Measurement Uncertainty and System Assessment for Weather Radar

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1. Introduction

A well-designed and constructed radar system is a premise to acquire high quality radar data. In practice, measurement precision and system stability are primary questions to be answered for an operational weather radar system. For weather radar, the measurement uncertainty can be discerned as the variation of radar moment estimates. Considering the random nature of the radar return from hydrometeors, the sampling effect is generally the major factor contributing to the statistical fluctuation of moment estimates. Here, this uncertainty is regarded as "sampling-induced uncertainty". On the other hand, the system hardware imperfectness such as noise and instability may cause the "system-induced uncertainty". The latter uncertainty, which has less dependence on the sampling configuration and has been less addressed in previous literatures, is of more importance for radar users to assess the quality of a radar system.

Recently, the Enterprise Electronics Corporation (EEC) has proposed a robust and easily implemented approach to quantify the measurement error of weather radar. The proposed method applies the point-mode scanning strategy, which helps to quantify the measurement error more accurately than popular texture analysis method. More importantly, the system-induced error can be isolated from the total measurement error. As a result, it is particularly helpful for assessing the overall quality of an operational weather radar system.

2. Measurement Uncertainty

The measurement uncertainty is usually characterized by the statistical fluctuation of radar moment estimates. Mathematically, the measurement uncertainty is quantified as a standard deviation (SD) of the estimates.

❑ Sampling-induced uncertainty

Based on the sampling theory of random hydrometeors, the sampling-induced uncertainty of six radar moments: reflectivity (Z), radial velocity (V), spectrum width (W), differential reflectivity (Z_{DR}), differential phase (Φ_{dp}), and cross-correlation coefficient (ρ_{hv}) are given in the following formulas.

$$SD(Z) = 3.24(\sigma_{vn}M)^{-0.5} \quad (1)$$

$$SD(V) = \frac{\lambda}{T}\left(\frac{\sigma_{vn}}{32\sqrt{\pi}M}\right)^{0.5} \quad (2)$$

$$SD(W) = \frac{\lambda}{T}\left(\frac{3\sigma_{vn}}{128\sqrt{\pi}M}\right)^{0.5} \quad (3)$$

$$SD(Z_{DR}) = 4.62\left(\frac{1-\rho_{hv}^2}{\sigma_{vn}M}\right)^{0.5} \quad (4)$$

$$SD(\Phi_{dp}) = 30.3\left(\frac{\rho_{hv}^{-2}-1}{\sigma_{vn}M}\right)^{0.5} \quad (5)$$

$$SD(\rho_{hv}) = 0.53\frac{1-\rho_{hv}^2}{(\sigma_{vn}M)^{0.5}} \quad (6)$$

where σ_{vn}=4W•T/λ is the normalized spectrum width; λ the radar wavelength (m); T the pulse repetition period (PRT, second); M the number of pulses; and W the Doppler spectrum width (m/s). Eqs. (1-3) are adapted from Doviak and Zrnic (1993) and Eqs. (4-6) are taken from Melnikov (2004). These formulas assume radar echoes having a high signal-to-noise-ratio (SNR) (e.g., >20dB).

Fig. 1 shows the theoretical sampling-induced errors of radar data sampled with a dwell time of 80 ms. It is seen that the errors crucially depend on the spectrum width of weather signal. The errors of polarimetric variables (the 2nd row) also rely on the magnitude of cross-correlation coefficient ρ_{hv}.

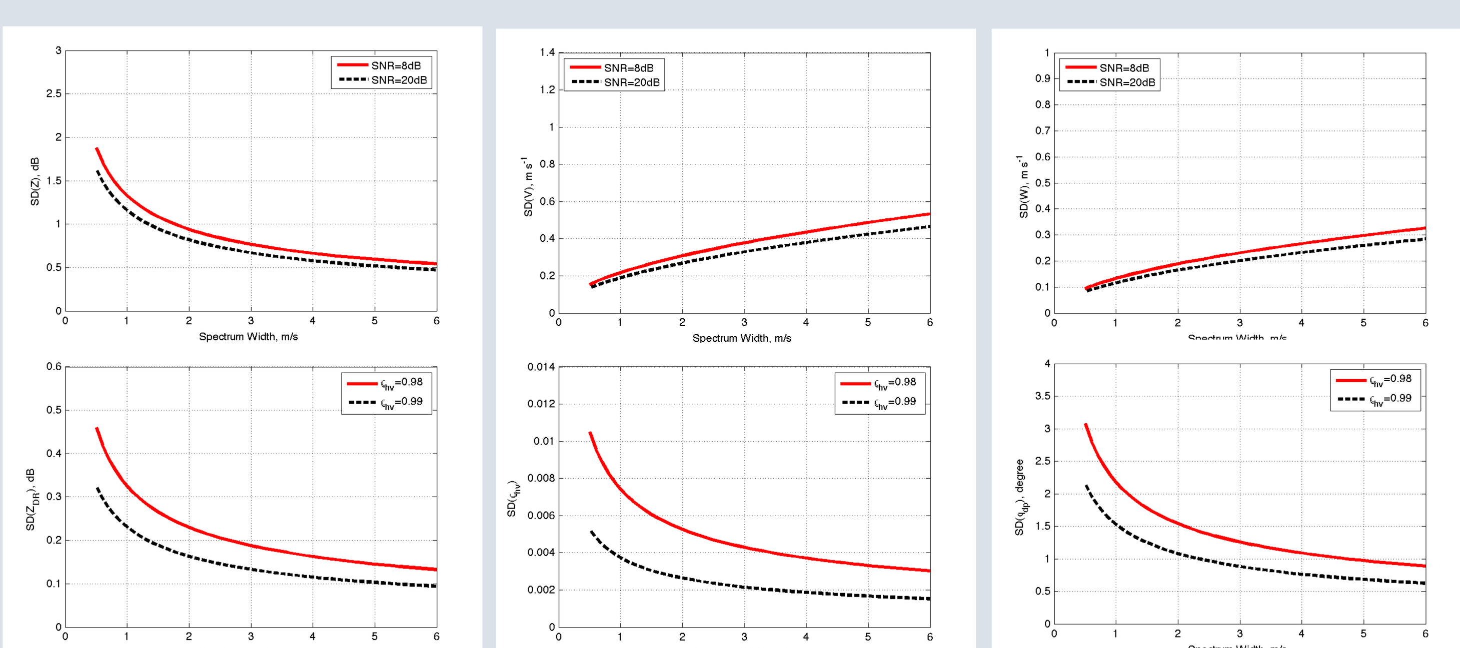

Figure 1. Example of C-band (5 cm) radar theoretical sampling-induced errors (SD values) for six moments: Z, V, W, Z_{DR}, Φ_{dp}, and ρ_{hv}. The dwell time is 100 ms (e.g., PRF=600Hz, sample number=60). Low SNRs (or ρ_{hv}) would enlarge the errors.

❑ System-induced uncertainty

The system-induced uncertainty (due to system noise, instability, and other system imperfectness) is one of major concerns in assessing the quality of radar system. However, it is usually hard to be quantified through the radar data because the sampling-induced error is ubiquitous. It is important to exclude the sampling-induced effect when quantify the system-induced uncertainty. The next section introduces a novel method to quantify the system-induced uncertainty for the purpose of radar system assessment

3. System Assessment

❑ Quantification of Measurement Error Using Point-Mode Data

The point-mode surveillance indicates that the radar data are collected with radar antenna pointing at one specific direction. It is reasonable to assume that the microphysics of precipitation in the same radial would keep the same within a very short time period (dwell time is only up to a couple of seconds). Therefore, the measurement error (standard deviation σ_x) can be quantified with two consecutive point-mode measurements (i.e., moment estimates), x_1 and x_2, by Eqs. (7-9).

$$x_1 = \langle x\rangle + \varepsilon_1; \quad x_2 = \langle x\rangle + \varepsilon_2 \quad (7)$$

$$\langle|x_1 - x_2|^2\rangle = \langle|\varepsilon_1 - \varepsilon_2|^2\rangle = 2\sigma_x^2 \quad (8)$$

$$\sigma_x = \sqrt{0.5\times\langle|x_1 - x_2|^2\rangle} \approx \sqrt{0.5\times\overline{|x_1 - x_2|^2}} \quad (9)$$

- *Eq. (7) assumes that the measurement consists of the truth and measurement error ε.*
- *Eq. (8) shows that the variance of (x_1-x_2) should be twice of the error variance.*
- *Eq. (9) gives the error estimate using data averaging by assuming the ergodic precipitation process.*

❑ Quantification of System-induced Error by Different Samplings

The measurement error estimated in Eq. (9) includes both system-induced and sampling-induced errors. The system-induced error can be isolated from the total error through removing the sampling-induced error with the following equations.

$$\sigma_{data1}^2 = \sigma_{system}^2 + \sigma_{sampling1}^2$$

$$\sigma_{data2}^2 = \sigma_{system}^2 + \sigma_{sampling2}^2 \quad (10)$$

$$m = \frac{\sigma_{sampling1}^2}{\sigma_{sampling2}^2} = \frac{M_2\times \mathrm{PRT}_2}{M_1\times \mathrm{PRT}_1} \quad (11)$$

$$\sigma_{system}^2 = (m\sigma_{data2}^2 - \sigma_{data1}^2)/(m-1) \quad (12)$$

- *Eq. (10) indicates that the two datasets have same system-induced error but different sampling-induced error.*
- *Eq. (11) gives the ratio of sampling-induced errors, which is inversely proportional to their dwell time ratio.*
- *Eq. (12) estimates the system-induced error by cancelling the sampling-induced error.*

❑ Data Collection and Processing

From Eqs. (7-12), quantification of system-induced error requires at least two consecutive point-mode measurements with the same sampling configuration and two set of such datasets with different sampling configurations.

The case study has used the data collected by the German Meteorological Service (DWD)'s C-band polarimetric weather radar (MHP). Two different sampling settings as follows were used.

Setting one:
- *PRF:* *800Hz*
- *Pulse number:* *39*
- *Gate width:* *25 m*
- *Gate number:* *4800*

Setting two:
- *PRF:* *300Hz*
- *Pulse number:* *255*
- *Gate width:* *25 m*
- *Gate number:* *4800*

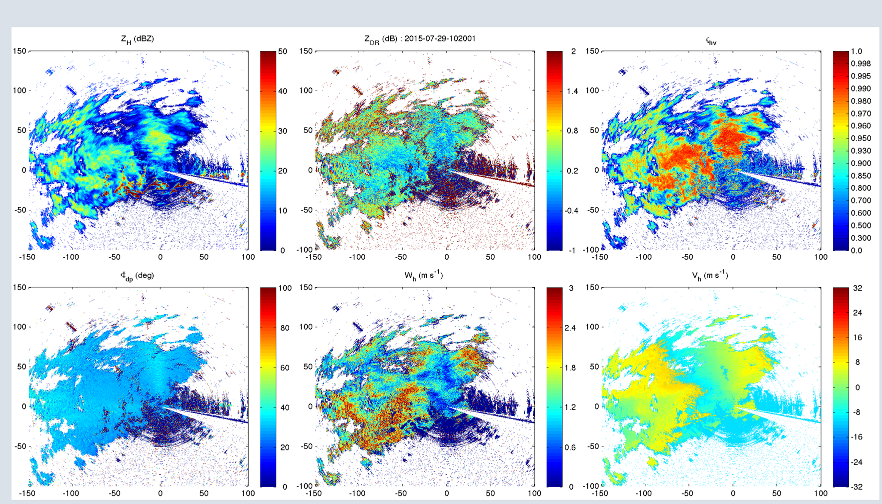

Figure 2. PPI images of Z_H, Z_{DR}, ρ_{hv}, Φ_{dp}, W_h, and V_h raw data collected by DWD's C-band MHP radar using the setting one (10:20:01UTC, 29 July 2015).

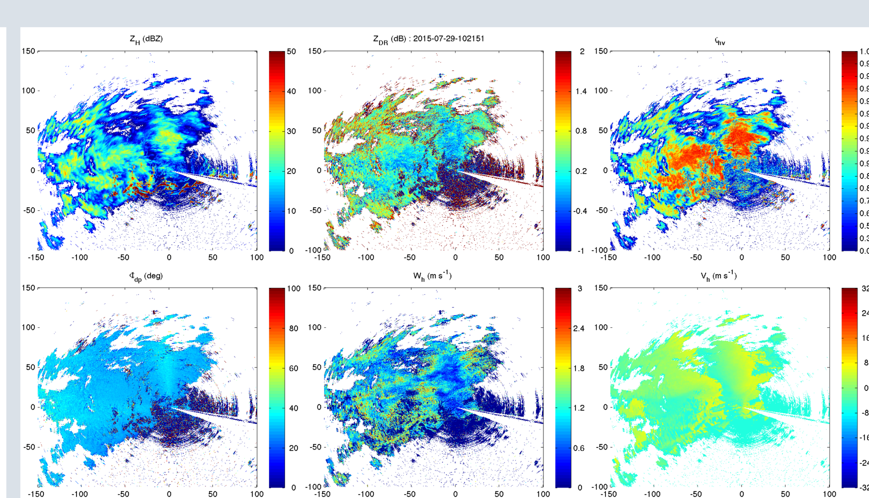

Figure 3. Same as Fig. 2 except for using the setting two (10:21:51UTC, 29 July 2015). The velocity-aliasing is clearly seen but the data quality of all the moments looks better.

4. Result Analysis

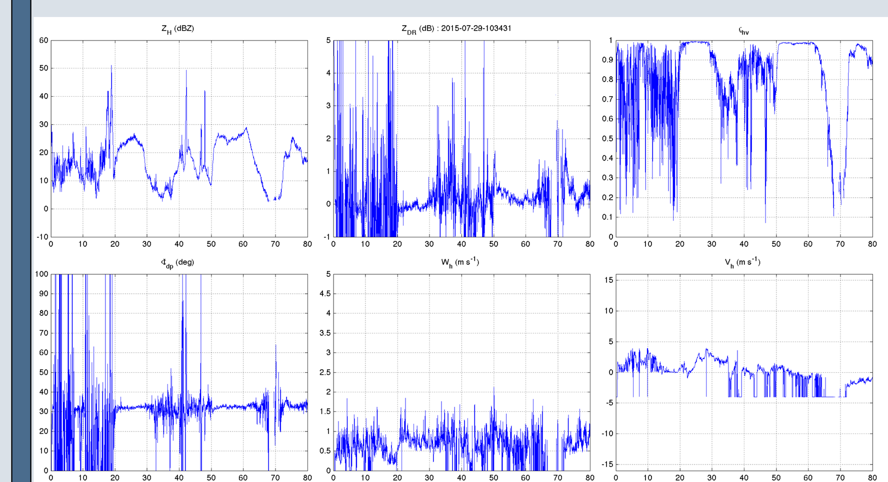

Figure 4. A-scope of point-mode raw data (Z_H, Z_{DR}, ρ_{hv}, Φ_{dp}, W_h, and V_h) collected by C-band MHP radar using the setting one (10:34:31UTC, 29 July 2015). These images show quite noisy moments in precipitation region (with high ρ_{hv}) due to the short dwell time (=0.05 s) data sampling.

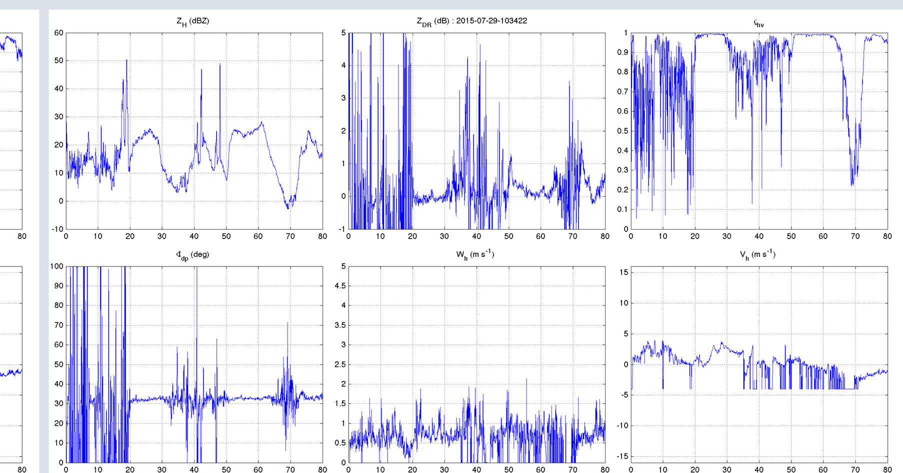

Figure 5. The same as Fig. 4 except for using the setting two (10:34:22UTC, 29 July 2015). As compared to Fig. 4, the noisiness of moments have been much reduced. The ρ_{hv} data also tend to be slightly higher, implying the better data quality, which is due to a long dwell time (0.85 s) data sampling.

The following filtering criteria are utilized to find continuous precipitation region with high SNR weather data and less contamination.

- SNR>20 dB
- ρ_{hv}>0.98
- Texture of ρ_{hv} >0.05

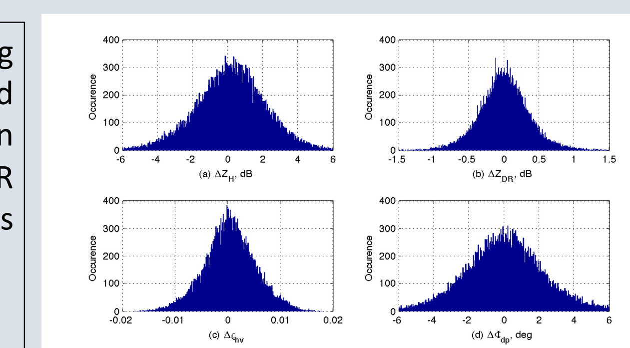

Figure 6. The histogram of the moment differences between two consecutive rays: (a) ΔZ_H, (b) ΔZ_{DR}, (c) $\Delta\rho_{hv}$, and (d) $\Delta\Phi_{dp}$. The data were collected with setting one and limited by 0.1<*W*<2 m/s. The histograms show a large variation of sample difference.

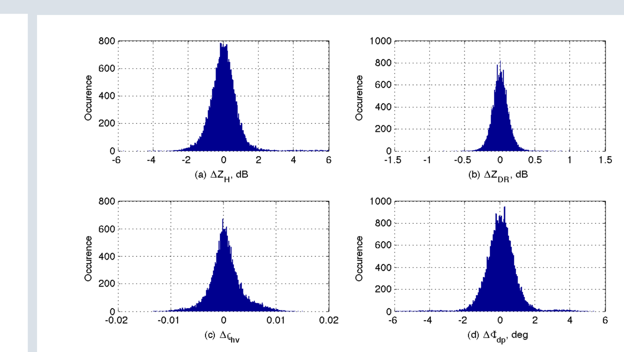

Figure 7. The same as Fig. 6 except for the setting two. It is shown that the variation of sample difference has been effectively reduced with longer dwell time data sampling.

- The sampling-induced error may have the major effect on radar data quality because operational radar generally uses a short dwell time data sampling.
- The system-induced error is small in MHP radar.
- The system-induced error is less affected by the sampling effect.
- The system-induced error is less affected by the physical property of weather signal.

Table: Statistics of SD values for four radar moments (event 07/29/2015)

Datasets	Criteria for Data Filtering	SD(Z_H)	SD(Z_{DR})	SD(ρ_{hv})	SD(Φ_{dp})	Data Points
Setting One (pulse_number=39, PRF=800Hz)	ρ_{hv}>0.98 & 0.5>W>0.1 m/s	1.673	0.310	0.0036	2.050	7140
	ρ_{hv}>0.98 & 1>W>0.5 m/s	1.550	0.273	0.0036	1.867	23496
	ρ_{hv}>0.98 & 1.5>W>1 m/s	1.366	0.229	0.0033	1.545	22123
	ρ_{hv}>0.98 & 2>W>1.5 m/s	1.185	0.184	0.0030	1.228	15269
Setting Two (pulse_number=255, PRF=300Hz)	ρ_{hv}>0.98 & 0.5>W>0.1 m/s	0.726	0.086	0.0022	0.588	5080
	ρ_{hv}>0.98 & 1>W>0.5 m/s	0.691	0.074	0.0020	0.572	18629
	ρ_{hv}>0.98 & 1.5>W>1 m/s	0.501	0.068	0.0020	0.525	5515
	ρ_{hv}>0.98 & 2>W>1.5 m/s	0.375	0.062	0.0021	0.431	582
Estimated System Error	ρ_{hv}>0.98 & 0.5>W>0.1 m/s	0.6232	0.0443	0.0021	0.3330	
	ρ_{hv}>0.98 & 1>W>0.5 m/s	0.6002	0.0366	0.0019	0.3671	
	ρ_{hv}>0.98 & 1.5>W>1 m/s	0.3906	0.0415	0.0019	0.3837	
	ρ_{hv}>0.98 & 2>W>1.5 m/s	0.2516	0.0454	0.0020	0.3250	
Mean System Error		**0.4664**	**0.0419**	**0.0020**	**0.3522**	

5. Conclusion

This study investigates the measurement uncertainty of weather radar, which can be ascribed to two types: sampling-induced and system-induced. A novel method, which is based on the processing/analysis of weather data collected in radar surveillance with the point-mode, is proposed to isolate the system-induced error from the total measurement error. The proposed method can be used as an effective tool for the system assessment of weather radars.

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