Estimating Systematic WSR-88D Differential Reflectivity (Z_{DR}) Biases Using Bragg Scattering

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1. Introduction

Radar calibration is crucial for the production of high quality weather radar data, especially, in estimating rainfall rates. In May 2013, a dual polarization upgrade was completed on the Next Generation Weather Radars (NEXRAD) in the contiguous United States. The upgrade enables NEXRAD Weather Surveillance Radar-1988 Doppler (WSR-88D) radars to transmit a horizontally and vertically polarized signal at the same time. The difference in received power and phase in the horizontal and vertical polarized channels provides valuable information about target hydrometeors. Although good calibration of reflectivity is paramount, the upgrade presents opportunities for improving rainfall estimates using new parameters such as Differential Reflectivity (Z_{DR}), Correlation Coefficient (CC), and Differential Phase (PHI) that also require precise measurements.

Polarimetric measurements serve two purposes. First, they allow for correct hydrometeor classification and second, they help improve quantitative precipitation estimates. Z_{DR}, a measure of the difference between the horizontal and vertical reflectivity, is essential for estimating hydrometeor shape and size (Rinehart 2010). For accurate rainfall measurements the systematic bias should be less than 10% of Z_{DR} (Zrnić et al. 2010).

While the WSR-88D's Quantitative Precipitation Estimate (QPE) algorithm makes use of all the dual polarization fields, the rainfall rate equation currently employed for light, moderate, and heavy rain (including big drops) is

$$R(Z, ZDR) = 6.7010^{-3} Z^{0.927} Z_{DR}^{-3.43}$$

where Z is reflectivity and Z_{DR} is as previously defined. At a constant reflectivity, every 0.25 dB decrease in Z_{DR} yields a 21.8% increase in rainfall rate and accumulations (D. Berkowitz 2013, personal communication). Thus, Z_{DR} greatly affects calculated rainfall rates.

For certain meteorological conditions such as very small spherical drops in drizzle or from Bragg scatter, Z_{DR} can reasonably be expected to have values close to 0 dB. When the expected Z_{DR} is close to zero, any deviation from zero may be assumed to be a systematic Z_{DR} bias. The goal of this paper is to demonstrate the feasibility of using Bragg scatter targets to quantify the systematic Z_{DR} biases of operational WSR-88Ds

2. Background

For weather radars, several methods have been developed for estimating systematic Z_{DR} biases. Vertically pointing at small rain drops in light rain, yields the best complete estimate (Ryzhkov et al. 2005). However, this method is not possible in the WSR-88D network because of mechanical constraints (Ryzhkov et al. 2005; R. Ice 2013, personal communication). The radar antenna has a 60° elevation limit determined by the structural configuration of the antenna's pedestal. In this study, the true values of the systematic Z_{DR} bias are assumed to be those found by a pseudo-operational alternate weather method that uses plan position

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indicator (PPI) scans to identify light precipitation (Cunningham et al. 2013). The light precipitation method was developed by A. Ryzhkov (2011, personal communication) and computes median Z_{DR} value of radar bins with reflectivity values between 20-30 dBZ. From the computed Z_{DR} values climatological correction values are subtracted (Table 1). This adjusts the Z_{DR} value downward to be near zero in the absence of a systematic Z_{DR} bias. In the case of systematic Z_{DR} bias, a non-zero value will result.

Unfortunately, the scanning weather method described here can produce variable results. Modeled relationships for different elevation angles show increasing variability at low elevation angles. An elevation angle as high as 60° yields estimates that can vary between 0.0-0.4 dB (Ryzhkov et al. 2005). Such variability is too high to ensure absolute calibration of Z_{DR} within the required accuracy of 0.1-0.2 dB but is sufficiently accurate to identify radar calibration trends and hardware problems. To minimize the variability, a median value of Z_{DR} over several hours is computed. For more detailed documentation of this method please see Cunningham et al. (2013).

3. Bragg Scattering

Bragg scattering is typically found at the top of the convective boundary layer (CBL) where mixing of moist and dry air occurs (Melnikov et al. 2011). Temperature and moisture variations cause density and refractive index perturbations, enhancing clear air return of the radar beam. Melnikov et al. often found Bragg Scatter during maximum surface heating when thermal plumes occur most frequently. The turbulent eddies that cause Bragg scattering should have no preferred orientation (i.e., distributed randomly in the plane of polarization), therefore, Bragg scattering should have a Z_{DR} of 0 dB.

Figure 1 shows a layer of Bragg scatter at the top of the CBL and above a layer of biota and ground clutter. It demonstrates the near symmetrical shape (Z_{DR} = 0 dB) associated with Bragg scatter compared to the non-symmetrical shape (Z_{DR} > 0 dB) of biota and ground clutter. Histograms of Z_{DR} values from Bragg scattering cases are examined to determine the most frequently occurring Z_{DR} value. The peak of the histogram should be centered near zero. The difference between zero and the histogram peak is the systematic Z_{DR} bias. All values found using Bragg scattering were compared to the weather method for validation.

4. Methods

Hoban et al. (2013) initially examined the feasibility of using Bragg scatter for estimating systematic Z_{DR} biases on six radars in different climate regions for May and June on WSR-88D Level-II data from the ROC. This study builds upon Hoban et al. (2013) by refining the methodology and expanding the data analysis to include three months and the entire fleet of WSR-88Ds.

Based on a brief survey of cases from Hoban et al. (2013), we decided to examine radar data for Bragg scattering during a 2 hour period from 17 to 19 UTC each day during the 3 month period. We chose this time period for identifying Bragg scatter based on guidance from Melnikov (2013, personal communication), subjective analysis, and the authors' meteorological experience. Histograms of Z_{DR} for each 2 hour period of Bragg scattering were plotted.

Bragg scatter is associated with weak signals and can be easily contaminated by other non-Bragg scatter targets (sometimes found between layers of biota, e.g., birds and insects) (Melnikov et al. 2005). To isolate Bragg scatter from ground clutter, biota, and most precipitation, several data filters were applied (Table 2). Because Bragg scatter is best observed during clear air, only volume coverage patterns (VCP) 32, 34 (at KLGX), and 21 were used in this study. Other VCPs can be used for detecting Bragg scatter and may be explored in future work. For descriptions of WSR-88D VCPs please refer to the ROC's Interface Control Document for the RDA/RPG. The data filters were found to be necessary, but insufficient to identify Bragg scatter during 2-hour periods. Statistical filters were added to provided robustness and sufficiency in identifying 2-hour periods with Bragg scatter.

a. Step 1 – Data Filters

To avoid contamination by ground clutter or biota due to low radar beam height, no data within 10 km of the radar were considered. Data beyond 80 km were excluded to avoid contamination from the melting layer and ice crystals. Further refinement is needed to exclude such contamination during winter months. Only elevations at or above 2.5° were used. Typically, lower elevations were contaminated by clutter and insects and did not show the turbulence at the top of the CBL.

Bragg scatter, by its nature, provides only weak echo returns. Therefore, to avoid contamination from all but the lightest precipitation (drop sizes ≅ drizzle) and contamination from ground clutter, only radar bins with Z < 10 dBZ and signal-to-noise ratios between -5 and +15 dB were used. A ring of reflectivity values that meet the criteria can be seen in the top right of Figure 3. Reflectivity is not sufficient to isolate Bragg scatter so other data filters must be applied.

Because biota tend to have CC values lower than 0.95, only radar bins with CC greater than 0.98 were allowed. Raindrops that uniformly fill a sample volume are known to have CC values greater than 0.98 and Bragg scatter is considered to have similar properties to drizzle (Melnikov et al. 2011). CC was also capped at < 1.05 to eliminate exceptionally weak signal since CC = 1.05 is a catchall category for unreasonably high values. (CC > 1.00 is possible due to a numerical artifact with WSR-88D data processing). A ring of CC values for Bragg scatter can be seen in the top left of Figure 3.

Bragg scatter results from turbulent mixing at the top of the CBL, therefore velocity and spectrum width should be non-zero. Although the measured *radial* velocity for Bragg scatter could be zero, we require that its absolute value be ≥ 2 ms^{-1} and spectrum width be ≥ 0.5 ms^{-1} to ensure removal of ground targets.

Finally, because Bragg scatter should have no preferred orientation it should cause little or no shift in the differential phase (PHI) in either direction. PHI changes when a hydrometeor is larger in either the horizontal or vertical reflectivity than it is in the other. PHI should be very close to the initial system differential phase (ISDP). Typically, the ISDP is set to be 25° for WSR-88Ds. Hoban et al. (2013) used values of PHI between 25° and 35°. A ring of PHI values corresponding to Z_{DR} from Bragg scatter can be seen in the bottom left of Figure 3. At the time of this study, a number of WSR-88D sites had an ISDP error, therefore a PHI filter was not applied. An application of the complete process to isolate the good cases of Bragg scatter is shown in Figure 4. Figure 4a is a scatter plot of Z_{DR} filtered only by range and elevation. Figure 4b shows a scatter plot of the Z_{DR} values after the remaining data filters have been applied. Finally, Figure 4c shows the resulting histogram by combining the values from cuts at 2.5°, 3.5° and 4.5°. Statistical filters must next be applied.

b. Step 2 – Statistical Filters

Three statistical filters were developed to further isolate "good" cases of Bragg scattering. First, to ensure populating the Z_{DR} histograms with a reasonable number of points, any case with fewer than 10,000 bins was omitted.

Next a symmetry test, the Yule-Kendall Index (YKI), was examined. It is defined as

$$YKI = \frac{q_{0.25} - 2q_{0.50} + q_{0.75}}{q_{0.75} - q_{0.25}}$$

where q represents the quartiles (Wilks 2006). If the YKI value is greater than zero the distribution has a right skew and if the YKI value is less than zero the distribution has a left skew. For this study, we were not necessarily concerned with the direction of the skewness, but only whether there was any skewness. Therefore we examined the absolute value of YKI ($|YKI|$). Skewed distributions (collected in Step 1) tended to occur as a result of biota or unknown non-spherical targets contaminating the sample of data. Using the absolute value of the YKI, the top two panels of Figure 5 illustrate how skewness varies in time with different 2-hour daily estimates of systematic Z_{DR} bias with the Bragg scatter filters.

Our examination found the symmetry test insufficient for filtering out cases with biota. We found that a uniform distribution, even though positively skewed from biota, passes the symmetry test, may not provide a good distribution for estimating systematic Z_{DR} bias. To avoid this problem we devised a third "spread" test. The third test uses the 25th and 75th quartiles to determine the interquartile range (IQR) or the spread of the data points. It has the following form: $IQR = q_{0.75} - q_{0.25}$. We assume that cases sampling mostly Bragg scatter will have sharp distributions about 0 dB for unbiased WSR-88Ds. Distributions will be centered about a non-zero value if the system has a bias. Results from two sites are demonstrated in the bottom two panels of Figure 5. Estimates with smaller spread (lower IQR) are grouped more tightly around the system bias (estimated by 30-day median value on each panel). Note that Site A has a positive systematic Z_{DR} bias of 0.31 dB and Site B has a negative systematic Z_{DR} bias of -0.5 dB. Cases with IQR < 0.9 dB were used for validation (Section 5).

5. Validation

Since the spring of 2013, the ROC has used light precipitation targets found in archived Level II data to monitor systematic WSR-88D Z_{DR} biases across the fleet (Cunningham et al. 2013). Estimates of systematic Z_{DR} bias based on the light precipitation method are susceptible to large drop contamination and seasonal changes in drop size distribution. Ideally, we would evaluate Z_{DR} bias estimation methods with data derived from a more accurate method, such as vertically pointing at small drops. Because of the WSR-88D's mechanical limitations, the Bragg scatter method must be evaluated against estimates from the pseudo-operational scanning method that targets light precipitation.

a. Site examples

Site-by-site review of systematic Z_{DR} biases reveals mostly consistent behavior between the light precipitation and the Bragg scatter methods for estimating Z_{DR} bias. Figure 6 illustrates the change in systematic Z_{DR} bias from 01 September to 30 November 2013 for two sites. For light precipitation based estimates (top panel), the scatter points represent 3-hour median Z_{DR} bias estimates. The small plus signs represent periods characterized as stratiform precipitation and the small dots represent periods characterized as non-stratiform (or convective) (Cunningham et al. 2013). The small dots for the Bragg scatter based estimates are based on estimates from 17-19 UTC. The shading for all panels represents the 7-day median Z_{DR} bias estimate. Note in Figure 6 both methods for estimating systematic Z_{DR} bias have the same sign (Site A and Site B). This is not necessarily true at all sites but changes in systematic Z_{DR} bias in one method are reflected in the other method.

b. Fleetwide

Systematic Z_{DR} bias estimates based on Bragg scatter targets have a moderate to strong linear correlation with estimates from light precipitation targets (Figure 7). Specifically, for September, October, and November, the two methods have Pearson correlation coefficient values of 0.65 to 0.82 (statistically significant, $p - value \ll 0.05$). There seems to be a slight trend for the light precipitation estimates to have a more negative Z_{DR} bias as the months progressed through the fall season. It may be that with fewer convective events in the late fall, that the Z_{DR} offset for light precipitation (Table 1) is overcompensating.

6. Conclusions

An automated method for estimating systematic Z_{DR} bias using Bragg scattering on operational NEXRAD WSR-88Ds Level II data was developed. Bragg scattering was isolated from weather, clutter, and biota using several data filters. Those filters were shown to be necessary, but not always sufficient leading to the application of statistical filters to isolate the good cases of Bragg scattering. The statistical filters make this a more robust method for estimating systematic Z_{DR} bias. In conclusion, we expect the Bragg scatter method to provide an alternative method that is less susceptible to large-drop contamination and seasonal changes in the drop size distribution that could affect the precipitation method. Additional work is needed to assess the climatology of Bragg scatter across the continental United States.

7. Acknowledgments

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8. References

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TABLES

Table 1. Average empirical values of Z_{DR} corresponding to Z bins at S band as established by Ryzhkov (2011, personal communication).

Z (dBZ)	20	22	24	26	28	30
Z_{DR} (dB)	0.23	0.27	0.32	0.38	0.46	0.55

Table 2. Data filters used in Step 1 of identifying Bragg Scatter.

Parameter	**Filter**
VCP	21,32
Elevations	2.5^{O} & above (batch modes) ; VCP 32 (cuts 5,6,7), (VCP 34 at KLGX), VCP 21 (cuts 5,6,7,8)
Range	10-100 km
Reflectivity	-32< Z < 10 dBZ
Correlation Coefficient	0.98< CC <1.05
Velocity	V<-2 or V>2 ms-1
Spectrum Width	W > 0 m/s
Signal to Noise Ratio	-5 < SNR <15
Differential Phase	25< phi $<35^{O}$ (Only used in initial investigation, not during validation)

FIGURES

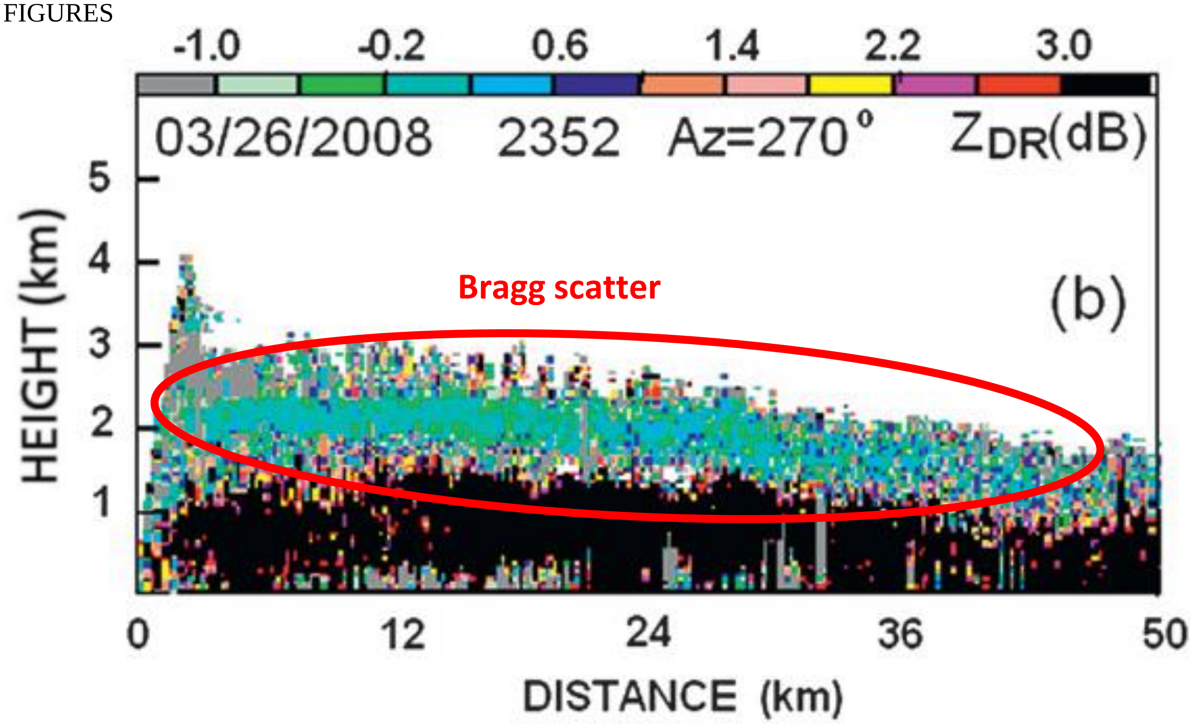

Figure 1. Vertical cross section of Z_{DR} above Norman, OK at 0000 UTC 21 Feb. 2008 (Melnikov et al. 2011). Return from Bragg scatter is colored blue and green. Biota are colored black.

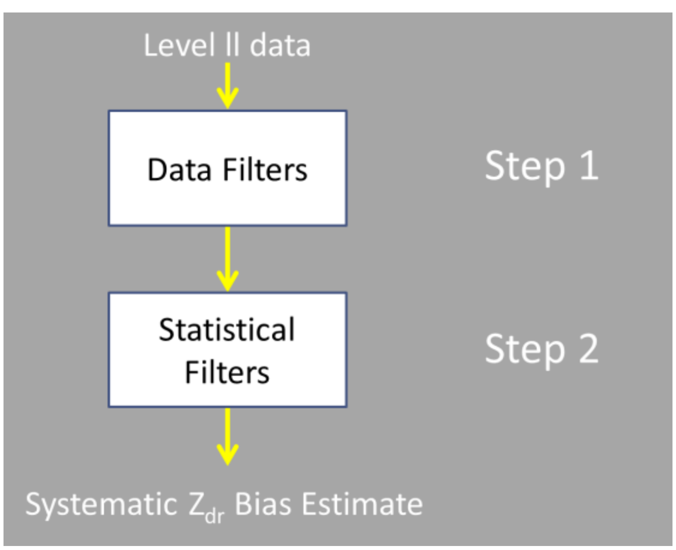

Figure 2. Flow chart for automated Bragg Scatter identification process

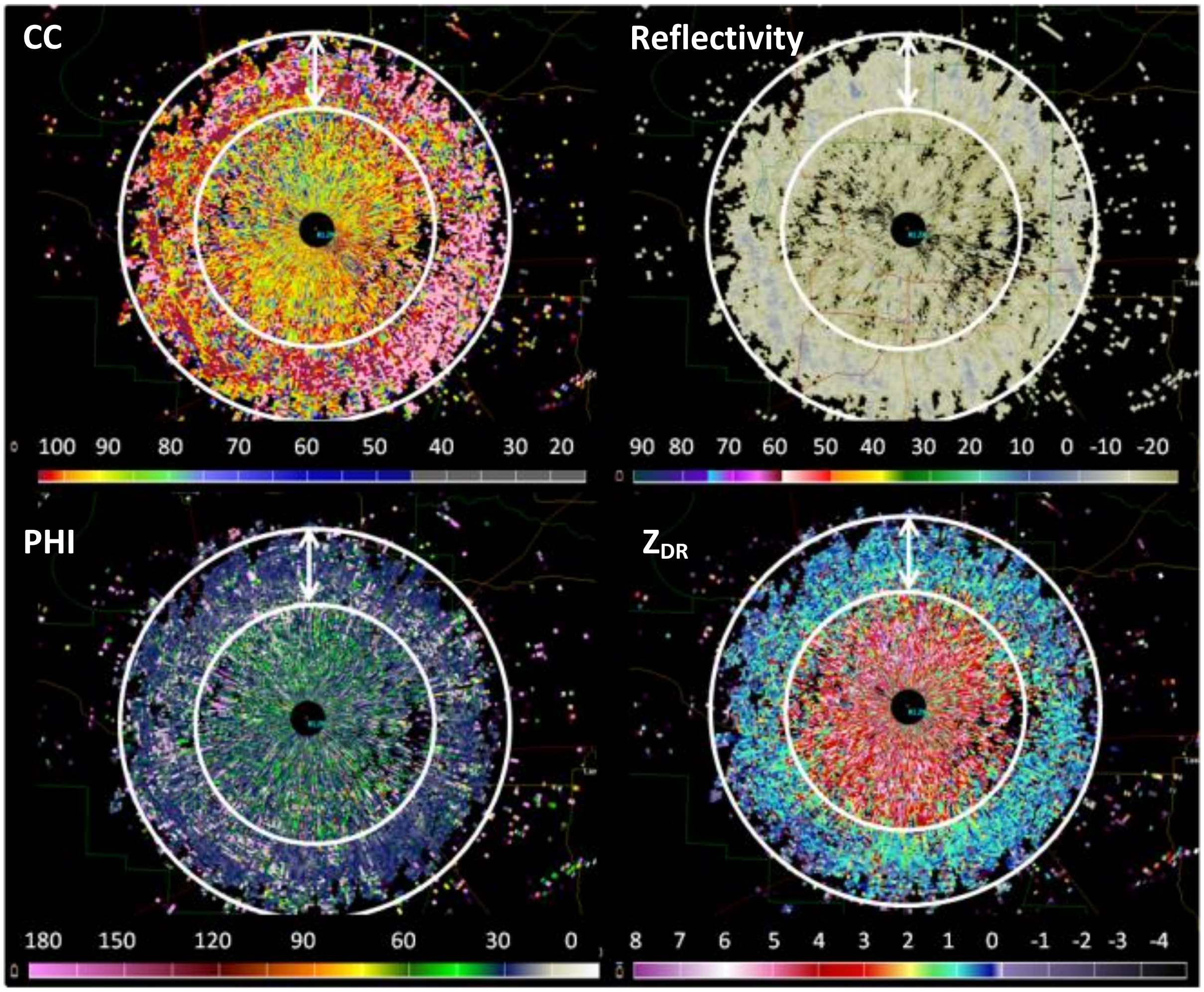

Figure 3. Image from an operational WSR-88D from KLZK on 12 May 2013, at 15:43:08 UTC at 3.5°. Top left is CC, top right is reflectivity, bottom left is PHI and bottom right is Z_{DR}. The rings bound the area where Bragg scatter is indicated.

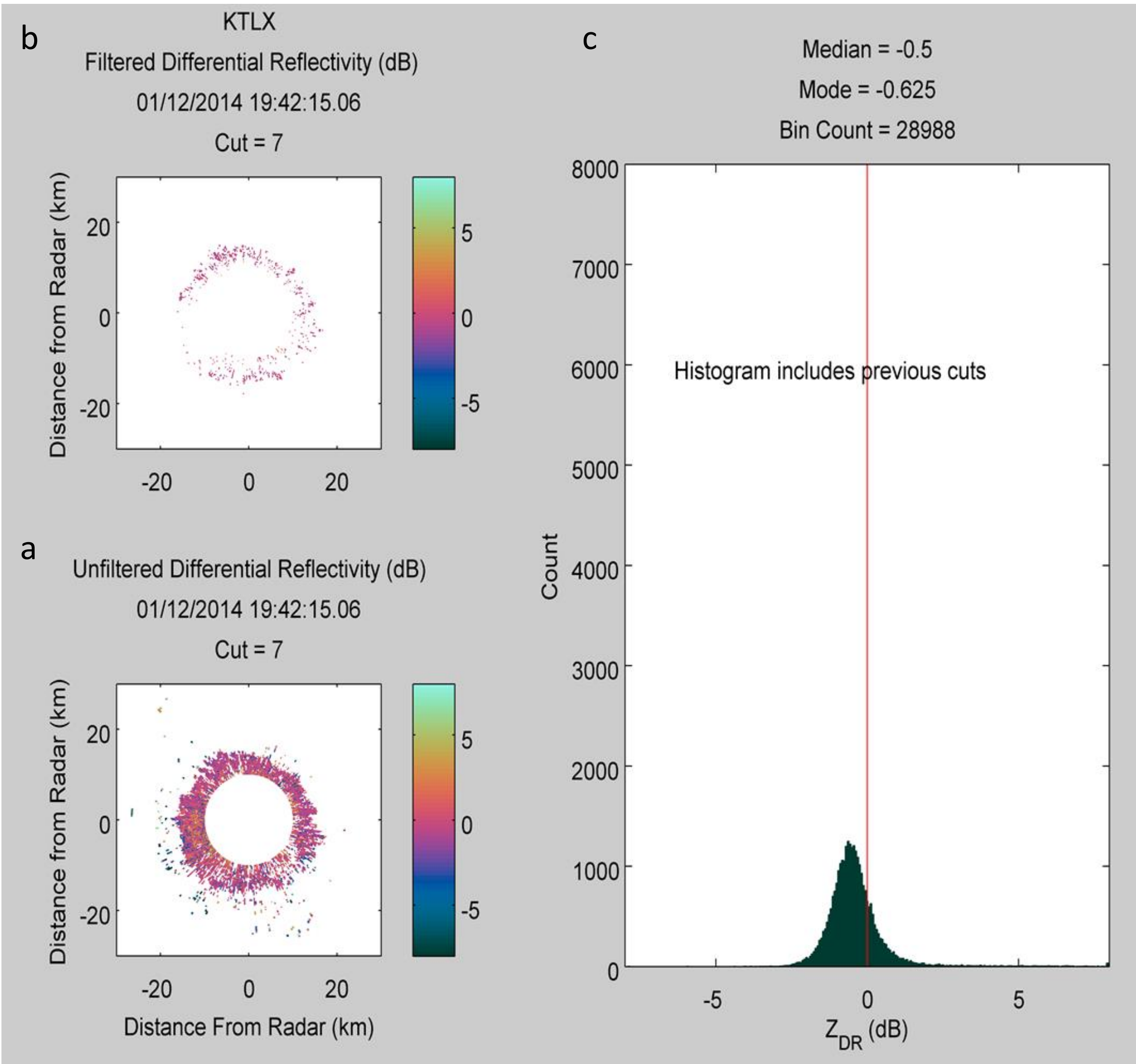

Figure 4. Lower left scatter plot (a) from the Norman, OK WSR-88D (KTLX) on January 12, 2014 at 19:42 UTC has no filtering except for range limits at cut 7 (4.5°). Upper left (b) shows a scatter plot for the same time and elevation with all filters applied. Values of Z_{DR} are color-coded with magenta being near zero. Range was truncated because there was no data beyond ± 30 km and to improve visualization. Chart on right (c) shows a cumulative histogram from cuts at 2.5°, 3.5°, and 4.5°. From the mode the system Z_{DR} bias is -0.625 dB.

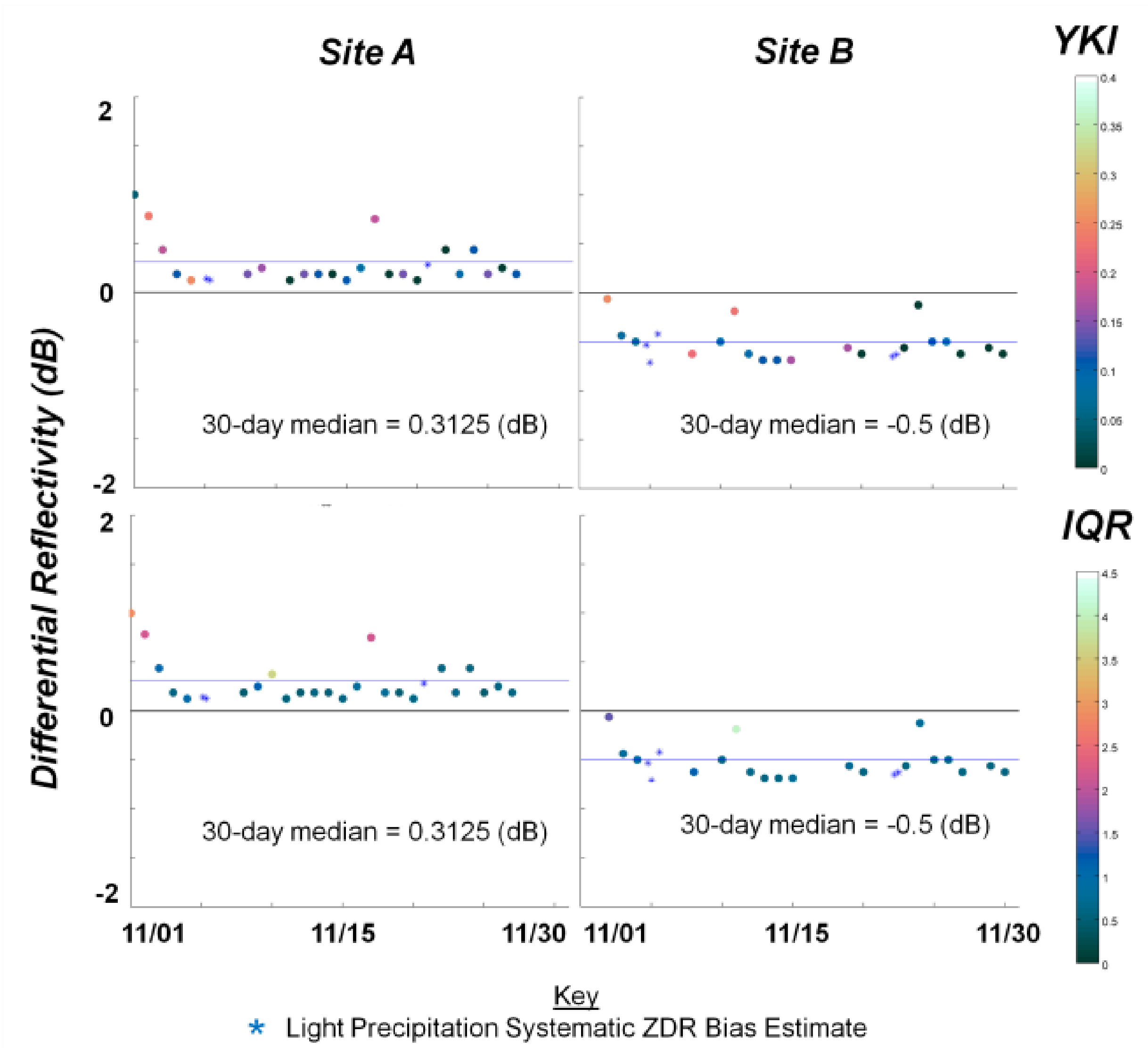

Figure 5. Examples of statistical filters applied to two WSR-88D sites. The x axis is time (month/day) and the y axis is the differential reflectivity value (dB). Each point represents an estimate of the systematic Z_{DR} bias for the given site. The shading indicates the statistical filter value. The top row is the absolute value of the Yule-Kendall Index (YKI) and the bottom row is the Interquartile Range (IQR). The estimate from the light precipitation method is represented as a blue star.

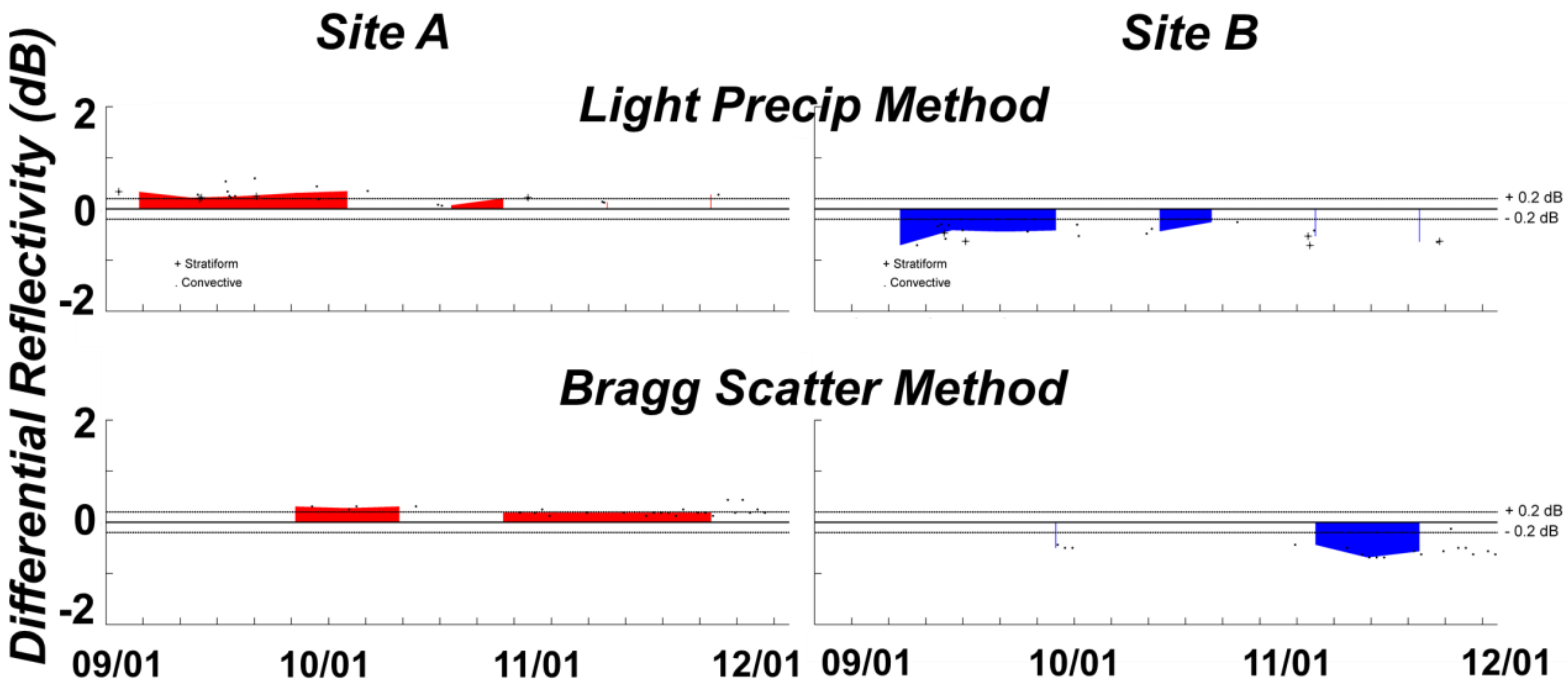

Figure 6. A site-to-site comparison of systematic Z_{DR} bias estimates based on the light precipitation method (top panel) and the Bragg scatter method (bottom panel). The x axis is time (month/day) and the y axis is the differential reflectivity (dB). Shaded areas represent the 7-day median systematic Z_{DR} bias estimate. An absence of shading or scatter points means that no estimates of systematic Z_{DR} bias were made.

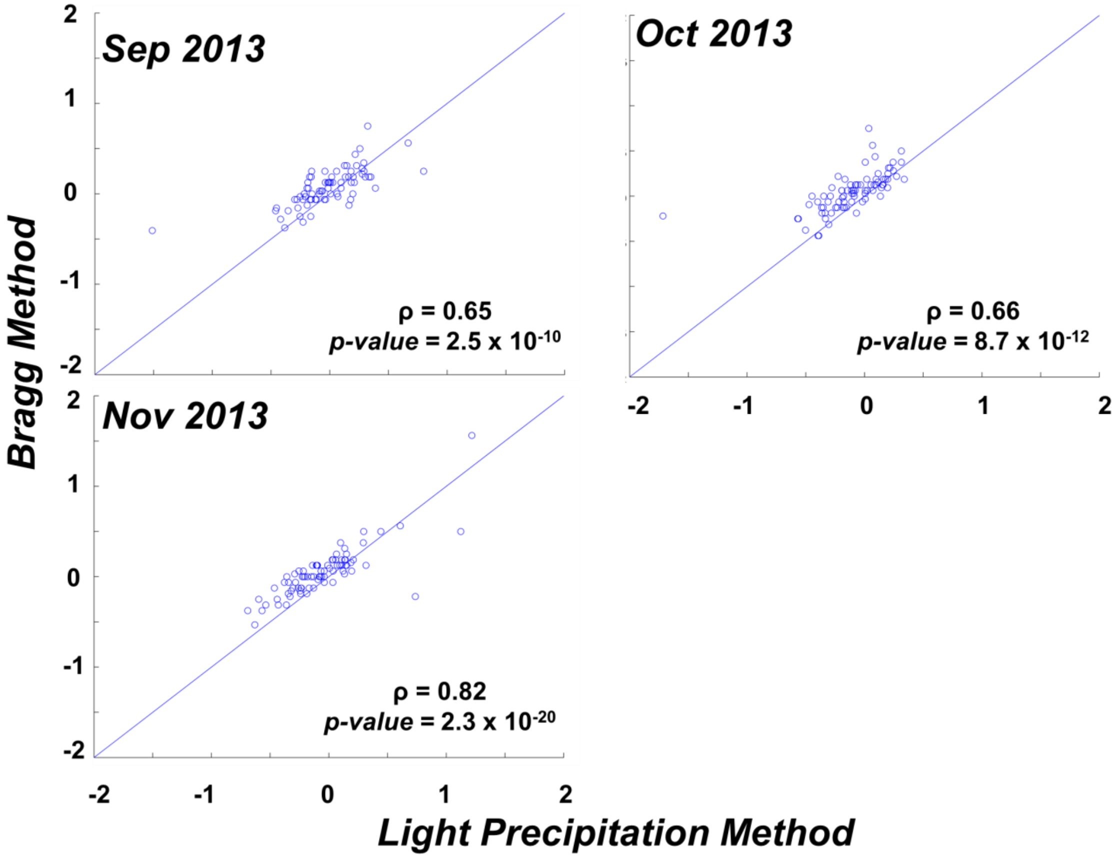

Figure 7. Scatter plots comparing three months of systematic Z_{DR} bias estimates from the Light Precipitation method to the systematic Z_{DR} bias estimate from the Bragg Scatter Method. Rho (ρ) is the Pearson correlation coefficient and the p-value is the probability of correlation coefficient being equal to zero (based on Student's two-tail t-distribution).