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, routine sun tracking, "bird bath" scanning, etc., have been widely used in the weather radar community. 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 could overcome these limitations and would be desirable by the operational weather radars, especially within a regional or national network.

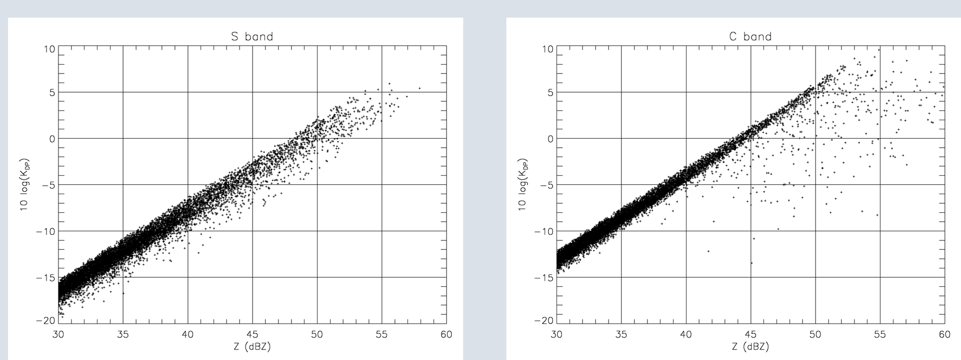
Recently, Enterprise Electronics Corporation (EEC) in Alabama, collaborated with the U.S. National Severe Storms Laboratory (NSSL), have developed a novel automatic calibration method (ACAL), which facilitates on-line calibration for S-band and C-band polarimetric weather radars. The ACAL method is based on the physical consistency among polarimetric radar measurements of precipitation, i.e., reflectivity, differential reflectivity, and differential phase. With the continuous execution of ACAL, the radar system can generate the automatically-calibrated reflectivity and differential reflectivity products in real-time.

2. Methodology

❑ Self-consistency in radar data

For weather signals, the physical consistency is generally found among polarimetric radar measurements: radar reflectivity (Z), differential reflectivity (Z_{DR}), and specific differential phase (K_{dp}), and can be quantified with the following relation (Ryzhkov et al. 2005, JTECH).

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



Right two figures give the scatterplots of 10 log(K_{DP}) versus Z for rain data collected in Oklahoma: (left) S band and (right) C-band.

❑ Assumption of Z_{DR} bias

To achieve the accurate for reflectivity calibration, one assumption for the self-consistency method is that the Z_{DR} bias is well corrected. In practice, the birdbath method is a useful tool for Z_{DR} calibration, which generally has a well-accepted accuracy as good as 0.1 dB. For example, German Meteorological Service (DWD) has setup regular birdbath mode to monitor their radar network in quasi-real time so that good Z_{DR} data can be obtained.

❑ Quantification of Z bias

It is assumed that the radar reflectivity bias ΔZ is determined as a difference between measured and true reflectivity:

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

According to the concept of self-consistency in rain, the bias ΔZ is determined as

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

where $Z_m^{(i)}$ is the measured reflectivity in the i^{th} gate in rain, $Z_{DR}^{(i)}$ is the measured differential reflectivity in in the i^{th} gate, and $K_{DP}^{(i)}$ is the measured specific differential phase in the i^{th} gate. In (3),

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

3. Procedures of Data Processing

❑ Initial Φ_{dp} offset estimation

The raw Φ_{dp} data points are sorted out from near to far range by evaluating at least consecutive 1 km (6 gates) of data points with 10< Z_H <40 dBZ and ρ_{hv} >0.95. The initial Φ_{dp} is estimated with the peak of their density distribution. The consistence of initial Φ_{dp} is checked over different sweeps/volumes.

❑ Φ_{dp} data smoothing

Use 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.

❑ 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. Current study uses the smoothed Φ_{dp} with the following equations, 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}.

$$Z^{(m)} = Z^{(bc)} + \alpha(\Phi_{DP} - \Phi_{DP}^{(sys)}) \qquad Z_{DR}^{(m)} = Z_{DR}^{(bc)} + \beta(\Phi_{DP} - \Phi_{DP}^{(sys)}) \quad (5)$$

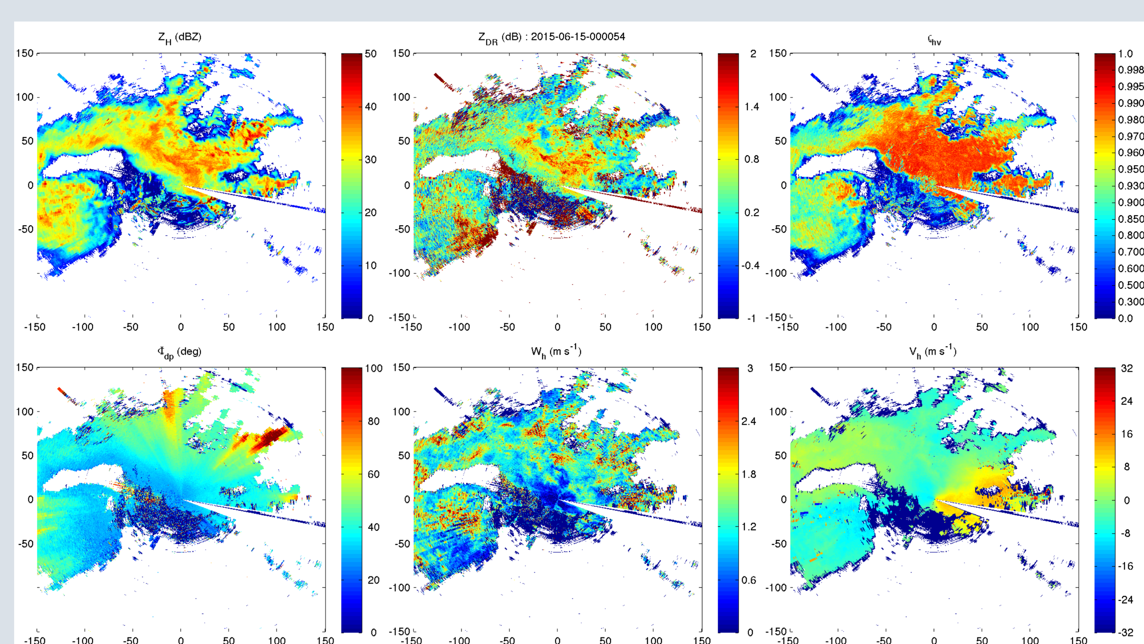
❑ K_{dp} estimation

This study uses the following equation to estimate K_{dp}. The data window is 2 km (i.e., 9 gates) before and after the current gate.

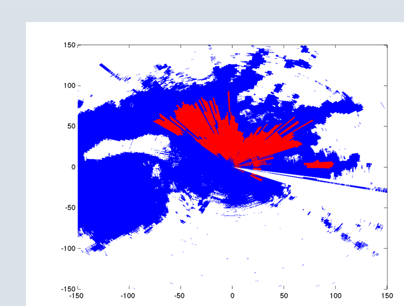
$$K_{DP}(n) = [\mathrm{median}(\Phi_{DP}(n,...,n+8)) - \mathrm{median}(\Phi_{DP}(n-8,...,n))]/2/2 \quad (6)$$

❑ 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} that depend on range averaging. For better data processing, radar data with a large coverage of precipitation are desirable. Therefore, we have only considered the data points with at least continuous 20 range gates (i.e., 5 km) that satisfy ρ_{hv}>0.95 and SNR>20 dB.



Left six figures show an example of DWD MHP radar measurements (from left to right, top to bottom, are Z_H, Z_{DR}, ρ_{hv}, Φ_{dp}, W_V, and V_h) at 00:00:54UTC on 15 June 2015.



Above figure identifies the precipitation region (red), which has good quality for the purpose of reflecitvity calibration.

❑ Data filtering for bias estimation

Within the identified region, use the following criteria to find available data points for bias estimation.

- 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 radar site).

❑ Z bias estimation

The bias estimation applies the equations (3-4) and the data points processed and filtered out following above procedures.

In equation (4), a_0 = 6.70, a_1 = -4.42, a_2 = 2.16, a_3 = -0.404 for C band. For S-band, a_0 =3.19, a_1 =-2.16 , a_2 =0.795, a_3 = -0.119.

It is noted that Z_{DR} is expressed in dB. The unit of $Z_m^{(i)}$ is dBZ and the unit of $K_{DP}^{(i)}$ is deg/km.

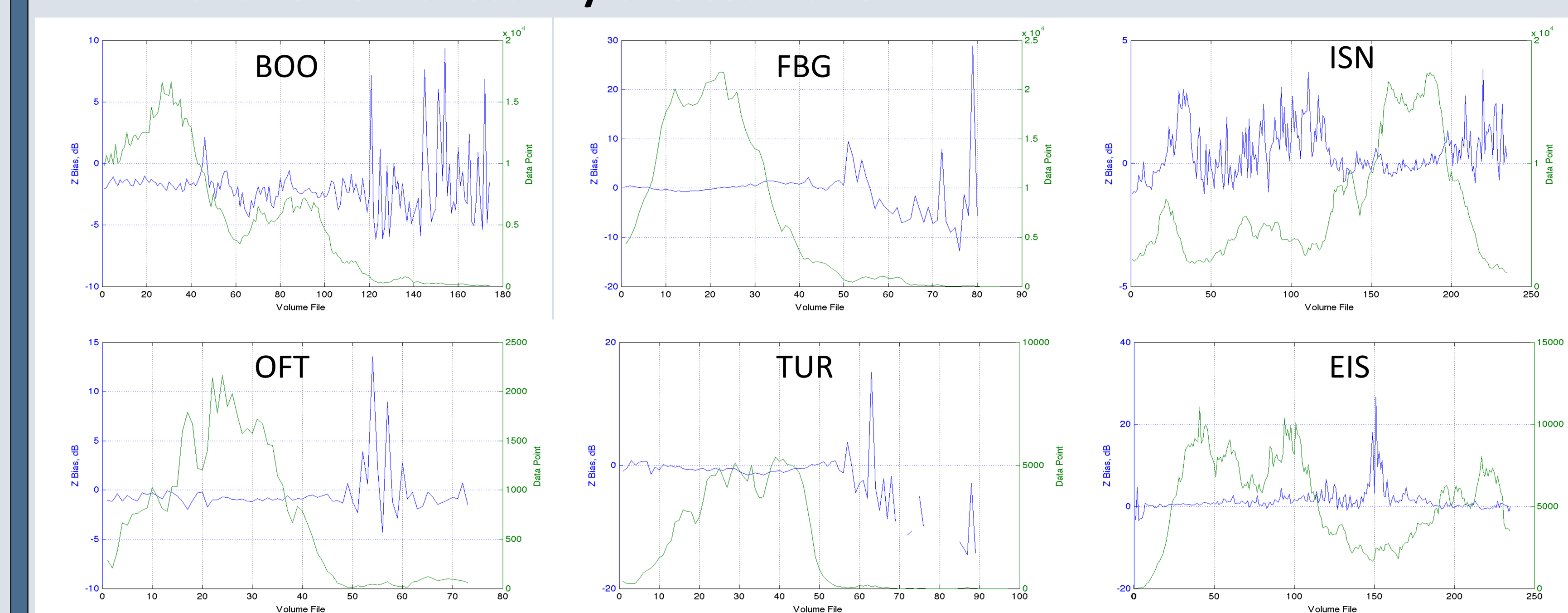
4. Result Analysis

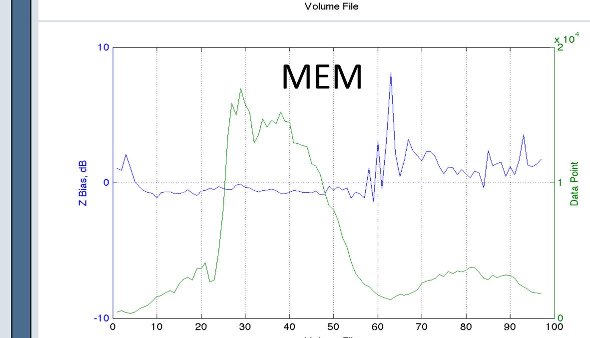
❑ Experimental datasets

The datasets used for the reflectivity bias estimation were collected by 7 C-band German radars (DWD network). The time interval between two volume files is about 5 minutes, which means the total time for these datasets is about 83 hours. It is noted that DWD radars have a good Z_{DR} good calibration through a long-term monitoring with the bird bath mode.

	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

❑ Variation of reflectivity bias estimation





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.

	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 right table*

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

The variation of bias estimate tends to be small for DWD radars. Although the highly inhomogeneous precipitation may increase the uncertainty of bias estimation. The negative effect, however, can be mitigated by using a large amount of data points for the statistics.

5. Conclusion

The analysis results of DWD radars show consistent bias estimates throughout the whole rain event, implying the proposed self-consistency method be robust. Although small number of data points might still give good bias estimate, data points >10000 per sweep are recommended for reliable results. Given the promising results from DWD radars, the propose reflectivity calibration method could be a useful tool for real-time data quality control in polarimetric weather radar.

Acknowledgment

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