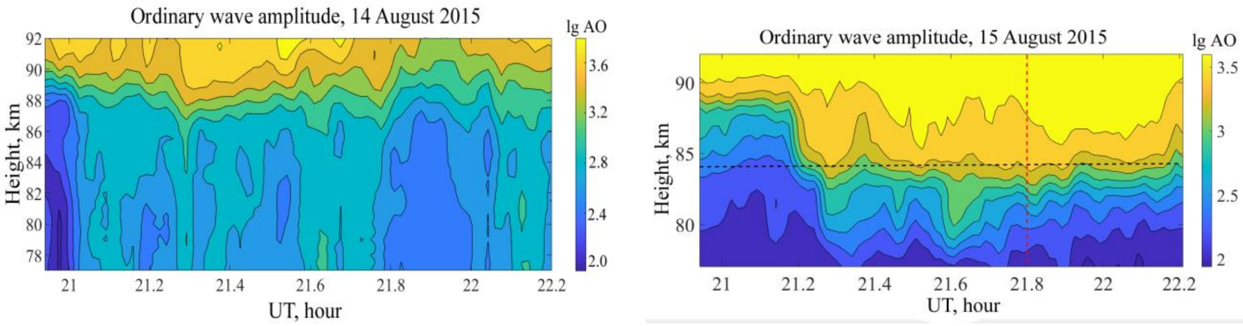
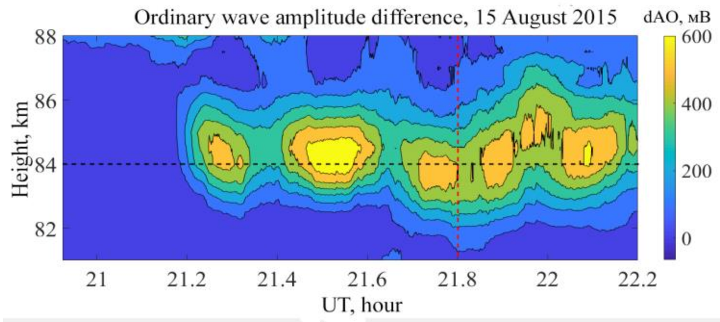


Figure 1. Left figure: two-dimensional picture of ordinary wave amplitude distribution on 14 August 2015; right figure: the same for 15 August 2015.

To find the change in the amplitude of the reflected signal with the height, the amplitude of the reflected signal at a lower height was subtracted from the amplitude at a higher height. The amplitudes of the reflected signal were recorded every 0.5 km, thus, the figure shows the difference in amplitudes every 0.5 km of altitude. In fig. 2a (left figure) the difference in amplitudes every 0.5 km during PMSE recording is shown. It can be seen that the main change in the amplitudes was at the altitudes of 83-86 km.

The calculation of the height temperature profile was carried out for 21:48 UT, in the middle of the period of stable existence of the PMSE. To calculate the spectra, we used the one-second data of the hourly amplitude of the partially reflected ordinary wave, which includes half an hour before and half an hour after 21:48 UT. Spectra of temporal variations in the amplitude were calculated from the time series of the amplitude of the partially reflected ordinary wave at each of the heights. From the experimental amplitude spectra, the spectral components corresponding to atmospheric resonances were identified, and the neutral temperature was calculated. The calculated height profile of the neutral temperature for 21:48 UT is shown in Fig. 2b (the considered time is shown by a vertical dashed line). The horizontal lines at the profile show the temperature errors. At 84 km, the temperature shows a sharp decrease. The horizontal dashed line in Fig. 2a shows the height of 84 km, at which the temperature reached its minimum value. This height corresponds to the heights at which the change in the amplitude of the reflected signal is greatest. Low temperatures may indicate the mechanism of signal reflection associated with the formation of charged aerosols at low temperatures.

During Polar Mesospheric Summer Echoes over the Kola Peninsula on August 15, 2015, the neutral temperature for the heights from 70 km till 90 km and the time of 21:48 UT was considered. The temperature was determined from spectral characteristics of the partially reflected ordinary wave amplitude using the previously proposed method for determining the mesospheric temperature. At the heights of the PMSE, the temperature showed a sharp decrease to 160 K.



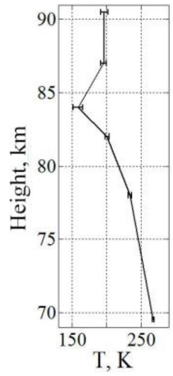


Figure 2a. Height ordinary wave amplitude difference on 15 August 2015.

Figure 2b. Height variation of neutral temperature at 21:48 UT 15 August 2015.

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