Structures of Bragg Scatter Observed with the Polarimetric WSR-88D

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ABSTRACT
Enhancements to signal processing and data collection in the dual-polarization Weather Surveillance Radar-1988 Doppler (WSR-88D) to increase its detection capability yield observations of “fine” structures from Bragg scatterers. Several types of the fine structures observed in and above the boundary layer are discussed. These Bragg scatter structures include the top of the convective boundary layer, nonprecipitating clouds, strong convective plumes above the boundary layer, and a layer of weak reflections associated with decaying boundary layer turbulence. A conclusion that data from polarimetric WSR-88Ds can be used to obtain the depth of the convective boundary layer is made.

1. Introduction
The intensity of Bragg backscatter from refractive index perturbations, at scales half the centimetric and metric wavelengths of atmospheric radars, is measured to estimate the refractive index structure parameter \( C_n^2 \) (e.g., Tatarskii 1971; Doviak and Zrnić 2006, section 11.6). The value of \( C_n^2 \) strongly depends on turbulent mixing in gradients of the potential refractive index; these gradients are typically strongest at boundaries of water vapor layers. Large values of \( C_n^2 \) typically occur at the top of the convective boundary layer (CBL) (e.g., Wyngaard and LeMone 1980; Fairall 1991), where there is strong mixing of moist and dry air.

Monitoring of the CBL is very important for forecasting the timing and likelihood of storm initiation. Heinselman et al. (2009) and Elmore et al. (2012) show that if the reflectivity field obtained with the Weather Surveillance Radar-1988 Doppler (WSR-88D) in “clear air” exhibits an elevated maximum, its height correlates well with the top of the CBL. Our observations show that this type of reflectivity field is only one of several types that can be detected from Bragg scatterers, which we describe herein. To observe the “fine” structure of \( C_n^2 \) fields, the detection capability of the KOUN [the National Severe Storms Laboratory (NSSL)’s research and development polarimetric WSR-88D] was enhanced as described by Melnikov et al. (2011a). A minimal detectable \( C_n^2 \) at 10 km for KOUN of \( 3.5 \times 10^{-15} \text{ m}^{-2/3} \) is achieved in the short-pulse mode of operation. This level is more than two orders of magnitude below the mean \( C_n^2 \) value of \( 5 \times 10^{-13} \text{ m}^{-2/3} \) measured with radar and an airborne refractometer in the maritime boundary layer air over Oklahoma by Doviak and Berger (1980), indicating that the sensitivity of KOUN is sufficient to observe the structures present in \( C_n^2 \) fields.

In absence of echoes from atmospheric biota, radar wind profilers estimate \( C_n^2 \) above their sites, but they do not map the horizontal structure of this parameter but provide a time–height profile. Flying birds and insects are known to cause problems with the interpretation of radar wind profiler data (Wilczak et al. 1995; Lehmann 2012) and WSR-88D wind measurements (Wilson et al. 1994; Holleman et al. 2008). However, the scanning polarimetric WSR-88D has the capability to distinguish between echoes from atmospheric biota and Bragg scatterers, and thus it has the potential to provide

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information on the temporal and spatial structure of $C_n^2$. Specifically, median differential reflectivities of Bragg scatterers, measured with KOUN, lie in the interval $-0.1$ to $0.1$ dB and the distributions of the measured Bragg scatter correlation coefficients $\rho_{hv}$ have peaks between 0.998 and 1.0 (Melnikov et al. 2011a). These values of $Z_{DR}$ and $\rho_{hv}$ are drastically different from values measured in echoes from airborne insects and birds for which $Z_{DR}$ can reach few decibels and $\rho_{hv}$ is less than 0.9 (e.g., Wilson et al. 1994; Zrnić and Ryzhkov 1998; Lang et al. 2004). These features are used to distinguish Bragg scatter from clutter due to airborne biota.

In the next section, we discuss types of scatter from and above CBL observed with KOUN running the enhanced detection capability mode.

2. Types of structures from Bragg scatter

a. Two layers of Bragg scatter

Various types of reflectivity fields in clear air are apparent from observations with the KOUN dual-polarization radar. An example of elevated layers is from 1627 UTC 19 February 2008 (Fig. 1a), where three layers of echo are seen. The lowest layer is from the ground to around 500 m above ground level (AGL) and stretches horizontally across the entire cross section from the radar location to 50 km. The 1200 UTC Norman, Oklahoma, sounding captured a strong stable layer from the ground to 950 hPa with weak northerly winds (Fig. 2a). This stable layer is associated with a shallow frontal boundary that moved into southern Oklahoma overnight. Above the shallow stable layer is a nearly isothermal layer that extends to 900 hPa. By the time of the 1627 UTC radar observations, the 2-m temperatures approached 9°C, suggesting a convective boundary layer depth of approximately 500 m from the sounding. This depth is estimated by assuming that a dry adiabatic layer, characteristic of CBLs, stretches from the surface upward until it connects with the temperature profile from the 1200 UTC sounding. The potential temperature of this layer is calculated using the observed 2-m temperature and surface pressure, and it is assumed that the sounding structure above the CBL does not evolve with time. An
examination of Rapid Update Cycle (RUC) analyses (Benjamin et al. 2004) from 1700 UTC also indicates a boundary layer depth of near 500 m. These boundary layer depth estimates agree well with the depth of the lowest echo layer from the KOUN radar (Fig. 1a). This result suggests that the dual-polarization radar observations can provide information on the depth of the convective boundary layer.

Two other layered echoes are seen between 1.5 and 2.5 km and between 7.5 and 9.5 km AGL (Fig. 1a). Such layers appear differently in different azimuthal directions. Visible and infrared satellite imagery (not shown) indicates the presence of thin upper-level clouds across central Oklahoma. Observers from Tinker Air Force Base (AFB) and Oklahoma City at 1650 UTC reported cloud bases at 7.6 and 8.5 km AGL, respectively. These reported cloud bases agree well with the layer between 7.5 and 9.5 km in Fig. 1a, indicating the layer is produced by particulate scattering (\( Z_{DR} \) of about 1 dB) from nonprecipitating clouds. The potential of the WSR-88D to map cloud structures is shown by Melnikov et al. (2011b). However, no clouds are reported at lower levels, whereas the radar shows a layer near 2 km AGL. The radar operator (V.M.M.) visually confirmed the lack of low-level clouds at this time during the data collection period. Furthermore, the corresponding 1700 UTC RUC analysis has relative humidity (RH) values below 50% between 2 and 3 km AGL, suggesting that sufficient moisture is not present for cloud formation. Closest in time rawinsonde profiles from 1200 UTC (Fig. 2a) exhibit a strong gradient of relative humidity (thus, a strong gradient in potential refractive index), wind speed, and direction near the height of the layer. The top of this echoing layer is just below the stable temperature stratification seen in Fig. 2a. Thus, we hypothesize that this layered radar echo is produced by intense refractive index perturbations associated with shear-induced turbulent mixing within a strong vertical gradient of potential refractive index. The height of maximal reflectivity obtained from a nearby National Oceanic and Atmospheric Administration (NOAA) wind profiler (Fig. 1b) also is in accord with the height of maximum reflectivity observed with KOUN, providing further support for the hypothesis that shear-induced turbulent mixing produced the layer of larger \( C_n^2 \).

b. Convective mixing above a layer of Bragg scatter

Another example of the potential use of \( C_n^2 \) observations is from 2309 UTC 7 April 2008 (Fig. 3). Two distinct features are seen in the vertical cross section. The first feature is a strong vertical gradient of reflectivity extending from the surface to about 1.5 to 2.0 km AGL and stretching 100 km (i.e., the maximum distance displayed). The top of this feature is wavy, located at heights...
between 0.8 and 2.0 km, with the feature top extending to higher heights to the south of the radar. While broken clouds were observed over central Oklahoma for much of the day in association with a weak front that passed to the south, by 2309 UTC the front had shifted northward. The 2-m temperatures were near 25°C, so the boundary layer was quite warm with strong southeasterly winds reported. The 0000 UTC 8 April sounding from Norman shows a boundary layer top around 1.5 km AGL (Fig. 2b), as indicated by the top of the dry adiabatic layer coincident with the top of a layer of near-constant mixing ratio. This sounding-estimated boundary layer depth again agrees well with the depth of the lowest layer observed with KOUN.

More curious is the layer of enhanced scatter from 1.5 to 4 km AGL (Fig. 3). Although conditions at the radar site indicated clear skies directly overhead, broken cloud cover was reported at Oklahoma City and Tinker AFB, with cloud bases at 1.5 and 2.0 km, respectively, although cloudy conditions were observed at KOUN an hour earlier. The horizontal distance between KOUN and Oklahoma City is roughly 32 km, and the radar cross section in Fig. 3a extends from KOUN toward Oklahoma City. The 0000 UTC sounding from Norman indicates a cloud mixing layer from the top of the boundary layer to around 3 km AGL (Fig. 2b). A visible satellite image (not presented here) shows cumulus congestus clouds in north-central Oklahoma just to the north of KOUN. We submit that developing clouds are responsible for the power increase of echoes observed with the Purcell profiler for the heights between 1.5 and 4 km. The presence of developing clouds suggests that the larger values of $C_n^2$ between 1.5 and 4 km measured by KOUN are from Bragg scatter within the cumulus congestus clouds prior to the development of precipitation echo. The national composite of radar reflectivity indicates the first 30-dBZ echoes are seen north of KOUN at 2324 UTC. 15 min after the $C_n^2$ observations were taken, with more of these cumulus congestus clouds developing into cumulonimbus by 0100 UTC. Several of these thunderstorms produced damaging hail over the next hour.

c. A layer of Bragg scatter with more complex inner structure

The final example of Bragg scatter is from the period 1–2 March 2008 (Fig. 4, profiler data are not available for these days). One can see a weakly reflecting layer up to 2 km AGL that stretches horizontally across the entire

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**Fig. 3.** (a),(b) Vertical cross sections of $\log(C_n^2 \text{ (m}^{-2/3})])$ obtained from KOUN radar along 0° and 180° azimuths (north–south) from 7 Apr 2008. (c) Height profile of returned power from the NOAA Profiler Network (NPN) profiler at Purcell, OK, at 2306 UTC 7 Apr 2008.

**Fig. 4.** Vertical cross sections of $\log(C_n^2 \text{ (m}^{-2/3})])$ obtained from KOUN along 180° azimuth at (a) 2309 UTC 1 Mar 2008 and (b) 0002 UTC 2 Mar 2008. (c) Rawinsonde profiles of temperature (°C), wind speed (m s$^{-1}$), and RH (%) from the 0000 UTC 2 March sounding at Norman, OK.
cross section, with locally stronger scatter at heights of about 1.7 km (Fig. 4a). This stronger reflectivity layer coincides with the height of strong gradients of relative humidity (Fig. 4c) capped with a temperature inversion, indicating the top of the convective boundary layer. Thus, the boundary layer depth estimated from the sounding again agrees well with the depth of the 1.7-km-deep reflectivity layer. However, sunset on 1 March 2008 occurred at 2326 UTC, in between the times of the two cross sections shown in Fig. 4. While the intermittent reflections at heights of about 1.7 km decreased gradually between the two observation times, separated by 53 min, the reflectivity layer depth remained nearly constant. This suggests that the radar is observing a residual layer of active turbulence above the developing stable surface layer as modeled in a large-eddy simulation by Sorbjan (1997). This layer was visible by the radar for a few hours after sunset, suggesting that the radar can provide information on the time scale over which turbulence dissipates in the convective afternoon to the stable evening boundary layer transition.

3. Conclusions

Radar observations from KOUN, running the enhanced detection capability mode, exhibit various types of Bragg scatter: reflectivity layers corresponding to the convective boundary layer (the lowest layers in Figs. 1a, 3a,b, and the layer in Figs. 4a,b), turbulent layers within strong gradients in relative humidity (Fig. 1a), non-precipitating cloud (Fig. 1a), strong convective plumes (Fig. 3) with developing weakly reflecting clouds above them, and a layer of weak reflectivity associated with decaying boundary layer turbulence (Fig. 4). Refractive index perturbations, associated with the mixing of humidity gradients at the top of the CBL, scatter a sufficient amount of radar signals to be detected by the WSR-88Ds. Thus, one of meteorological applications of mapping of Bragg scatter is monitoring of the depth of the CBL. It was demonstrated in section 2 that enhanced radar detection capability allows observations of not only layers of Bragg scatter but also developing cumulus congestus clouds prior to the onset of thunderstorms.

Our analysis of Bragg scatter structures shows that the tops of the lowest echo layers correlate well with estimates of the CBL depth obtained from atmospheric rawinsonde soundings. Radar also shows the changes in the mixing layer depth (slope $\gg 10^{-2}$ km$^{-1}$; Fig. 3) that might be associated with larger-scale meteorological phenomena (e.g., horizontal inhomogeneity of surface heating). Rabin and Doviak (1989) show surface heating eclipsed by clouds can have a profound and observable effect on the reflectivity field. Radar observations of CBL depth could provide an important constraint on the changes in water vapor, pollutants, and turbulence within the boundary layer. Current model predictions of CBL depth often differ from observations by a factor of 2 (Bright and Mullen 2002; Stensrud and Weiss 2002), suggesting that routine observations of CBL depth would provide new information that could be used advantageously in data assimilation systems.

We collected radar data and presented our results in the RHI format because this format shows the vertical profiles naturally, whereas the operational WSR-88Ds collect data in conical scans [plan position indicator (PPI) format]. However, RHIs can easily be obtained from a dense collection of PPIs. Because the monitoring of the boundary layer is typically performed in a pre-storm environment, there is sufficient time to make a dense PPI scanning. We have collected data in the short-pulse mode (the range resolution of 250 m) to have a more meaningful estimate of $C_n^2$. To obtain the CBL depth, while reducing the time of data collection, the long-pulse mode can be used. The long-pulse mode will boost the returned signal by 9 dB and reduce the standard deviation of the returned power estimates, but it also will worsen the range resolution to 750 m. This is too large for quantitative estimations of $C_n^2$ at short ranges (at ranges beyond 45 km, angular resolution is worse than the long-pulse range resolution and this might vitiate making quantitative measurements of Bragg scatter layers at long ranges). KOUN was not capable of working in the long-pulse dual-polarization mode, but observations in the long-pulse mode are being planned for future work. The upgraded WSR-88Ds of the national network can operate in the dual-polarization long-pulse mode.

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