691 A NOVEL PHYSICAL CONSISTENCY-BASED CALIBRATION TOOL FOR POLARIMETRIC WEATHER RADAR

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1. INTRODUCTION

The calibration of radar reflectivity and differential reflectivity is essential for accurate quantitative precipitation estimation (QPE) using polarimetric weather radar. Mature calibration methods, which are based on a standard signal source, the routine sun tracking, the “bird bath” scanning method, etc., have been widely used in the weather radar community (Bringi and Chandrasekar, 2001; Melnikov et al. 2003). However, those methods are generally off-line calibration techniques and may interrupt the operational data collection. In addition, the calibration should be done frequently because the calibration term might vary with time. It is also noted that the calibration term might vary in radar sweeps with different elevation angles. Using conventional calibration techniques, frequent calibration becomes impractical. An automatic on-line calibration approach could overcome these limitations and would be desirable by the operational weather radars, especially within a regional or national network.

Collaborating with the U.S. National Severe Storms Laboratory (NSSL), Enterprise Electronics Corporation (EEC) located in Enterprise, Alabama has recently developed a novel automatic calibration algorithm (ACAL), which facilitates the online reflectivity calibration for S-band and C-band polarimetric weather radars. The ACAL algorithm is based on the physical consistency among polarimetric radar measurements of precipitation, i.e., radar reflectivity (Z), differential reflectivity (Z_{DR}), and differential phase (Φ_{dp}). With the continuous execution of ACAL, the radar system is capable of generating the reflectivity products being calibrated in real-time. The current study evaluates ACAL reflectivity bias estimation using the data collected with seven C-band polarimetric weather radars operated by German Meteorological Service (DWD).

2. METHODOLOGY

For radar echoes of pure rain, the physical consistency is generally observed among the polarimetric radar measurements (Bringi and Chandrasekar, 2001). The relation among radar reflectivity Z, differential reflectivity Z_{DR}, and specific differential phase (K_{dp}) can be quantified with the following equation (Ryzhkov et al. 2005).

$$Z = a + b\log(K_{dp}) + cZ_{DR} \quad (1)$$

If the radar reflectivity measurement has a bias ΔZ, the resulting Z_{DR} and K_{dp} data may statistically show a deviation from the physical consistency relation so that the deviation can be used to estimate the bias ΔZ. The ΔZ is defined as the difference between measured reflectivity (Z_m) and true reflectivity (Z_t).

$$\Delta Z = Z_m - Z_t \quad (2)$$

Based on the self-consistency relation given by equation (1), the reflectivity bias ΔZ can be estimated with the following formula

$$\Delta Z(dB) = 10\log\left(\frac{\sum_i 10^{0.1Z_m^{(i)}} f(Z_{DR}^{(i)})}{\sum_i K_{dp}^{(i)}}\right) \quad (3)$$

where $Z_m^{(i)}$, $Z_{DR}^{(i)}$, and $K_{DP}^{(i)}$ are measured reflectivity, differential reflectivity, and specific differential phase, respectively, at the i^{th} gate in the rain region. The function *f* in (3) is a polynomial function of Z_{DR} given as

$$f(Z_{DR}) = 10^{-5}(a_0 + a_1 Z_{DR} + a_2 Z_{DR}^2 + a_3 Z_{DR}^3) \quad (4)$$

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The coefficients in equation (4) have been quantified with polarimetric radar and disdrometer measurements in Norman, Oklahoma. For C-band radar, a_0 = 6.70, a_1 = -4.42, a_2 = 2.16, a_3 = -0.404. For S-band radar, a_0 =3.19, a_1 =-2.16, a_2 =0.795, a_3 = -0.119. In this equation Z_{DR} is expressed in unit of dB. The unit of $Z_m^{(i)}$ is dBZ and the unit of $K_{DP}^{(i)}$ is deg/km.

It is worth noting that the usage of formula (3) relies on the unbiased Z_{DR} measurement in order to achieve an accurate estimate of reflectivity bias. In practice, the well-calibrated Z_{DR} can be achieved by the implementation of birdbath method, which generally can obtain 0.1 dB accuracy for Z_{DR} calibration. This accuracy is desirable for estimating the reflectivity bias reliably.

3. PROCEDURE OF DATA PROCESSING

The major objective of ACAL is to find the reliable estimate of reflectivity bias. The data processing of ACAL is described in the following subsections.

3.1 Initial Φ_{dp} offset estimation

The raw Φ_{dp} data points at near range are sorted out by evaluating the consecutive 6 gates of data points with 10< Z_H <40 dBZ and ρ_{hv} >0.95. The initial range for data evaluation is 5 km. If more than 200 data points are found within the 5 km range, calculate the initial Φ_{dp} value based on the peak of density distribution of those Φ_{dp} values. If satisfactory data points are less than 200, increase the range by 1 km interval and repeat the above procedure until the initial Φ_{dp} is found. If the raw Φ_{dp} data points sorted out in one sweep are insufficient (i.e., <200), use data from other sweeps/volumes to estimate the initial Φ_{dp}. Finally, the consistence of initial Φ_{dp} is checked over different sweeps/volumes.

After the initial Φ_{dp} is found, shift the raw Φ_{dp} with the initial Φ_{dp} offset and let Φ_{dp} approximately start with zero degree for the whole sweep.

3.2 Φ_{dp} data smoothing

Use the 2 km moving average to smooth Φ_{dp} data in the radial direction. For example, if the range gate is 250 m, the average window length is 9. For Φ_{dp} data with a large variation (e.g., greater than 2°), use the median value instead of mean value for the smoothing.

3.3 Attenuation correction

For C-band data, observed Z and Z_{DR} need to correct the attenuation in order to estimate the reflectivity bias. The attenuation correction can use various mature algorithms in the literatures. Current study uses the smoothed Φ_{dp} with the following equations (Bringi and Chandrasekar, 2001),

$$Z^{(m)} = Z^{(bc)} + \alpha(\Phi_{DP} - \Phi_{DP}^{(sys)}) \quad (5.1)$$

$$Z_{DR}^{(m)} = Z_{DR}^{(bc)} + \beta(\Phi_{DP} - \Phi_{DP}^{(sys)}) \quad (5.2)$$

where $Z^{(bc)}$ and $Z_{DR}^{(bc)}$ are measured reflectivity and differential reflectivity before attenuation correction. $\Phi_{DP}^{(sys)}$ is the system Φ_{dp} offset, i.e., the initial Φ_{dp} found in previous section 3.1.

3.4 K_{dp} estimation

The self-consistency-based bias estimation is sensitive to the error in K_{dp} estimation. For simple implementation, the ACAL algorithm uses the following procedures to estimate K_{dp}. Firstly, find the median values of smoothed Φ_{dp} within 2 km range (i.e., 9 data points) before and after a given range gate. The Φ_{dp} difference between the two median values is then calculated. Finally, the K_{dp} value for the given range gate is calculated with the Φ_{dp} difference divided by 2 km range. The equation is given as:

$$K_{DP}(n) = [\mathrm{median}(\Phi_{DP}(n,...,n+8)) - \mathrm{median}(\Phi_{DP}(n-8,...,n))]/4 \quad (6)$$

3.5 Quality control

Low-quality radar echoes (e.g., noise, non-hydrometeor contamination, and low SNR signals) may effectively degrade the data quality, especially for Φ_{dp} and K_{dp} data that depend on the range averaging. In order to have a more reliable data processing, the radar data with a large coverage of precipitation are desirable. For the purpose of data quality control, the ACAL algorithm only uses the data points with at least continuous 20 range gates (i.e., 5 km) that satisfy ρ_{hv}>0.95 and SNR>20 dB.

Figs. 1 and 2 give an example of DWD radar measurements (Z_H, Z_{DR}, ρ_{hv}, Φ_{dp}, W_h, and V_h) and the result of quality control. The red color region in Fig. 2 shows the identified precipitation region, where the radar data can be used for the further processing.

3.6 Data filtering

Given the identified region after the initial quality control, use the following criteria to sort out available data points that are suitable for the reliable estimation of reflectivity bias.

- SNR > 25 dB
- $0.2 < Z_{DR} < 2$ dB
- $\Phi_{DP} - \Phi_{DP}^{(sys)} < 30°$
- Range gates are at least 0.5 km below the melting layer and outside of the range of massive ground clutter contamination (depending on the location of radar site).

3.7 Bias estimation

The bias estimation applies equations (3) and (4) as well as the radar data selected and processed with aforementioned procedures.

4. DATA DESCRIPTION

The datasets used for the evaluation were collected by seven C-band German radars (DWD network) during the rain events on 6-8 October 2015. The brief descriptions of the datasets and radar configurations are given in Table 1. It is noted that the time interval between two volume files is about 5 minutes. As a result, the total time for these datasets is about 83 hours. It is also noted that DWD radars generally have a good Z_{DR} calibration through a long-term monitoring of Z_{DR} data using the birdbath method. DWD has set-up regular birdbath scan mode to monitor and calibrate the Z_{DR} data in quasi-real time (several times within one hour) so that the well-calibrated Z_{DR} data can be obtained in the whole radar network.

The data files provided by DWD are in HDF format. The 'UZh', 'UZDR', 'URHOHV', 'UPHIDP', 'Wh', 'Vh', and 'SNRh' were loaded as the raw radar data (e.g., Z_H, Z_{DR}, ρ_{hv}, Φ_{dp}, W_h, V_h, and SNR_h etc.) for the data analysis. The attenuation correction and consequent reflectivity calibration mainly rely on raw data 'UZh', 'UZDR', and 'UPHIDP'. The data filtering and quality control also use the data of ρ_{hv}, SNR_h, and V_h.

Because the temperature information was not included in the radar data, the heights of bright band top/bottom were approximately estimated from the ρ_{hv} data. The height of bright band bottom was estimated to be about 1.8 km. To exclude the BB effect, the data points were considered for the processing only when radar beam center was below the height of 1.8-0.5=1.3 km.

4. RESULT ANALYSIS

The reflectivity biases estimated from the datasets of seven DWD radars are shown (blue lines) in Fig. 3. The numbers of available data points used for the estimation are also displayed in the same plot with green solid lines. The x-axis denotes the index number of volume scans executed by the radars. The corresponding statistics of bias estimates are given in Tables 2 and 3. The statistic results are categorized with different thresholds of available data points. The findings obtained from these figure and tables are briefed as follows.

The consistent reflectivity bias estimates over different volumes can be obtained through the processing of a large amount of data points. For example, the BOO, FBG, ISN, and MEM radars have many volumes (>20), each of which has more than 10000 data points satisfying the criteria of data selection described in section 3.7. Correspondingly, their reflectivity bias estimates using these data points have a small standard deviation within 0.197-0.525 dB, as listed in Table 2. This fact implies that the sufficient data points could mitigate the possible errors in the proposed algorithm.

The estimates of reflectivity bias might not be robust using a limited number of data points. As shown in the results of BOO, FBG, ISN, and MEM radars, the volume files with less than 10000 data points generally give noisy bias estimates. It is worth noting that OFT and TUR radar data tend to produce very stable bias estimates even with a much smaller number of available data points than using data of other radars. As shown in Table 3, with a much smaller threshold (e.g., 1000 data points), the standard deviation of bias estimate is about 0.4 dB only for OFT. This fact implies that different precipitation properties might be one of factors that affect/degrade the bias estimation. The underlying reason is likely the uncertainty of K_{dp} estimation, to which the reflectivity bias estimation is sensitive. The highly inhomogeneous precipitation (e.g., scattered precipitation cells) could increase K_{dp} estimation error and consequently add difficulty for accurate bias estimation. It is found (not shown) that the precipitation of more stratiform type tends to need fewer data points for a robust bias estimation.

There might exist model errors regarding the proposed algorithm because the physical consistency constraint is based on a statistically mean relation. This is likely one of reasons why bias estimation has a large variation when data points are insufficient. According to the data analysis, the negative effects can be mitigated by using a large amount of data points. To get reliable bias estimate, the available data points are generally suggested to be greater than 10000 per sweep.

As shown in Fig. 3 and Tables 2 and 3, all seven radars have a small bias (mostly within +/-1 dB) although the BOO radar has a slightly larger bias, which is -1.64 dB. FBG and ISN radars show well-calibrated data and their reflectivity biases are less than 0.1 dB. DWD has put a lot of efforts into the long term monitoring of radar calibration and system tuning. The analysis results in this study provide good evidence that DWD radar systems are generally well tuned.

5. CONCLUSIONS

The current study presents a novel reflectivity bias estimation algorithm (ACAL) proposed by EEC, which is used for the reflectivity calibration of polarimetric weather radar. The analysis results using the data collected by seven DWD radars show consistent bias estimates throughout the studied rain events, implying the proposed self-consistency-based algorithm would be robust. The variation of bias estimates attributed with the potential imperfect self-consistency model tends to be small if sufficient data points are used for the estimation. Although small number of data points might still give good bias estimate, data points >10000 per sweep are recommended for producing reliable results. Given the promising results with DWD radar data, the proposed reflectivity bias estimation method can be a useful tool for online reflectivity calibration and can be operated as a long-term monitoring function for radar quality control.

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REFERENCES

Alexander V. Ryzhkov, Scott E. Giangrande, Valery M. Melnikov, and Terry J. Schuur, 2005: Calibration Issues of Dual-Polarization Radar Measurements. *J. Atmos. Oceanic Technol.*, **22**, 1138–1155.

Bringi, V.N. and V. Chandrasekar, 2001: Polarimetric Doppler Weather Radar: Principles and Applications. *Cambridge University Press*, 648 pp.

Melnikov, V. M., D. S. Zrnic, R. J. Doviak, and J. K. Carter, 2003: Calibration and performance analysis of NSSL's polarimetric WSR-88D. NOAA/NSSL Rep., 77 pp. [Available online at http://www.nssl.noaa.gov/88d-upgrades/WSR-88D_reports.html]

Table 1. Description of experimental data files

	Description
Radar Sites	BOO, FBG, ISN, OFT, TUR, EIS, MEM
Events	10-06-2015, 10-07-2015, 10-08-2015
Radar Configurations	• Frequency: C-band (~5.3 cm) • Range: 150 km • Gate width: 250 m • PRF: 600 Hz • Pulse Number: 50 • Scan rate: 12°/s • Angle Sync: 1° • Elevation: 0.8°
Data Files (Volumes)	174, 85, 235, 73, 97, 235, 97

Table 2. Statistics of reflectivity bias estimated from the datasets of seven DWD radars

	Number of Available Estimates			Mean Estimate of Reflectivity Bias (dB)			Standard Deviation (dB)		
Data Thresholds	10000	6000	4000	10000	6000	4000	10000	6000	4000
BOO	**39**	73	97	**-1.6410**	-1.6509	-1.8748	**0.2898**	0.6896	0.8586
FBG	**26**	33	39	**-0.0547**	0.1233	0.2094	**0.5249**	0.6420	0.6403
ISN	**45**	92	134	**0.0144**	0.1222	0.2638	**0.3425**	0.5216	0.6840
OFT*	0	0	0	N/A	N/A	N/A	N/A	N/A	N/A
TUR*	0	0	23	N/A	N/A	-0.8624	N/A	N/A	0.3386
EIS	3	**102**	140	1.4644	**0.8646**	0.8200	1.1380	**0.8851**	0.9224
MEM	**22**	27	32	**-0.5726**	-0.5543	-0.5574	**0.1970**	0.2050	0.2235

** indicates the small data points but have good estimates shown in table 3.*

Table 3. Statistics of reflectivity bias for radars having small datasets

Radar Sites	Data Threshold	Number of Estimates	Mean Bias (dB)	Standard Deviation (dB)
OFT	1000	24	-0.9094	0.4181
TUR	2000	35	-0.7721	0.4025

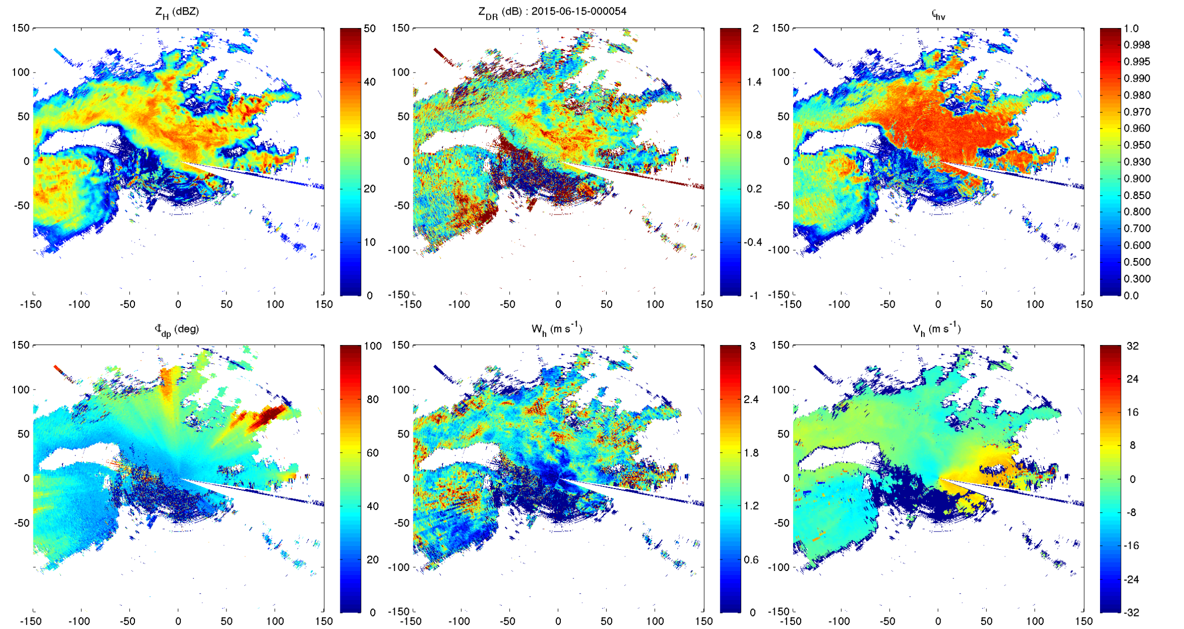


Figure 1. Example of DWD MHP radar measurements (from left to right, top to bottom, are Z_H, Z_{DR}, ρ_{hv}, Φ_{dp}, W_h, and V_h, respectively) at 00:00:54UTC on 15 June 2015.

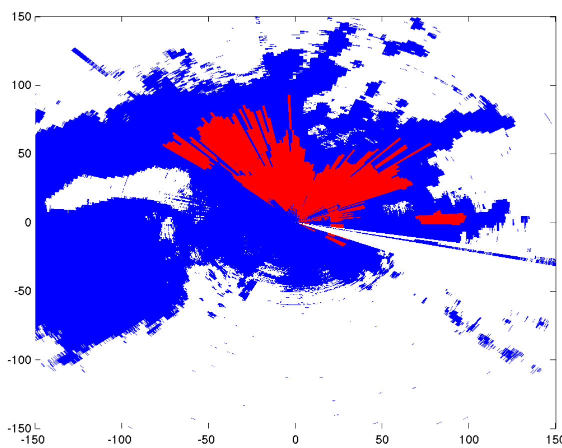
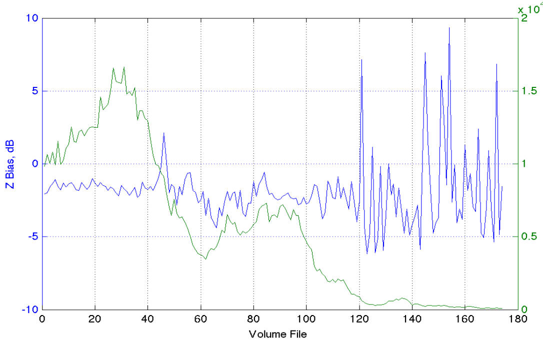
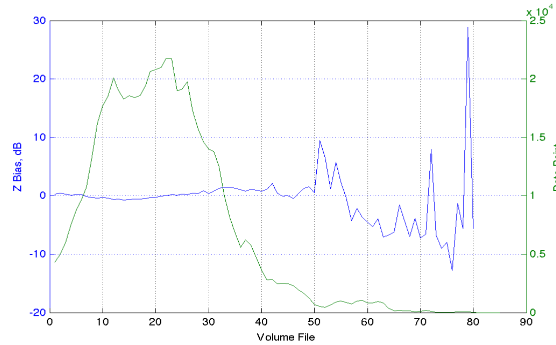


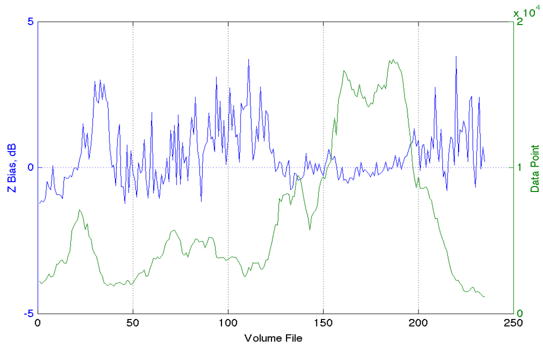
Figure 2. The identification of precipitation region (red), where the data have good quality for the estimation of reflectivity bias.



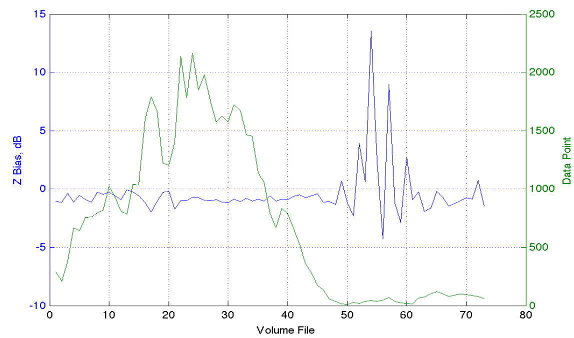
(a) BOO



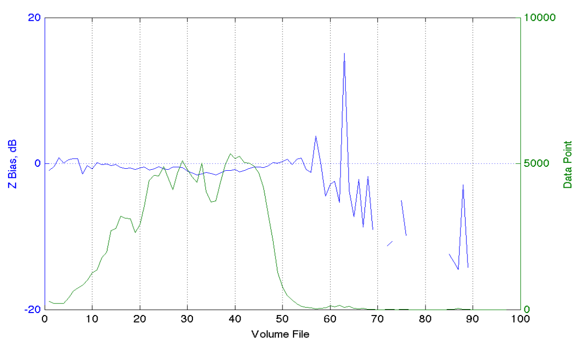
(b) FBG



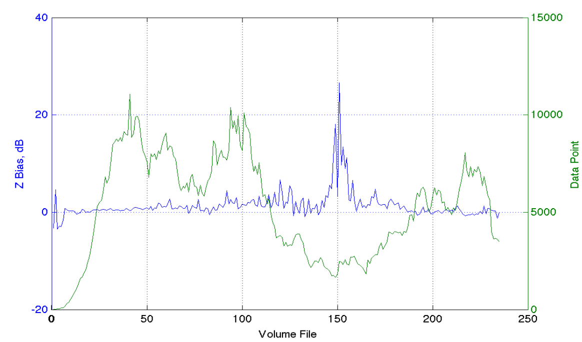
(c) ISN



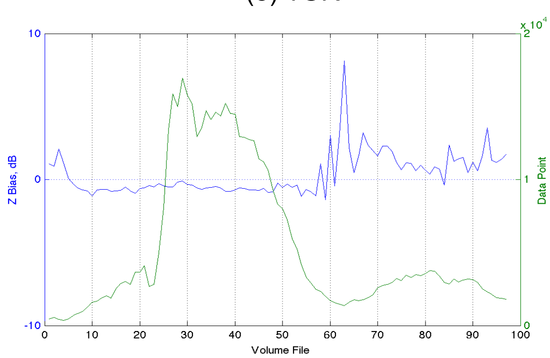
(d) OFT



(e) TUR



(f) EIS



(g) MEM

Figure 3. These figures show the bias estimation results using the data at different volume scans/radars. The blue lines indicate the variation of estimated reflectivity bias and the green lines show the number of available data points used for the data analysis. Subplots from left to right, up to down, represent radars BOO, FBG, ISN, OFT, TUR, EIS, and MEM, respectively.