Processing Millimeter Wave Profiler Radar Spectra

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15 August 2000 and 19 December 2000

ABSTRACT

Spectral processing algorithms employed in millimeter-wave profiling radars typically obtain good signal-to-noise ratios from weakly scattering clouds by incoherently averaging many spectra. Radar operating characteristics dictate sampling times on the order of a few seconds. Presented here are analyses showing that changes in the vertical wind during the sampling period can be a major contributor to the measured spectrum width. Such broadened spectra violate the assumptions made in spectral inversion techniques, and may lead to incorrect interpretations of the turbulent and microphysical characteristics of the radar volume. Moreover, it is shown that there are several factors involved in determining the measured spectral shape: the averaging time window and horizontal advection velocity of the cloud, as well as horizontal inhomogeneities in cloud vertical velocity and microphysical fields. Current processing algorithms do not allow for distinction between these effects, leading to potential for large errors in retrievals. In this paper a simple technique is presented to remove this effect for monomodal spectra. A side product of this algorithm is high temporal resolution estimates of the volume-mean vertical wind.

1. Introduction

Researchers have become increasingly interested in the potential to determine cloud properties remotely from power spectra measurements of cloud profiling radars (Gossard et al. 1997; Babb et al. 2000; Babb and Verlinde 1999; Kollias et al. 1999). Ground-based radar provides an inexpensive alternative to in situ cloud measurements, enabling the collection of large datasets at high temporal and spatial resolutions. Such datasets provide views of cloud and precipitating systems otherwise unobtainable, and hence new ways to investigate the interaction between the microphysics and kinematics. Millimeter-wave cloud profiling radars operate in a vertically pointing mode, have narrow beams ($\sim$0.2°, 5–10-m diameter in boundary layer clouds) and short range-gate spacing ($\sim$30–90 m). The scatterers are cloud droplets (diameters typically less than 200 μm).

There is a strong physical link between vertically pointing radar measurements and drop size distributions in the Doppler velocity power spectrum (e.g., Gossard et al. 1997). Unlike a single measure of received radar power, a Doppler velocity spectrum is a measure of backscattered energy per unit radial velocity. The measured velocity is calculated using phase shifts caused by individual scatterers' motions along the radar beam. The radar-perceived motion of the drops is a combination of the drop quiet-air fall velocity and ambient air motions. For liquid clouds, the drop fall velocities can be assumed a function of hydrometeor diameter, while received power is assumed proportional to the sum of the diameter raised to the 6th power of all hydrometeors within the illuminated volume. Since each power spectrum is strongly related to the hydrometeor population in a radar volume, the information exists to calculate the number of drops per unit diameter.

Although a link has been established between power spectra and drop size distributions, inversions of these relationships are not straightforward because of the modification of the drop quiet-air fall spectrum by ambient fluid motions. These ambient motions can be divided into radar-volume-mean and turbulent subvolume components. Volume-mean wind components act upon all scatterers uniformly, displacing the entire spectrum equally along the velocity axis. However, turbulent wind components vary throughout the extent of the illuminated radar volume, impacting the perceived motion of any hydrometeor in a quasi-random manner. Therefore, similar-sized drops located in different regions within a radar volume will likely experience different ambient effects, and hence have different radar-perceived velocities. Given the additive nature of these effects, sum-

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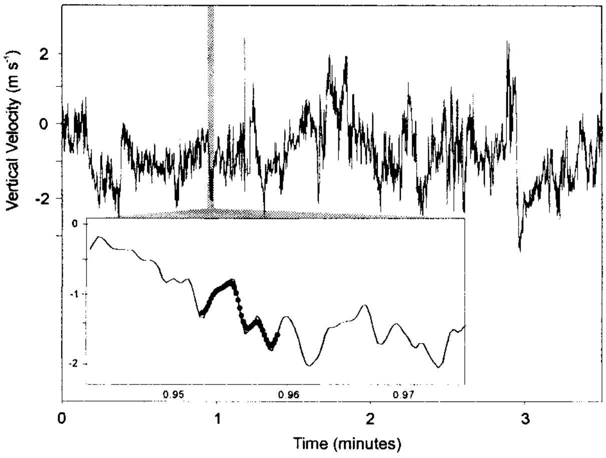

FIG. 1. Measurements of 50-Hz vertical velocity in continental stratocumulus. The inset shows the section of the data used in this study as input to the simulation. The 40 points on the subset curve represent the actual values selected for each spectral calculation. These points are representative of the volume sampled by the radar in 4 s under the assumption that there is a 10 m s^{-1} horizontal wind advecting the clouds over the radar site.

ming ambient air motions with the expected drop fall velocity for a known drop distribution results in a significantly broadened spectrum compared to its quiet-air counterpart. Thus, the turbulent wind components prohibit the direct calculation of a drop size distribution from Doppler velocity power spectra because the radar cannot discriminate between air and drop motions.

Several studies have accounted for the problems of turbulent broadening and noisy measurements (e.g., Wakasugi et al. 1987; Gossard 1988; Gossard et al. 1997; Babb et al. 2000). However, these studies assume that all spectral broadening is due to radar subvolume turbulence and not artifacts introduced by the signal processing. One such artifact broadening can be attributed to a changing volume-mean wind component during the acquisition of the data necessary to determine a single (averaged) power spectrum. For example, to provide high velocity resolution, 94-GHz (3-mm wavelength) cloud radar often operate at a relatively low pulse repetition frequency (PRF) of 2500–5000 pulses per second. This PRF corresponds to a small Nyquist velocity (2–4 m s^{-1}) appropriate for cloud drop studies. Typical at 94-GHz cloud radar studies, hardware and target characteristics dictate that roughly forty 512-point power spectra be averaged to establish a clear signal above the radar noise floor. Quantitatively, each spectral average therefore requires over 20 000 pulses. At the PRFs used, the total time needed for data acquisition of an entire spectral average will be on the order of 4–8 s, neglecting processing time considerations. Assuming a modest stratocumulus cloud advection on the order of 5 m s^{-1}, a radar volume will sweep roughly 40–80 m in the data collection period.

Figure 1 shows a time series of vertical velocity measurements taken by a Honeywell Lasertrack IRS 5 on the University of Wyoming King Air in a continental stratocumulus cloud over State College, Pennsylvania. The dotted curve in the inset represent volume-mean winds over a typical sampling period (4 s) of a cloud radar. It can be seen that the volume-mean wind changes by approximately 1 m s^{-1} during this time. These data suggest that local changes in volume-mean winds may produce drastic changes from the initial to the final measured spectrum in the averaging period, with a resulting broader distribution. The contribution to the observed spectrum width results from the physical characteristics of the system observed and the long sampling periods used with cloud radars, and has not been considered before in processing cloud radar data. However, the effect has been studied in the context of upper atmospheric profiling (Hocking 1983; Murphy et al. 1994).

In this paper, we will demonstrate the effect of volume-mean wind changes on the perceived spectrum width when using current signal processing algorithms; we will present a simple technique to alleviate the problem for single-mode power spectra. We will proceed to demonstrate the effect of this processing-induced broadening on the retrieval of cloud drop size distributions and turbulence characteristics.

2. Methodology

To quantify volume-mean broadening effects, we look at both model simulations and actual cloud radar data. The model produces realistic 94-GHz cloud radar measurements that can be manipulated in a controlled manner, and allows us investigate the broadening effect in a situation where all variables are known. The actual time series data from a profiling cloud radar allow us to get away from the artificial (and possible unphysical) data, albeit with no supporting measurements. Together, these two approaches provide a comprehensive look at the problem.

The model used in this study was developed by Babb (1996) to simulate 94-GHz cloud radar returns, and is based on ideas presented by Zrnic (1975). Droplets of a known number distribution in size are randomly placed in a specified volume. Droplet motions are determined by adding a known volume-mean and a turbulent air motion contribution to the drop terminal velocity. Droplets are allowed to fall in this turbulent field, resulting in new sample realizations about the population with each measurement. Turbulent contributions over the entire volume adhere to a normal distribution of known width.

For the simulations performed in this study, we applied parameters typical of a drizzle distribution in stratocumulus clouds. Drops are assumed gamma-distributed in size:

$$n(D)dD = \frac{N_t}{\Gamma(\upsilon)}\left(\frac{D}{D_n}\right)^{\upsilon-1}\frac{1}{D_n}\exp\left(-\frac{D}{D_n}\right)dD,$$

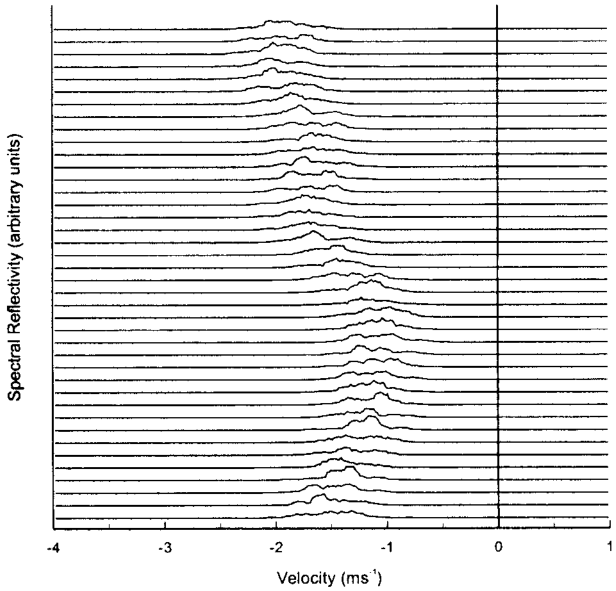

FIG. 2. Doppler power spectra derived from the cloud radar simulation model. Forty consecutive 512-point spectra are displayed, each with a small offset.

where $N_t = 30$ cm^{-3} is the total concentration, $\upsilon = 23$ is the shape factor, and $D_n = D_m/\upsilon$ is a characteristic diameter with $D_m = 60$ μm the mean diameter of the distribution. The subvolume turbulence is approximated (following Gossard 1994) with a normal distribution as

$$\mathrm{PDF} = \frac{1}{\sqrt{\pi\sigma^2}} \exp\left[-\left(\frac{w_j - w_i}{\sigma}\right)^2\right],$$

where $\sigma = 0.2$ m s^{-1} is the standard deviation. Volume-mean wind contributions are taken from the Honeywell Lasertrack IRS five 50-Hz vertical velocity measurements observed in stratocumulus clouds by the University of Wyoming King Air (shown in Fig. 1). These data have a variance of 0.6 m^2 s^{-2}, which is typical for convective continental stratocumulus clouds. The aircraft-measured velocity variance includes the full turbulence spectrum, whereas the model resolves some of the larger turbulent eddies, and hence has a lower variance. The model velocity variance was determined by looking at the measured aircraft velocity variance on beamwidth scales. A seven-point running mean is applied to the aircraft measurements to simulate the pulse degradation due to beamwidth considerations with a typical 94-GHz radar and an advecting velocity of 10 m s^{-1}. A time series of Doppler spectra produced by this model is shown in Fig. 2. These spectra were smoothed a posteriori for presentation purposes; however, all processing is done on the noisy data.

The time series of spectra illustrated in Fig. 2 comprises a representative number of spectra required by processing algorithms to produce a single observed spectrum with a good signal-to-noise ratio. Shifting in the spectra due to changes in the volume-mean contribution is clearly visible. These shifts point to the necessity to remove this contribution before averaging procedures.

The selection of a shifting algorithm is constrained by signal processing time limitations that dictate a computationally simple design. The simplest algorithm to implement entails calculating signal statistics, such as a spectral power-weighted mean (first moment), to account for the shifts in the spectrum. In this paper, we used an algorithm where the first moment from each individual spectrum in the averaging window is shifted to align with that of the first spectrum before performing the averaging operation. Information on the amount of shifting for each spectrum is recorded. Once the averaging has been performed, the deconvolution algorithm developed by Babb et al. (2000) is used to remove the turbulent broadening effects. The volume-mean vertical velocity for this spectrum is the velocity where the retrieved spectrum disappears in the noise at the slowest falling drops (right-hand side of the spectrum using the convention that positive velocities are away from the radar). Here the assumption is made that the smallest detectable drops are tracers of the air motion. The vertical velocity for subsequent spectra are determined using the recorded shift value.

Finally, the same technique is also applied to time series data taken by the National Oceanic and Atmospheric Administration (NOAA) Environmental Technology Laboratory (ETL) 35-GHz cloud radar. The data were collected during the Atlantic Stratocumulous Transition Experiment (ASTEX) (Albrecht et al. 1995) on the island of Porto Santo in the Madeiras. Beginning at 2109 UTC on 12 June 1992, in a stratocumulus event, the radar collected time series data for a period of 3 min while the antenna was pointing vertically. The radar was operating with a pulse repetition frequency of 2000 pulses per second and recorded data for 11 gates continuously. An initial analysis of these data and a further discussion on the radar hardware can be found in Gossard et al. (1997). A time series of 40 consecutive power spectra calculated from these data for a cloud-top gate is presented in Fig. 3. This set of observations is not unusual for this dataset.

3. Results

a. Simulated data

With all the variables in the problem known, the simulated set (shown in Fig. 2) provides an opportunity to evaluate impacts of signal processing algorithms on the desired results. Figure 4 contrasts spectral averages calculated from these data: the lighter curve represents the conventional average, whereas the black curve is the average after the first moment of all spectra were aligned prior to averaging. Also shown in this figure is an ''ideally'' shifted average, the values of which were deter-

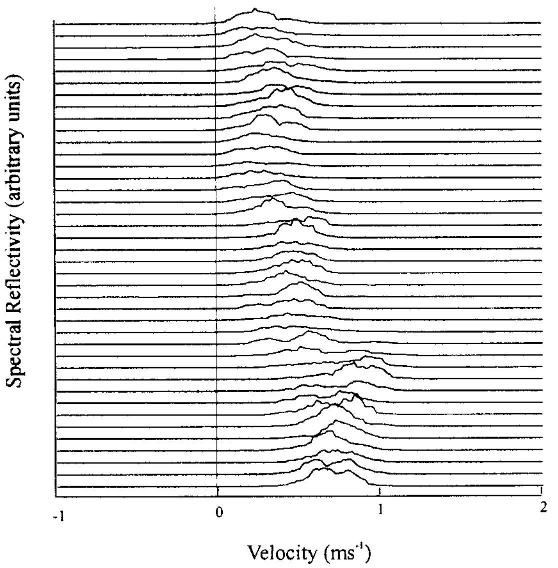

FIG. 3. Doppler power spectra derived from the 12 Jun ASTEX stratocumulus dataset. Forty consecutive 512-point spectra are displayed, each with a small offset.

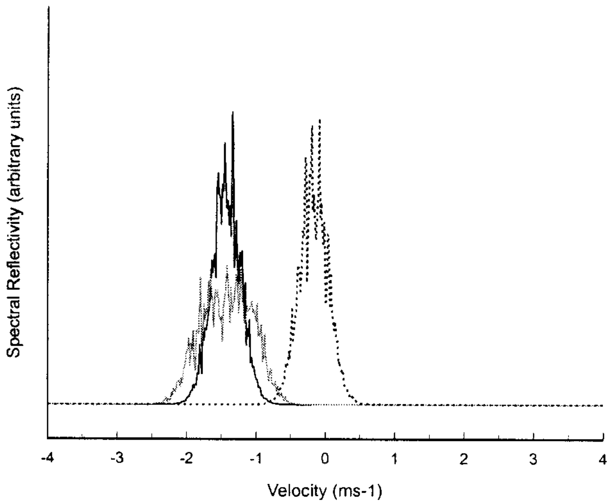

FIG. 4. Averaged Doppler power spectra for the simulated stratocumulus data. The three curves represent conventional incoherent average (gray), first moment–shifted average (black), and an average where the known vertical velocity values are removed (black, dotted), known as the optimal average.

mined by subtracting the known volume-mean wind contribution in each spectrum (dotted curve).

The averages in Fig. 4 clearly indicate spectral broadening between shifted and conventional averages. As an initial step, we quantify the broadening by looking at the second moment of the spectra. Spectral widths are observed to be 0.375 m s^{-1} for the average computed without shifting, compared to 0.233 m s^{-1} for the first moment shifted. These values correspond to a 0.142 m s^{-1} broadening on cloud spectral averages, which translates to a 61% decrease in the second moment. For reference, the second moment of the ideal spectrum is 0.227 m s^{-1}, which is within 3% of the first-moment-shifted average spectrum.

Moreover, a side product of our shifting algorithm is a higher frequency estimate of the volume-mean wind. Figure 5 shows the derived volume-mean wind values (determined from the shift value for each individual spectrum) versus the known vertical wind contribution. For this comparison, we have used the known mean vertical velocity of the first spectrum as a reference. All subsequent vertical velocities were calculated relative to this value using the amount of shifting required relative to the first spectrum. The rms difference between the two is 0.042 m s^{-1}. This value is similar to the spectral resolution of the dataset from which it is derived, suggesting that the derived volume-mean velocity values are accurate to within the measurement spectral resolutions. We have also used the technique described in the methodology section to derive the required offset for the first spectrum. This method yielded an offset in error by 0.08 m s^{-1}, suggesting that we can retrieve that actual vertical velocity to within 0.1 m s^{-1}.

The slope of the small-drop end (right-hand side of spectrum) of the convolved spectrum is evaluated next. This region of the spectrum is very important in some retrieval techniques since it carries the information about the subvolume turbulence (Gossard et al. 1997). Two slopes are measured for each spectrum, the values of which are determined by comparing changes in spectral reflectivity over defined velocity ranges. One slope is representative of the extreme tail in which turbulence is characterized, while the other slope is representative of the small-drop side that contains most information on the median of the droplet distribution.

As illustrated in Fig. 4, the shifted averaged spectrum exhibits steeper negative slopes indicative of a narrowed spectral velocity range comparable to the quiet-air spectrum. These features were characterized by looking at

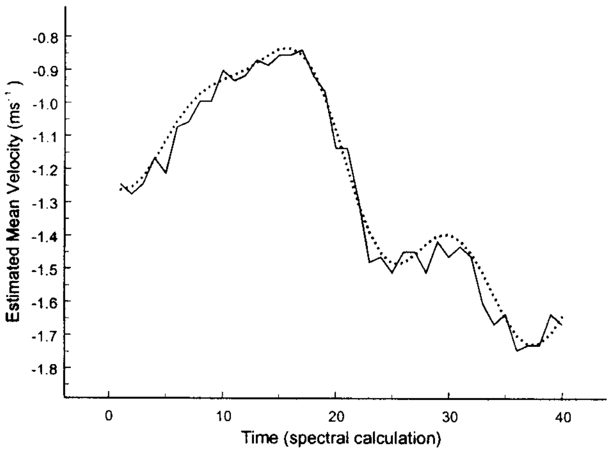

FIG. 5. Retrieved volume-mean vertical velocity field over the data sampling period (solid line) compared to the known vertical velocities of the simulated data (dotted line).

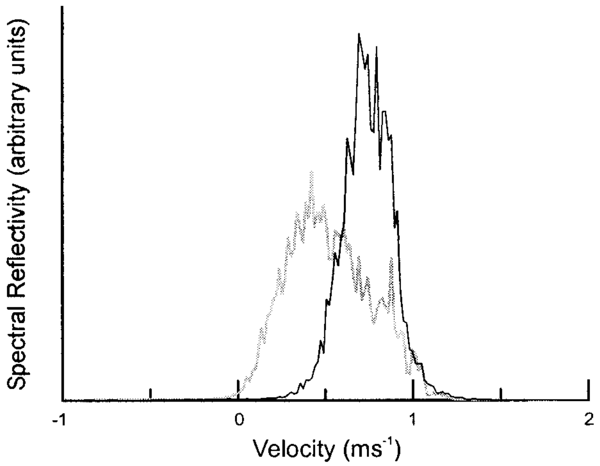

FIG. 6. Averaged Doppler power spectra for the 12 Jun ASTEX stratocumulus case. The two curves are the conventional incoherent average (gray) and the first-moment shifted average (black).

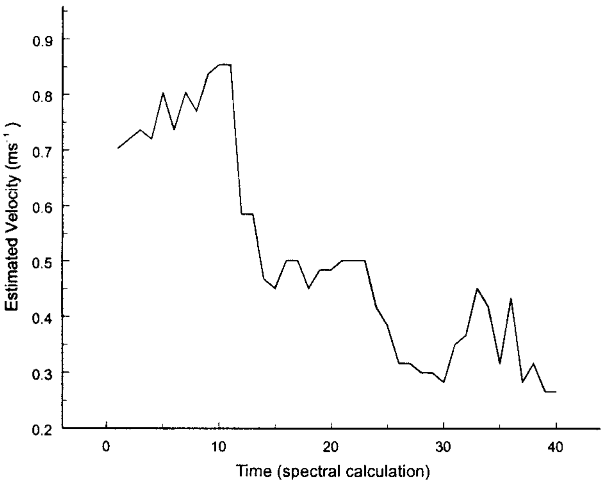

FIG. 7. Retrieved volume-mean vertical velocity field for the 12 Jun ASTEX stratocumulus case.

the slope over 0.156 m s^{-1}(10 bins) and 0.625 m s^{-1} (40 bins) intervals starting from a point where the signal rises consistently above the radar noise floor. Slope calculations on the conventional average produce values of 10.2 for the 10-bin and 17.2 for the 40-bin sections, where the units of slope are the same. For the first-moment shifted spectrum, slope values are recorded to be 5.25 and 25.95. In the small-drop range, the values indicate a 50% steeper slope. Conceptually, a steeper slope in the tail region combined with a flatter slope toward the small-drop region would be characteristic of a broader drop distribution. Therefore, it can be seen that shifting tends toward narrower, but higher-peaked drop distributions.

b. Observed data

The simulated experiments point to the potential for significant spectral broadening due to volume-mean wind changes during data collection. Figure 3 illustrates shifts in the observed spectra similar to those in the modeled data. In contrast to the modeled spectra, however, greater changes in the shape of individual spectra can be noticed. These changes in the spectra presumably result from microphysical changes in the volume.

The results of the different averaging techniques are shown in Fig. 6, while the estimated volume-mean wind contribution for this set is shown in Fig. 7. The latter figure displays vertical velocity changes from 0.2 to 1.3 m s^{-1} over this 10-s averaging period—values that are similar to ASTEX observations (Albrecht et al. 1995). Second moments are observed to be 0.33 m s^{-1} for the conventional processes spectrum and 0.276 m s^{-1} for the shifted average, which corresponds to a 16% decrease from shifting. A pulse-pair (Lhermitte and Serafin 1984) estimate applied to the entire set produced a spectrum width value of 0.27 m s^{-1}, similar to the shifted value. The decrease resulting from shifting is less than that from the simulation; however, Fig. 6 shows a similar distinct change in the spectral shape following shifting. Slope calculations of the conventional average produce values of 0.5629 for the 10-bin region and 1.89 for the 40-bin region, where the units remain constant between all measurements but are arbitrary. Slope calculations on the shifted spectrum produce values of 1.3 and 6.7 for similar ranges. The 254% increase in slope in the small-drop region is much greater than that derived for the simulated set. This sharp increase is balanced by a 130% increase in the slope of the tail compared to a 50% drop in the simulation set. The increase in the slope of the tail suggests that the conventional averaging procedure produces results that would tend to overestimate the turbulence in the volume, while the shape of the spectrum points to an overestimation of the drop distribution width. These results are qualitatively similar to the simulation results, lending credence to the previous interpretations.

4. Discussion

The results presented indicate that changes in the volume-mean wind component during data collection contribute to the observed spectrum width similar in magnitude to the subvolume turbulence. The assumption made in the inversion methods of Gossard et al. (1997) and Babb et al. (2000) that the observed spectral shape is purely the result of the convolution of the quiet-air fall spectrum and the (Gaussian) subvolume turbulent probability density function is thus violated. Using these spectra in the inversion methods could result in unrealistically broad drop size distributions and incorrect estimates of the subvolume turbulence, or in the worst case, cause the inversion to fail. If, however, the distribution of the volume-mean wind over the averaging period is changing smoothly, the resulting turbulence distribution (the average of many displaced Gaussian

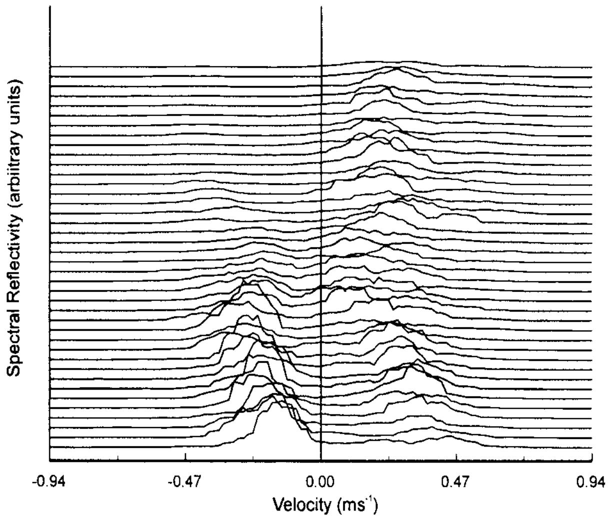

FIG. 8. Drizzle power spectra derived from the 12 Jun ASTEX stratocumulus dataset. Forty consecutive 512-point spectra are displayed, each with a small offset. Note the drizzle peak (toward faster fall velocities) fading away as the edge of a rain shaft moves away from the radar in the sampling period.

distributions) may be Gaussian. In this case, the inversion methods' assumptions remain valid.

Moreover, any physical interpretation of spectral shapes has to be done with great caution. A wide or bimodal spectrum may be the result of strong shear over the averaging period, a bimodal particle size distribution, or a combination of both. Results from this study suggest that the volume-mean velocity broadening effects will depend on both the averaging time as well as the microphysical and velocity characteristics of the cloud. In particular, radar observations of clouds that have large advection speeds, such as cirrus clouds, would be strongly affected by horizontal inhomogeneities in the cloud structure, even at relatively shorter averaging periods. Confusion as to the dominant cause for the spectral shape can be reduced by implementation of simple techniques such as those presented in this paper, or by reducing the real-time averaging window to a fraction of what is commonly used today.

While the data for this study were confined to nonprecipitating stratocumulus clouds, horizontal gradients in the cloud field may produce large changes in the measured spectral characteristics over the averaging period. Figure 8 shows a 35-GHz cloud radar time series collected during an earlier time period during a drizzling event. The first few spectra are clearly bimodal, but as time progresses, the leftmost (drizzle) peak fades away. This disappearance may result from measurements across the boundary of a precipitation shaft, and/or changes in the microphysical processes in the 10-s period for these observations. It is clear that such spectra will severely impact the results of first moment shifting approximations. These measurements point to the need for additional work on designing an optimal algorithm for shifting.

5. Summary and conclusions

In order to better understand fundamental atmospheric cloud processes, researchers must be able to collect microphysical properties from a wide variety of cloud targets. In recent years, one specific quantity of interest has been the measurements of cloud drop size distributions. Drop size distributions can provide valuable insight into the radiative properties of a cloud, as well as cloud precipitation processes. However, most traditional methods of measuring drop size distributions are costly and lack the temporal resolution to perform most studies in detail.

Vertically pointing ground-based Doppler radar possibly offers these needed datasets at a low cost and higher temporal resolution. Although a link has been established between radar-measured power spectra and drop size distributions, background radar noise and air turbulence corrupt the spectral relationships vital to retrieve drop distribution data. While recent studies have addressed the issues of subvolume turbulence within the radar volume (Gossard et al. 1997), most studies have overlooked the contributions of the volume-mean wind on radar-measured spectral averages, required for spectral noise reduction.

Through simple calculations and observables, it was shown that the volume-mean wind contribution can be comparable to the subvolume turbulence. These calculations suggest that the volume-mean wind may equally impact the resulting spectral average. As a result, techniques that average Doppler spectral sets in an effort to mitigate radar turbulent noise must recognize the impacts of a nonrandomly changing volume-mean component. Moreover, it was shown that there are several factors involved in determining the measured spectral shape: the averaging time window and horizontal advection velocity of the cloud, as well as horizontal inhomogeneities in cloud vertical velocity and microphysical fields. With current processing techniques, contributions from these factors cannot be separated a posteriori, pointing to the need for changes in the processing algorithms for cloud profiling radars if spectral observations are to be useful.

Acknowledgments. The paper benefited from discussions with Eugene Clothiaux. We would also like to thank Shelby Frisch, Jan Gibson, and Bruce Bartram at NOAA ETL for the ASTEX time series data. We thank Dusan Zrnic and the anonymous reviewers for their comments on the paper. This work was supported under NSF Grants ATM-9942009 (REU) and ATM-9873643.

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