P3C.1 EVALUATING THE CALIBRATIONS OF RADARS: A SOFTWARE APPROACH

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1. INTRODUCTION

The accuracy of radar reflectivity measurements impacts quantitative precipitation estimates which rely on nonlinear reflectivity-to-rainfall equations. These precipitation estimates are used operationally by the National Weather Service in the U.S. for flash flood forecasting and warning, by the precipitation forecasts and more recently for assimilation into numerical weather prediction models. Bolen and Chandrasekar (2000) noted variability in the calibrations of the Weather Surveillance Radars-1998 Doppler (WSR-88Ds) in comparison with a space-born radar. It is the intention of this study to develop an automated technique to evaluate the relative calibrations of the WSR-88D radars, provide this information to the large community of radar data users, and ultimately improve the radar calibrations in an absolute sense.

Atlas (2002) provides a concise background on traditional and newer approaches taken toward radar calibration. All techniques outlined employ targets with known radar cross-sections or other standards, such as rainfall collected by a disdrometer (Joss et al. 1968), in order to compare reflectivity measurements to a known value. The approach taken herein is unique in that it compares reflectivity measurements at collocated grid points in space and time from adjacent radars comprising a network. After examining a long period of significant precipitation, this technique elucidates the *relative* differences in calibrations between neighboring radars. It is hoped that this software can be used in conjunction with absolute calibration methods to calibrate an entire network in a timely, cost-effective manner.

2. SOFTWARE DESCRIPTION

Grid points between adjacent WSR-88D radars that have the same locations in 3D space and similar beam volumes are identified. This grid point matching procedure (described below) is performed one time and the matched grid points are stored in a static look-up table. The spatial locations of grid points between WSR-88D radars are generally fixed for all volume coverage patterns (VCP) from 0.5 to 4.3 degrees, but their temporal displacement can vary by as much as three minutes for radars operating in precipitation mode. Quality control measures are developed to ensure that the reflectivity measurements for matched grid points are taken within a threshold time window. Additional quality control criteria are placed on the matched data pairs to ensure that their reflectivity values are physically comparable and are a result of scattering from significant precipitation.

2.1 Grid point matching procedure

The grid point matching procedure evaluates the degree of collocation of candidate grid points from two adjacent radars' lowest, unblocked tilts (i.e., hybrid scans) up to an elevation angle of 4.3 degrees. Grid points are deemed to be matched with grid points from a neighboring radar if <u>all</u> of the following criteria are met:

1. The horizontal displacement between candidate grid points must be less than 500 m. This criterion refers to the maximum displacement in terms of latitude and longitude of the grid points projected down to the earth's surface.
2. The vertical displacement between candidate grid points must be less than 50 m. The centers of beam heights for candidate grid points are computed using the 4/3 earth's radius model with the elevation of the radars included. The units of the heights are in meters above sea level and must be within 50 m of one another in order to satisfy this criterion.
3. The beam volumes between candidate grid points must be similar within a 5% tolerance. In flat terrain, this criterion forces matched grid points to be nearly equidistant from the two radars. Grid points can be identified as matching even if they come from different elevation angles as long as the radars are sited at different elevations.
4. The temporal displacement between candidate grid points must be less than 3 minutes. Note that both radars must be operating in either VCP 21 or VCP 11.

2.2 Quality control measures on reflectivity at matched grid points

Reflectivity data are collected and compared at the matched grid points that have been previously identified and stored in a look-up table. Results are produced in the event that significant precipitation is observed at matched grid points. In addition, the quality control measures ensure that the differences in reflectivity between matched grid points are physically realistic. <u>All</u> of the following criteria must be met in order for the developed software to calculate radar reflectivity differences:

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1. The reflectivity from both matched grid points must be greater than or equal to 15 dBZ. This criterion is used to compare reflectivity from hydrometeors as opposed to returns from clear air echo.
2. The absolute difference in reflectivity from matched grid points must be less than or equal to 8 dB. This criterion is used to screen out data that may be significantly different due to anomalous propagation of the beam caused by spatially variable temperature, humidity, and/or pressure profiles.
3. At least 5 matched grid points must meet the above criteria per 5-min period in order for the data to be considered statistically significant. These reflectivity differences are then averaged, stored, and presented to the users through the Internet.

TABLE 1. Site identification codes and locations of WSR-88D radars used in this study.

Site ID	Site Location
KAKQ	Norfolk, Virginia, U.S.
KFCX	Roanoke, Virginia, U.S.
KRAX	Raleigh/Durham, North Carolina, U.S.
KMHX	Morehead City, North Carolina, U.S.
KLTX	Wilmington, North Carolina, U.S.
KGSP	Greer, South Carolina, U.S.
KCAE	Columbia, South Carolina, U.S.
KCLX	Charleston, South Carolina, U.S.
KDDC	Dodge City, Kansas, U.S.
KICT	Wichita, Kansas, U.S.
KVNX	Vance AFB, Oklahoma, U.S.
KINX	Tulsa, Oklahoma, U.S.
KTLX	Oklahoma City, Oklahoma, U.S.
KSRX	Chaffee Ridge, Arkansas, U.S.
KAMA	Amarillo, Texas, U.S.
KFDR	Frederick, Oklahoma, U.S.
KLBB	Lubbock, Texas, U.S.
KFWS	Dallas, Texas, U.S.

3. RESULTS

Evaluation of radar calibration differences between 8 radars has been ongoing in S. Carolina, N. Carolina, and Virginia, U.S. (see Fig. 4) from 15 Nov 2002 through 1 May 2003 and on 10 radars in Oklahoma, N. Texas, S. Kansas, and W. Arkansas, U.S. (see Fig. 5) from 15 Feb 2003 through 1 May 2003. It should be noted that 6 additional radars in and surrounding Arizona, U.S. are being evaluated, but the lack of significant precipitation since the software was installed in Mar 2003 precludes further discussion. Table 1 lists the radar names and 4-letter codes for the WSR-88D radars used in this study.

The radar reflectivity differences between 2 given radars are presented in the form of relative frequency histograms (e.g., Fig. 1a) and time series plots (e.g., Fig. 1b). In addition, all average differences for a given region are combined on a single, plan-view map (e.g., Fig. 4). The relative frequency histograms utilize 17 classes of reflectivity differences ranging from –8 to +8 dB. These plots reveal the data distribution from which measures such as central tendency and variability are derived. Periods of no data (precipitation) are not included in the relative frequency histograms or the time series plots. The time series plots reveal the temporal evolution of reflectivity differences leading to the identification of the times at which sudden changes in radar calibration occur. The calibration differences presented in plan view highlight radars that are either consistently low (cold), high (hot), or in agreement with respect to measurements from nearby radars. The focus of this study is on the long-term results and not storm-to-storm differences, as there may be reflectivity discrepancies caused by variable refractivity gradients yielding different beam propagation paths and differing radar cross-sections dependent on viewing angle for some hydrometeors.

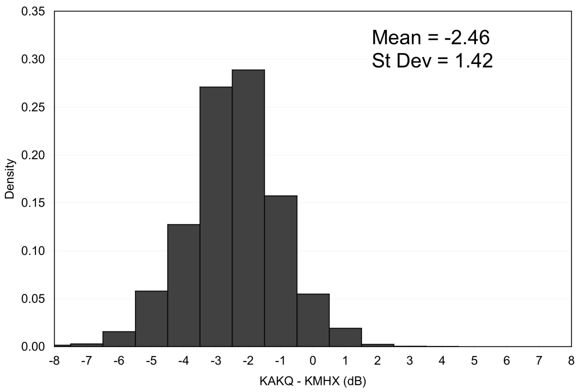

Fig. 1a – Relative frequency histogram of the reflectivity difference (in dB) between the KAKQ and KMHX radars between 15 Nov 2002 and 1 May 2003.

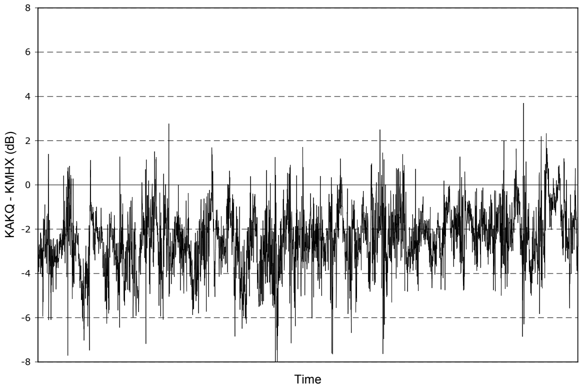

Fig. 1b – Time series of the reflectivity difference (in dB) between the KAKQ and KMHX radars for raining periods between 15 Nov 2002 and 1 May 2003.

Fig. 1a,b reveals that the 6-month difference in calibration (containing 3753 data points) between the KAKQ radar and the KMHX radar is consistently large and negative with a mean value of –2.46 dB. This example has a normal data distribution typical of the entire database, but the bias is the largest one discovered up to this point. One notable exception to the Gaussian data distribution is shown in Fig. 2a,b comparing the calibration differences between the KCAE and KCLX radars. In this case, the relative frequency histogram indicates a bimodal distribution. Further analysis of the time series plot reveals 2 distinct modes of behavior with a step-change occurring near 21 Mar 2003. This result alone indicates that either KCLX suddenly became 3 dB hotter or KCAE became 3 dB colder. Comparisons between other nearby radars are used to identify the radar that underwent this sudden change. Fig. 3a,b, showing the calibration differences between the KLTX and KCLX radars, reveals a non-Gaussian data distribution and a step-change also occurring around 21 Mar 2003. Based on this result alone, either KLTX became about 3 dB colder or KCLX became about 3 dB hotter after that time. Additional comparisons between KLTX and KCAE with nearby radars (not shown) reveal no step-changes. The software has thus indicated that KCLX became approximately 3 dB hotter around 21 Mar 2003 using reflectivity measurements from actual precipitation. Later, we consulted the Radar Operations Center (ROC) about this finding and they concurred that there was an entry in their database documenting signal-degraded errors from the KCLX radar which resulted in low reflectivity measurements. The problem was addressed a few days following the initial report filed on 17 Mar 2003.

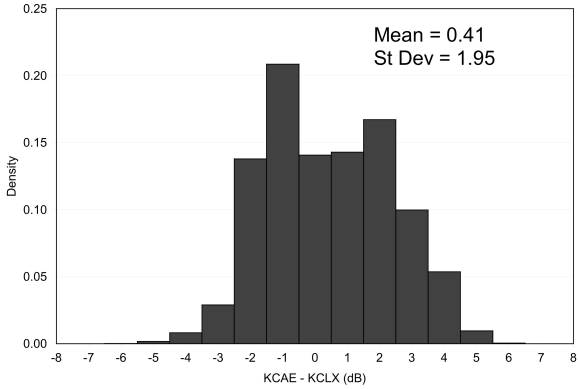

Fig. 2a – Same as in Fig. 1a, but for the KCAE and KCLX radars.

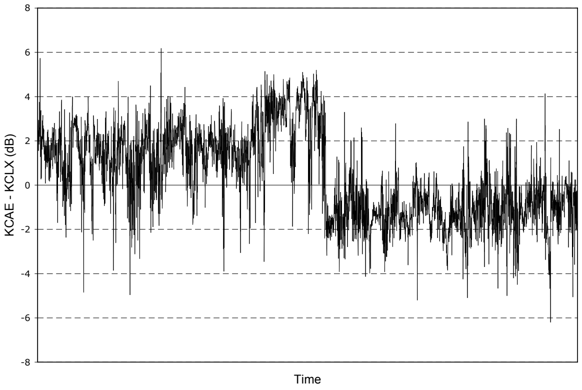

Fig. 2b – Same as in Fig 1b, but for the KCAE and KCLX radars.

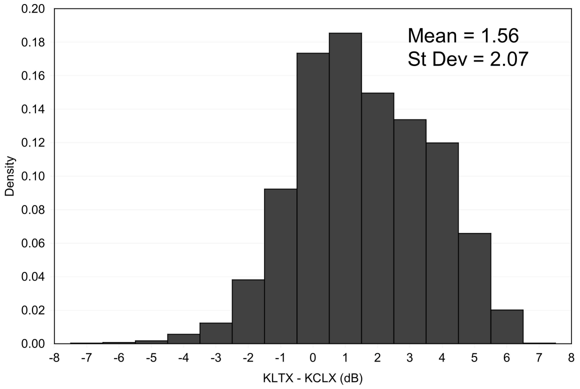

Fig. 3a – Same as in Fig. 1a, but for the KLTX and KCLX radars.

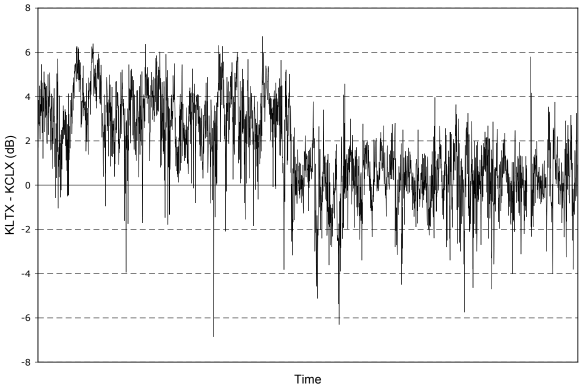

Fig. 3b – Same as in Fig 1b, but for the KLTX and KCLX radars.

The plan view of radar calibration differences for the 8 radars in the Carolinas region is shown in Fig. 4. The reflectivity differences between adjacent radars have been averaged over the duration of 6 months or after the step-change occurred on 22 Mar 2003 for KCLX and its neighbors. The arrows point to the relatively hot radars while the darkness of the colors in the arrows reveals the magnitude of the average differences. The graphic reveals that KLTX is hot in a relative sense while KCAE and KAKQ appear cold. The statistical analysis undertaken also enables us to assess the self-consistency of the results shown in Fig. 4. To do this, the residuals of the differences are calculated in a closed, triangular loop. For example, in Fig. 4 we see that KCLX, KCAE, and KLTX are all compared with one another. A residual can thus be computed by summing the differences around the triangle to determine the degree of closure (measured by its closeness to 0). The absolute values of the residuals are plotted on Fig. 4 in boxes within the respective closure loops. The largest residual in this region is quite small with a value of 0.36 dB. The residuals have been found to decrease as more data points are included in the calibration differences. For example, in the Carolinas region, the number of data points involved in each comparison ranges from 350 to 6624, while in the Oklahoma region, the range varies from 102 to 1809. This difference is attributed to climatological precipitation patterns and the time at which the software was installed for the different regions.

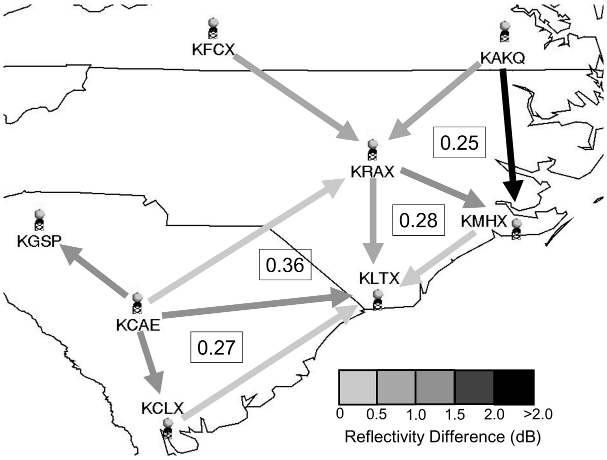

Fig. 4 – Plan view of the average reflectivity differences (in dB) for 8 WSR-88D radars in the Carolinas region from 15 Nov 2002 to 1 May 2003. The arrows point to radars with relatively high reflectivity measurements. The absolute values of the residuals computed in summing the reflectivity differences in triangular loops are shown in boxes within each respective loop.

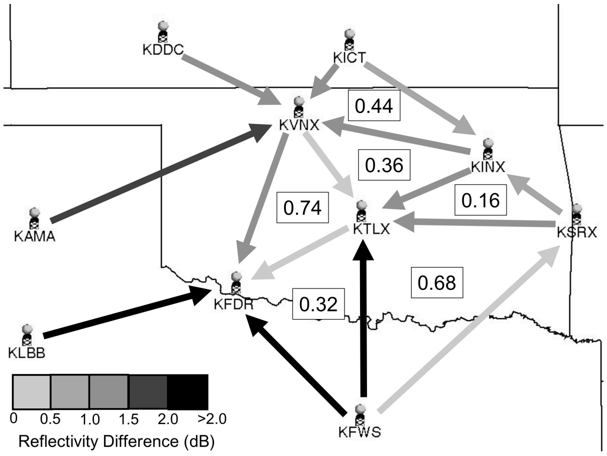

Fig. 5 – Same as in Fig. 4, but for 10 WSR-88D radars in Oklahoma region. The average reflectivity differences are based on data collected from 15 Feb 2003 to 1 May 2003.

Fig. 5 shows the plan view of radar calibration differences for 10 WSR-88D radars in the Oklahoma region. In this case, the arrows indicate that the KFDR radar is hot as are the KTLX and KVNX radars, respectively. Many other radars in Texas and Kansas appear to be cold (e.g., KFWS), but they are being predominately compared against relatively hot radars such as KFDR, KTLX, and KVNX. The absolute values of the residuals computed in triangular loops are slightly higher than in the Carolinas region, but are all still less than 1.0 dB.

4. CONCLUSIONS

As noted in Atlas (2002), to this day there is no universal method of radar calibration. In this study, we recommend a software solution to evaluate the calibration differences between adjacent radars in a network. It is shown how the software can effectively identify radars that have undergone maintenance resulting in increases as large as 3 dB. The same tools can be used to identify radars that have experienced unknown hardware failures causing sudden changes in calibration. As opposed to calibrating an entire network of radars independently, we recommend calibrating a few, centrally located radars within a network. The software described herein can then be used to apply correction factors so that adjacent radars are in agreement with the calibrated radars. In essence, this leveling technique can be applied outward from the calibrated radar. This blend of absolute and relative radar calibration methods can be timely and cost-effective.

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