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Long-term aspect-sensitivity measurements of polar mesosphere summer echoes (PMSE) at Resolute Bay using a 51.5 MHz VHF radar

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ABSTRACT

Polar Mesosphere Summer Echoes (PMSE) are now a well recognized summer phenomenon in the polar regions. For more than a decade, the echoes have been continuously monitored at Resolute Bay (75.0°N, 95.0°W) using a 51.5 MHz VHF radar, which has a narrow vertically pointing beam as well as four tilted beams at 10.9° from zenith. The radar site is located inside the northern polar cap, and remains a true polar cap radar at any level of geomagnetic activity. PMSE at this location show some unique features compared with other high latitude radars operating at similar frequencies. In this paper, we investigate the aspect-sensitivity of the PMSE at Resolute Bay. This feature of PMSE, which led to debate among researchers regarding the scattering mechanisms of these echoes, has not been extensively studied, especially on a long-term basis. In this study, we use a decade-long data-set collected during 1998–2009 to investigate the aspect-sensitivity parameter by comparing the absolute backscattered powers in four off-zenith beams with the vertical beam. We concentrate on conditions when electron precipitation is weak or not present, in order to simplify comparison (precipitation is present less than 8% of the time during PMSE). It was found that the aspect-sensitivity of PMSE can be broadly categorized into three groups based on the PMSE signal strengths of strong, moderate and weak. The height profiles of the calculated aspect angle show a good agreement among all four off-zenith beams, especially in the cases of strong and moderate PMSE strengths. Our long-term investigation reveals that when PMSE are strong, they show a median aspect angle of 8° at around 84 km and a 11° at around 88 km, meaning lower PMSE layers are associated with more anisotropic scattering. These values are about 2–3° higher, when PMSE are only "moderate" strength at Resolute Bay. The height dependence of aspect-sensitivity remains consistent in the cases of strong and moderate PMSE strengths. The results are compared with the observations made by a similar radar at another polar cap location at Eureka (80.0°N, 86.0°W). The comparison shows agreement in terms of the shape of the aspect-sensitivity height profiles, but the values are about 2–3° smaller. Possible explanations are discussed.

1. Introduction

PMSE are a unique form of strong coherent radar echoes from the cold summer mesosphere at high latitudes. Initially, the echoes were observed as backscattered signals with Bragg scales of 3 m, but soon they were able to be observed by other radars, which have Bragg scales less than a metre (e.g., Röttger et al., 1988). Peculiar spatial, temporal and spectral features of these radar echoes, along with the fact that they were too strong to originate from classical turbulent scatter, made PMSE studies popular among researchers (e.g., Kelley et al., 1987; Röttger and La Hoz, 1990; Hoppe et al., 1990). As a result, several active radar campaigns with high-resolution in situ measurements were carried out, especially in the northern hemisphere, in order to analyze these echoes (e.g., Ulwick et al., 1988, 1993; Lübken et al., 1993). These studies clearly indicated that some highly unexpected physics is operative in the polar summer regions, and convinced the researchers that a new theory needed to be developed. Several theories were proposed. Most explanations have been based on the fact that electrons maintain spatial scales much smaller than the spatial scales of neutral gas when suitable conditions are present (see Cho and Kelley, 1993; Cho and Röttger, 1997; Rapp and Lübken, 2004; La Hoz et al., 2006 and references therein). Advancements in theoretical work show that such suitable conditions could arise in the polar summer mesopause with the existence of very cold temperature ($T\sim 130$ K) and production of nanometer size charged ice particles. Heavily charged ice particles could reduce diffusivity of electrons, so that they can maintain density fluctuations at much smaller scales than the neutrals (Cho et al., 1992; Rapp and Lübken, 2003).

However, some of the observed features of PMSE still need explanation. One of them is the aspect-sensitivity of the PMSE. Some of the early work with 50 MHz radar by Czechowsky et al. (1988) has shown that the echoes are highly aspect sensitive. Aspect-sensitivity

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is a property of the scatterers, which describes the variation of radar backscattered signal when the beam is tilted from the vertical direction. In general, a strong decrease in signal in the tilted beam relative to the vertical beam is seen when the scatterers are more specular in nature. On the other hand, a lack of variation with tilt angle is usually identified with isotropic scatterers. In the case of PMSE, many experiments have been carried out over the years, but only a few have been involved with aspect-sensitivity measurements (e.g., Czechowsky et al., 1988; Hoppe et al., 1990; Huaman and Balsley, 1998; Zecha et al., 2001; Chilson et al., 2002; Zecha et al., 2003). PMSE studies in the southern hemisphere have also been conducted but are limited in number, since they started more recently (e.g., Woodman et al., 1999; Jarvis et al., 2005; Morris et al., 2007).

In this paper, we present long-term aspect-sensitivity measurements for PMSE observed at Resolute Bay (75.0°N, 95.0°W). Data were collected in the months of June, July and August during years 1998–2009. The aspect-sensitivity parameter is calculated by comparing all four off-zenith beams with the vertical beam on a monthly basis. The results are then compared with observations from another similar frequency radar, located at Eureka (80.0°N, 86.0°W) in northern Canada.

2. The radar system

The Resolute Bay radar system consists of a total of 128 two-element Yagi antennas. It uses an array in the form of a cross, with four separate arms such that the north arm is aligned 19° anti-clockwise azimuthally from true north. Each arm comprises eight groups of four antennas (quartets), and covers an area of 500 m^2 with a length of 50 m (Hocking et al., 2001). Each Quartet is coupled together and connected with the transmit-receive building using a coaxial cable. The antenna array setup produces a narrow polar diagram with a one-way half-power-half-width (HPHW) of 2°. The beam not only points in the vertical direction, but also can be steered from the vertical to 10.9° along the nominal north arm, east arm, south arm and west arm. We refer to these off-zenith beams as "north-beam", "east-beam", "south-beam" and "west-beam". The system is operated at 51.5 MHz with 12 kW peak pulse power. In order to observe PMSE, 8-bit complementary coded signals are transmitted with a Pulse Repetition Frequency (PRF) of 1200 Hz. The received signals are sampled using a 750 m pulse and also are averaged using 16-point coherent integrations. Recently the radar system was absolutely calibrated using cosmic noise variations with the additional help of a commercially available calibrated noise source (Swarnalingam and Hocking, 2006, 2007). This allowed us to express the absolute signal strength of PMSE at this location in terms of backscatter cross-sections (Swarnalingam et al., 2009a). The radar has been properly maintained. The noise level at this radar location has been continuously monitored. The performance of the radar was consistent over the last decade.

3. Method of analysis

The main scattering mechanisms relevant to VHF radars had been initially classified as turbulent scatter, Fresnel (partial) reflection and thermal scatter. The turbulent scatter arises from spatial variations at the radar's Bragg scales due to turbulent process, in which case no significant level of power loss at off-zenith angles is expected compared with the vertical direction if the turbulence is isotropic. On the other hand, Fresnel reflection occurs from horizontally stratified and stable layers that extend over a horizontal width of at least one Fresnel zone (Röttger and Liu, 1978). In this case, a significant level of loss in backscattered power is expected once the beam is pointed slightly away from the vertical direction. Nevertheless, since many radar observations in the middle atmosphere were not entirely consistent with these two extreme scatter mechanisms, models with the concepts of anisotropic turbulent scatter and Fresnel scatter were later introduced (e.g., Gage and Balsley, 1980; Röttger, 1980; Gage et al., 1985; Hocking, 1987; Woodman and Chu, 1989; Hocking and Hamza, 1997 and several others). Anisotropic turbulence models can explain the observations for the case that the backscattered power changes fairly uniformly for up to a 30° of off-zenith angle. The Fresnel scatter models, which propose horizontal layers with vertically varying refractive index, can better explain the situation when the power drops dramatically as a function of zenith angle.

In order to investigate the aspect-sensitivity of the scatterers viewed by a narrow beam VHF radars, a model was proposed by Hocking (1987, 1989) (see also Briggs and Vincent, 1973; Woodman and Chu, 1989), which subsequently has been applied to study the aspect-sensitivity of the PMSE. In this model, the individual scatterers were assumed to be on average oblate spheroids, with a Gaussian increase or decrease in refractive index from the edge towards the center. The aspect-sensitivity parameter is expressed as the 1/e half-width of the angular polar diagram of the individual scatterers. Based on this, the polar diagram of the backscattered signal power, $P_s(\theta)$ as a function of off-zenith angle θ is given by

$$P_s(\theta) = \exp\left(-\frac{\sin^2\theta}{\sin^2\theta_s}\right) \tag{1}$$

where, θ_s is the 1/e half-width of the angular polar diagram of the scatterer, and is called the aspect-sensitivity parameter.

Taking into account the fact that the radar beam has a two-way finite beam width, and has a polar diagram of the form $\exp(-\sin^2\theta/\sin^2\theta_0)$ for the vertically pointing direction, where θ_0 is the 1/e half-width, and if the radar points off-vertically by angle θ_t in the azimuthal direction of $\phi = 0$, then the polar diagram of the radar beam in the direction (θ,ϕ) will be given by

$$P(\theta,\phi) = \exp\left[-\frac{(\sin\theta\sin\phi)^2 + (\sin\theta\cos\phi - \sin\theta_t)^2}{\sin^2\theta_0}\right] \tag{2}$$

(e.g., Hocking et al., 1986). If the radar observes the above type of scatterers, the effective polar diagram in the direction of (θ,ϕ) with inclusion of the polar diagram of scatter will be the product of (1) and (2). This will be maximum when the derivative of the exponent with respect to $\sin\theta$ is zero. Thus, the power received by the tilted beam in the direction of $(\theta_{\theta=t},\phi_{\phi=0})$ relative to the power received on vertical beam is given by

$$\frac{P(\theta_t)}{P(0)} = \exp\left[-\frac{(\theta_{eff}-\theta_t)^2}{\theta_0^2} + \frac{\theta_{eff}^2}{\theta_s^2}\right] \tag{3}$$

where,

$$\theta_{eff} = \arcsin\left[\sin\theta_t\left[1+\frac{\sin^2\theta_0}{\sin^2\theta_s}\right]^{-1}\right] \tag{4}$$

Solving for the aspect-sensitivity parameter θ_s (e.g., Hooper and Thomas, 1995; Hobbs et al., 2001), and also using radar backscatter cross-section will lead to

$$\theta_s = \arcsin\sqrt{\frac{\sin^2\theta_t}{\ln[\eta(0)/\eta(\theta_t)]} - \sin^2\theta_0} \tag{5}$$

where $(\eta(0)/\eta(\theta_t))$ is the ratio of the recorded backscattered cross-section on the vertical beam relative to that on an off-zenith beam at the direction of θ_t.

Several short term aspect-sensitivity studies have been conducted on PMSE at high latitudes, especially in the European sector (Reid et al., 1988; Czechowsky et al., 1988; Hoppe et al., 1990; Zecha et al., 2001).

The results of these studies showed that θ_s has a value of 5–6° especially in the lower altitude PMSE layers. At higher altitudes θ_s has larger values. A four year study in the North American sector was conducted by Huaman and Balsley (1998), and they found 10° at around 80 km and 14° at around 90 km for θ_s.

The examination of long-term aspect angle of PMSE scatterers at Resolute Bay was conducted with the two major aims. The first aim was to compare the aspect-sensitivity among the four off-zenith beams, and the second aim was to investigate how they vary from year to year.

We use hourly averages of the ratio $(\eta(0)/\eta(\theta_t))$, and consider the aspect-sensitivity distributions and their medians in one month clusters. However, in some cases only a few days of data were available per month, and these will be indicated when required. As the first step in the calculation process, the background noise was removed in all five beams. This is an important procedure, especially for the Resolute Bay radar system since the surrounding noise level at the site is high as described by Swarnalingam et al. (2009a). Once the noise was removed, the PMSE backscatter cross-sections were determined using the method described by Swarnalingam et al. (2009a). Consequently the backscatter cross-section ratio between the vertically pointing beam and the off-zenith beams were estimated separately for each off-zenith beam. During this, we also have taken into account the relative efficiency of each radar beam. This was possible since the radar system has been already absolutely calibrated (Swarnalingam and Hocking, 2006, 2007; Swarnalingam et al., 2009a). Using Eq. (5), a distribution of θ_s was produced for each height gate, considering each off-zenith beam separately. From the estimated distributions, the median values are considered for the aspect angle for that height gate. Fig. 1 shows two such distributions calculated at heights of 84 and 87.5 km for the west beam during the month July, 2000. In the figure, the calculated aspect angle distribution for the height of 84 km is marked by dark-grey bars, whereas the distribution for the height of 87.5 km is marked by light-grey bars. The first distribution has a median of 8.1° (marked by dot-dot line), and the second distribution has a median of 10.1° (marked by solid line).

One issue with Eq. (5) is that it is very sensitive when the power ratio $(\eta(0)/\eta(\theta_t))$ is very close to one. Due to this reason, we have avoided such situations in our calculations. We have considered the cases, for which $\eta(0)/\eta(\theta_t) > 1.04$. In addition, we have only considered the situations in which the aspect-sensitivity occurred in at least three height gates in the height range 81–90 km. However, cases in which these conditions were not met were few in number, and on average more than 85 percent of our data satisfied the above two conditions.

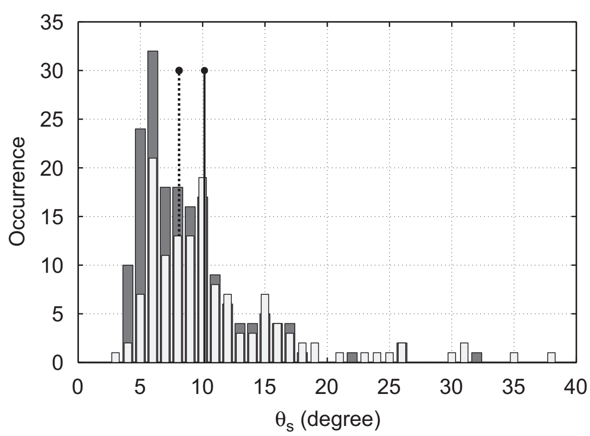

Fig. 1. An example of calculated aspect angle distributions at 84 km (dark-grey) and 87.5 km (light-grey), respectively. The median of the first distribution (at 84 km) is marked by the dot-dot line, and the median of the second distribution (at 87.5 km) is marked by the solid line. The aspect angles were estimated using hourly averaged west-beam data, collected during July 2000.

4. The variability of PMSE aspect-sensitivity and its dependence on the absolute signal strength

4.1. Representative examples

The calculated aspect-sensitivity angles appear to take different profile shapes based on the PMSE signal strengths. The first category is shown in Fig. 2. The figure shows the height profiles for the calculated aspect angles (panel (a)), when the radar recorded many occurrences of strong PMSE backscattered power (during July 2000). The right panel of the figure shows the hourly mean backscatter cross-section profiles, calculated in the vertical and the off-zenith beams during the same period. Note that the calculated aspect angles and their variations with height show a good agreement in all four off-zenith beams. This implies the existence of the stable PMSE layering structures extending to several km so that they can cover all four off-zenith beams.

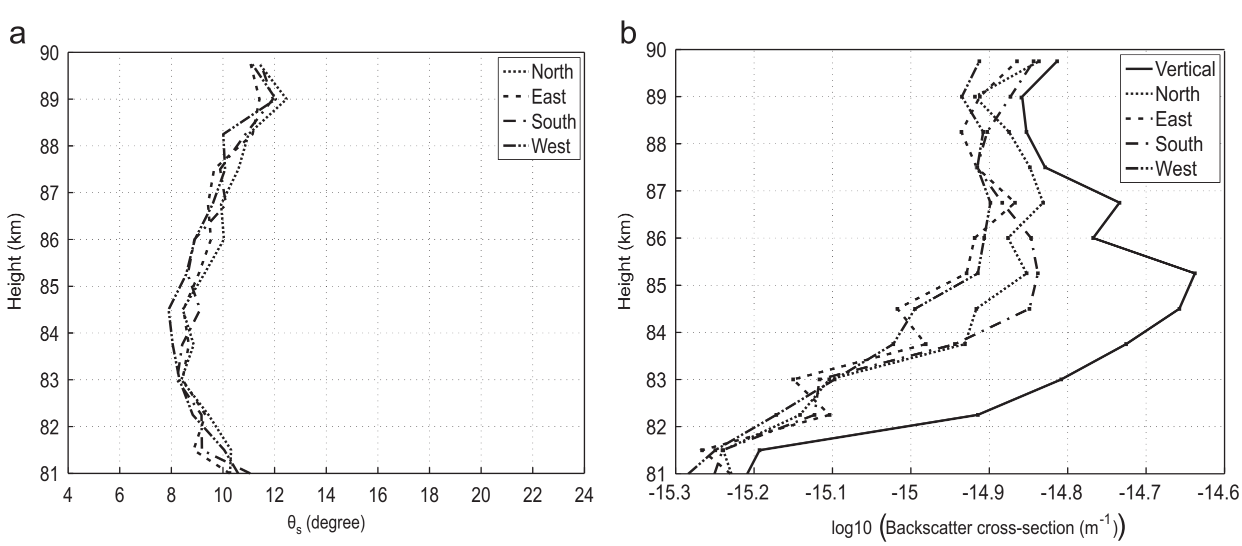

Fig. 2. Panel (a): an example of calculated hourly averaged aspect-sensitivity profile at Resolute Bay when PMSE were strong in strength. Panel (b): the corresponding backscatter cross-section profiles in the vertical and four off-zenith beams. The data used here were collected during July 2000.

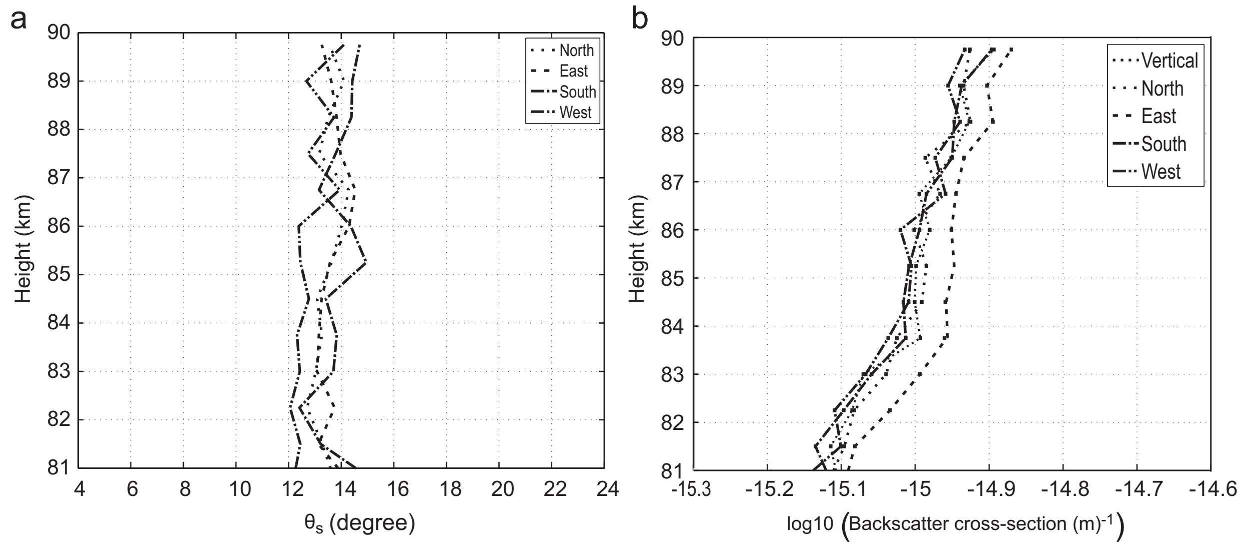

Fig. 3. Panel (a): an example of calculated aspect-sensitivity profile when PMSE were weak in strength at Resolute Bay. Panel (b): the corresponding backscatter cross-section profiles in vertical and four off-zenith beams. The data used here were collected during July 2006.

However, we do not rule out some patchy PMSE structuring for the shorter time scales, since our data are hourly averaged values. Typical θ_s values for this category are of the order of 8–12°.

The second category of the height profile is shown in Fig. 3. It shows the aspect-sensitivity measurements for the month July 2006, during which occurrences of strong PMSE backscattered power were less in number (i.e. weak PMSE strength, as it will be defined shortly). In such situations, the calculated aspect angle shows almost no variation with height and are generally larger than 12°. It can be seen from the right panel of Fig. 3 that the calculated backscatter cross-sections were significantly lower in all four beams compared with the previous case (Fig. 2-panel (b)). The estimated backscatter cross-sections in the four off-zenith beams show a steady increase from 81 to 90 km. Note that the Resolute Bay radar system is operated only with 12 kW transmitter peak power. Also, as it will discussed later, the noise level at the site is high (Swarnalingam et al., 2009a). Therefore, it is quite possible that the radar is unable to detect the weakest echoes. We verified the aspect-sensitivity angle profile with other weak PMSE seasons at Resolute Bay. The results were almost the same as shown in Fig. 3.

4.2. Long-term analysis

Representative examples of strong and weaker echoes were presented in the previous sub-section. In this section, we extend the analysis to a more complete data-set. From the work by Swarnalingam et al. (2009a), it has been noticed that the PMSE strength (in terms of backscatter cross-sections) at Resolute Bay shows variability from year to year. From the estimated backscatter cross-section distributions, it was noticeable that while the median strengths remain approximately the same, higher strength echoes are highly variable from year to year (see Swarnalingam et al., 2009a, Fig. 6). Therefore, in our long term aspect-sensitivity study, we sub-divided the estimated PMSE aspect-sensitivity profiles into three groups based on the absolute backscattered power of PMSE. We have categorized the PMSE months into strong, moderate and weak PMSE months based on the estimated backscatter cross-sections during the years 1998–2009. The strong, moderate and weak PMSE strengths at Resolute Bay were defined as shown in Table 1. The range of values of backscatter cross-sections allocated for each group were decided based on our pervious long term study of PMSE strength at this location (see Swarnalingam et al., 2009a, Fig. 6). For each month, the distribution of PMSE backscatter cross-section was calculated for the height range 80–90 km, and subsequently the 90th percentile of the distribution was compared with Table 1 to decide the PMSE strength for that month.

Fig. 4 shows the estimated aspect-sensitivity height profiles when the absolute strengths of PMSE were strong at Resolute Bay

Table 1
Defined PMSE groups at Resolute Bay based on absolute backscatter strengths observed during 1998–2009. The aspect-sensitivity angles were calculated and categorized based on these three backscatter cross-section ranges.

PMSE strength groups	Defined backscatter cross-section range
Strong	Higher than $1\times10^{-13}\ m^{-1}$
Moderate	$1\times10^{-14}\ m^{-1}$–$1\times10^{-13}\ m^{-1}$
Weak	Lower than $1\times10^{-14}\ m^{-1}$

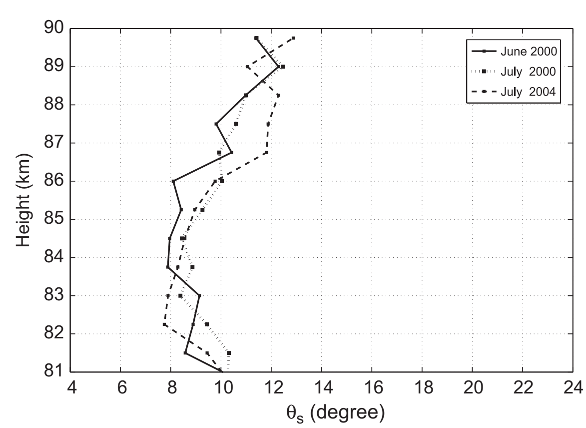

Fig. 4. Calculated monthly aspect-sensitivity profiles during strong PMSE occurrences at Resolute Bay. To determine the aspect-sensitivity height profile, aspect angle distributions were calculated at each height gate and the median values were considered. For all months, hourly averaged data from the west-beam were used. Profiles for other beams are very similar.

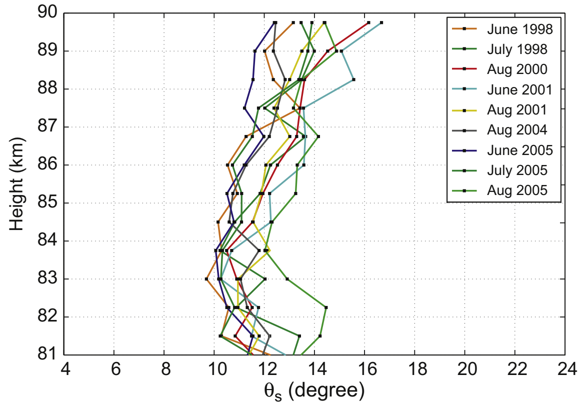

Fig. 5. Calculated median aspect-sensitivity profiles at Resolute Bay when PMSE absolute strengths were moderate during 1998–2009. Hourly averaged data from the west-beam were used. Profiles were determined by considering the medians of the aspect angle distributions at each height gate.

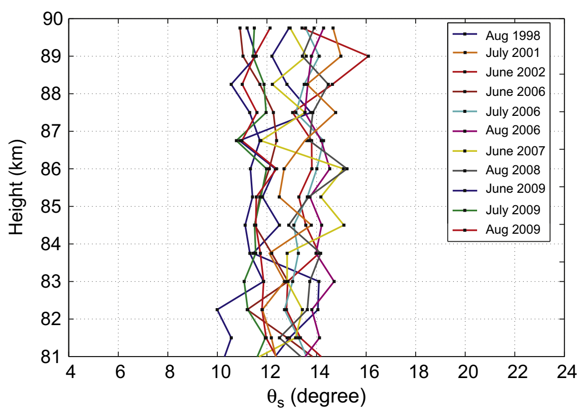

Fig. 6. Calculated aspect-sensitivity profiles at Resolute Bay when PMSE absolute strengths were weak during 1998–2009. Profiles were determined using hourly averaged data from the west-beam. Profiles were determined by considering the medians of the aspect angle distributions at each height gate.

during the years 1998–2009. That is, the estimated backscatter cross-section distributions for the vertical beam in the height range 80–90 km had its 90th percentile value equal or higher than $1\times10^{-13}\,m^{-1}$ for the months shown in the figure. The profiles were produced by calculating the aspect angle distributions for all height gates using hourly averaged data, and then by considering the median values of the distributions. The west-beam data was used for all analysis. It can be seen from the figure that when PMSE were strong, the median aspect angle is about 8–9° at around 84 km, and is about 11–12° at around 88 km. Figs. 5 and 6 show the monthly aspect-sensitivity profiles for the interval 1998–2009, in which PMSE strengths in the vertical beams were moderate and weak, respectively. The aspect angle profiles, which are associated with moderate PMSE strength (Fig. 5) also show similar shapes to those observed in the case of strong PMSE signal strengths (Fig. 4). However, their values are about 2° higher (compared to Fig. 4). In the case of weak PMSE strength, the calculated aspect angles vary on average from 11° to 15°, and remain almost constant for all height gates (Fig. 6). The aspect-sensitivity profiles for years 1999, 2002 (July and August), 2007 (August) and 2008 (June and July) were not included in these figures. PMSE strengths during these months were weak at Resolute Bay. The radar captured occasional precipitation-like events in all five beams during these periods but these were not included in our analysis, and will be a topic of future research. Data for year 2003, 2004 (June) and 2007 (July) are not available.

Our studies indicate that PMSE are more aspect nature, especially in the lower PMSE heights when they are strong or at least moderate in strength. The calculated aspect angle clearly depends on the strength of PMSE. Comparison of these values with the Poker Flat radar's mean aspect angles, which were calculated by Huaman and Balsley (1998) shows a good agreement. However, the shapes of the height profiles were variable at Poker Flat, whereas at Resolute Bay the shapes remain consistent, especially when PMSE strength is either strong or moderate.

4.3. *Long-term height dependence*

Since the calculated aspect angles show a reasonable differences between lower and upper PMSE heights, we also calculated the aspect angles for these two height regions separately. Fig. 7 shows the estimated aspect angles for the lower and upper PMSE heights during the interval of 1998–2009. The upper panel of the figure contains the median of the aspect angle distributions, calculated by only considering the height range 87.5–89 km. The lower panel contains the same for the height range 83.0–84.5 km. For each height range, hourly averaged aspect angle distribution was produced using one month of data, and then median aspect angle was determined. The west-beam data were used for each month. The strong and moderate PMSE months are marked by solid circles and solid stars, respectively. It can be noticed that the calculated aspect angles in the lower PMSE heights show a clear consistency, especially in the case of strong and moderate PMSE. While the aspect angle for strong PMSE remains under 10°, the aspect angle for moderate PMSE stays between 10 and 13°. In the upper PMSE heights (upper panel), there is no clear separation in aspect angle between strong and moderate PMSE strength, but both values fall in the range of 11–15°. The calculated aspect angles in the case of weak PMSE appear highly variable over the years.

4.4. *Correlation between power and aspect-sensitivity*

From our long term study, it is apparent that PMSE show some level of aspect-sensitivity, especially for lower heights. This feature of PMSE triggered active debate among researchers about the possibilities for two different types of scattering mechanisms associated with PMSE upper and lower layers (e.g. Ulwick et al., 1993; Lübken et al., 1993; Cho et al., 1993 and several others). While upper layers are most likely associated with turbulent scatter (either isotropic or anisotropic), the lower layers could be associated with Fresnel reflections or Fresnel scatter. If this is the case, then one would expect echo spectral widths to positively correlate with recorded power in the upper layers whereas the two quantities should correlate negatively in the lower layers. While Czechowsky and Rüster (1997) reported a sudden bursts of PMSE activity with an enhancement of spectral widths, Hoppe et al. (1990) reported that they could observe a negative correlation between spectral width and backscattered power with the EISCAT 224 MHz radar. At Resolute Bay, such features could not be generally observed. However, we have studied the relationship between backscattered power and the aspect angle. Fig. 8 shows such an example, in which the calculated aspect angles for the height range 83.0–84.5 km are plotted against recorded absolute backscattered powers in the vertical beam during July 2004. Although an obvious correlation does not exist, it can be seen from the figure that strong PMSE signals tend to have low aspect angles, and weak signal strengths are associated with a broader spread of aspect angles. We have verified the relationship between backscattered power and aspect angle in other months, and found very similar features, especially when PMSE are strong at Resolute Bay.

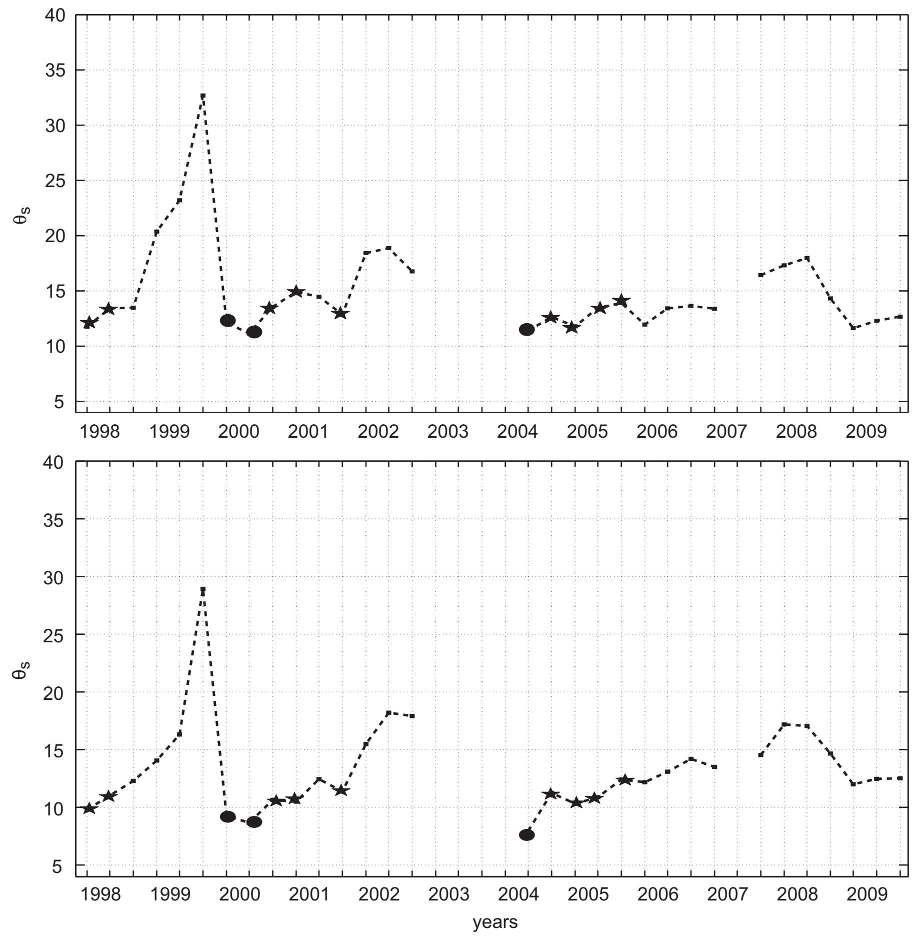

Fig. 7. Comparison of the calculated monthly median aspect angles in the height range 87.5–89 km (upper panel) and 83.0–84.5 km (lower panel) during the years 1998–2009. Data from months June, July and August were used. For each month, aspect angle distributions for upper and lower height regions were produced separately using hourly averaged data, collected in the west-beam. From the distribution, the median values were estimated. The strong PMSE months are marked by solid circles, and moderate PMSE months are marked by solid stars.

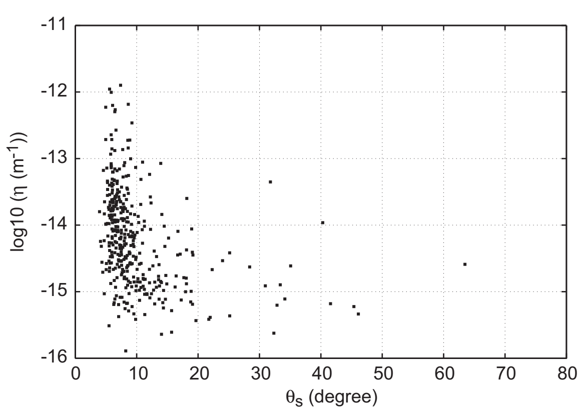

Fig. 8. Scatter plot of backscatter cross-section verses aspect angle in the height range 83.0–84.5 km during July 2004. Hourly averaged data from the west-beam were used to estimate the aspect angle.

5. Aspect-sensitivity measurements for Eureka VHF radar

A new 51.0 MHz VHF radar was recently installed at Eureka (80.0°N, 86.0°W) in northern Canada during summer 2007. The design of this new radar is similar to the Resolute Bay radar, but it is operated with a transmitter peak power of 36 kW. As in the case of Resolute Bay, the antenna array at Eureka is also a cross structure array comprising a total of 128 three-element Yagi antennas. The radar has five narrow beams with the same off-zenith angle as for Resolute Bay (10.9°) and also with a one-way HPHW of 2.75°, but with lower sidelobes than the Resolute Bay radar. The new polar cap radar started its operation for PMSE observation from late July 2007. Table 2 compares the system parameters and the PMSE experimental configurations for the Resolute Bay radar and the Eureka radar.

Table 2
A summary of the system and experimental parameters for the Resolute Bay and Eureka radars.

	Resolute Bay	Eureka
Frequency (MHz)	51.5	51.0
Peak power (kW)	12	36
Range resolution (vertical) (m)	750	750
Antenna gain (transmission) (dB)	24	24.3
Antenna gain (reception) (dB)	24	24.3
HPHW	2°	2.75°
PRF (Hz)	1200	1200
Code	8-bit comp.	4-bit comp.
Coherent integration	16-point	16-point

We performed aspect-sensitivity measurements at the Eureka radar using the same method as that applied to the Resolute Bay radar. Although a reasonable agreement appear in general in terms of the shape of the aspect-sensitivity profiles, the calculated aspect angles at Eureka are on average 2–3° lower than the aspect angles at Resolute Bay. Fig. 9 shows the calculated aspect angles at the two radars during

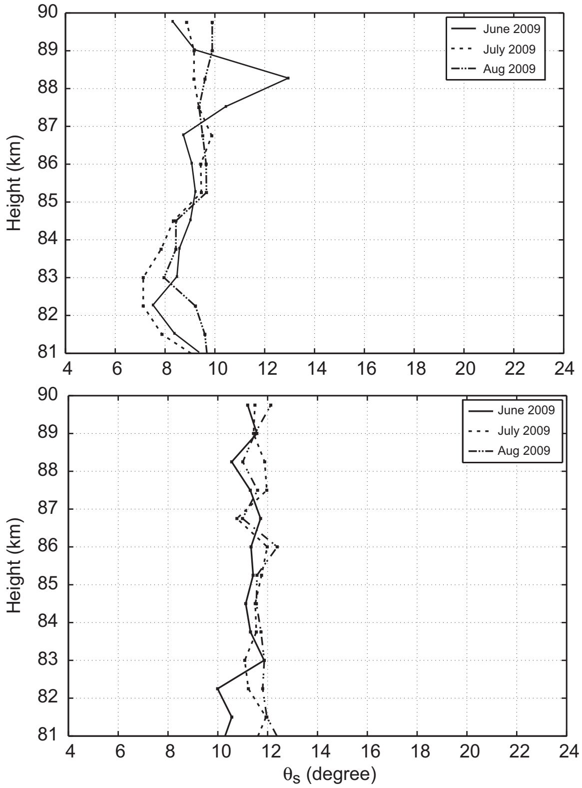

Fig. 9. Comparison of aspect-sensitivity profiles calculated at Eureka (upper panel) and Resolute Bay (lower panel). The data were collected during 2009.

the year 2009. The PMSE strength has remained weak at Resolute Bay since 2006. The PMSE observations reveal that PMSE strengths at Eureka are comparable with Resolute Bay, and both are weaker than at Andenes (69.3°N, 16.0°E) (Swarnalingam et al., 2009a, b).

The reason for low aspect angles at Eureka compared with Resolute Bay is not known at this stage. However, some suggestions can be made. First and foremost, it has to be remembered that the two sites are over 500 km apart, so it is not essential that they should have the same detailed characteristics. The weather at the ground is quite different at each site, and so production of gravity waves at the two sites (often associated with production of turbulence in the upper atmosphere) may differ. Another potential issue is the different transmitter powers and noise levels at the sites. The Resolute Bay radar is operated with a transmitter peak power that is three times lower than that of Eureka. In addition, as described by Swarnalingam et al. (2009a) the surrounding noise level at Resolute Bay is significantly higher than at Eureka, due to the fact that it has to share the transmitter and receiver location with other instruments. In contrast the Eureka radar has its own building, giving significantly lower noise at this location compared with Resolute Bay. These two factors make the Eureka radar more efficient, and able to detect weaker PMSE. Nevertheless, as long as the noise is properly removed, this difference should not be a major concern for the stronger echoes, though it certainly may play a role for the weaker ones. At this time we simply note that the general behaviour of the aspect-sensitivity as a function of height at the two sites are similar, but some noticeable differences occur which need to be monitored in the coming PMSE seasons.

6. Conclusions

We have presented long-term aspect-sensitivity measurements for observed PMSE backscattered power at Resolute Bay using data collected during 1998–2009. The aspect-sensitivity angles were calculated by comparing the recorded backscatter cross-sections in four off-zenith beams with the vertical beam. The calculated values show good agreement among all four off-zenith beams. This shows the existence of stable PMSE layering structures extending to a horizontal distance in the order of few tens of kilometers when using large time scale averaging of hourly values over a month. The estimated aspect-sensitivity height profiles takes different shapes based on the PMSE strengths broadly categorized as strong, moderate and weak at Resolute Bay. When PMSE are strong, the estimated median aspect angle at 84 km is about 8°, and the estimated median aspect angle for 88 km is about 11°, possibly meaning that the lower PMSE layers are associated with more anisotropic scatterers than the upper PMSE layers. When the strength of PMSE is moderate, the aspect-sensitivity height profile appears to be similar in shape to that of strong PMSE, but shows a median aspect angle of about 11° at 84 km and 13° at 88 km. When PMSE are weak at Resolute Bay, the estimated median aspect angle takes a range 11–15° for all heights. The calculated aspect-sensitivity profiles show consistency over the years, especially with the cases of strong and moderate PMSE strengths.

Our long-term height dependence study reveals a clear consistency in the lower PMSE heights, especially in the case of strong and moderate PMSE strengths. While the aspect angle for strong PMSE remains under 10°, the aspect angle for moderate PMSE stays between 10 and 13°. Furthermore, it was noticed in the lower heights that strong PMSE signals tend to have low aspect angles, and weak signal strengths are associated with a broader spread of aspect angles. Such features could not be seen in the upper heights.

The Resolute Bay aspect-sensitivity profiles were also compared with the Eureka VHF radar. Comparison shows reasonable agreement in general in terms of the shape of the aspect-sensitivity profiles, but Resolute Bay values are about 2–3° higher than Eureka. Possible explanations for this difference were discussed, but await further validation in the coming PMSE seasons.

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