Should interpolation of reflectivity be performed in Z or dBZ?



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Results Interpretation Summary • The relative accuracy of performing linear interpolation of radar • We can understand our results by examining the curvature of the Results computed over all triads (Table 2) are consistent with those reflectivity in units of Z and dBZ is assessed of Lakshmanan (2012) reflectivity field in Z and dBZ• Interpolating in dBZ produces smaller errors overall; however, at • For the central bin of each triad, we compute the normalised For all radars and coordinate directions, interpolating in dBZ gives high reflectivities interpolating in Z is better, particularly when the lower mean absolute error (MAE) distance, δ , and normalised reflectivity, ζ , in Z and dBZ: reflectivity difference is large Bias is positive for interpolation in Z and negative for interpolation $\delta = \frac{\chi_i - \chi_{i-1}}{2}$ $\chi_{i+1} - \chi_{i-1}$ • A simple blending of interpolation in Z and dBZ produces small in dBZerrors across the full range of reflectivities considered $\zeta_Z = \frac{Z_i - Z_{i-1}}{Z_{i+1} - Z_{i-1}}$ Errors for heta are larger than those for ϕ which in turn are larger than

Introduction

- those for r; this is due to the large distances involved when interpolating in the azimuth and elevation directions at long range
- On average, interpolating in dBZ is better for around 55 % of triads
- Spatial interpolation of radar reflectivities is commonly required when remapping data from its native spherical coordinates to a Cartesian or latitude–longitude grid (e.g. Zhang et al. 2005) or estimating echo top heights (Lakshmanan et al. 2013)
- It is often argued that this processing should be performed in the measurement units, Z (mm⁶ m⁻³), rather than dBZ
- However, for linear interpolation, the better quantity to operate on is whichever varies more linearly in space
- Using a simple analysis method applied to reflectivity data from a single WSR-88D site, Lakshmanan (2012) showed that interpolation in dBZ produces consistently smaller errors
- Here, we extend Lakshmanan's analysis to examine in detail the dependence of interpolation errors on reflectivity, reflectivity difference, interpolation direction, and geographic location

Data and Methodology

- We use data for one year (2011) from three operational radars in Australia, covering diverse rainfall regimes (Table 1)
- Days with precipitation in the vicinity of each site were identified using gridded rain gauge data
- To reduce computational expense, only eight radar scans were used per day: those closest to 00, 03, 06, 09, 12, 15, 18, and 21 UTC

Table 1. Details of the three radars used in this study. Climates are defined using the Köppen–Geiger classification system. Symbols have the following meaning: ω = angular beam width, r_{max} = maximum range, Δr = range gate spacing, $\Delta \phi$ = angular beam spacing.

Location $\Delta \phi$ Tilts Band Δr r_{max} ω

Table 2. Summary of interpolation errors computed across all triads for each radar and coordinate direction. The bias and mean absolute error (MAE) are given in dB. The last column shows the percentage of triads for which interpolation in dBZ produces a smaller absolute error.

Radar	Dir.	No. triads	Inte	r p. <i>Z</i>	Interp	% dBZ		
			Bias	ΜΑΕ	Bias	MAE	better	
Brisbane	r	1.9 x 10 ⁷	0.8	1.3	-0.3	1.2	54.5	
	ϕ	2.3 x 10 ⁷	1.3	1.8	-0.6	1.6	54.0	
	θ	2.0 x 10 ⁷	2.2	2.7	-0.8	2.3	55.7	
Darwin	r	3.7 x 10 ⁷	0.9	1.3	-0.2	1.2	55.0	
	ϕ	4.2 x 10 ⁷	1.4	1.9	-0.4	1.6	55.9	
	θ	2.9 x 10 ⁷	2.1	2.6	-0.6	2.1	56.8	
Melbourne	r	2.5 x 10 ⁷	0.8	1.3	-0.2	1.2	54.4	
	ϕ	3.2 x 10 ⁷	1.2	1.8	-0.5	1.5	54.9	
	θ	2.7 x 10 ⁷	2.4	2.9	-0.9	2.4	55.6	

- When the results are broken down according to the central bin reflectivity and the absolute reflectivity difference between the two outer bins, ΔdBZ , a different picture emerges (Fig. 2)
- As we would expect, errors increase with increasing ΔdBZ , but not uniformly across the range of reflectivities
- Interpolation in Z produces positive biases which decrease with increasing reflectivity
- Interpolation in dBZ produces negative biases which increase with increasing reflectivity
- Overall, interpolation in dBZ is better at low reflectivities (< 20 dBZ) and interpolation in Z is better at high reflectivities (> 40 dBZ),

• We then bin the triads by reflectivity and reflectivity difference, average the values in each bin, and plot ζ_Z and ζ_{dBZ} versus δ (Fig. 3)

 $dBZ_i - dBZ_i$



Figure 3. Illustration of the curvature of the reflectivity field in Z and dBZ as a function of the central bin reflectivity and the absolute reflectivity difference between the two outer bins. In each of the 25 panels, the normalised reflectivity, ζ , is plotted as a function of normalised distance, δ , with both variables on a scale of 0–1. The bottom-left and top-right corners thus correspond to the first and last bin in each triad, respectively. Blue and red dots show the central bin values in Z and dBZ, respectively, with the associated coloured lines indicating the curvature in those units. The black dot which lies on a straight line connecting the bottom-left and top-right corners (dotted) shows the result of linear interpolation. When the black dot lies *above* the blue/red dot it indicates that interpolation in Z/dBZ will produce an *overestimate*. When the black dot lies below the blue/red dot it indicates that interpolation in Z/dBZ will produce an underestimate. The distance between the black and coloured dots measures the normalised interpolation error, $\varepsilon/\Delta dBZ$. Values shown here are for azimuth triads from the Brisbane radar.

(Climate)			(km)	(m)	(°)	
Brisbane (Humid Subtropical)	S	1.0	150	250	1.0	14: 0.5–32.0°
Darwin (Tropical Savannah)	С	1.0	150	250	1.0	15: 0.5–43.1°
Melbourne (Temperate Oceanic)	S	1.0	150	250	1.0	14: 0.5–32.0°

- Triads (sets of three neighbouring bins) with monotonically increasing or decreasing reflectivity were identified in the three coordinate directions: range, azimuth, and elevation (Fig. 1)
- The three reflectivity values were stored together with the distances (in metres or degrees) between the central and two outer bins
- The true reflectivity at the central bin, dBZ_i , was then compared with estimates found by linearly interpolating between the two neighbouring bins, dBZ_{i+1} , in both Z and dBZ

• The error associated with linearly interpolating in Z is

$$\varepsilon_Z = 10 \log_{10} \left[w \ 10^{\text{dB}Z_{i-1}/10} + (1-w) \ 10^{\text{dB}Z_{i+1}/10} \right] - \text{dB}Z_i$$

• The error associated with linearly interpolating in dBZ is

$$\varepsilon_{\mathrm{dB}Z} = w \ \mathrm{dB}Z_{i-1} + (1-w) \ \mathrm{dB}Z_{i+1} - \mathrm{dB}Z_i$$

• Here, w is the interpolation weight given by

$$w_{\chi} = \frac{\chi_{i+1} - \chi_i}{\chi_{i+1} - \chi_{i-1}} = \frac{\Delta \chi_2}{\Delta \chi_1 + \Delta \chi_2}$$

- where $\chi = r, \phi$, and θ for triads in the range, azimuth, and elevation directions, respectively
- Range gate and azimuthal spacing are fixed so $w_r = w_{\phi} = 0.5$; however, since tilts are unevenly spaced, w_{θ} varies

- consistent with Mohr and Vaughan (1979)
- Virtually identical patterns are seen for the other coordinate directions and radars (not shown)
- Low reflectivities occur much more frequently and therefore dominate the results for all triads

	25	(a)			Sa	mpl	e S	ize				25	(b)	F	Perc	ent	age	dB	ΖB	ette	r	
	20	773	769	709	650	579	480	357	200	75	22	25	70	55	49	44	41	35	27	18	16	
	~~~	780	777	730	637	585	493	367	221	104	25	20	63	54	49	47	43	39	30	20	20	
(dB)	20	780	779	756	664	598	495	386	242	108	25	20	59	54	51	48	45	41	34	23	19	29
ence	15	780	779	756	704	603	492	402	264	116	38	15	58	55	52	50	47	43	36	27	23	17
iffere	15	780	780	769	700	600	504	405	281	124	39	15	57	55	53	51	49	45	40	30	26	26
ity D	10	780	779	772	725	580	496	400	277	122	42	10	57	56	54	52	49	46	41	34	29	29
ectiv	10	780	780	770	634	574	494	386	259	130	40	10	56	56	<b>5</b> 4 <b>+</b>	52	50	46	43	37	32	35
Refl	5	780	780	770	657	552	480	371	250	120	42	5	55	55	54	52	50	47	45	41	36	37
	5	780	778	750	630	526	447	347	230	111	36	5	54	54	53	52	51	48	47	47	42	43
	0	780	772	651	537	462	375	274	170	74	22	0	52	52	52	52	51	50	49	50	47	48
	1	0	2	0	3 Rofi	0 Activ	4 vitv (c	0 187)	5	0	6	0 1	0	2	0	3 Rofl	0 Activ	4 itv (c	0 1BZ)	5	0	6
																- <b>NE</b>						
	1				neii		ity (C	102)												_		
		1	10	10	nen	10 ³	10	4 1	0 ⁵	10 ⁶			25	5 30	35	40 4	45 5	0 55	5 60	65	70 7	75
		1 (C)	10	10	) ²	10 ³	10 ⁴ s: Z	⁴ 1	0 ⁵	10 ⁶			(d)	5 30	35	40 4	45 5	0 55	5 60 Z	65	70 7	75
	25	1 (C) 7.1	10	10	4.3	10 ³ Bia:	10 ⁴ s: Z	⁴ 1 2.6	0 ⁵	10 ⁶		25	25 (d)	5 30	35	40 4 B	45 5 ias: -4.9	0 55 dB –5.5	5 60 Z -6.3	65	70 7	75
	25	1 (C) 7.1 5.7	10 5.6 4.8	10 4.9 4.3	4.3 4.0	10 ³ Bia: 3.9	10 ⁴ s: Z 3.3	⁴ 1 2.6 2.3	0 ⁵ 1.8 1.5	10 ⁶ 1.5 1.3		25	(d) -1.7 -1.9	5 30 -3.3 -2.8	35 -4.0 -3.3	40 4 B -4.5 -3.6	45 5 ias: -4.9	0 55 dB -5.5 -4.5	5 60 Z -6.3	65 -7.1 -6.1	70 7 -7.4 -6.3	75
dB)	25 20	(C) 7.1 5.7 4.6	10 5.6 4.8 4.1	10 4.9 4.3 3.8	4.3 4.0 3.5	10 ³ Bia: 3.9 3.6 3.2	10 ⁴ 3.3 3.1 2.8	⁴ 1 2.6 2.3 2.1	0 ⁵ 1.8 1.5 1.3	10 ⁶ 1.5 1.3 1.0	1.5	25 20	25 (d) -1.7 -1.9 -1.8	-3.3 -2.8 -2.3	35 -4.0 -3.3 -2.6	40 4 B -4.5 -3.6 -2.9	45 5 ias: -4.9 -4.0	0 55 dB -5.5 -4.5 -3.6	5 60 Z -6.3 -5.3	65 -7.1 -6.1 -5.1	70 -7.4 -6.3 -5.4	-4.9
nce (dB)	25	(C) 7.1 5.7 4.6 3.7	10 5.6 4.8 4.1 3.4	10 4.9 4.3 3.8 3.2	4.3 4.0 3.5 3.0	10 ³ Bia: 3.9 3.6 3.2 2.8	10 ⁴ s: Z 3.3 3.1 2.8 2.4	⁴ 1 2.6 2.3 2.1 1.8	0 ⁵ 1.8 1.5 1.3 1.2	10 ⁶ 1.5 1.3 1.0 0.8	1.5	25 20	(d) -1.7 -1.9 -1.8 -1.5	-3.3 -2.8 -2.3 -1.7	35 -4.0 -3.3 -2.6 -2.0	40 4 B -4.5 -3.6 -2.9 -2.2	45 5 ias: -4.9 -4.0 -3.2 -2.4	0 55 dB -5.5 -4.5 -3.6 -2.8	5 60 Z -6.3 -5.3 -4.3 -3.3	65 -7.1 -6.1 -5.1	70 -7.4 -6.3 -5.4 -4.4	-4.9 -4.7
ference (dB)	25 20 15	(C) 7.1 5.7 4.6 3.7 3.0	10 5.6 4.8 4.1 3.4 2.8	10 4.9 4.3 3.8 3.2 2.6	4.3 4.0 3.5 3.0 2.5	Bia: 3.9 3.6 3.2 2.8 2.2	10 ⁴ s: Z 3.3 3.1 2.8 2.4 2.0	⁴ 1 2.6 2.3 2.1 1.8 1.5	0 ⁵ 1.8 1.5 1.3 1.2 0.9	10 ⁶ 1.5 1.3 1.0 0.8 0.7	1.5 0.5 0.7	25 20 15	<pre>25 (d) -1.7 -1.9 -1.8 -1.5 -1.1</pre>	-3.3 -2.8 -2.3 -1.7 -1.2	35 -4.0 -3.3 -2.6 -2.0 -1.4	40 4 B -4.5 -3.6 -2.9 -2.2 -1.5	45 5 ias: -4.9 -4.0 -3.2 -2.4 -1.8	0 55 dB -5.5 -4.5 -3.6 -2.8 -2.1	5 60 Z -6.3 -5.3 -4.3 -3.3 -2.5	65 -7.1 -6.1 -5.1 -4.0 -3.1	70 7 -7.4 -6.3 -5.4 -4.4 -3.3	-4.9 -4.7 -3.3
ty Difference (dB)	25 20 15	(C) 7.1 5.7 4.6 3.7 3.0 2.2	10 5.6 4.8 4.1 3.4 2.8 2.1	10 4.9 4.3 3.8 3.2 2.6 2.0	4.3 4.0 3.5 3.0 2.5 1.9	Bia: 3.9 3.6 3.2 2.8 2.2 1.7	10 ⁴ s: Z 3.3 3.1 2.8 2.4 2.0 1.5	⁴ 1 2.6 2.3 2.1 1.8 1.5 1.2	0 ⁵ 1.8 1.5 1.3 1.2 0.9 0.8	10 ⁶ 1.5 1.3 1.0 0.8 0.7 0.5	1.5 0.5 0.7 0.5	25 20 15	25 (d) -1.7 -1.9 -1.8 -1.5 -1.1 -0.7	-3.3 -2.8 -2.3 -1.7 -1.2 -0.8	35 -4.0 -3.3 -2.6 -2.0 -1.4 -0.9	40 4 B -4.5 -3.6 -2.9 -2.2 -1.5 -1.0	45 5 ias: -4.9 -4.0 -3.2 -2.4 -1.8 -1.2	-5.5 -4.5 -2.8 -2.1 -1.4	5 60 5 60 Z -6.3 -5.3 -4.3 -3.3 -2.5 -1.7	65 -7.1 -6.1 -5.1 -4.0 -3.1	70 7 -7.4 -6.3 -5.4 -4.4 -3.3	-4.9 -4.7 -3.3 -2.4
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Reflectivity Difference (dB)	25 20 15 10 5	(C) 7.1 5.7 4.6 3.7 3.0 2.2 1.5 0.9 0.4	10 5.6 4.8 4.1 3.4 2.8 2.1 1.5 0.9 0.4	10 4.9 4.3 3.8 3.2 2.6 2.0 1.4 0.8 0.3	4.3 4.0 3.5 3.0 2.5 1.9 1.3 0.7 0.3	<ul> <li>Line</li> <li>Line<td>10⁴ 3.3 3.1 2.8 2.4 2.0 1.5 1.0 0.5 0.2</td><td>⁴ 1 2.6 2.3 2.1 1.8 1.5 1.2 0.8 0.5 0.2</td><td>0⁵ 1.8 1.5 1.3 1.2 0.9 0.8 0.6 0.3 0.2</td><td>10⁶ 1.5 1.3 1.0 0.8 0.7 0.5 0.3 0.1 0.1</td><td>1.5 0.5 0.7 0.4 0.2 0.1</td><td>25 20 15 10 5</td><td>25 (d) -1.7 -1.9 -1.8 -1.5 -1.1 -0.7 -0.4 -0.2 -0.0</td><td>-3.3 -2.8 -2.3 -1.7 -1.2 -0.8 -0.4 -0.2 -0.0</td><td>35 -4.0 -3.3 -2.6 -2.0 -1.4 -0.9 -0.5 -0.2 -0.2 -0.1</td><td>40 4 B -4.5 -3.6 -2.9 -2.2 -1.5 -1.0 -0.6 -0.3 -0.1</td><td>45 5 ias: -4.9 -4.0 -3.2 -2.4 -1.8 -1.2 -0.7 -0.3 -0.1</td><td>-5.5 -4.5 -3.6 -2.8 -2.1 -1.4 -0.9 -0.5 -0.2</td><td><ul> <li>102)</li> <li>102)<td>65 -7.1 -6.1 -5.1 -4.0 -3.1 -2.1 -1.3 -0.7 -0.2</td><td>70 7 -7.4 -6.3 -5.4 -4.4 -3.3 -2.4 -1.6 -0.9 -0.3</td><td>-4.9 -4.7 -3.3 -2.4 -1.5 -0.8 -0.3</td></li></ul></td></li></ul>	10 ⁴ 3.3 3.1 2.8 2.4 2.0 1.5 1.0 0.5 0.2	⁴ 1 2.6 2.3 2.1 1.8 1.5 1.2 0.8 0.5 0.2	0 ⁵ 1.8 1.5 1.3 1.2 0.9 0.8 0.6 0.3 0.2	10 ⁶ 1.5 1.3 1.0 0.8 0.7 0.5 0.3 0.1 0.1	1.5 0.5 0.7 0.4 0.2 0.1	25 20 15 10 5	25 (d) -1.7 -1.9 -1.8 -1.5 -1.1 -0.7 -0.4 -0.2 -0.0	-3.3 -2.8 -2.3 -1.7 -1.2 -0.8 -0.4 -0.2 -0.0	35 -4.0 -3.3 -2.6 -2.0 -1.4 -0.9 -0.5 -0.2 -0.2 -0.1	40 4 B -4.5 -3.6 -2.9 -2.2 -1.5 -1.0 -0.6 -0.3 -0.1	45 5 ias: -4.9 -4.0 -3.2 -2.4 -1.8 -1.2 -0.7 -0.3 -0.1	-5.5 -4.5 -3.6 -2.8 -2.1 -1.4 -0.9 -0.5 -0.2	<ul> <li>102)</li> <li>102)<td>65 -7.1 -6.1 -5.1 -4.0 -3.1 -2.1 -1.3 -0.7 -0.2</td><td>70 7 -7.4 -6.3 -5.4 -4.4 -3.3 -2.4 -1.6 -0.9 -0.3</td><td>-4.9 -4.7 -3.3 -2.4 -1.5 -0.8 -0.3</td></li></ul>	65 -7.1 -6.1 -5.1 -4.0 -3.1 -2.1 -1.3 -0.7 -0.2	70 7 -7.4 -6.3 -5.4 -4.4 -3.3 -2.4 -1.6 -0.9 -0.3	-4.9 -4.7 -3.3 -2.4 -1.5 -0.8 -0.3

- For low dBZ_i, reflectivity has positive curvature in Z and near-zero curvature in dBZ; thus, interpolation in Z produces an overestimate while interpolation in dBZ is quite accurate
- For high  $dBZ_i$ , reflectivity has negative curvature in dBZ and nearzero curvature in Z; thus, interpolation in dBZ produces an underestimate while interpolation in Z is quite accurate
- In general, curvature increases with increasing  $\Delta dBZ$ , so the normalised interpolation error ( $\varepsilon/\Delta dBZ$ ) also increases

## **Blended Interpolation**

- Based on Fig. 3, we propose a weighted average of the interpolation estimates in Z and dBZ, with the weight a function of reflectivity
- For this new method, the interpolation error is

 $\varepsilon_{\text{new}} = W \varepsilon_Z + (1 - W) \varepsilon_{\text{dBZ}}$ 

where W increases from 0 at 10 dBZ to 1 at 60 dBZ

- This method was tested using both the Z- and dBZ-based estimates for  $dBZ_i$  to calculate W, but the former gave better results
- The new method produces more accurate results with bias and MAE values generally less than  $\pm 1$  dB and 4 dB, respectively (Fig. 4)
- Future work could investigate more sophisticated interpolation methods as an alternative to this simple blending





Figure 1. Schematic illustrating the identification of triads in the (a) range, (b) azimuth, and (c) elevation directions. Panels (a) and (c) show a side view while panel (b) shows a plan view.



Figure 2. Interpolation results for azimuth triads from the Brisbane radar expressed as a function of the central bin reflectivity and the absolute reflectivity difference between the two outer bins. Variables shown are (a) sample size, (b) percentage of triads where interpolation in dBZ produces a smaller absolute error, bias (dB) for interpolation in (c) Z and (d) dBZ, and mean absolute error (MAE; dB) for interpolation in (e) Z and (f) dBZ. Crosses indicate the mean reflectivity and reflectivity difference.

Figure 4. Blended interpolation results for azimuth triads from the Brisbane radar expressed as a function of the central bin reflectivity and the absolute reflectivity difference between the two outer bins. Variables shown are (a) bias (dB) and (b) mean absolute error (MAE; dB). Crosses indicate the mean reflectivity and reflectivity difference.

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