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# The response time of PMSE to ionospheric heating

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[1] During July of 1999, experiments were conducted in northern Norway to investigate the effects of ionospheric heating on polar mesosphere summer echoes (PMSE). The experiments were conducted using the European incoherent scatter (EISCAT) VHF radar and heating facility. It was shown that heating can dramatically reduce the backscattered echo power of PMSE. Here, we reexamine the high temporal resolution data of the PMSE backscattered power from three of the experiments as a function of ionospheric heating. Particular attention is paid to the transitions from the heater off-to-on and on-to-off states. The transition times of the PMSE echo power from high to low and low to high, respectively, is estimated in both cases to be less than 30 ms. It is suggested that enhancement of the electron diffusivity during heating is unlikely to account for such a fast decrease of radar backscattered power when the heater is switched on. We consider that an increase of the electron Debye length up to a significant fraction of a radar wavelength due to electron heating will change scattering character that might explain the observed heating effect on PMSE. *INDEX TERMS:* 2427 Ionosphere: Ionosphere/atmosphere interactions (0335); 2403 Ionosphere: Active experiments; 3332 Meteorology and Atmospheric Dynamics: Mesospheric dynamics; *KEYWORDS:* PMSE, polar mesosphere, ionospheric heating, radars

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## 1. Introduction

[2] The polar mesosphere/ionosphere plays host to a wide range of dynamic and chemical processes. There are breaking atmospheric waves, which deposit momentum and energy, precipitating energetic particles that affect the ion composition, and in the summer months, cold temperatures, which lead to aerosol formation. Furthermore, an understanding of the dynamical coupling between the upper mesosphere and lower thermosphere across the mesopause is complicated by the disparate physics that dominate in these two domains, especially at high latitudes [*Hocking*, 1996]. Unfortunately, obtaining data from the polar mesopause region is difficult, which makes the data that we have all the more valuable when trying to unlock some of its mysteries.

[3] The mesosphere-stratosphere-troposphere (MST) class of Doppler VHF radars has been a great asset in advancing our knowledge of the polar mesosphere. VHF radar signals are weakly backscattered from meter-scale irregularities of the refractive index, which at mesospheric altitudes are caused by fluctuations of electron density. The radar returns from these heights are particularly weak and are only detected from intermittently occurring layers of thin vertical extent. However, *Ecklund and Balsley* [1981] reported the observation of abnormally strong and persistent radar returns from the mesopause region (around 85 km altitude) above Alaska during the midsummer months. This phenomenon has been termed polar mesosphere summer echoes (PMSE) [*Röttger et al.*, 1988], although they have also been observed at midlatitudes [e.g., *Reid et al.*, 1989; *Thomas et al.*, 1992; *Chilson et al.*, 1997]. Overviews of PMSE are given by *Cho and Kelley* [1993] and *Cho and Röttger* [1997].

[4] The intriguing aspect of PMSE lies in the fact that traditional radar scattering theory cannot explain the large backscattered powers observed in connection with them. At mesospheric heights, radar signals are dominated by Bragg scatter, resulting from turbulent fluctuations of the free electrons. That is, the observed backscattered power results from a single component of the three-dimensional refractive-index spectrum sampled at the Bragg wave vector. In the inertial subrange, the three-dimensional spectrum decays as $k^{-11/3}$, where k is the wave number. See for example, *Tennekes and Lumby* [1972] and *Hinze* [1975] for a discussion of the Kolmogorov spectrum and its different slope regimes. The decay is much faster for wave numbers within the dissipation range. Turbulent fluctuations near the mesopause generally exist at spatial scales that lie within the dissipation range for those frequencies used by MST radars. Near the mesopause, the ratio of the neutral atmospheric molecular diffusion rate $\nu$ and the electron diffusion rate $D$ is typically close to one. This ratio is known as the Schmidt number, and is defined as $Sc = \nu/D$. However, when $Sc > 1$,

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*Kelley et al.* [1987] showed that the Bragg match for MST radars occurs within an extension to the fluctuation spectrum that appears just beyond the viscous cutoff. In the viscous-convective subrange, the energy of the three-dimensional turbulence spectrum drops off as $k^{-3}$. The enhancement in the Schmidt number can be attributed to suppression of electron diffusivity in the presence of low mobile charged aerosols or dust particles [*Cho et al.*, 1992].

[5] Nevertheless, neutral turbulence as a source of electron density fluctuations cannot fully account for all types of PMSE. At least four nonturbulent mechanisms have been proposed to generate electron density fluctuations in the mesopause region (see, for example, the review by *Cho and Röttger* [1997]). Whatever the mechanism of PMSE generation, the fluctuations in electron density are being smoothed out by electron diffusion. Reduced electron diffusivity seems to play a significant role in both turbulent and nonturbulent theories of generation of PMSE. If neutral turbulence is responsible for PMSE, the aerosols are thought to reduce electron diffusivity and allow electron fluctuations to exist on smaller spatial scales than those for the neutral gas. Constraints on electron diffusivity are included in almost all generation mechanisms proposed in the nonturbulent theories.

[6] The EISCAT (European incoherent scatter) VHF radar located near Tromsø has been used for PMSE observations in many experiments [e.g., *Röttger et al.*, 1988, 1990; *Chilson et al.*, 2001; *Goldberg et al.*, 2001]. PMSE observed with this radar show similar features as those observed with MST radar [*Hoppe et al.*, 1988]. The same site is the location of the EISCAT powerful HF heating facility. Electromagnetic waves transmitted with this facility are capable of heating electrons in the ionosphere and thus modifying the plasma state [*Rietveld et al.*, 1993]. Through application of this method, electron temperatures at mesospheric heights can be increased by up to an order of magnitude [*Belova et al.*, 1995].

[7] The first successful joint PMSE/heating experiment was conducted in July 1999. The experiment was motivated by the intention of influencing the electron temperature near the mesopause using the EISCAT heating facility during a PMSE event. Some of the processes such as aerosol charging and electron diffusivity, which are likely important for PMSE generation, are dependent on the electron temperature. By analyzing the reaction of PMSE to heating, we expected to obtain new information regarding the role of these processes in the formation of PMSE.

[8] The effect of electron heating on PMSE power as measured with the EISCAT VHF radar was observed as a decrease when the heating facility was switched on [*Chilson et al.*, 2000]. We found also that the reaction time of the modulation in PMSE power to the heating was less than two seconds [*Chilson et al.*, 2000]. Such a quick response of PMSE to heating allowed us to suggest that increasing the electron diffusion might be responsible for the dissipation of PMSE. Irregularities in electron density, which we detect as PMSE, can dissipate due to enhanced diffusion caused by the electron temperature increase. *Rapp and Lübken* [2000] have reported a theoretical study of diffusion in a multicomponent plasma under enhanced electron temperature conditions. According to their calculations, for the case of $T_e = 20 \times T_n$, where $T_e$ and $T_n$ are the electron and neutral temperature, respectively, and for a ratio of attached to free charge of 20, the diffusion decay time is about 0.1 s. In order to make more definitive conclusions, further analysis of the experimental data is needed, which takes full advantage of the available higher temporal resolution.

[9] We begin by reviewing the radar and heater parameters used during the experiment. Then data examples from three of the experiments are presented at a higher temporal resolution than was given in *Chilson et al.* [2000]. Based on these results, a new mechanism is proposed as being responsible for the decay in PMSE power due to the heating.

## 2. Experimental Configuration

[10] The joint PMSE/heating experiment reported here was conducted at the EISCAT site near Tromsø, Norway (69.58°N, 19.22°E), on July 9–11, 1999. The EISCAT VHF radar was used to detect PMSE and the EISCAT heating facility to heat the ionosphere. A description of the experiment can be found in *Chilson et al.* [2000], however, we repeat some of the salient features here for the sake of convenience to the reader.

[11] The EISCAT VHF radar was operated at a frequency of 224.0 MHz, which corresponds to a radar wavelength of 1.33 m. Pulses were transmitted with an inter–pulse period of 2.487 ms, and 12 samples were coherently averaged to produce a single complex (in–phase and quadrature) data point. This results in a time resolution of 29.85 ms. A total of 64 data points were stored as a single data record before writing the information to a disk. The resulting dwell time was 1.88 s, but the data dump interval was 2 s. A technical description regarding the radar can be found in *La Hoz et al.* [1989].

[12] The EISCAT heating facility is capable of transmitting powerful radio waves in the frequency range of 3.85 to 8 MHz [*Rietveld et al.*, 1993]. The facility was operated over a large range of configurations for the collective set of experiments, so the parameters are discussed on a case-by-case basis in the next section. The time intervals of heating that we discuss below were either 10 s or 20 s; i.e., both were proportional to the dump interval of the radar. The heating on/off transitions were also synchronized to the radar's sampling interval start times.

## 3. Data Analysis and Results

[13] In a previous study [*Belova et al.*, 2001] it was shown that the effect of heating on PMSE depended strongly on the background level of the PMSE, which in turn showed high variability. To eliminate this effect we have here selected three time-height ranges with a fairly stable background level of PMSE and have analyzed the data with a time resolution of 29.85 ms. These cases are denoted as exp01, exp04, and exp07. Here we have adopted the original experimental numbering as given in *Chilson et al.* [2000]. The relevant heating parameters for these three cases are provided below.

[14] Experiment 1 (exp01) was conducted on July 9, and we have chosen to use a 14-minute-long data segment during the time interval of 22:29–22:43 UT. The heater was operated in the extraordinary mode (this is likewise true for the other two experiments considered) at a transmitting

frequency of 4.04 MHz and with an effective radiated power (ERP) of 194 MW. The transmitted signals were directed vertically. The heater was switched on for 10 s and then switched off for 10 s, and this modulation pattern was repeated many times.

[15] We use a 15-minute-long data segment from experiment 4 (exp04), which took place on July 10. The time interval ran from 01:04 to 01:19 UT. The heater transmitted at a frequency of 5.423 MHz with an ERP of 629 MW. This was the highest value of ERP for all of the experiments. Again the heater was directed vertically, but for this experiment, the heater modulation pattern was 20 s on and 20 s off.

[16] Finally, we consider a 5-minute-long data segment from experiment 7 (exp07), which was carried out on July 10. The time interval in this case is 22:32–22:37 UT. The heater was operated at a frequency of 4.04 MHz with an ERP of 183 MW. This time the heater was left on for the entire time of the experiment. Modulation of the heating effect was accomplished by steering the heater beam 10 s in the vertical direction and then 10 s 16° off zenith toward the south. In the latter case, the heater does not illuminate the same volume as observed by the radar, so it can be considered as if the heater were off. Beam steering is implemented electronically using antenna array phase modulation within 0.2 ms, which is much shorter than the radar's data sampling rate of 30 ms. Therefore, from the perspective of the radar data, one can consider that the beam steering was accomplished almost instantaneously.

[17] *Chilson et al.* [2000] mentioned that the transmitted radar power was slightly reduced when the heater was on. Thus, radar backscattered power should be corrected for exp01 and exp04 to obtain the real heating effect in PMSE. However, from Figure 4 of *Chilson et al.* [2000], it is clear that the transmitted power was reduced only by about 10%; this figure also exhibits a time constant in the transmit power corresponding to the activation of the heater of about 8 s. During the time of the 1999 experiment, the transmitter high voltage was smoothed digitally and the transmitted power then was calculated. Therefore, the apparent time constant results from this smoothing process and actual variations in the transmitted power could have occurred on a shorter timescale. However, we still only expect an average drop in transmit power of about 10%, which is less than the observed reduction in PMSE power that corresponded with the heating. Note that by leaving the heater on continuously as in experiment 4, one need not consider dips in the radar's transmitted power as a function of the heater state.

[18] The backscattered powers during those time intervals and heights chosen for analysis have first been separated relative to the heater state at the time of the observations, that is, relative to whether the heater was on or off. Outliers in the time series data for the power were identified as those that occurred beyond three standard deviations of the mean calculated for every time interval chosen for analysis. The outliers were then removed from the time series. The signals for all intervals corresponding to heater on or off states have been averaged in the following way. The first data point collected after the heater was turned on was averaged together with all of the other first data points. This is then likewise done for the subsequent points. An example of the average backscattered power obtained is presented in Figure 1, where the abscissa shows the time relative to the heater being switched on (upper panel) or off (lower panel). Gaps of 0.12 s in every two-second interval are clearly seen from the plots.

[19] The temporal behavior of the PMSE power for exp01, exp04, and exp07 is presented in Figures 2, 3, and 4, respectively. For each experiment there are two plots corresponding to the transitions of heater on to heater off and heater off to heater on. Time is shown along the abscissa and is measured in seconds from the beginning or from the end of a heater-on interval, depending on the sequence of the heater status. We show in the figure only four-second intervals containing the most interesting region; i.e., when the heater is switched from on to off (or vice versa). Mean values and standard deviations obtained for the entire intervals of heater on and off are shown with solid and dashed lines, respectively.

[20] The effect of heating on PMSE power is seen distinctly for all three experiments. The greatest reduction of PMSE power occurred as might be expected for exp04, when the heating was most powerful.

## 4. Discussion

[21] First we consider the reaction time of the PMSE power to heating. Unfortunately, due to the data-sampling arrangement, there is a gap in the PMSE power data corresponding to the last 0.12 s of each heating-on or heating-off period. Consider, for example, exp04 and the sequence of heater on for 20 s and heater off for the next 20 s. A mean value of PMSE power for the heater-on interval is $1.9 \times 10^5$ (arbitrary units) with a standard deviation of $7 \times 10^4$. The corresponding quantities for the period when the heater was off are $1.8 \times 10^6$ and $7 \times 10^5$, respectively. One might reasonably expect that during the last 0.12 s of each 20 s period, the PMSE power would lie within the limits defined by the same mean and the same standard deviation as for the previous 19.88 s. The heater was switched off exactly (within 0.6 ms) at the time corresponding to the time mark of 20 s on the plot in Figure 3. The first data point was obtained 30 ms after this time (but in an average of the power over 30 ms), and the corresponding PMSE power at this moment has already increased to the PMSE background level. One can conclude that the time for the PMSE to react to heater switch-off is close to or less than our time resolution, i.e., 30 ms or less. Similar considerations apply for the opposite sequence, heater off - heater on, for exp04, and for both switching directions for exp01. The situation is not so clear for exp07 due to the smaller heating effect and relatively high standard deviation.

[22] Close examination of the bottom panels in Figures 2, 3 and 4, which correspond to the sequence of heater off to heater on, reveals one further feature. The first data points obtained just 30 ms after heater switch-on have values higher than one standard deviation above the mean for the heater-on state. This could mean that the time constant for the transition from background to heated state is slightly longer than the time resolution of 30 ms. However, we cannot make a firm conclusion when considering only three data points (one for each experiment), since significant numbers (16%) of individual points in the time series will exceed one standard deviation above the mean by pure chance.

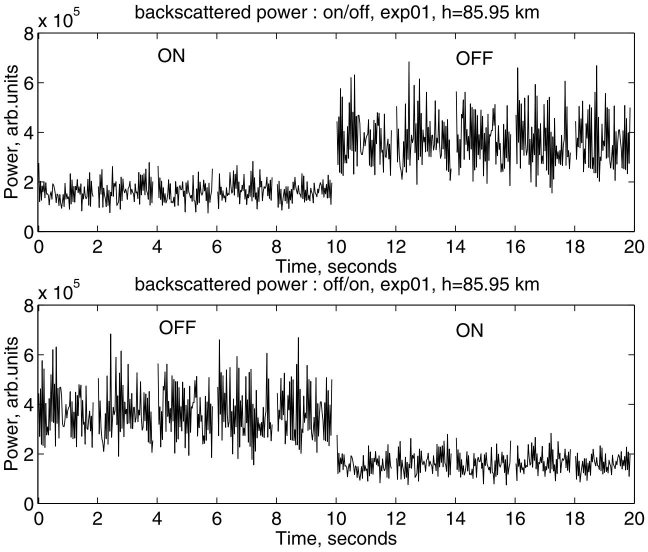

**Figure 1.** Examples of the transition in averaged PMSE backscattered power as a function of electron heating. Transition in the state of the heater from on to off and off to on are depicted in the upper panel and lower panel, respectively. Measurements used for both examples are taken for the same height.

[23] In order to suggest a possible mechanism which is responsible for such a quick response of PMSE to ionospheric heating we will begin by considering radar wave scattering. At mesospheric altitudes the radar signals are backscattered by electron density irregularities with the spatial scale being equal to a half radar wavelength (the Bragg condition). Radar backscattered power is proportional to the square of an electron fluctuation magnitude.

[24] *Hill* [1978] obtained for timescales longer than those for the free electron diffusion a relationship between spatial spectra of electron and ion density fluctuations $n_e$ and $n_i$, respectively:

$$n_e(k,t) = \frac{\sum\limits_{\beta \neq e} S_\beta n_\beta(k,t)}{1 + (k\lambda_D)^2}, \tag{1}$$

where $S_\beta$ is the ratio of the charge of species β (other than electrons) to electron charge, k is the spatial Fourier component, and $\lambda_D$ is the electron Debye length. For our case k is equal to the radar's Bragg wave number. The electron Debye length is given by

$$\lambda_D = \left(\varepsilon_0 k_B T_e / N_e e^2\right)^{1/2}, \tag{2}$$

or

$$\lambda_D(m) = 6.9 \cdot 10^5 \cdot \left[T_e(K)/N_e\left(m^{-3}\right)\right]^{1/2}, \tag{3}$$

where $\varepsilon_0$ is the permittivity of free space, $k_B$ is the Boltzmann constant, $N_e$ is the free electron density, and e is the electronic charge. For $k_{Br}\lambda_D \ll 1$ Equation (1) coincides with the expression for charge neutrality.

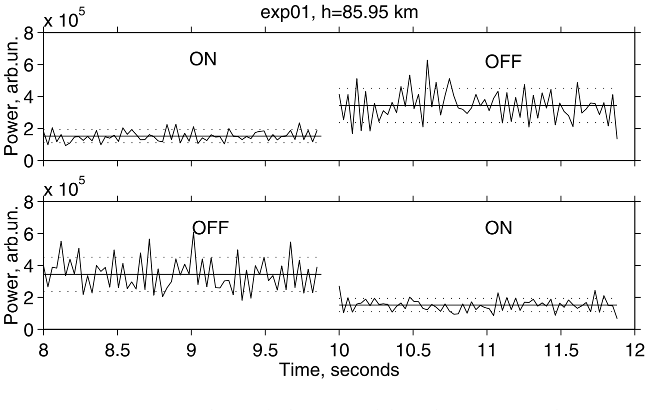

**Figure 2.** Examples of the transition in averaged PMSE backscattered power as a function of electron heating for experiment 1. The state of the heater is indicated. Mean values and standard deviations of the measurements are shown with solid and dashed lines, respectively. See text for additional information.

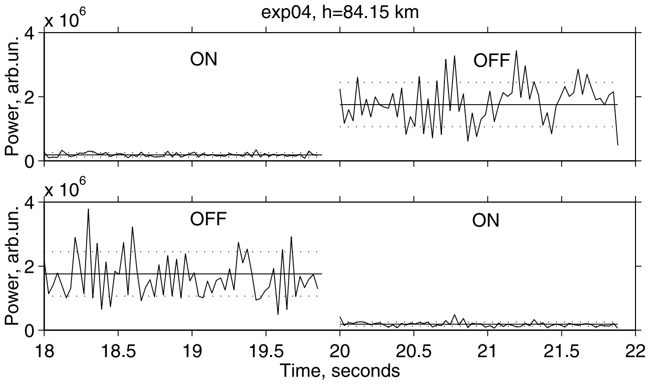

**Figure 3.** The same as in Figure 2 but for experiment 4.

[25] Applying (1) for undisturbed PMSE conditions (when the heater was switched off) and for periods of ionospheric heating, one can get:

$$\frac{P(on)}{P(off)} \propto \frac{n_e^2(on)}{n_e^2(off)} = \left(\frac{1 + (k_{Br}\lambda_D)^2}{1 + (k_{Br}\lambda'_D)^2}\right)^2, \tag{4}$$

where P (on), P(off) are PMSE powers for heating and for undisturbed conditions, respectively, $\lambda_D$ and $\lambda'_D$ are the Debye lengths calculated for undisturbed and enhanced electron temperature, respectively.

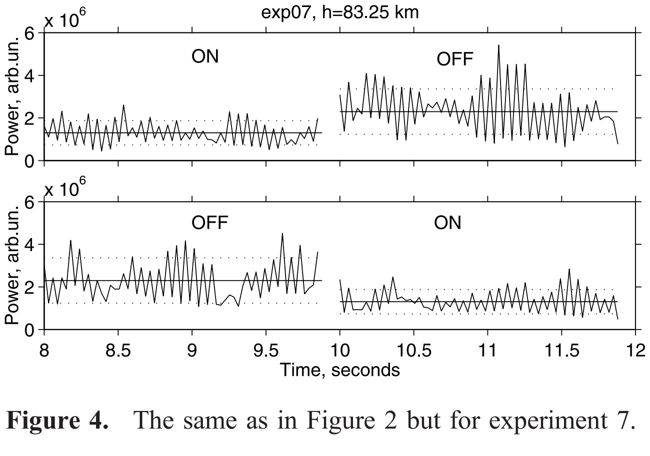

**Figure 4.** The same as in Figure 2 but for experiment 7.

[26] At the summer mesopause for the case of thermal equilibrium $T_e = T_n \sim 130$ K [*Lübken*, 1999]. Assuming $N_e = 5 \times 10^8$ m$^{-3}$ we obtain $\lambda_D = 0.035$ m, which is much smaller than $\lambda_{Br}$ for the EISCAT VHF radar of 0.67 m. Thus, the numerator at the right-hand side of (4) is close to unity.

[27] When we heat electrons their temperature can increase by a factor as large as 20 [*Belova et al.*, 2001], which leads to an increase of the electron Debye length. Let us estimate a critical electron temperature, $T_c$, and density, $N_c$, for which $\lambda'_D$ becomes equal to $1/k_{Br}$ for the case of the EISCAT VHF radar. From (3) we obtain:

$$N_c\left(m^{-3}\right) \approx 4 \cdot 10^5 \cdot T_c(K). \quad (5)$$

[28] Thus, for an electron temperature of 2500 K (roughly 20 times the thermal equilibrium value), and if $N_e$ is much less than $10^9$ m$^{-3}$, the inequality $k_{Br}\lambda_D \gg 1$ is met. Consequently, if electrons are heated enough and the electron density is not high, then the ratio described by (4) will be less than unity. This can explain the drop of PMSE power during the experiment when the heater was in operation.

[29] This can be expressed by other words, in terms of different types of radio wave scattering. If $k_{Br}\lambda_D \ll 1$, where $k_{Br}$ is a radar's Bragg wave number, then the electrons illuminated by the radio wave with approximately the same phase have to participate in plasma screening and hence, to follow thermal ion fluctuations and to participate in collective plasma motions. In the latter case, scattering of radio waves occurs on plasma irregularities and is called coherent. These electrons have also to maintain charge neutrality. This implies that electron density fluctuations are in balance with fluctuations of others charged species such as molecular and cluster ions, and aerosols. PMSE is an example of coherent scattering. This is confirmed by the strength of the echoes and narrowness of the Doppler spectra [e.g., for EISCAT observations see *Röttger et al.*, 1988].

[30] If on the other hand, $k_{Br}\lambda_D \gg 1$, then in a volume illuminated by an incident radio wave with about the same phase, the electrons can be considered as individual charged particles moving according to their thermal velocity distribution. Scattering occurring under these conditions is that on the thermal fluctuations of the free electrons. This is termed Thomson scattering. The electrons don't needs to keep charge neutrality, and fluctuations of electron density no longer follow those of ion density. Regarding the case of ionospheric heating one can say that fluctuations of electron density which lead to a strong "coherent" VHF backscatter under undisturbed (unheated) conditions get "washed away" with increase of electron temperature, and hence, of parameter $k_{Br}\lambda_D$. Due to this the radar signal power goes down.

[31] The question is how long time it will take for changes in electron density due to changes of the electron Debye length. When the heater was switched on, the electron temperature (and hence, the Debye length) increased with the characteristic time of 0.2 ms at a height of 80 km [*Gurevich*, 1978; *Rietveld et al.*, 1986]. Electron density has to adjust to a new state of charge balance described by (1). The time constant of this process is determined by free electron diffusion for enhanced electron temperature [*Hill*, 1978]; i.e.

$$\tau = \left(k_{Br}^2 D_e\right)^{-1} = \frac{\lambda_r^2 \cdot m_e \nu_{en}}{16\pi^2 \cdot k_B T_e}, \quad (6)$$

where $D_e$ is the electron diffusion coefficient, $m_e$ is the electron mass, $\nu_{en}$ is the electron-neutral collision frequency. For the EISCAT VHF radar and for undisturbed and enhanced electron temperatures of 130 K and 2500 K the transition times described by (6) are 3 and 2 μs, respectively. Thus, one can conclude that the reaction time of PMSE to ionospheric heating is defined by the time needed to heat or cool electrons.

[32] It remains to find out whether it is realistic to have a value of $N_e$ less than $10^9$ m$^{-3}$ during PMSE. *Rapp et al.* [2002] analyzed PMSE data together with all available data on electron density measured by rocket-borne instruments. According to their Table 1, PMSE were not observed in three cases when the electron density was $10^8$, $1.2 \times 10^8$ and $3 \times 10^8$ m$^{-3}$. They were observed for the remaining nine cases when the electron density was as high as $1.5 \times 10^9$–$10^{10}$ m$^{-3}$, and only once when it was $6.8 \times 10^8$ m$^{-3}$. On the basis of such a sparse data set it is difficult to confirm or reject the possibility that PMSE can exist for electron densities lower than $10^9$ m$^{-3}$.

[33] To estimate the electron density during our PMSE/heating experiments *Belova et al.* [2001] used a model for the lower ionosphere and the cosmic noise absorption data as an input parameter (see references therein). We should note that there were not any strong variations of the radio noise absorption during our experiments, indicating quiet nighttime conditions without any strong electron or proton precipitations. Model calculations give us an electron density value of about $10^8$ m$^{-3}$ at the altitudes of PMSE. This means that for an electron temperature enhanced by up to 2500 K, the Debye length could be long enough, compared with the radar wavelength, to result in Thomson scattering, and according to (4), in a decrease of radar backscattered power.

[34] *Rapp and Lübken* [2000] proposed an explanation of heating effect on PMSE based on consideration of electron diffusion in multicomponent plasma with taking into account enhanced electron temperatures. However, they modelled electron diffusion for the charge neutrality case only. We have shown above that it is not the case when we heat electrons strong enough that the electron Debye length becomes comparable with the radar's Bragg wavelength.

## 5. Conclusions

[35] We have analyzed here measurements of PMSE power sampled with high time resolution using the EISCAT VHF radar during ionospheric heating experiments. We have been able to determine an upper limit for the time required for PMSE power to respond to switching the heater on or off. We are able to conclude that this characteristic time is less than 30 ms, which was the time resolution of the radar data recorded during the experiments. We have proposed an explanation of obtained results based on changes in the electron Debye length. During heating the electron temperature at PMSE heights is expected to grow

significantly on a timescale of less than 1 ms. Increased electron temperature leads to an increase of the Debye length in the plasma. The Debye length exceeds a significant fraction of the radar wavelength if electron density is low enough. Then the radar wave scattering will change from being coherent scatter from plasma irregularities to Thomson scatter from the individual electrons, and the backscattered signal power will fall. The time constant for this process is expected to be a few μs.

[36] To determine more accurately the time constant of the response of PMSE to heating, more experiments are needed. The next experiment should have a higher time resolution. It would also be advisable to have no gap just before the heater switch-on or switch-off. However, more important would be to check that PMSE react exactly to electron temperature enhancements. This could be accomplished by measuring the incoherent spectrum or by other means.

[37] **Acknowledgments.** The EISCAT Scientific Association is funded by SA (Finland), CNRS (France), MPG (Germany), NIPR (Japan), RCN (Norway), NFR (Sweden), and PPARC (UK).

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