Computation of Radar Backscatter from Realistic Turbulence Volumes, II: Backscatter Moments Throughout the Lifecycle of a Kelvin-Helmholtz Instability

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Abstract

A companion paper by Franke et al. (2009) describes the computation of radar backscatter from turbulence volumes obtained by direct numerical simulation of Kelvin-Helmholtz shear instability. Its focus is on formulation of the method, the moments and character of backscatter power, their dependence on radar parameters, and the potential for measurement biases for systems that obtain backscatter from refractive index fluctuations. We present in this paper the morphology of computed radar moments throughout the lifecycle of a Kelvin-Helmholtz shear instability for two canonical radar configurations in order to reveal the evolving character of radar backscatter, to compare the radar velocity estimates with true velocities, and to provide guidance, and cautions, for the interpretation of these dynamics where they occur in observational data. Results reveal strong variations in backscatter moments and character, as well as dependence on radar measurement parameters, that should be beneficial in the interpretation of such measurements in the atmosphere. Our results also reveal a potential for significant vertical velocity biases, and their variations throughout the Kelvin-Helmholtz instability evolution.

1 Introduction

Kelvin-Helmholtz (KH) shear instability is one of the most common causes of turbulence throughout the atmosphere from Earth's surface to the lower thermosphere. It is of meteorological interest because it contributes vertical mixing of heat, momentum, and constituents, it acts to limit the maximum shears that can occur and the amplitudes of motions contributing these shears, it poses flight risks for aircraft in extreme cases, it impacts optical propagation in laser and astronomical applications, and it creates much of the persistent small-scale turbulence, and associated refractive index variations, that enable us to measure atmospheric flows with various radars. KH instability also plays an important role in the small-scale dynamics of the oceans. As such, it has received considerable research attention in the past, and it remains an area of active research interest (see Woods and Wiley, 1972; Thorpe, 1973a, b; Fritts and Rastogi, 1985, and Thorpe, 1987, for reviews of earlier observations and Fritts and Alexander, 2003, and Peltier and Caulfield, 2003, for discussions of more recent results).

KH billow wavelengths and depths span a wide range of scales throughout the atmosphere. Maximum wavelengths are as large as several to 10's of km at all altitudes, minimum wavelengths leading to turbulence vary from a few meters or less in the planetary boundary layer, where kinematic viscosity is small, to 10's of meters in the stratosphere and 100's of meters or greater in the mesosphere and lower thermosphere (MLT) (Witt, 1962; Browning, 1971; Gossard et al., 1971; Røyrvik, 1983; Fritts and Rastogi, 1985; Eaton et al., 1995; Chilson et al., 1997; Blumen et al., 2001; Hecht, 2004; Hecht et al., 2005; Kelley et al., 2005; Lehmacher et al., 2007; Woodman et al., 2007). Billow development depends on various parameters, most critically the Richardson number, Ri, which measures the tendency for the available kinetic energy in wind shear to overcome the stabilizing influences of stratification, and the Reynolds number, Re, which measures the influence of kinematic viscosity. Values of Ri close to zero favor strong instability, deep billows (~ ½ the horizontal wavelength), and relatively intense turbulence, whereas values of Ri closer to ¼ favor weak instability, shallow billows, a very different instability and turbulence evolution, and much less intense turbulence (Thorpe, 1973a; Werne et al., 2005). Values of Re = Uh/ν (where U is half the velocity difference of the shear layer, h is half the initial shear depth, and ν is kinematic viscosity) less than a few hundred tend to remain laminar, independent of Ri. However, values of Re of ~1000 or greater, especially at lower Ri, favor rapid instability growth and strong three-dimensional (3D) turbulence (Klaassen and Peltier, 1985, 1991; Thorpe, 1987; Fritts et al., 1996, 2003; Smyth, 1999; Werne and Fritts, 1999a, 2001). One must nevertheless be careful in relying on simple linear theory in assessing KH or other instability dynamics in stratified and sheared flows, as the linear eigenmodes are not orthogonal, allowing for other "optimal" perturbations to occur. Despite the potential for such optimal perturbations, those modes we see most often (or perhaps recognize!) at finite amplitude appear to be consistent with guidance from linear asymptotic theory, though signatures of local optimal solutions are apparent in the billow cores at early stages of the KH evolutions described by Werne et al. (2005). Further discussion of KH instability dynamics is provided in the reviews by Thorpe (1987) and Fritts and Alexander (2003) and references therein (see also Peltier and Caulfield, 2003).

KH instability is a major cause of the turbulence than enables radar backscatter at frequencies ranging from MF to UHF. MF and HF systems (typically ~2 to 3 MHz), either spaced antenna or Doppler, are sensitive to altitudes from ~60 to 100 km, while VHF (~50 and 224 MHz) and UHF (~430 MHz and ~1 GHz) systems are employed for measurements from Earth's surface into the thermosphere. At higher frequencies and/or higher altitudes, however, free electrons, and elevated electron density fluctuations (due to high Schmidt numbers under summer mesopause conditions), and/or sharp electron density gradients are necessary to enhance refractive index fluctuations due to neutral densities and achieve useful measurements (Balsley and Gage, 1980; Röttger, 1994; Cho and Röttger, 1997; Lübken et al., 1998; Hill and Mitton, 1998; Hill et al., 1999). We note that some of the radars that rely on refractive index fluctuations at lower altitudes (typically the VHF and UHF frequencies, ~50, 224, and 430 MHz and above) also obtain incoherent scatter returns at MLT altitudes that are not likely to be sensitive to the biases that are the subject of this paper. They are, nevertheless, capable of measuring the same dynamics and may, therefore, be in a position to contribute to a more complete understanding of these measurement biases.

Whether backscatter occurs primarily due to neutral density fluctuations in the lower atmosphere or to electron density fluctuations at higher altitudes, correlations of the refractive index fluctuations with the underlying dynamics have been implicated in a number of measurement biases noted to date. Several authors have noted a potential for biases in radar Doppler wind measurements (Kudeki et al., 1993; Muschinski, 1996; Muschinski et al., 1999; Gibson-Wilde et al., 2000; Tatarskii and Muschinski, 2001; Worthington et al., 2001). Others have reported mean vertical motions that differ from expectations in both sign and magnitude (Balsley and Riddle, 1984; Nastrom et al., 1985; Fritts and Yuan, 1989; Meek and Manson, 1989; Rüster and Reid, 1990; Wang and Fritts, 1990; Fritts et al., 1990; Fukao et al., 1991). Specifically, Nastrom and VanZandt (1994) noted a correlation between upward motions and enhanced high-frequency variances in tropospheric wind profiler data and suggested that a bias towards negative mean vertical velocities resulted from a correlation between higher radar backscatter power with the higher refractive index fluctuations accompanying the downward (more stable and with reduced high-frequency velocity variance) phases of the gravity waves (GWs) modulating atmospheric stability and turbulence intensities. Hoppe et al. (1990) and Hoppe and Fritts (1995a, b) assessed the correlations between backscatter power, vertical velocity, and spectral width using the EISCAT 224 MHz radar under summer mesopause PMSE conditions and found high power to be well correlated, in general, with narrow spectral widths and downward motions. Hoppe et al. (1990) also noted similar correlations using the SOUSY 53.5 MHz radar. These latter studies, employing neutral and electron fluctuations, suggest that the downward phase of GW motions, where we expect turbulence to be weak or decaying (Fritts et al., 2009a, b), enables sharper gradients, higher backscatter power, suppressed vertical motions, and narrower spectral widths than in the upward, and less stable, phase of the GW motion. Tatarskii and Muschinski (2001) provided a theoretical framework demonstrating that differences between real and measured radial velocities arise due to correlations between radial velocity and refractive index fluctuations, with potential additional contributions due to higher-order correlations.

Measurement biases accompanying radar observations of KH instability were first suggested by Muschinski (1996), who argued that the systematic slopes of layered features accompanying KH evolution in mean shear could lead to errant vertical velocity estimates. Other biases are suggested by many observations of the familiar Kelvin’s “cat’s eye” structures in radar backscatter power, which clearly delineate the KH billows but appear to fail to capture the stronger turbulence often occurring within the billow cores (see Fritts and Rastogi, 1985, and references therein; Fritts et al., 2003). The more recent spectacular measurements of such structures in the boundary layer, the troposphere, and the MLT by Eaton et al. (1995), Woodman et al. (2007), and Lehmacher et al. (2007), provide additional compelling evidence of the prevalence and character of such dynamics throughout the atmosphere.

The first detailed assessment of such biases by Gibson-Wilde et al. (2000) employed a direct numerical simulation (DNS) of KH instability at an initial Re = 2000, and the isotropic plasma turbulence model developed by Hill and Mitton (1998) and Hill et al. (1999) extending refractive index fluctuations to smaller spatial scales, to evaluate the classical theories and assumptions related to mixing and energy dissipation rates in stratified flows (Weinstock, 1981). The result was that the theory, and its predictions, appear to have major deficiencies because the underlying assumptions (i.e., that turbulence is stationary, homogeneous, and isotropic) are not an accurate description of the turbulent flow due to KH instability in a sheared and stratified fluid at ***any*** stage in its evolution.

The potential for biases in radar measurements arises, from the departures of turbulence from isotropy and homogeneity during both its active and decaying phases in stratification and shear, and its influences on laminae that may contribute non-turbulent radar backscatter. Departures from turbulence isotropy due to stratification and shear were first addressed theoretically by Uberoi (1957), Townsend (1959), Bolgiano (1959, 1962), and Lumley (1963). Reviews of early work addressing turbulence anisotropy were provided by Champagne (1978), Mestayer (1982), Brown et al. (1987), Hunt et al. (1991), Shreenivasan (1991), and Van Atta (1991). More recent experimental, numerical, and theoretical studies further quantified our understanding of the departures from isotropy due to shear and/or stratification for various geophysical flows (Durbin and Speziale, 1991; Werne and Fritts, 1999a, b, 2000, 2001; Smyth and Moun, 2000; Pettersson-Reif et al., 2002; Fritts et al., 2003; Pettersson-Reif and Andreassen, 2003; Wroblewski et al., 2003; Ruggiero et al., 2005; Werne et al., 2005, Fritts et al., 2009a, b).

The companion paper by Franke et al. (2009, hereafter F09) employs the Born approximation for radar backscatter developed for isotropic turbulence by Tatarskii (1961, 1971) and extended to more general anisotropic turbulence and Fresnel backscatter by Doviak and Zrnic (1984), Muschinski et al. (1999), and Muschinski (2004). Backscatter power and mean Doppler shift are computed for representative turbulence volumes defined by a large-eddy simulation (LES) of KH instability at Re = 10,000 (evaluated for realistic descriptions of turbulence against our DNS simulations at Re = 2,500) and compared with vertical velocities obtained directly from the LES data. These comparisons reveal a potential for radar measurement biases that depend on measurement parameters and the character of the turbulence field.

Our purposes in this paper are to employ the LES description of turbulence due to KH instability and the method for computation of radar backscatter described by F09 to exhibit expected radar responses throughout the life cycle of a KH instability. Specifically, we assess radar backscatter power and the first moment of the Doppler spectrum for an assumed vertical beam and compare these quantities with the turbulence intensities (quantified by the mechanical energy dissipation rate, ε) and the vertical velocities computed directly (without radar biases) from the same LES volumes. These comparisons indicate 1) that radar estimates of turbulence intensities are biased by an insensitivity of radar measurements to the regions of strongest turbulence within the well mixed billow cores and 2) that biases in radar estimates of vertical velocities occur throughout the active and decaying phases of KH instability and may impact interpretations of both instability dynamics and mean motions. Our assumptions for the character of the KH instability evolution, the environment in which it occurs, and the radar sampling parameters are described in Section 2. We show in Sections 3 and 4 how this evolution would appear as viewed by 10 and 3 MHz radars having very high spatial resolution and vertical beams.

In these applications, the 10 MHz sampling frequency is employed as a surrogate for higher-frequency VHF systems at MLT altitudes in order to describe sampling volumes and KH spatial scales within the resolution constraints of our modeling capabilities. These same results allow computation of equivalent 50 MHz responses to the same KH dynamics in the lower stratosphere (assuming high radar bandwidth and spatial resolution) because of the much smaller typical scales of these dynamics (and the higher effective simulated spatial resolution) at these altitudes. Section 4 provides our summary and conclusions.

2 Backscatter Environment and Virtual Radar Measurement Parameters

We assume radar backscatter from the life cycle of a KH instability described by an LES description of KH instability evolution for an initial Richardson number $Ri = N^2/ U_z^2 = 0.05$, a Reynolds number $Re = Uh/\nu = 10{,}000$, and a Prandtl number $Pr = \nu/\kappa = 1$. We impose an initial horizontal mean wind given by $U(z) = U \tanh (z/h)$, with $U = 5\ ms^{-1}$ and $h = 150$ m, such that $U_z = U/h = 0.0333\ s^{-1}$, the KH instability has a horizontal wavelength $L = 12.566\ h$, and the billow and turbulence layer will approach a typical depth of $D \sim 6h \sim 900$ m and allow radar sampling representative of such measurements in the MLT. The quantities ν and κ are kinematic viscosity and thermal diffusivity, respectively, and Pr differs from that of the atmosphere, ~0.7, in order to achieve uniform resolution requirements in the velocity and potential temperature fields. These choices imply a time scale h/U, a buoyancy frequency $N = Ri^{1/2}/30 \sim 0.0075\ s^{-1}$, and a buoyancy period $T_b = 2\pi/N = 28h/U = 843$ s. The LES was performed in a computational domain of dimensions (12.566, 4.2, 25)L, and employed spatial resolution of (720, 240, 1440). This yielded a spatial resolution of $\Delta z \sim 2.6$ m to ensure sufficient resolution of structures at the assumed radar Bragg scales of 15 and 50 for our radar backscatter assessments. To ensure resolved radar phase variations and Doppler velocities, we chose a sampling interval of 1.5 s and 64 samples per spectral computation. This implies a sampling interval of 96 s or ~0.11 T_b.

Radar backscatter assessments were performed for two radar frequencies for which the LES described above provides explicit resolution of the Bragg scales. Our first assessment of radar backscatter characteristics and accuracy is performed with the following assumptions:

1) a 10 MHz Doppler radar with a vertical beam of full width, half maximum (FWHM) of 180 m at MLT altitudes, and a sinx/x shape with sidelobes suppressed;

2) a radar baud length yielding a Gaussian FWHM pulse width of 90 m (and an altitude resolution of 45 m);

3) the radar samples successive spatial positions within the KH billow, separated by the FWHM beam width in the streamwise direction, simultaneously in order to achieve the optimal definition of the KH billow structure and evolution in space and time;

4) there is no background noise; and

5) the moments of the Doppler spectrum can be assessed using the method described by F09.

This set of radar parameters will be referred to as Case A. A second set differing from Case A only in the pulse length (increased from 6 to 20 Bragg scales) will be referred to as Case B. Finally, Case C comprises parameters representing a 3 MHz radar frequency, a 50 m Bragg scale, a 300 m (FWHM) pulse width, and a 300 m beam width. The radar parameters for each of these cases are listed in Table 1 for ease of comparison.

We choose times of t = 37, 54, 84, 129, 256, 312, and 364 spanning ~11 T_b to illustrate the KH evolution from the late 2D flow through the turbulence transition, billow mixing and breakdown, and formation and restratification of the turbulence layer at late times. Streamwise-vertical cross sections of potential temperature, vertical velocity, and vorticity magnitude, for these times are shown in Figure 1 for reference. Units of time are h/U, as defined above, and the buoyancy period is then T_b = 28 h/U. Doppler spectra for each set of radar parameters, from which the power and Doppler velocities are obtained, are determined from 64 LES turbulence volumes spaced by 1.5 s (spanning ~ $T_b/3$) for each of the times displayed. We will use units of h/U to denote time hereafter.

Radar frequency	Bragg scale	Pulse width	Vertical resolution	Beam width
(A) 10 MHz	15 m, 6 Δz	90 m, 36 Δz	45 m, 18 Δz	180 m
(B) 10 MHz	15 m, 6 Δz	300 m, 120 Δz	150 m, 60 Δz	180 m
(C) 3 MHz	50 m, 20 Δz	300 m, 120 Δz	150 m, 60 Δz	300 m

Table 1. Radar frequency and resolution combinations assessed in this paper.

3 Simulated 10 MHz Backscatter Moments

a. High-resolution measurements in altitude at 10 MHz (Case A)

Backscatter power obtained for each of the times displayed in Figure 1 is shown in the left column of Figure 2 for the assumed radar beam configuration described above (denoted A in Table 1). Corresponding vertical velocities are shown in the second column of Figure 2. Considering first the backscatter power, we see that the dominant returns come, in all cases, from the billow or turbulence layer edge regions. At the earliest times (t = 37 and 54), backscatter is relatively strong but occurs only where potential temperature gradients are large, relatively coherent, and aligned nearly vertically, as there are developing instability structures at t =54, but no turbulence inertial range at these times. At intermediate times (t = 84 and 129), turbulence is well developed within the outer billow or the billow core itself, backscatter power is now much weaker, and it maximizes at the outer edges of the billow and turbulence layer and decreases strongly within the billow core. It is only at the latest times (t = 256 and after) that backscatter power suggests that the turbulence is finally achieving a quasi-horizontally homogeneous state, and in the later stages of restratification (t = 312 and 364) that backscatter power becomes significant within the turbulence layer.

Given these results, what are the implications for scattering processes for these radar parameters? At the earliest time, the dominant backscatter power occurs where Bragg-scale quasi-coherent flow structures are nearly horizontal and must contribute largely through specular backscatter. The backscatter at this time is quite strong, suggesting that specular contributions to total power may dominate when they occur. At intermediate times (t = 84 and 129), turbulence is well developed and has largely eradicated thermal and refractive index gradients within the billow. This results in the dominant backscatter accompanying the smaller turbulence intensities within the re-formed thermal gradients within the billow edge regions. Backscatter power is also highest where these gradients are more nearly horizontally aligned than where the quasi-2D dynamics impose significant slopes. At these times, there is strong turbulence, first in the outer billow and later throughout the entire billow and at all horizontal locations, though it requires ~1 T_b for turbulence to penetrate into the billow core and another ~2 T_b for the turbulence layer to become nearly horizontally homogeneous (see Figure 1 and the more complete evolution shown in Figures 1 and 2 of F09). At later times, both the surviving turbulence and the large-scale potential temperature gradients become more uniform horizontally, and radar backscatter is more uniform horizontally, suggesting that specular reflections are again making significant contributions to total backscatter.

Vertical velocities obtained from the first moments of the Doppler spectrum for each LES data set for Case A parameters are shown in the second column of Figure 2. The true vertical velocity field sampled with the same spatial weighting, and the differences between the true and radar velocities, are shown at the same times for comparison in the 3rd and 4th columns of Figure 2. The first panel indicates non-zero velocity estimates only where there is sufficient backscatter power in the billow edge regions, but these estimates bear no resemblance to the true velocities at this time. The next three panels (t = 54, 84, and 129) exhibit relatively coherent upward and downward motions at the left and right sides at times during which the billow is fairly coherent, and spanning turbulence formation and mixing of the billow core. The velocity estimates fail to capture the true velocity maxima within the billow core at these times, however, suggesting a lack of sensitivity to motions where refractive index variations are weak or have been largely destroyed by mixing. The radar velocities also systematically underestimate the true velocities at all locations (the velocity differences and true velocities are highly correlated from t = 37 to 129) except in a thin region corresponding closely to the region of highest backscatter power at each time from t = 54 to 129. Thus, unbiased velocity estimates at early and intermediate times occur only where backscatter is relatively strong and the Doppler spectrum is well defined.

At later times (t = 256 and after), there are both 1) spurious large velocities that are limited in altitude at the upper and lower edges of the decaying turbulence layer and 2) a lack of sensitivity to coherent, larger-scale true motions both within and external to the turbulence layer. Differences outside the billow or turbulence layer at all times occur where there is essentially no small-scale structure and where we should expect no radar backscatter. Lack of sensitivity to motions within the turbulence layer at t = 256 are a result of the strong mixing and eradication of thermal and refractive index gradients by turbulence that has not yet restratified (see the strong turbulence that persists throughout the layer at this time in the vorticity field in the right column of Figure 1). The significant radar vertical velocities at the edges of the turbulence layer at late times (t = 312 and 364, negative at the top and positive at the bottom) arise due to largely horizontal advection of slanted specular reflectors (see the potential temperature and vorticity fields in Figure 1 at these times), rather than vertical motions of specific scatterers, that we will discuss further below. Motions in the edge regions are now essentially horizontal (3D turbulence structures are largely absent) and the relative motion is to the right at the top of the layer and to the left at the bottom. These horizontal motions result in apparent downward (upward) motions at the top (bottom) of the layer due to the slight tilt of the potential temperature structures at these late times (and also seen in the vorticity) upward and to the right by the mean shearing motion of the expanded shear layer.

We now examine the character of the Doppler spectra from which the vertical velocity estimates are obtained. These are compared with the distributions of true vertical velocities within the same scattering volumes, weighted by the radar beam width and pulse length, for two representative locations at early, intermediate, and late times in Figure 3. The top two panels show true (solid) and radar (dashed) velocity spectra just left of the center of the billow (left) and in the edge region at the top of the billow just left of center (right) at t = 54, when instability structures are seen in the outer portion of the billow, but turbulence has not yet developed and the billow core is laminar. Both locations exhibit almost no correlation between true and radar velocities at this time. True velocities left of the billow center (left panel) are large and positive, as noted above, but the radar velocity spectrum appears to exhibit power near zero Doppler shift that comes from the strong refractive index variations in the billow edge regions above and below the sampling altitude due to the Gaussian pulse shape. The spectra within the upper portion of the billow likewise exhibit significant biases, again because the radar power comes preferentially from the billow edge region having strong refractive index gradients, and these are not uniformly distributed throughout the sampling volume at this time. There is, nevertheless, at least an overlap of true and measured velocities at this location.

At $t = 129$ (middle panels in Figure 3), there is considerably better agreement between true and radar velocities, because turbulence is now well developed and fills the sampling volumes. Both in the center of the turbulence layer and towards its upper edge (left and right panels), true velocities exhibit spectral widths of $\sim 1\ ms^{-1}$ and means of ~ -1.8 and $0.8\ ms^{-1}$, respectively. Radar velocity spectra now overlap the true velocities to a significant degree, but the mean radar velocities are ~ -1.5 and $0.6\ ms^{-1}$, respectively, or ~20% less than the true velocities because the Doppler spectral power is biased towards the edges of the turbulence layer where vertical velocities are smaller. This appears to explain the systematic underestimates of velocities noted above.

As turbulence decays and the layer restratifies, backscatter power occurs throughout the layer. However, systematic biases in radar velocity estimates occur as a result of the tilting and stretching of thermal and refractive index gradients by the mean shearing motions that accompany restratification, and which are more stratified and more coherent in the turbulence layer edge regions. This tendency can be seen clearly in the potential temperature and vorticity fields at $t = 312$ and 364 in Figure 1. The effects are illustrated in the bottom panels of Figure 3, which are near the lower and upper edges of the turbulence layer, respectively. The mean (horizontal) velocities at these times advect these structures to the left at lower altitudes and to the right at higher altitudes. The effect of this advection (with the slanted character of these gradients) is an apparent upward (downward) velocity in the lower (upper) edge of the turbulence layer as it restratifies. While the radar Doppler spectrum at the lower edge of the turbulence layer (bottom left panel) suggests both positive and negative velocities (both of which are outside the range of true velocities at this location), the power at positive velocities dominates, and the mean Doppler velocity is consistent with the apparent upward motion induced by the slanted gradients. The opposite is the case at the upper edge of the turbulence layer (bottom right panel), where the dominant power is at negative Doppler velocities and the mean again differs significantly from the true mean velocity. Thus, radar backscatter at late stages in the restratification of a turbulence layer arising from KH shear instability exhibits biases in radar Doppler vertical velocities that are anticipated to yield clear measurement errors that may impact the interpretation of the small-scale dynamics and associated mean motions.

In real applications, we expect finite radar S/N to mask velocity estimates where backscatter is very weak. But this will not preclude the biases noted above due to insensitivity to significant vertical motions within the billow cores, either prior to significant small-scale structures or after mixing and eradication of the refractive index variations. Nor will it avoid biases accompanying horizontal advection of slanted specular reflectors at late stages of the evolution. Indeed, these comparisons reveal that radar estimates provide only qualitative information on the large-scale KH velocity field at this spatial resolution and that there is a significant potential for measurement biases that could contribute to a misinterpretation of real radar measurements and to inaccurate assessments of the corresponding neutral dynamics.

b. Lower-resolution measurements in altitude at 10 MHz (Case B)

We now examine the results of employing the same radar parameters as in Case A above, but with a sampling pulse that is 300 m (Case B) rather than 90 m FWHM. The computed radar backscatter power and vertical velocities for Case B corresponding to those obtained in Case A are shown in the two left columns of Figure 4. These fields exhibit similarities to, and differences from, those shown for Case A, again with the only difference being the pulse length. First comparing the backscatter power, we see that the overall fields are very similar, with slightly elevated power in Case B at early and intermediate times, and spatial distributions having common shapes and intensity distributions through t = 256, apart from the obvious differences due to spatial resolution. As in Case A, the power distributions for Case B define the billow and turbulence layer outlines reasonably well, though the curved edges of the KH cat's eye structure are less distinct at the coarser resolution. In neither case does the radar observe significant power in the interior of the billow or the turbulence layer until very late times.

As the turbulence layer restratifies (t = 312 and 364), the broader pulse results in much less coherent structures in space and time, with isolated regions of high and low power interspersed, where Case A results are more smoothly varying in altitude and the horizontal. Both cases also exhibit significant relative backscatter power within the turbulence layer as it restratifies, but power levels remain low, and this is likely due to both an increase in stratification in the layer interior and greater coherence among the residual turbulence structures at later stages (see the vorticity images in the lower right panels of Figure 1). Overall, Case A power profiles appear to describe the early and late stages of KH instability evolution and structure more accurately, including the evolution of billow shape, the transition to a more nearly homogeneous turbulence layer, and the late-time restratification. At later stages, the two pulse lengths respond to very different features of the turbulence layer, with Case A capturing both edge and interior regions and Case B less sensitive overall and especially to the turbulence edge regions as it restratifies.

Vertical velocities for Case A and Case B are likewise very similar in their gross features, and more similar to each other than either is to the true velocity field at early and late times. There are also some interesting differences, however. At early times (t = 37 and 54), both cases exhibit different locations of maximum velocities (and weak velocities in the billow core) compared to the true velocity fields (see the third column of Figures 2 and 4). This is presumably linked to the lack of turbulence and radar backscatter in the billow core at early times, as discussed above. At intermediate times (t = 84 and 129), however, the longer radar pulse in Case B does a somewhat better job of defining the velocity field within the KH billow or turbulence layer, presumably because it samples a larger part of the flow. At later times, however, Case B appears to yield velocity estimates exhibiting comparable or greater errors compared to Case A, both in the turbulence edge regions and in the outer flow. Radar Doppler velocities also fail to capture the larger-scale coherent structures within and external to the turbulence layer, and they imply significant vertical motions in the edge regions not seen in the true velocity fields at these times due to largely horizontal advection of slanted features in the potential temperature field, as discussed for Case A above.

As in Case A, we display several comparisons of Doppler spectra obtained in Case B with the true velocity distributions for early, intermediate, and late times of t = 54, 129, and 312. The spectra shown in the top two panels (t = 54) are at the same horizontal position (just left of the billow center) and separated by 3 sampling volumes, or 450 m, in the vertical. Each Doppler spectrum appears to be better defined by the larger sampling volume, compared to that in Case

A. Indeed, the true and radar spectra now span largely the same velocities. The major difference is the power near zero velocity in the upper sampling volume (top right panel) that is outside the true velocity distribution and which must come from the upper billow edge region having large refractive index variations but small vertical velocities. The lower sampling volume (top left panel) is closer to the lower billow edge region, so that higher power at the smaller velocities yields a bias towards zero Doppler velocity, but no power at velocities outside the true velocity distribution at this position. Doppler spectra at t = 129 exhibit similar biases relative to the true velocities, again with relatively more power at small Doppler velocities because of the higher backscatter at the turbulence layer edge regions. Comparing Doppler and true velocities in the lower and upper portions of the turbulence layer at t = 312 (lower panels), we see that the biases identified in Case A are again present, with significant apparent motions due to horizontal advection of the slanted structures and gradients that are much larger than the true vertical motions, or the widths of these distributions, at these positions. Indeed, specular backscatter from slanted reflectors appears to yield systematic vertical velocity biases at late stages of turbulence restratification in mean shear, whether radar spatial resolution is relatively fine or more coarse.

To evaluate the biases accompanying specular backscatter in the turbulence layer at later stages in the KH evolution more completely, we display in the upper two panels of Figure 6 the mean vertical velocity profiles obtained by averaging over all horizontal beam positions for Case B at t = 312 and 364. Each profile exhibits maximum positive and negative mean Doppler vertical velocities at the lower and upper edges of the turbulence layer that span one or two altitudes and which are seen to decrease in magnitude with time. These profiles are entirely consistent with the discussion of individual Doppler spectra above, and the decrease in the biases with time can be traced to the decreasing tilt of the residual layered structures seen in the turbulence edge regions with time. Importantly, however, these biases are ~0.05 to 0.15 ms^{-1} at these times, and are thus comparable to, or much larger than, expected mean vertical velocities throughout the atmosphere. These suggest that such biases may contribute significant uncertainties in the use of radars to measure mean vertical motions or mean responses to dynamical processes that may otherwise be adequately described by such measurements.

4 3 MHz Measurement Biases and Parameter Dependence

We now examine the backscatter power and vertical velocity fields obtained for a 3 MHz radar having similar characteristics to those described for the 10 MHz radar above, except in this case having a Bragg scale of 20 Δz (50 m), a pulse length of 120 Δz (a vertical resolution of 150 m), and a beam width (FWHM) of 300 m. These correspond to Case C in Table 1 above. The computed radar backscatter power and vertical velocities for Case C corresponding to those obtained in Cases A and B are shown in the two left columns of Figure 6.

The backscatter power fields exhibit similarities to, and differences from, those shown for Cases A and B, apart from the obvious differences in spatial sampling. These fields are most similar to those of Case B, but with slightly elevated power at earlier times and significant power enhancements at later times. Backscatter power at $t = 37$ is large and confined to those portions of the flow where the refractive index gradients are large and nearly vertical. Indeed, the 3 MHz Bragg scale is obviously much better matched to the billow thermal structures than the 10 MHz Bragg scale at this time. Thereafter, the power profiles closely resemble those discussed for Cases A and B, but with somewhat elevated power at intermediate times and increasing power enhancements at later times ($t = 256$ and beyond). However, Case C power differs from the distributions seen in Cases A and B at later times in several respects. First, peak power increases from comparable values at $t = 54$ to an ~2 times enhancement at $t = 129$ and 256 and an ~100 times enhancement at t = 312 and 356. Case C power also differs from Cases A and B in having power confined to the turbulence layer edge regions at t = 256 and beyond, where Case A had comparable power in the layer edge regions and center and Case B had peak power shifting from the edges to the center at later times. Clearly, the 50-m Bragg scale in Case C is much better matched to the spatial scales of the refractive index variations than the 15-m Bragg scale in Cases A and B at these times.

Vertical velocities for Case C, and their biases relative to the true velocities (see the right two columns of Figure 6), are seen to be more simi8lar to those discussed above for Case B than for Case A. Again, the longer radar pulse appears to enable somewhat better definition of the KH billow velocity structure at early and intermediate times. Doppler velocity errors are comparable in both magnitude and spatial distribution to those seen in Case B out to t = 129. Thereafter, however, large biases in the turbulence layer edge regions, and outside it, yield velocity biases that become substantially larger than seen in either Case A or B (by factors of ~2 to 5). These biases are most pronounced, and of the same signs as seen in Cases A and B, in the turbulence layer edge regions. But their larger magnitudes imply a greater potential for misinterpretation of dynamics based on such measurements.

As for Cases A and B, we display comparisons between radar Doppler spectra and the true velocity distributions within the same sampling volumes at early, intermediate, and later times (t = 54, 129, and 312) in Figure 8. While the Doppler spectral resolution is ~3 times coarser in Case C (at 3 MHz) than in Cases A or B (at 10 MHz), similar common features and differences are observed. Significant power is seen at Doppler velocities outside the range of true velocities at all times, biases in this case yield velocity estimates both larger and smaller than the corresponding true velocities (unlike the early and intermediate times for Cases A and B), and the extrema of the biases appear to increase with time (also noted in the discussion of Figure 7 above). The differences at later times are also apparent in the mean Doppler vertical velocity profiles displayed for Case C at t = 312 and 364 in the lower panels of Figure 6. Comparing these profiles to the upper panels for Case B, we see that the biases in Case C exhibit very similar structures in altitude, but are larger in magnitude and with peaks more extended in altitude (including outside the turbulence layer) than for the 10 MHz sampling frequency with the same pulse length and resolution.

In most respects, the results obtained for Case C closely parallel those for the 10 MHz radar described in Cases A and B above. The velocity fields, spectra, and profiles arising in the three cases considered here indicate tendencies for both radar frequencies and pulse lengths 1) to capture the large-scale structure of the KH billow evolution up to the time of billow decay, 2) to underestimate the vertical velocities prior to billow decay, and 3) to experience biases in vertical velocity estimates following billow decay and accompanying restratification of the turbulence layer at late times. Despite capturing the large-scale flow structure, there are also clear systematic biases that arise and suggest that similar biases are likely present in real radar measurements of similar dynamics in the atmosphere.

5 Comparison with Previous Studies

Our simulations of radar backscatter throughout the lifecycle of a KH instability exhibit many similarities to observed radar backscatter accompanying these dynamics throughout the atmosphere. The most obvious similarity is between the simulated and observed power profiles, both of which exhibit the strongest responses surrounding active KH billows and at the edges of the turbulence layer following billow breakdown. Both observed and simulated backscatter power exhibit the Kelvin's "cat's eye" shape at early stages when the billows are clearly delineated (Browning, 1971; Gossard et al., 1971; Fritts and Rastogi, 1985). Well-resolved billow structures have also been observed from the boundary layer to the MLT (Eaton et al., 1995; Woodman et al., 2007; Lehmacher et al., 2007). All suggest very little backscatter in the billow interiors, despite the clear evidence from our previous DNS studies and the current LES that the billow cores, and the interior of the turbulence layer, contain the most intense mechanical turbulence. Indeed, it is the mixing accompanying this turbulence that drives the maximum potential temperature gradients and wind shears to the edges of the billows and the subsequent turbulence layer. The stronger potential temperature gradients at the edge regions dominate the refractive index variations, and the radar backscatter power, extending to late times. Indeed, the negative correlation between backscatter power and turbulence intensity implied by these simulations also correspond closely to those observed or anticipated to lead to measurement biases in previous studies (see Hoppe et al., 1990; Nastrom and VanZandt, 1994; Hoppe and Fritts, 1995a, b; Tatarskii and Muschinski, 2001; and references therein). The potential "bias" in the measurement of backscatter power is the suggestion that the billow cores and the subsequent turbulence layer may exhibit relatively smaller turbulence intensities and mixing than indicated by our previous DNS studies and the LES results shown in F09. This arises from the inability of most radars to measure turbulence spectral widths due to limited S/N within strong turbulence having very small refractive index gradients.

Our radar backscatter simulations also demonstrate an expectation of radial velocity biases at various positions within KH billows and the subsequent turbulence layer throughout the KH lifecycle. These biases are difficult to compare with direct measurements of these dynamics, but our comparisons with the real radial velocities determined by our LES simulations reveal 1) insensitivity to velocities within the billow core, where strong mixing has largely eradicated the refractive index gradients, 2) a tendency to underestimate velocities where they are significant, especially within the billow cores, 3) potential biases in estimated velocities outside the billow and turbulence layer where refractive index variations are small or nonexistent, and 4) apparent vertical velocities at the edges of the turbulence layer at late times where persistent slanted structures having small slopes induce phase variations in radar backscatter due to horizontal advection. Of the velocity measurement biases noted above, only the last was suggested by Muschinski (1996) prior to this study, and our results appear to confirm that suggestion. Specifically, persistent tilted structures accompanying large-scale shears appear likely to cause biased radial velocity estimates for both vertical and off-vertical beams for the reasons discussed above. The tendency for radial velocity estimates to be biased towards those portions of the billow having the largest refractive index fluctuations also suggests a potential for correlations of radial velocities and refractive index fluctuations that may bias mean velocity estimates in more general flows, as discussed by Hoppe et al. (1990), Nastrom and VanZandt (1994), Hoppe and Fritts (1995a, b), and Tatarskii and Muschinski (2001). While we have not addressed Doppler spectral widths in this paper, we anticipate that, like the velocity estimates, such estimates may be biased towards those regions of the flow having the dominant refractive index fluctuations. For KH billows and the subsequent turbulence layers, this would likely yield a stronger weighting of the least turbulent and most stratified regions and overall underestimates of spectral widths and turbulence intensities in cases with limited (finite) S/N.

6 Summary and Conclusions

We have employed a high-resolution large-eddy simulation of the transition to, and evolution of, turbulence accompanying Kelvin-Helmholtz (KH) instability, and a general numerical description of radar backscatter from these turbulence fields, to assess the backscatter power and Doppler vertical velocities throughout the KH evolution. Our intentions were to provide descriptions of radar measurements of such dynamics to aid the interpretation of these dynamics seen by real radars and to note where radar measurements are likely to be absent, deficient, or biased because of either the radar method and/or assumptions, or the character of the scattering medium.

For these purposes, we assumed a KH billow having a Richardson number Ri = 0.05, a Reynolds number Re = 10,000, a horizontal wavelength of 1.8 km, and a depth of ~900 m, as these values are representative of KH parameters at MLT altitudes where our community expends considerable resources on such measurements. We computed 7 sequences of backscatter volumes spanning the KH instability evolution, each composed of 64 data sets spaced by 1.5 sec and having a mesh of 720x240x1440 points with a spatial resolution of 2.6 m, to allow Doppler spectra to be assembled for each sequence. These volumes extended from prior to and during the transition to turbulence, through the expansion of turbulence throughout the KH billow, and accompanying the billow and turbulence layer decay at late times. They thus allow radar Doppler spectra to be computed before turbulence arises, as well as at various stages of turbulence evolution, from transitional to fully-developed to decaying and restratified.

We also assumed radar frequencies of 10 and 3 MHz, somewhat lower than often used for MLT studies, but allowing us to perform radar backscatter assessments with numerical turbulence data sets that explicitly resolve these radar Bragg scales. Finally, we performed our radar backscatter assessments for short and medium pulse lengths at 10 MHz and for medium pulse lengths at 3 MHz. This was done to assess both the effects of different pulse lengths at one frequency and the different responses at two frequencies for the same pulse lengths. The 10 MHz radar, with a Bragg scale of 15 m (or 6 Δz), was assumed to have a FWHM beam width of 180 m and a pulse length of either 90 or 300 m, while the 3 MHz radar, with a Bragg scale of 50 m (or 20 Δz), was assumed to have a beam width of 300 m and a pulse length of 300 m.

A summary of these results includes the following key findings:

1) the 10 MHz radar with a short pulse did a very good job of defining the KH billow morphology in the backscatter power profiles, where it was able to describe the characteristic cat's eye signature beginning before significant billow turbulence and extending to well after decay and restratification of the turbulence layer;

2) the 10 MHz radar with the short pulse provided only a qualitative description of the true vertical velocity field. Specifically, it failed to provide valid estimates within the billow core, the subsequent turbulence layer, or the external flow, and it exhibited significant biases at late times;

3) the 10 MHz radar with the medium pulse likewise described the KH billow morphology adequately in the power plots, but with less sensitivity to billow form and edges, much more variable backscatter power than obtained with the short pulse, and more returns in regions of the flow without high refractive index fluctuations;

4) the 10 MHz radar with the medium pulse was also able to provide somewhat better vertical velocity estimates than the same frequency with a shorter pulse at most locations

across the KH billow and turbulence layer, beginning after turbulence formation and extending to late stages of restratification;

5) the 10 MHz radar, however, also tended to systematically underestimate the true vertical velocities at essentially all locations and to yield biased estimates at late times;

6) the 3 MHz radar performed much more like the10 MHz radar having the same (medium) pulse length. It was able to describe the large-scale KH dynamics fairly realistically, it captured the KH cat's eye signature morphology, but it also underestimated true vertical velocities following turbulence formation; it also exhibited biases at late times consistent with those seen at 10 MHz, but led to larger maximum velocity errors than seen at 10 MHz with either pulse length;

7) backscatter power for both radar frequencies and pulse lengths was seen to be maximum in regions of the flow having large thermal and refractive index gradients and relatively small turbulence intensities, suggesting 1) a strong anti-correlation between backscatter power and turbulence spectral widths and intensities and 2) systematic underestimates of turbulence energy dissipation based on measured spectral widths; and

8) biased vertical velocities obtained with the 3 and 10 MHz radars at late times arose due to specular backscatter due to tilted surfaces in the restratifying turbulence flow that were significant when true vertical velocities were very small.

The bottom line is that our virtual radars performed sufficiently well to identify the KH instability dynamics underlying radar backscatter from early in the turbulence transition through billow collapse, formation of a quasi-homogeneous turbulence layer, and its subsequent restratification. There were, nevertheless, clear biases in assessments of backscatter power and

Doppler vertical velocities due to the character and distribution of the associated thermal and refractive index gradients at various stages of the KH evolution. Systematic under-estimates of true vertical velocities within the KH billows suggest less than full quantification of such events by real radars. Biases in vertical velocity estimates due to specular reflections from slanted structures at late stages suggest systematic biases in estimates of mean vertical motions, and likely in the vertical profiles of horizontal winds with off-zenith beams. Though these results were obtained for sampling frequencies lower than employed for typical radars making such measurements, we anticipate these results to be indicative of what is seen at higher frequencies because of the character at the various stages of the KH instability and turbulence evolution. Additional aspects of radar backscatter from realistic turbulence data to be addressed in future papers will include aspect sensitivity, turbulence due to breaking gravity waves, and biases accompanying correlations of turbulence character with the larger-scale motion field.

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