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Amplitude enhancements in Antarctic MF radar echoes

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Abstract. Enhancements in the amplitude of returns from a medium-frequency (MF) radar at Davis, Antarctica, have been identified and their potential use as a measure of polar mesosphere summer echoes (PMSE) has been explored. A method for finding these enhancements has been applied to data spanning the period from mid-1995 to the end of 1997. The character of these enhancements on short and long timescales has been studied, and factors that may affect their detection have been considered. It has been found that they are short-lived (2 min or less being most common) and largely limited to the months around summer. Apart from describing the character of these amplitude enhancements, this study illustrates the potential pitfalls associated with identifying a proxy measure of PMSE.

1. Introduction

The polar mesosphere has become a region of increasing interest in recent years. Temperatures at the solstices depart significantly from radiative equilibrium values, presumably because of the effects of gravity wave driving [e.g., *McIntyre*, 1989]. Rocket measurements show that temperatures in the summer polar mesosphere at northern latitudes are the coldest anywhere in the Earth's environment [*von Zahn and Meyer*, 1989; *Lübken and von Zahn*, 1991]. The cold temperatures lead to the formation of ice particles near the mesopause which are visible as noctilucent clouds (NLCs) from the ground and as polar mesospheric clouds visible from space. That NLC have apparently been observed only in the last 100 years has lead to suggestions that summer polar mesosphere is showing manifestations of climate change [*Thomas*, 1996].

Polar mesospheric summer echoes (PMSE) are also associated with the cold polar mesopause temperatures. They appear as anomalously strong radar echoes at VHF and UHF frequencies; see reviews by *Cho and Kelley* [1993] and *Cho and Röttger* [1997]. There has been a debate for some time as to whether conditions suitable for the formation of PMSE exist at the southern polar summer mesopause. *Balsley et al.* [1995] reported the absence of PMSE using VHF radar observations from King George Island (62.1°S, 58.5°W), and this lack was discussed by *Balsley and Huaman* [1997] and *Huaman and Balsley* [1999] in terms of possible differences in temperatures and water vapor concentrations between the northern and southern polar mesospheres. However, recent rocket measurements from the Antarctic Peninsula have shown summer mesopause temperatures very close to Northern Hemisphere values [*Lübken et al.*, 1999].

Clearly, further observations are required to determine the degree to which conditions at the respective hemispheric polar mesospheres differ. A problem is that only a small number of VHF radar observations of PMSE have been made in the Antarctic, and then only in a region centered on the Antarctic Peninsula. Lower-frequency MF radars operating near 2 MHz offer another possible way of exploring the characteristics of the Southern Hemisphere polar mesosphere. *Fraser and Khan* [1990] found variations in the fading of echoes from the summer mesopause made with an MF radar at Scott Base (77.8°S, 166.67°E), which they suggested were a manifestation of PMSE. *Bremer et al.* [1996] identified characteristics of MF radar signal-to-noise ratio (SNR) data and associated them with PMSE through comparison with a collocated VHF radar. However, the characteristics they identified are common in MF radar SNR data and, in the absence of a corroborating VHF radar, could not be used to unambiguously identify PMSE. Their data illustrate a problem associated with the search for PMSE signatures at MF. The presence of a non-PMSE background that varies as a function of height, time of day, and season limits the usefulness of identification of PMSE through SNR enhancements (as is done at VHF). Therefore some other potential indicator of PMSE must be sought and, importantly, tested against known characteristics of MF radar data to ensure that it does not hide or falsify the

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identification of PMSE. The character of this indicator can then be compared to PMSE in full knowledge of its limitations.

Despite these limitations, the increasing use of MF radars in the Antarctic offers the opportunity to look for PMSE-like phenomena and to explore the character of the Southern Hemisphere mesosphere. During the installation of an MF radar at McMurdo base, Antarctica (78°S, 167°E) in January 1996, the presence of strong, localized, enhancements in signal strength versus height profiles were observed at heights near 85 km (*D. C. Fritts and R. A. Vincent, personal communication,* 1996). A search of data obtained with an MF radar system located at Davis (68.6°S, 62.9°E) revealed

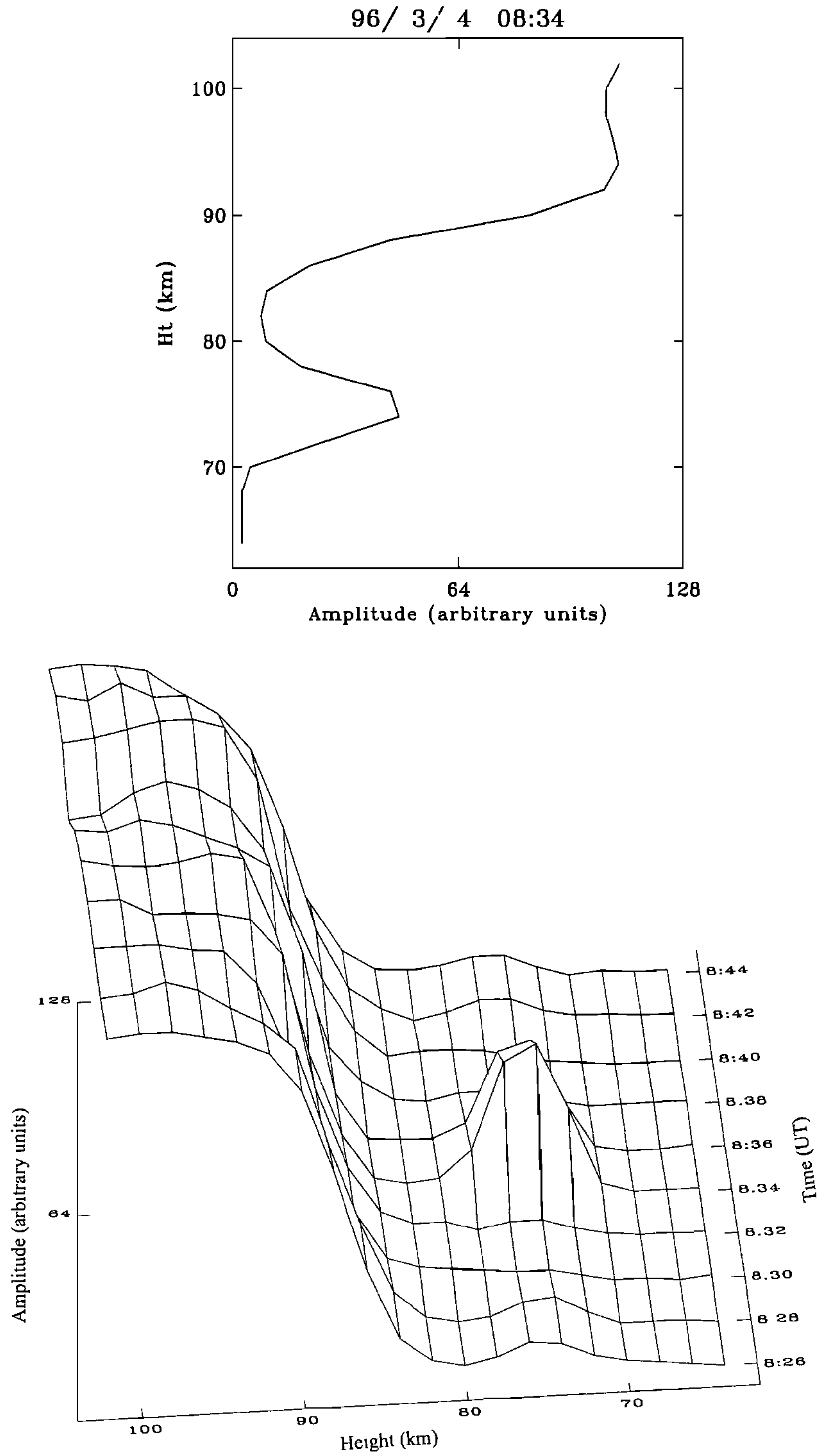


Figure 1. (a)Echo amplitude, averaged over three receivers, plotted as a function of height. The profile was collected at 0834 UT on March 4, 1996. (b) A time series of echo amplitude profiles that includes 0834 UT on March 4, 1996. The data are for receiver 1.

similar structures. Echo amplitudes would grow rapidly from usually small background values, persist for a short time, and then decay away. Here we explore the characteristics of these amplitude enhancements as a function of height and season.

In the following sections the MF radar system at Davis is briefly described and a strategy for searching for amplitude enhancements in the radar data is outlined. The temporal character of these enhancements and the processes that could distort this character are considered on both short and long timescales. The results and implications of the search over 3 years of observations, and the problems of associating them with PMSE, are then discussed.

2. Brief Description of the Radar

The data considered in this study were obtained using the MF radar system located at Davis (68.6°S, 62.9°E) in the Australian Antarctic territory. The radar operates at a frequency of 1.94 MHz and consists of a square transmitting array (approximately 40° in beam half width at half maximum) and three cross-dipole receiving arrays. Time series of complex signal strengths were represented in eight bits (giving them a range of zero to 255) and were 102.4 s in duration. The three complex time series were analyzed using full correlation analysis to produce winds and a number of other parameters. These include the echo amplitude for each channel and the correlated to uncorrelated signal ratio. Echo returns were sampled at 2 km intervals between the heights of 64 km and 102 km. The range of heights contributing to a single height sample (5 km) is half the transmitted pulse length, so successive height bins were not completely independent. Transmission and reception can be in either O or X polarization by virtue of the antenna geometry and phasing. The Davis radar was operated in O mode throughout most of the data set discussed in this paper, with the exception of the period up to January 2, 1996, when O mode was used during the day and X mode at night.

3. Search Method

The primary parameter used in the analysis presented in this paper is the echo amplitude. An example of a 102.4 s average amplitude profile that contains an enhancement is shown in Figure 1a. The echo amplitude profiles recorded around the time of the event shown in Figure 1a are displayed in Figure 1b. It is apparent that the enhancement grows and decays on a short timescale and that no similar structures are present immediately before or after the event of Figure 1a. The general character of the echoes when little or no enhancement is present can also be seen in Figure 1b. This is sometimes referred to here as the background profile.

A search method was developed to search objectively for similar echo enhancements. The algorithm was based on the strong negative gradient in amplitude found above the echo peak shown in Figure 1a. A threshold gradient was used to discriminate against the weak negative gradients sometimes observed, such as above 90 km in Figure 1a. Amplitude profiles where the values in the lowest heights were noise-like due to low SNR were not uncommon and were precluded. In some cases, radio wave absorption or reduced reflectivity decreased the amplitudes at upper heights. These caused a negative gradient in the echo amplitude that was greater than the threshold value. Although it is possible that events like that in Figure 1a could be present when absorption effects are apparent, there is enough doubt to warrant the removal of such events. The parameters used in the search method are presented in Table 1.

The application of the above search method yields events at a range of heights. For reasons that are discussed below, these events are broken down into subsets consisting of profiles that satisfy the criteria of Table 1 at a single height. The results for 77 km are presented in Figure 2. This figure contains 231 profiles collected throughout the 28 months of observation between August 26, 1995 and January 5, 1998. To put the results in perspective, it is noted that up to 720 amplitude profiles are collected each day, so the profiles presented in Figure 2 represent a small subset of the whole radar data set.

4. Seasonal Character

The MF radar system at Davis is used primarily to measure winds in the mesosphere and lower thermosphere and contains control logic that acts to maximize the signal from that region. The three receivers that it utilizes have linear responses that are invariant with height, but the gain of each receiver can be varied. The gain setting is chosen independently for each receiver by considering the variations of the output at a specified height (usually between 86 and 90 km). If the receiver is approaching saturation at that height, the gain is reduced for the next time series. If the signal is too small (compared with some preset value), the gain is increased. Thus the gain of the system may vary as a function of time of day or season.

It is important to take the gain variability into account when considering the seasonal character of the amplitude enhancements. In order for an amplitude en-

Table 1. Parameters Applied in Search for Amplitude Enhancements

Search Parameter	Amplitude Value (Arbitrary Units)
Threshold gradient	-10 over 2 km
Maximum average value in lowest three heights	15
Minimum average value in uppermost three heights	80

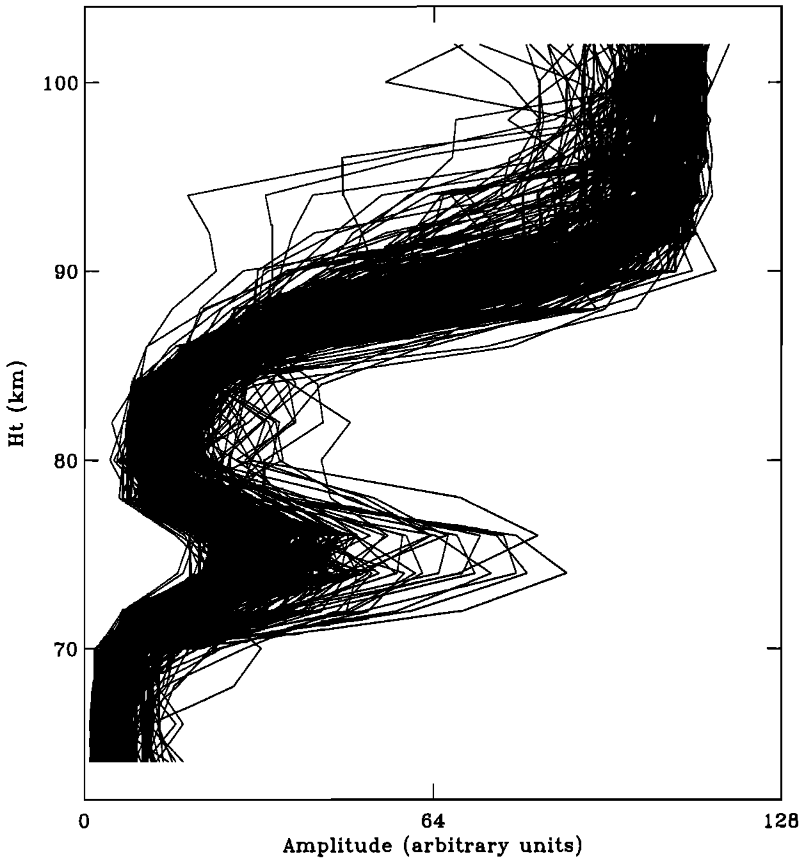


Figure 2. All of the profiles that satisfied the search criteria as applied to the gradient of the average amplitude at 77 km. A total of 231 profiles are presented.

hancement to be observed it is necessary for the radar to be in a configuration that will detect the enhancement. The latter may not be true if, for example, the gain of the radar happens to be too low. However, two characteristics of the data in Figure 2 suggest that the seasonal character of these enhancements can still be considered. Firstly, it is noted that the peak amplitudes of the enhancements shown in Figure 2 do not vary greatly, and there are no cases where the enhancement peak has reached the limiting value of 128, i.e., the signals have not "saturated." A compilation of the statistics of the receiver gain associated with each of the profiles (averaged over the three receivers) shows that 95% of the profiles fall within the range 78–97 dB with a mean value of 87.0 dB. Thus the gain of the radar system varied by 19 dB in collecting the profiles presented in Figure 2. In linear terms this represents a large factor, so the fact that none of the peaks have saturated the receiver (as is the case in the region above 90 km) is somewhat surprising.

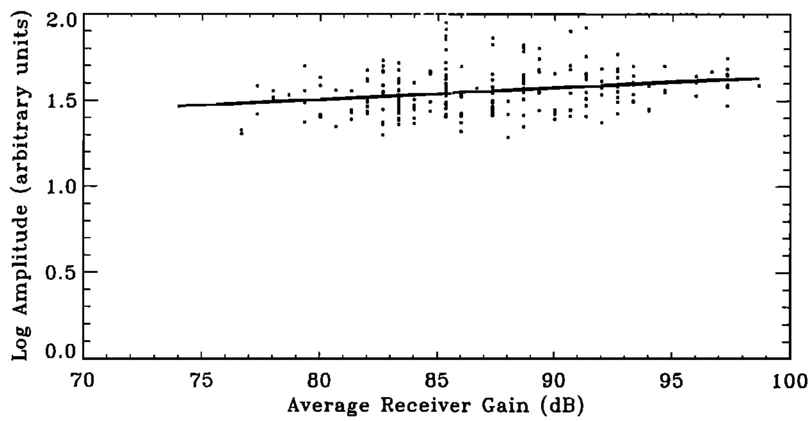


Figure 3. Log of the enhancement amplitude plotted against the average receiver gain for profiles that satisfied the search criteria. A line of best fit is included.

A log plot of enhancement amplitudes versus receiver gain is presented in Figure 3. The slope of a line fitted to this data is 0.0068 with an error of 0.0017. Consequently, the amplitude of these enhancements is almost independent of system gain, other than a requirement for the gain to be above a value of about 78 dB before a peak will be detected.

Histograms of echo occurrence and plots of percentage occurrence of receiver gain above 78 dB are shown in Figure 4. The three panels represent three 8 hour

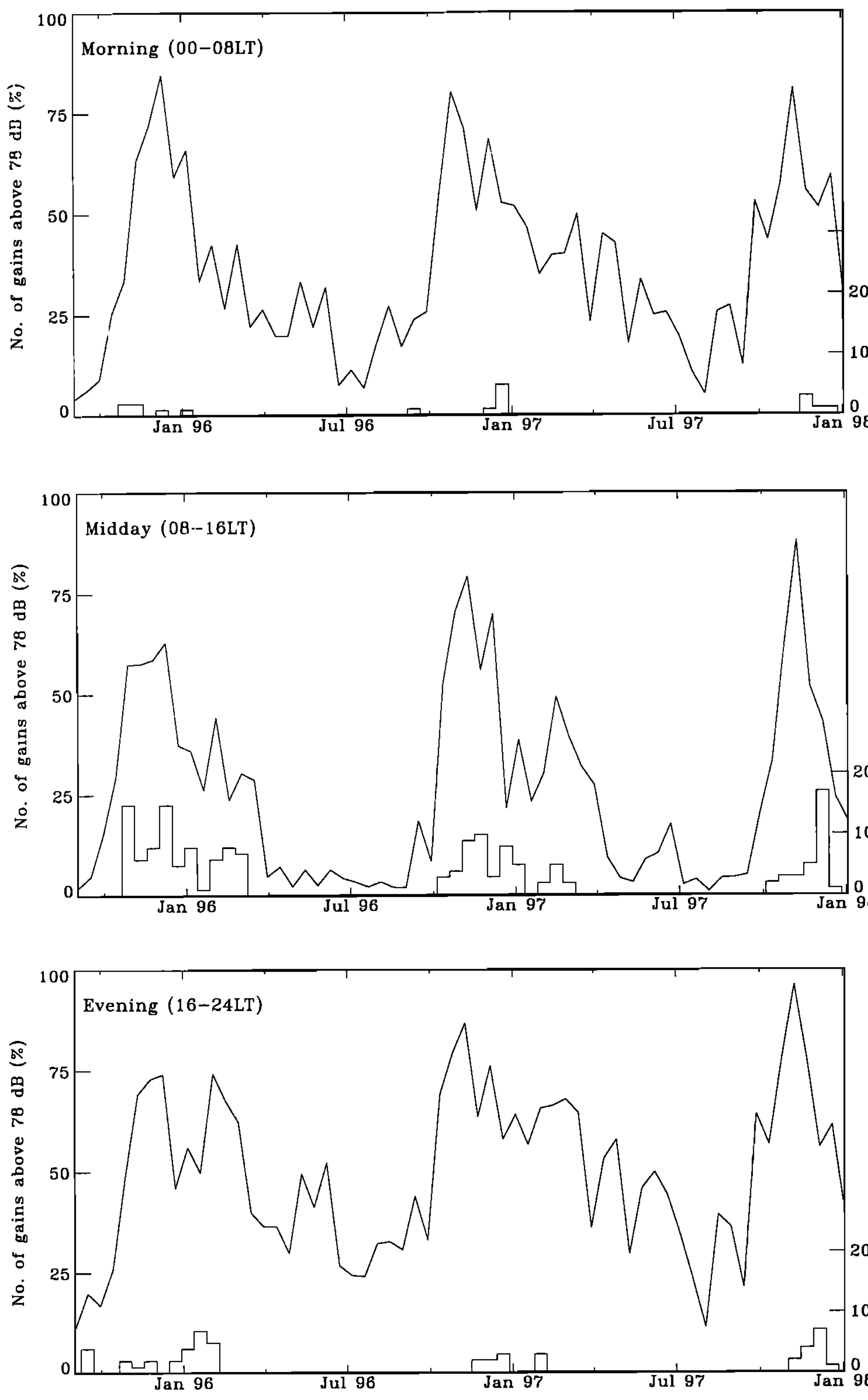


Figure 4. Frequency of occurrence of the amplitude enhancements and the percentage of the observing time that the average gain of the radar is above 78 dB. The three panels represent 0000–0800, 0800–1600, and 1600–2400 LT.

periods in local time. It is apparent that the ability of the radar to detect amplitude enhancement events does indeed vary on seasonal timescales. During southern winter the percentage of the time that the radar has a gain above 78 dB is less than in summer, falling below 10% for much of the time in the 0800–1600 LT band. However, this parameter shows less variation through the seasons for the 1600-2400 LT band. Thus for this band the lack of detections of amplitude enhancement events in the winter is not well explained by a decreased sensitivity of the radar.

The time of occurrence of the selected enhancement events is given in Figure 5, where each event is plotted as a dot against time of year and local time. The shaded areas correspond to times when the radar was transmitting and receiving in X mode. Enhancements observed during these periods were precluded from the analysis because a change to X mode will change the reflection coefficient of the scatterers, which is equivalent to changing the gain of the system without changing the receiver gains. It can be seen that the enhancements have a tendency to occur in the middle of the day and in the summer months.

The data presented in this section were for a search height of 77 km. The gradient of the amplitude profile is the sum of the background and enhancement-induced gradients. Thus seasonal and height variations in the background gradient could affect the results of the search. The uppermost height where the background gradient remained close to zero throughout the year was 77 km, making it the optimal search height for this study. However, the seasonal character of the amplitude enhancements at other heights where the search method can be applied is also of interest and are presented in Figure 6. It can be seen that amplitude enhancements generally occur in the summer at all of the heights presented but that some events do occur in the wintertime at 79 and 81 km. Inspection of these wintertime events show that their character is similar to those that occur in the summer.

5. Short-Term Character

In general, the echo enhancements had a duration of less than a 102.4 s record, but some events that span several consecutive records (clusters) are observed. Figure 7 shows a histogram of the duration of the events. The maximum duration is six records or 12 min, and 97% of the amplitude enhancement events have a duration of 8 min or less. To test whether short-term gain changes could bias the statistics, an event-centered average of the radar gain was calculated using intervals spanning the 12 min either side of the events. No significant variations in gain that are coherent with the

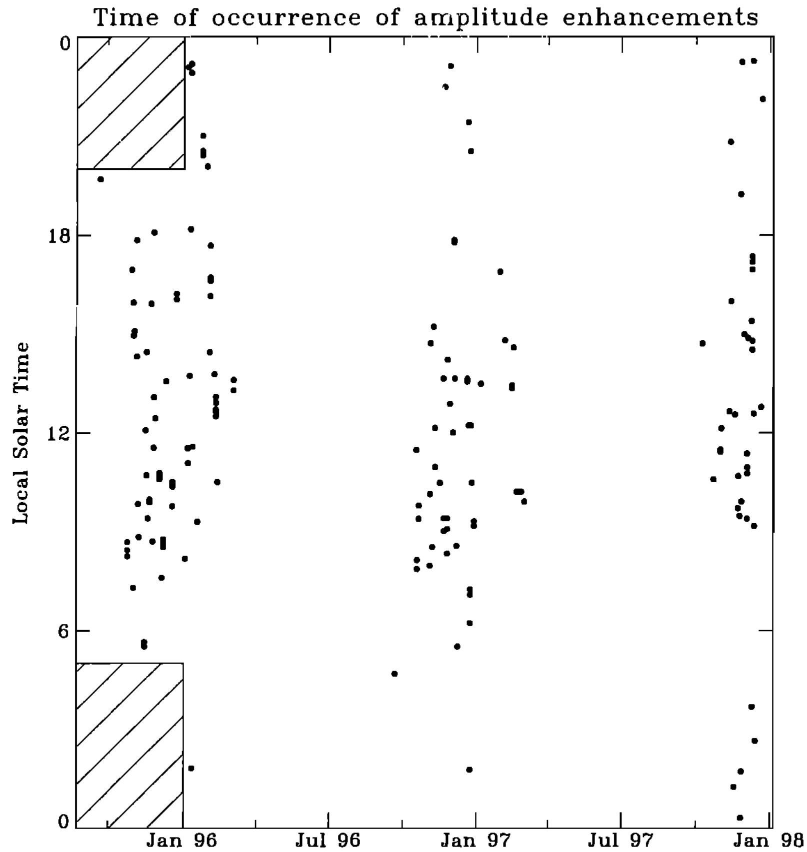


Figure 5. Time of occurrence of amplitude-enhancement events plotted against local time and season. Tick marks indicate the start of the month.

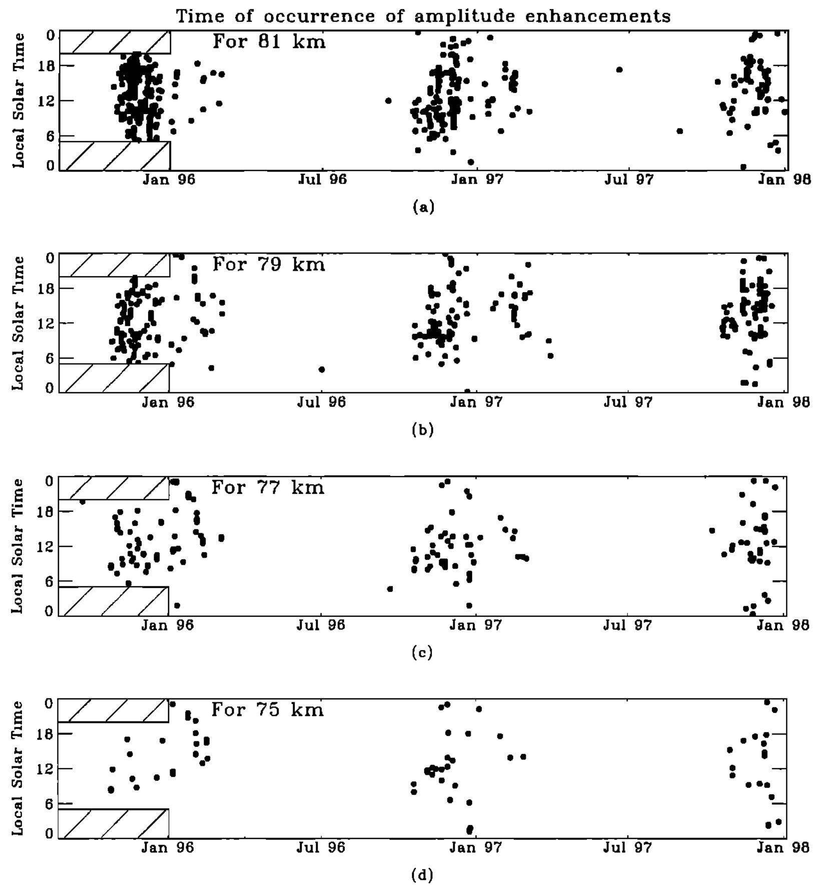


Figure 6. Time of occurrence of amplitude-enhancement events plotted against local time and season for a search height of 81, 79, 77, and 75 km. Note that the efficacy of the search method will be different for each of these heights.

events were found. Hence short-term gain changes do not appear to cause any change in the detectability of enhancements.

Detailed consideration of the enhancements is limited by the fact that most of the data is in the form of amplitudes that were averaged over each of the 102.4 s records. However, short data sets containing unprocessed or "raw" in-phase and quadrature components of the returned echoes were collected from time to time, some of which coincided with the presence of amplitude enhancement events. Figure 8a presents the components of the complex signal from receiver zero around the profile at 0834 UT on March 4, 1996 (as shown in Figure 1a). At the center of the event it can be seen that the locus of the end of the amplitude vector traces out a spiral, and the magnitude of the amplitude vector remains constant for a significant part of the record (as demonstrated by its circular path). This suggests that whatever irregularity is producing this echo it is not changing on a timescale of around 50 s. The rotation of the vector suggests motion of the scatterer radial to the radar. Figure 8b presents the phase ϕ of the amplitude vector as calculated using ϕ = arctan(quadrature/in phase). The regions of lin-

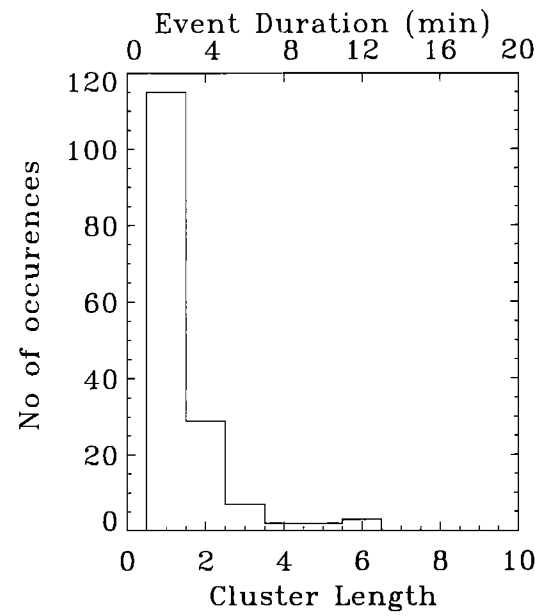
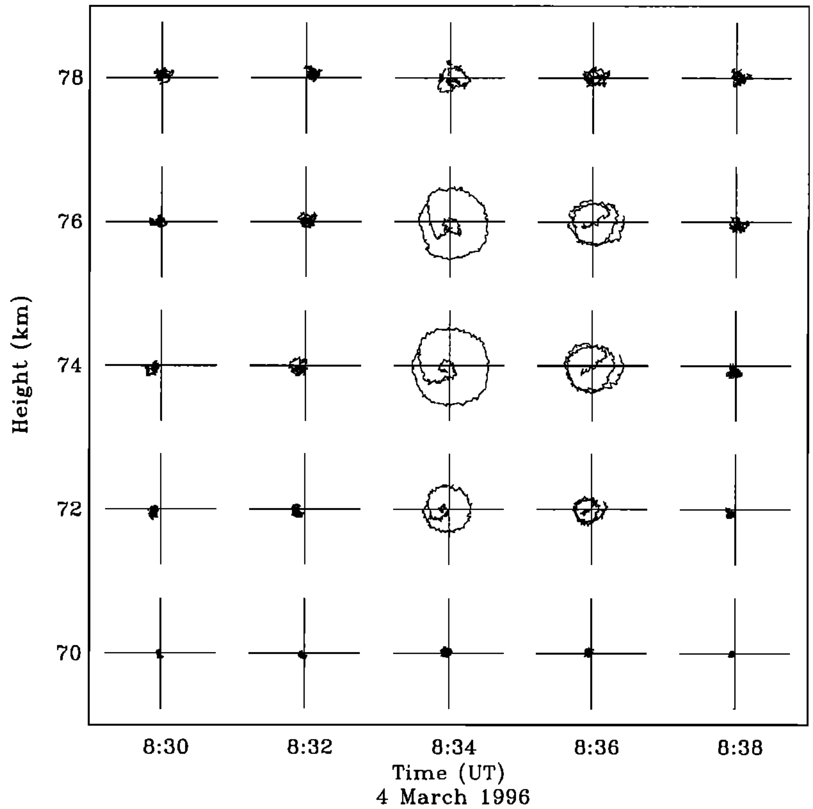


Figure 7. Cluster length statistics for a search height of 77 km. The equivalent duration in minutes is indicated on the top axis. Search parameters are noted in the text.



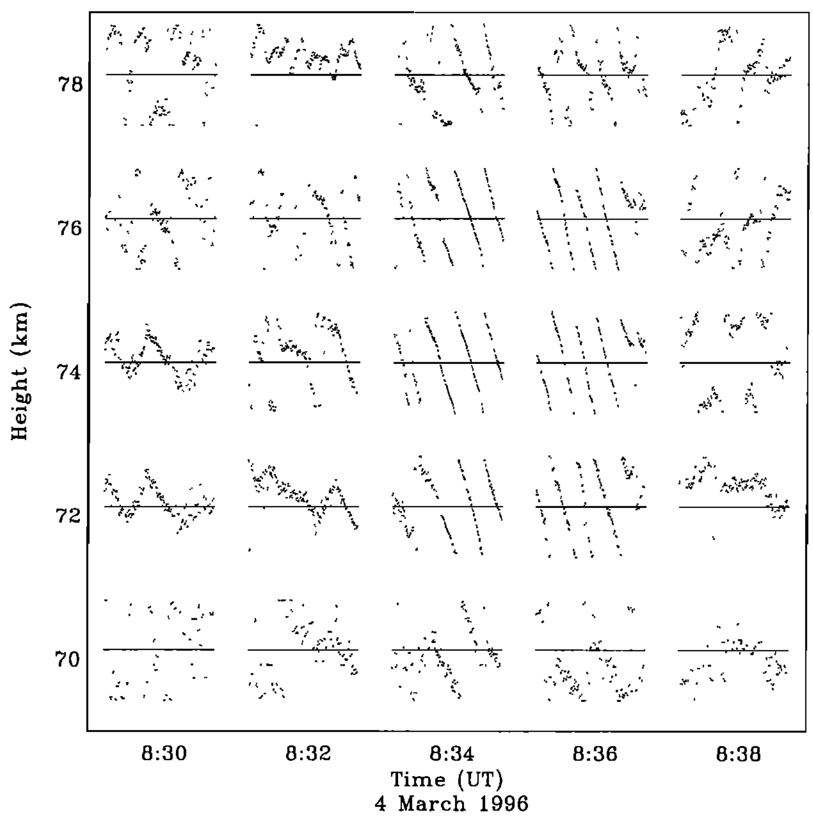


Figure 8. (a) In-phase (horizontal axes) and in-quadrature (vertical axes) components of the output of receiver zero during the evolution of an amplitude-enhancement event. Data are centered on the event that occurred at 0834 UT on March 4 1996. (b) As for Figure 8a except that the signal phase is presented.

ear phase variation correspond to the circular or spiral locus seen in Figure 8a. The spatial and temporal isolation of this event is clearly demonstrated in this figure. Note that the gain of the receiver remains at 82 dB foı the duration of the data presented in Figures 8a and 8b.

6. Discussion

This study reports short-term echo enhancements observed with the Davis MF radar in Antarctica. Signal amplitudes can increase by factors of 10 or more above background values over periods of just a few minutes. The events are isolated and typically have a duration of no more than 2 min, although events lasting up to 12 min were observed. At the heights that could be searched, almost all events occurred in the summer. There are at least two possible explanations for the summertime occurrence of the events. The variation could represent a real variation in the occurrence of the irregularities that cause the echoes. Alternatively, it could be an artifact caused by seasonal changes in system sensitivity, produced by changes in receiver gain required to encompass the large variation in signal strengths between seasons.

The ability of the radar to detect enhancements on short timescales does not seem to be gain dependent, as discussed in section 5. However, the results of Figure 4 are less conclusive when it comes to the question of seasonal variations in detectability. The middle panel of this figure (0800–1600LT) suggests that the ability of the system to detect enhancements is reduced shortly after they cease to be observed near the end of summer. Nevertheless, the top and bottom panels of this figure show much less variation in detectability. Given that there is evidence that the amplitude enhancements cease before the ability to detect them wanes, the occurrence patterns presented in Figures 4 and 5 suggest that the events are essentially a summer phenomenon.

The statistics shown in Figure 7 suggest that the most common duration of the events is 2 min or less. Whether this duration represents the time of transit of a scattering irregularity through the radar beam or the life of a scatterer can be considered by noting that the sampling volume of this radar is set by the transmitted beam width. Near 75 km (the height corresponding to the peak of the enhancements considered in Figure 2) this beam has a full width at half maximum of approximately 125 km. Although the horizontal cross section of the beam is not circular, the following argument is not changed by assuming that it is. If randomly positioned, long-lived scatterers are embedded in a steady horizontal flow then the transit time of the scatterers through a circular beam will be determined by the length of a chord through the beam that is parallel to the flow and by the speed of that flow. However, most of the chord lengths are of the order of the beam diameter; it is only those transits that lie near the edge of the circular beam which are significantly shorter than the beam diameter. Thus the distribution of transit times will peak near the time taken to transit through the center of the beam with fewer occurrences of shorter times. This is in contrast to Figure 7 in which most of the clusters appear to be of short duration, suggesting that the cluster length is an indicator of scatterer lifetime rather than beam-transit time. It is noted that a discrete, isotropically scattering irregularity passing through the center of the beam would require a horizontal velocity of around 1000 m s^{-1} to transit the whole of the beam in the average event duration of 2 min.

However, if the irregularities scatter radio waves anisotropically, that is they are aspect sensitive, then it is possible that they might not be detected even though they are present in the radar beam. *Lesicar et al.* [1994] found that irregularities in the Antarctic *D* region did exhibit some degree of anisotropy, especially below 80 km. The relatively rapid onset and decay of the small number of events captured in raw data suggest that anisotropy is not an explanation but that the duration is determined by the lifetime of the irregularities. This is an issue that needs further study.

Two other pieces of information should be noted. First, the radial velocities inferred from the rate of change of phase evident in Figure 8b are small. Of the seven events captured in raw data the mean radial velocity is only about 2 ms^{-1}. Since mean horizontal wind speeds are usually tens of meters per second, this suggests that the irregularities are being observed at near to the zenith. Second, the irregularities appear to be quite thin. It is not easy to determine their size because the 33 μs radar pulse length is equivalent to a range resolution of 5 km. However, since the apparent thickness of the features evident in Figure 2 and Figure 8 is of the order of 5 km, it is concluded that the scattering irregularities have thicknesses significantly smaller than 5 km.

7. Nature of Irregularities

In trying to determine the nature of the irregularities, two possibilities should first be discussed. Given the location of Davis near the auroral zone, one possibility is that the irregularities are associated with particle precipitation events. A comparison with 30 MHz riometer data found that there was no significant variation in the riometer data coincident with the enhancement events. This rules out the particle precipitation hypothesis.

Another possibility is that the events are simply caused by scattering from meteor trails. However, the amplitude and phase variations do not show the characteristics usually associated with meteor scatter (*W. G. Elford, personal communication,* 2000). In addition, the meteor hypothesis does not explain why the irregularities discussed here are essentially a summer phenomenon.

A motivation for carrying out this study was the consideration of the possibility that these amplitude enhancement events may be associated with PMSE. Although observations of PMSE have been made at a number of different frequencies, most have been at VHF or higher and few have been made at HF and MF. *Vlaskov et al.* [1995] noted the presence of thin layers in their 2.7 MHz returns when PMSE were present above EISCAT. *Karashtin et al.* [1997] noted a PMSE-like echo in the 8-9 MHz returns from their radar near Vasil'sursk (at 56°N, 46°E). The echo has a peak in the altitude range 83–90 km and persists for much of their 2 week summer observation period. (Note that winter data showing an absence of this echo is not included in this study.)

Bremer et al. [1996] used data from three closely spaced radars. The EISCAT-VHF (224 MHz) and the MF-Tromso (2.78 MHz) systems were collocated, while the ALOMAR SOUSY (53.5 MHz) was 130 km away. They present data that show a clear correspondence between PMSE as measured using the ALOMAR SOUSY system and enhancements in the MF SNR. The correspondence between the VHF and the MF echoes is excellent, particularly when potential differences in turbulence and radar reflectivity are noted. The Bragg scale for the Tromso MF system is 54 m, and eddies of this scale are expected to lie in the inertial range of turbulence [*Hocking* 1985]. The SOUSY system has a 3 m Bragg scale, and the link between turbulence at this scale and radar reflectivity during PMSE is the subject of continuing study [*Cho and Kelley* 1993]. The cause of nonturbulent refractive index variations could also vary; for example, the size of a Fresnel zone at these frequencies is quite different. It should be noted that a possible explanation for the results presented by *Bremer et al.* [1996] is that at MF they detected a component of PMSE (e.g. enhanced turbulence intensity) in their results rather than the product of all the physical mechanisms that produce a PMSE return at VHF.

A key problem in searching for manifestations of PMSE in MF radar echoes needs to be emphasized. The MF SNR profiles presented by *Bremer et al.* [1996] show a character that is common to MF radars at various latitudes and throughout the year. It was only through a comparison with nearby VHF radar systems that they were able to verify an association with PMSE. The characteristics they identified are not distinctive enough to be used in isolation as an indicator of PMSE. Attempts to identify PMSE in MF radar data must therefore use some other proxy measure. Identification of amplitude enhancements may be a suitable proxy. However, before these enhancements could be compared to PMSE, it was important to test the character of the enhancements (and their search method) against potential distortions. Consideration of the effects of radar gain and background profile variations ensured that the characteristics presented in the previous sections are real but have yielded results that are limited to the lower end of the height range over which PMSE are thought to occur.

If Northern Hemisphere observations are an appropriate indicator, the height range over which PMSE are observed extends from around 75 km to 100 km [*Ecklund and Balsley*, 1981; *Czechowsky et al.*, 1989]. The amplitude enhancements identified at Davis using a gradient search height of 77 km had their peaks at 75 km. Although this is at the bottom of the expected PMSE range, this aspect does not preclude a connection to PMSE. Figure 5 shows that they are also largely a summer phenomenon; the earliest enhancement event (in a year centered on the southern summer solstice) occurs on September 20 and the latest on March 4. Studies of the onset and decay of the northern PMSE have been carried out by *Balsley and Huaman* [1997] for Poker Flat data (65°N) and by *Kirkwood et al.* [1998] for ESRAD data (68°N). The latitudes of both of these data sets are comparable to that of Davis (69°S). They show a PMSE season that starts around day 140 and ends between days 220 and 240. In the Southern Hemisphere these equate to a start around November 19 and an end between February 7 and 27. Thus the onset of amplitude enhancement events at a search height of 77 km occurs two months before the start of PMSE at a similar northern latitude, but their decay occurs at a similar equivalent time. Note that the results presented in Figure 6, where the search was applied to other heights, show a filling of the occurrence distributions but little change in the onset and decay dates.

Another characteristic of amplitude enhancements that can be compared with those of PMSE is the duration of the enhancement events. It was noted above that 97% of events have a duration of 8 min or less, with a 2 min duration being the most common (see Figure 7). Inspection of PMSE echo power as measured using VHF radars (around 50 MHz) shows that although echoes last for periods of the order of hours, the structure of SNR variations during that interval often has a characteristic time of the order of minutes [*Czechowsky et al.*, 1989; *Cho et al.*, 1993; *Nussbaumer et al.*, 1996]. Thus the long-term character of PMSE is at odds with that of the MF radar amplitude enhancements, but the character of the echoes within a PMSE is not dissimilar to that of the amplitude enhancements.

An important characteristic of PMSE that should be compared to that of the amplitude enhancements (or any proxy measure) is the latitudinal extent. Although it would be preferable to apply the search method to the data from a similar midlatitude MF radar, this is not possible with the single station data set available for this study. A structure similar to the amplitude enhancements can be seen in the data obtained by *Hocking* [1979] using a 1.98 MHz radar near Adelaide at 35°S. *Gregory* [1956] describes similar echo characteristics using an MF radar at 44°S, as do *Gardner and Pawsey* [1953] in describing data obtained near 34°S. In all of the above cases it is not certain that these structures would have been identified using the search method described in this paper. Note that the observation of amplitude enhancements away from the regions where PMSE are observed does not preclude their association with PMSE in the polar regions. They may be associated with one ingredient of a PMSE (e.g., turbulence) but not another (e.g. low mesospheric temperatures), making them an indicator of the possibility of PMSE but not the observation of them.

8. Summary and Conclusions

We discuss the characteristics of short-lived echo amplitude-enhancement structures in MF radar data from Davis, Antarctica, and their possible utility as proxy measures of PMSE, which are normally observed at VHF. Various tests show that although there are times of the day and year when the radar may be less able to detect these enhancements, that these enhancements are largely a summer phenomenon. It is tentatively concluded that their temporal characteristics are similar to those of PMSE

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