Using Bragg Scatter to Estimate Systematic Differential Reflectivity Biases

on Operational WSR-88Ds

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Abstract

This study examines the feasibility of using Bragg scatter to estimate systematic differential reflectivity (ZDR) biases on operational WSR-88Ds. ZDR greatly impacts rain rate estimates. At constant reflectivity, a 0.25 dB bias in ZDR will yield a 22% error in rain rate estimates for the rain rate equation currently implemented in the WSR-88D radar product generator. Prior to this study, the Radar Operation Center (ROC) used plan position indicator scans of light rain (i.e. "scanning weather method") to monitor systematic ZDR biases on a fleet of 159 operational WSR-88Ds. While the scanning weather method is reliable for identifying radar calibration trends, it is too imprecise for absolute ZDR calibration because systematic ZDR biases estimates from the scanning weather method are subject to big drop contamination. Data filters based on single and dual polarization variables and two statistical filters were used to isolate Bragg scatter from clutter, biota, and precipitation. Six radars were examined in detail for May and June 2013 from 1400-2200 UTC each day. Systematic ZDR biases estimates from Bragg scatter were compared to reliable estimates from the scanning weather method. Bragg scatter derived systematic ZDR biases were comparable to those estimated by the weather method; most cases were within 0.20 dB. With these filters, Bragg scattering was found most frequently between 1400-2200 UTC. More cases of Bragg scattering were found in May than in June. This study demonstrates that Bragg scattering offers an alternative method for monitoring systematic ZDR biases on the WSR-88D fleet.

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 Next Generation Weather Radars (NEXRAD) in the contiguous United States. The upgrade enables the 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 hydrometers. The upgrade presents new opportunities for estimating rainfall rates using new parameters, such as Differential Reflectivity (ZDR), Correlation Coefficient (CC), and Differential Phase (PHI). However, here the parameters require precise radar system calibration. System calibration has been a problem since the dual-polarization upgrade, particularly with respect to estimating systematic ZDR biases.

ZDR, a measure of the difference in horizontal reflectivity versus the vertical reflectivity, is essential for estimating hydrometer shape and size (Rinehart, 2010). Polarimetric measurements serve two purposes. First, they allow for correct hydrometeor classification and second they help improve quantitative precipitation estimations. For accurate rainfall measurements the systematic bias should be less than 10% of ZDR (Zrnic et al., 2010). The rainfall rate equation currently employed by the WSR-88D radar product generator (RPG) for light to heavy rain is

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

where Z is reflectivity and ZDR is the differential reflectivity. At a constant reflectivity, every 0.25 dB decrease in ZDR yields a 21.8% increase in rainfall rate and accumulations (D. Berkowitz, personal communication). Thus, ZDR greatly affects calculated rainfall rates. The goal of this paper is to demonstrate the feasibility of using Bragg scatter targets to quantify the systematic ZDR biases of operational WSR-88Ds

2. Background

For weather radar, several methods have been developed for estimating systematic ZDR biases. Vertically pointing at small rain drops in light rain, yields the best complete estimate (Ryzhkov et al., 2005). However, this method is not operational in the WSR-88D network because of mechanical constraints. The radar antenna has a 60° elevation limit determined by the structural configuration of the antenna's pedestal (Ryzhkov et al., 2005). In this study, the true values of the systematic ZDR bias are assumed to be those found by an alternate weather method that uses plan position indicator (PPI) scans to identify stratiform rain. Using reflectivity values of 20-30 dBZ a corresponding climatological correction factor is subtracted from the obtained ZDR value. This corrects the ZDR value to be zero in the absence of a systematic ZDR bias. In the case of systematic ZDR bias, a non-zero value will result. The ZDR bias found by the weather method is averaged for an entire month to account for the limited days where stratiform rain is present. The systematic ZDR bias is the difference in ZDR trend from zero. The ROC Applications Branch has developed two methods for testing for statiform or convective rain events. The first looks close to the radar and finds the percentage of the number of weak bins (reflectivities between 20-30 dBZ). If the percentage is 80% or greater than the event is consider to be stratiform by the first test. The second test looks far from the radar to look above the freezing level and finds the number of bins with a reflectivity more than 40 dBZ. If the bin count is greater than 40 for a single volume scan the case is considered to be convective. All convective cases are thrown out to help eliminate big drop contamination. All values found using Bragg scattering were compared to the weather method for validation. Unfortunately, the scanning weather method described here can produce variable results within the 0.0-0.4 dB interval at an elevation of 60°. Such variability is too high to ensure absolute calibration of ZDR within the required accuracy of 0.1-0.2 dB (Ryzhkov et al., 2005), but is reliable for identifying radar calibration trends and hardware problems.

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). The 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.

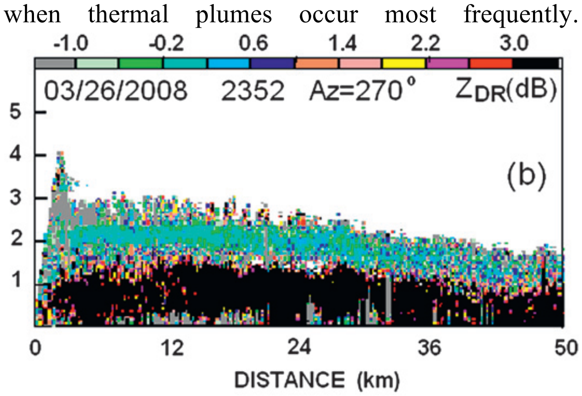

Figure 1. Vertical cross section of ZDR above Norman, OK at 0000 UTC 21 Feb. 2008 (Melinikov et al 2011).

Figure 1 shows a layer of Bragg scattering at the top of the CBL and on top of a layer of biota and ground clutter. It demonstrates the near zero nature of the ZDR values associated with Bragg scattering compared to the high ZDR values of biota and ground clutter. Bragg scattering is separate and often found on top of a layer of clutter and biota, which can be seen in Figure 1. 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 typically have a ZDR of zero. Histograms of the Bragg scattering are examined to determine the peak ZDR value of scattering for each radar. These values should be zero, but in the presence of systematic bias they will not be. The difference between zero and the histogram peak is the systematic ZDR bias.

4. Methods

In this study, Bragg scattering was tested on six radars in different climate regions for May and June on WSR-88D Level-II data from the ROC (Figure 2 and Table 1). These radars were also chosen because they had reliable weather method data for comparison.

Figure 2. Map of WSR-88Ds used in this study.

Table 1. List of WSR-88D site names and locations used in this study.

Radar	Location
KLZK	Little Rock, AR
KAMX	Miami, Fl
KRAX	Rayleigh, NC
KCBW	Caribou, ME
KTLX	Oklahoma City, OK
KLGX	Langley Hill, WA

For each month, data were examined for Bragg scattering during an eight hour period from 1400 to 2200 UTC and histograms of ZDR for each hour of Bragg scattering were plotted. This time period was determined by looking at an entire day's worth of data for multiple days and radars. More Bragg scattering was found during this time period than any other so this time became the focus of this study. This should also be the period of maximum daytime heating.

Bragg scatter is associated with weak signals and can be easily contaminated by other non-Bragg scatter targets (sometimes found between layers of biota) (Melnikov et al., 2005). To isolate Bragg scatter from ground clutter, biota, and weather, several data filters were applied. 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. Necessary, but insufficient data filters were developed to identify Bragg scatter during 1-hour periods (Table 2). Statistical filters were developed to be sufficient in identifying 1-hour periods with Bragg scatter. The complete process to isolate the good cases of Bragg scatter can be seen in Figure 3.

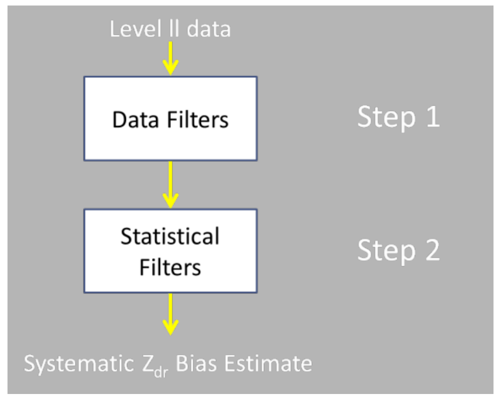

Figure 3. Flow chart for automated Bragg Scatter identification process

a. Step 1 – Data Filters

To avoid contamination by ground clutter or biota due to low radar beam height, no data within ten kilometers of the radar were considered. Data beyond 100 hundred kilometers were excluded to avoid contamination from the melting layer and ice crystals. 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.

Raindrops become more oblate as they increase in size and tend to fall with the largest diameter parallel to the horizontal dimension of the radar beam. This causes more power to be received in the horizontal channel, yielding a ZDR > 0. Raindrop contamination positively biases estimates of systematic ZDR bias. Therefore, to avoid raindrop and ground clutter contamination, only radar bins with Z < 10 dBZ and -5 < SNR < 15 dB were used. A ring of reflectivity values isolated by the filters can be seen in the top right of Figure 4.

Table 2. List of WSR-88D site names and locations used in this study.

Parameter	Filter
VCP	21,32
Elevations	2.5^{o} & above (batch modes)
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}

Biota tend to have CC values lower than 0.95. Only radar bins with Correlation Coefficient (CC) greater than 0.98 were allowed. Raindrops 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 its results are unreliable. CC > 1.00 is possible due to a numerical artifact with WSR-88D data processing. A ring of CC values isolated by this filter can be seen in the top left of Figure 4.

Bragg scattering is associated by turbulence at the top of the CBL, therefore the absolute radial velocity should be greater than 2 ms^{-1} and spectrum width should be greater than zero. Finally, turbulent eddies associated with Bragg scatter have no preferred orientation. Bragg scatter should cause little to no shift in the differential phase (PHI) in either direction. PHI changes when a hydrometer 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). It is standard for the ISDP to be set to 25° for WSR-88Ds. Only values of PHI between 25° and 35° were used to find Bragg scattering. A ring of PHI values isolated by this filters can be seen in the bottom left of Figure 4.

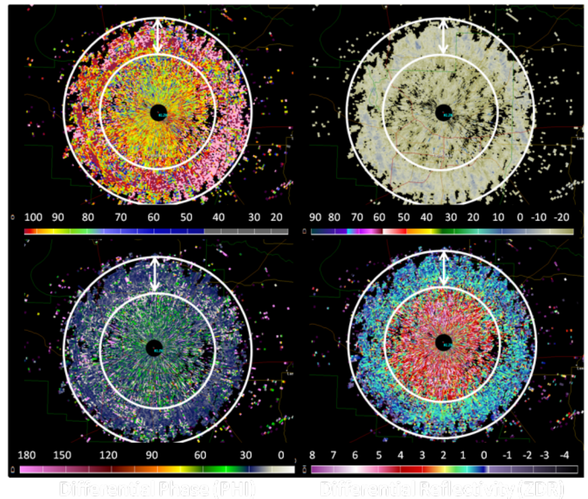

Figure 4. Image from an operational WSR-88D from KLZK on 12 May 2013, at 15:43:08 UTC at 3.5°. Top let is CC, top right is Reflectivity, bottom left is PHI and bottom right is ZDR. The areas between by the rings are indicated where to look for Bragg scattering.

Applying all the data filters to two hours of the KLZK data presented in Figure 4, yeilds the histogram shown in Figure 5.

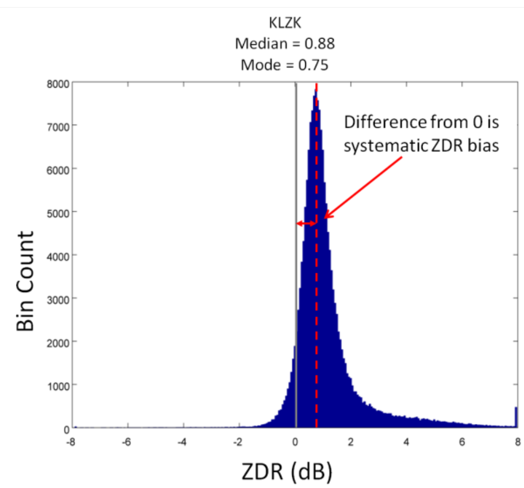

Figure 5. Histogram from KLZK on the 12^{th} of May 2013, from 1500-1700 UTC.

There is a distinct peak represented by the mode at 0.75 dB. Typically Bragg scattering should have a ZDR of zero. This difference from zero is systematic ZDR bias. This case has a Gaussian-like distribution as the median and mode are close in value. Another case from KTLX on the 19th of April 2013 can be seen in Figure 6. In this case there is again a peak separate from zero and this time the bias is negative. This case has a lot of contamination from higher ZDR values which shows that the data filters are necessary, but not sufficent. This leads to the addition of statistical filters.

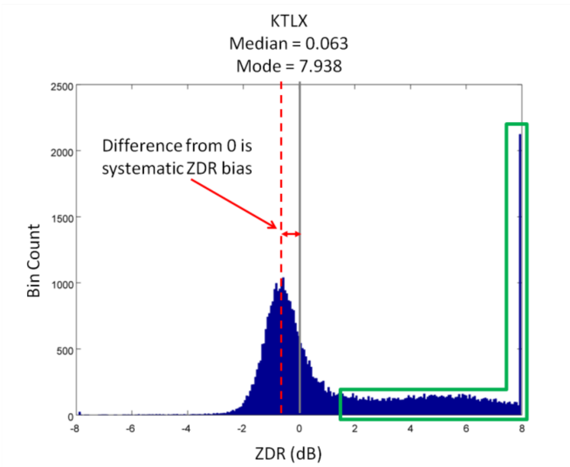

Figure 6. Histogram from KTLX on the 19th of April 2013, form 1900-2200 UTC.

b. Step 2 – Statistical Filters

Two statistical filters were developed to further isolate good cases of Bragg scattering. The first is the Yule-Kendal Index (YKI), a symmetry test. It has the following form:

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

where q represents the quartiles. The YKI is considered to be a robust and resistant alternative to sample skewness (Wilks 2006). If the YKI value is greater than zero distribution has a right skew and if the YKI value is less than zero a distribution has a left skew. For this study, the absolute value of the YKI was found and any graph with a larger absolute value greater than 0.1 was filtered out. The second test looks for a sufficient number of bins by applying a bin count filter. Any case with fewer bins than 35000 bins was thrown out. These two filters isolate the really good Bragg scattering cases.

5. Results

a. Case Study of KRAX

This method was used on all six radars and an extensive case study was performed on KRAX. Hourly histograms (1400-2200 UTC) were plotted for every day in May. Figure 7 is an example of one of the hourly histograms plotted for KRAX.

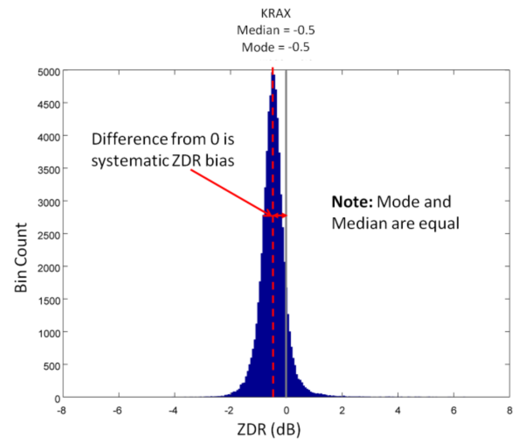

Figure 7. A histogram for KRAX on the 25th of May 2013, from 1500-1600 UTC.

The separation of the peak from zero indicates a systematic ZDR bias of -0.50 dB. This is an exceptionally good example of Bragg scattering. It has a Gaussian-like distribution where the median and the mode are exactly the same and there is no apparent skewness. This is an example of a histogram that easily passes the statistical filters. Figure 8 shows all of the modes from the hourly histograms for the entire month of May without any statistical filters applied.

With no statistical filters applied, there are many points. Both the weather and the Bragg scattering show a negative systematic ZDR bias; however there is a difference between the two values. Figure 9 illustrates when all the statistical filters are applied. Once all the statistical filters are applied, most of the data points are thrown out because they did not pass both the statistical tests. The remaining points are considered to be the good cases of Bragg scattering. After the filters were applied the Bragg scattering estimated systematic ZDR bias shifted down to -0.50 dB. Now the weather and Bragg scatter methods have very similar values. Since two independent methods show similar values, the radar has a systematic ZDR bias possibly due to calibration errors.

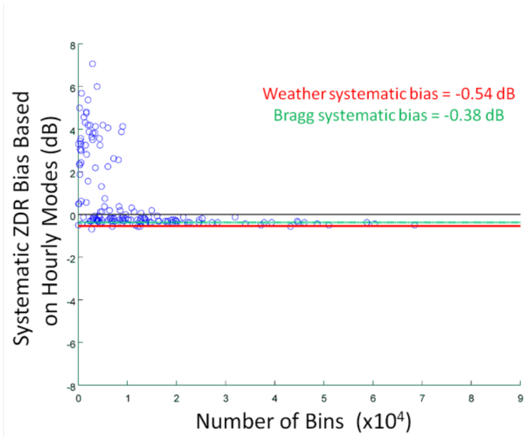

Figure 8. Plot of hourly modes with no statistical filters for KRAX in May. Blue circles are all of the modes for every hourly histogram Red line is the weather method's estimated systematic ZDR bias. Green line is Bragg scatter's estimated systematic ZDR bias found from the most frequently occurring mode.

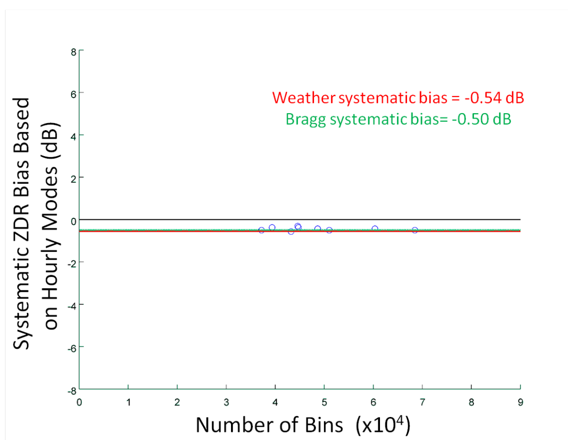

Figure 9. Same as figure 8 except statistical filters have been applied.

b. Case study for KTLX

This case study will focus on KTLX using the same methods previously presented for KRAX. Hourly histograms were plotted for the entire month of June for 1400-2200 UTC every day. Below is an example of one of the hourly histograms for KTLX.

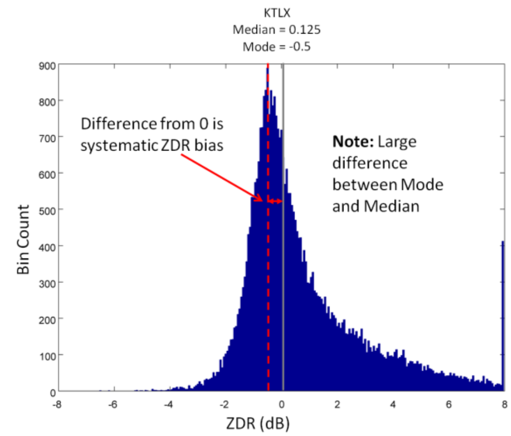

Figure 10. Histogram for KTLX on the 17 June 2013, from 1600-1700 UTC.

The separation from zero indicates a systematic ZDR bias of -0.50 dB. This case has a lot of contamination and is skewed. This is an example of a case that the statistical filter would throw out due too much skew. The following image is all of the modes from the hourly histograms for the entire month of June for KTLX without any statistical filters.

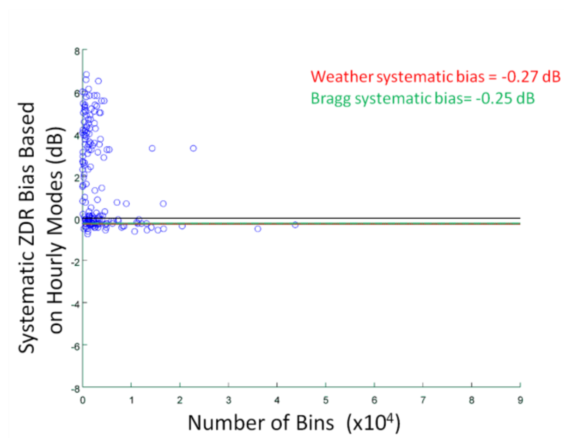

Figure 11. Plot of hourly modes with no statistical filters for KTLX in June. Blue dots are all of the modes for every hourly histogram Red line is the weather method's estimated systematic ZDR bias. Green line is Bragg scatter's estimated systematic ZDR bias found from the most frequently occurring mode.

With no statistical filters present there are many points. Both the weather method and the Bragg scatter show a negative systematic ZDR bias and are close in value, -0.27 and -0.25 dB, respectively. Figure 12 is with the statistical filters applied.

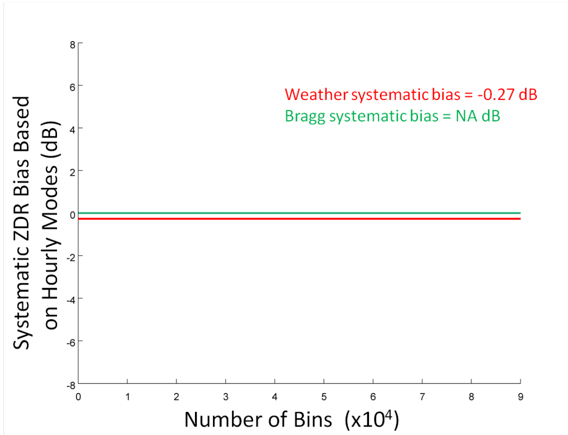

Figure 12. Same as figure 11 except statistical filters have been applied. Note all estimates of the hourly modes have been removed.

Now there are no points left. This means that all of the cases either had a lot of contamination (Fig. 11) or had too low of a bin count. The robust statistical filters used in this study reduce the number of systematic ZDR bias estimates, but ensures the remaining estimates are reliable.

c. Summary of Six WSR-88D Sites

The method demonstrated on KRAX and KTLX was applied to six radars. Figure 13 shows, by radar, the number of days per month for which Bragg scattering was identified for May and for June.

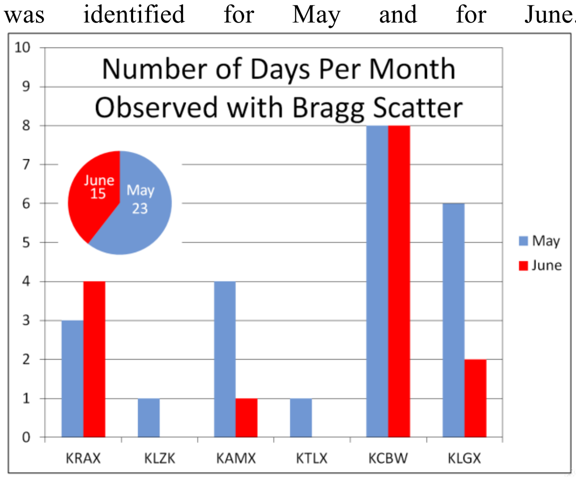

Figure 13. Graph of the number of days where good Bragg scattering was found for each radar. The blue represents May and the red represents June. The pie chart shows the total number of days where Bragg scattering was found for each month.

Overall more days with Bragg scattering were found in May than in June. More days with Bragg scattering were found but they did not meet the criteria of the statistical filters. KLZK and KTLX each had one day in May and no days in June with Bragg scattering. Both of the sites seemed to have more contamination from biota than other sites and there may have been a difference in the amount of low-level moisture present in the atmosphere. KAMX had four days in May, but only one day in June with Bragg scattering. This is most likely due to the presence of Tropical Storm Andrea and other tropical weather in June, since our data methods ignore bins with weather. KLGX had six days in May but only two days in June. KCBW had the same number of days for both May and June. KRAX actually had four days in June and only three days in May with Bragg scattering.

d. Comparison of Weather Method and Bragg scatter estimated systematic ZDR bias.

In this study, the weather method was used as the truth to test the estimated Bragg scatter values. Figure 14 shows a comparison of weather and Bragg scatter estimated systematic ZDR biases for May.

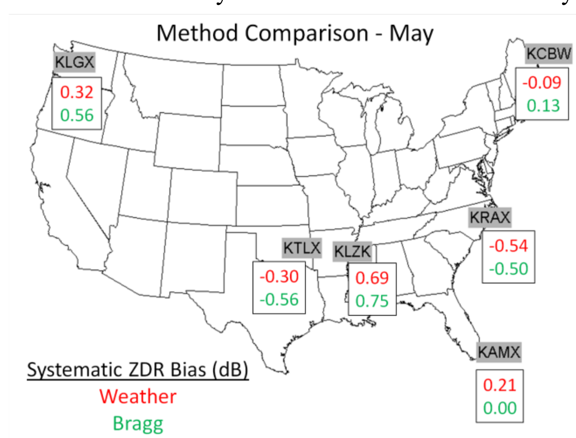

Figure 14. A comparison between the weather and Bragg estimated systematic ZDR bias for all six radars in May. In this figure the red values are the weather method's estimated systematic ZDR biases and the green values are the Bragg scatter estimated systematic ZDR values.

For four of the six cases the weather and Bragg estimates systematic ZDR biases are within 0.20 dB of each other. KTLX differs by 0.26 dB and KAMX differs by 0.21 dB. For KAMX case, the weather method may be inaccurate as it assumes stratiform rain to estimate the systematic ZDR bias. Anecdotally, it seems possible that convective precipitation processes leading to large drop contamination dominate the precipitation in south Florida. Other cases such as KLZK and KRAX have weather and Bragg estimates that are very similar. Since two independent methods show similar values it is likely that these radars have calibration errors.

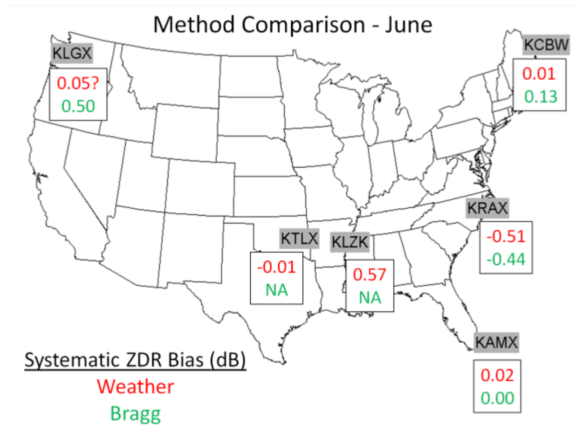

Figure 15. Same as figure 14 but for June. Note that KLZK and KTLX have no Bragg estimate.

Figure 15 shows the comparison between the weather method and Bragg scatter estimated systematic ZDR bias for June. KAMX, KRAX, KCBW are within 0.1 dB of each other. Weather data (not illustrated here) gives the author confidence that these estimates are accurate. KAMX in this case has a difference of 0.02 dB. KAMX has little to no systematic ZDR bias. KLGX, however has a difference of 0.45 dB. Reasons for this large difference are unknown and further research is needed. Using the filters applied in this study, KTLX and KLZK had no cases of good Bragg scattering for June. This is possibly due to a lack of moisture and/or contamination from biota.

5. **Conclusions**

In conclusion, an automated method for estimating systematic ZDR 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 two statistical filters to isolate the good cases of Bragg scattering. The statistical filters make this a robust method for estimating systematic ZDR bias. This method was applied to six regionally diverse radars with reliable weather method data. Cases studies were demonstrated with KRAX for May and KTLX for June. These examples showed how the data and statistical filters eliminated the majority of Bragg scatter cases, but left the truly good cases.

For the sites examined, Bragg scattering was found most often from 1400-2200 UTC and was found one and half more times in May than in June. Bragg scattering has comparable values for estimating systematic ZDR bias to the scanning weather method. For cases that the weather and Bragg methods show similar systematic ZDR bias, it can be concluded that the radar has a calibration error. Bragg scattering offers an alternative method for estimating systematic ZDR bias on operational NEXRAD WSR-88Ds.

6. **Acknowledgments**

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7. **References**

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