Development and validation of the R(A) algorithm for rainfall estimation

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A recently introduced algorithm for rainfall estimation based on specific attenuation A has already demonstrated efficient and robust performance at S, C, and X bands in different parts of the world

Ryzhkov, A., M. Diederich, P. Zhang, and C. Simmer, 2014: Utilization of specific attenuation for rainfall estimation, mitigation of partial beam blockage, and radar networking. *J. Atmos. Oceanic Technol.,* **31**, 599 – 619.

Wang, Y., P. Zhang, A. Ryzhkov, J. Zhang, and P.-L. Chang, 2014: The application of specific attenuation for tropical rainfall estimation in complex terrain. *J. Hydrometeorol.,* **15**, 2250 – 2266.

Boodoo, S., D. Hudak, A. Ryzhkov, P. Zhang, N. Donaldson, D. Sills, and J. Reid, 2015: Quantitative precipitation estimation from a C-Band Dual-polarized radar for the July 08 2013 flood in Toronto, Canada. *J. Hydrometeorology*, **16**, 2027 – 2044.

Diederich, M., S. Troemel, A. Ryzhkov, P. Zhang, and C. Simmer, 2015: Use of specific attenuation for rainfall measurements at X-band radar wavelengths. Part I: Radar calibration and partial beam blockage estimation. *J. Hydrometeorology,* **16**, 487 - 502.

Diederich, M., S. Troemel, A. Ryzhkov, P. Zhang, and C. Simmer, 2015: Use of specific attenuation for rainfall measurements at X-band radar wavelengths. Part II: Rainfall estimates and comparison with rain gauges. *J. Hydrometeorology,* **16**, 503 - 516

How to estimate A?

$$A(r) = \frac{[Z_a(r)]^b C(b, PIA)}{I(r_1, r_2) + C(b, PIA) I(r, r_2)}$$

$$I(r_1, r_2) = 0.46b \int_{r_1}^{r_2} [Z_a(s)]^b ds$$

$$C(b, PIA) = \exp(0.23bPIA) - 1$$

$$I(r, r_2) = 0.46b \int_{r}^{r_2} [Z_a(s)]^b ds$$

$$A = aZ^b$$

Z_a (r) is radial profile of attenuated (and possibly biased) reflectivity

PIA is two-way path-integrated attenuation

In this formulation, the A(r) estimate is immune to the Z_a biases caused by radar miscalibration, partial beam blockage, and wet radome

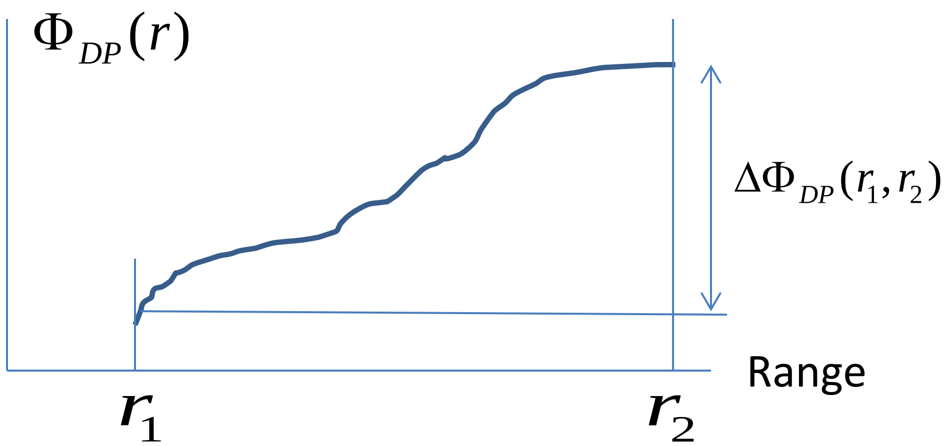
How to measure PIA?

PIA is estimated using total differential phase shift along the propagation path

$$PIA = \alpha \Delta\Phi_{DP}(r_1, r_2) \qquad \alpha = A / K_{DP}$$

$$R(A) = \gamma A^d$$

Factors α and γ generally depend on radar wavelength, temperature, and rain type

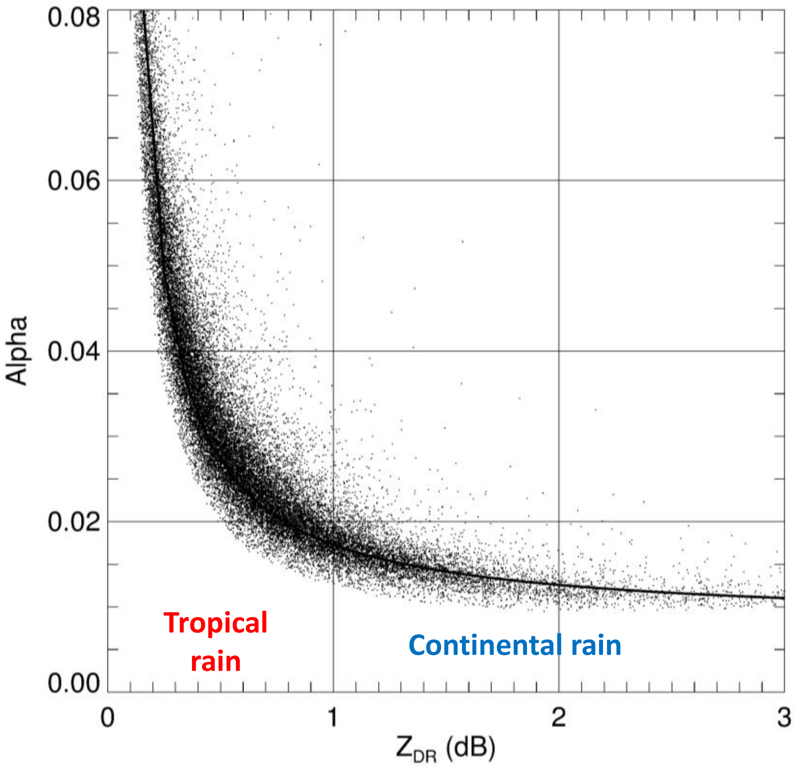


Reliable estimation of the radial profile of A is possible for $\Delta\Phi_{DP}$ as low as 1 - 3°

Impact of rain type on the R(A) performance

Dependence of α on Z_{DR}

S band, T = 20°C

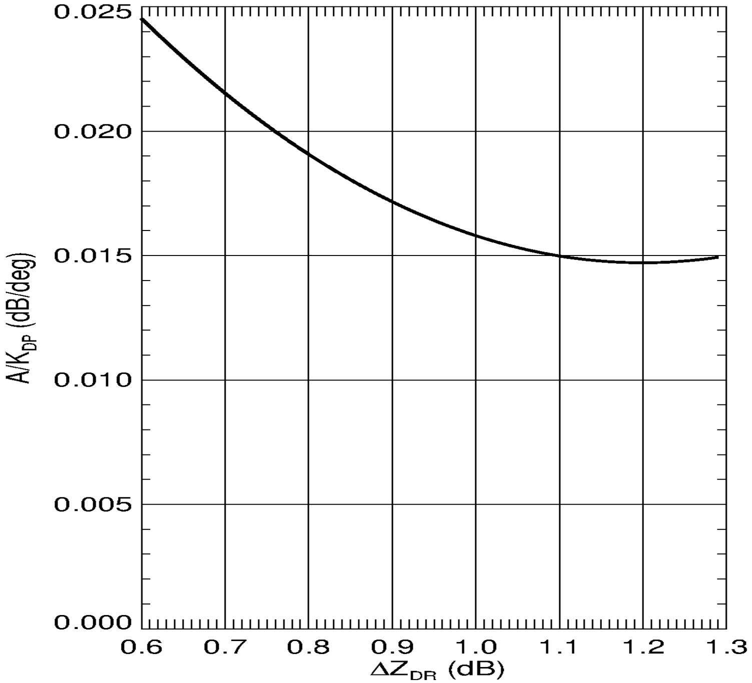


$$\alpha(dB/\deg) = A/K_{DP} = 0.008 + \frac{0.009}{Z_{DR}(dB) - 0.03}$$

Optimization of the factor α using the Z_{DR} slope

Z_{DR} slope = ΔZ_{DR} = <$Z_{DR}(40)$> – <$Z_{DR}(20)$>

S band



Default factor α at S band

$$\alpha = 0.015\, dB/\deg$$

$$\alpha = 0.0540 - 0.0655\Delta Z_{DR} + 0.0273(\Delta Z_{DR})^2$$

Three versions of the R(A) algorithm are being tested

For all three versions, the standard R(A) relation $R = 4120\ A^{1.03}$ is used in rain, and the standard $R(K_{DP})$ relation $R = 44\ K_{DP}^{0.802}$ is utilized in rain / hail mixture

Version 1. The parameter α is fixed and equal to the default value 0.015 dB/deg typical for continental rain

Version 2. The parameter α is variable as a function of time

Version 3. The parameter α has different values in convective and stratiform rain and varies with time

The value of α is optimized based on the Z_{DR} slope

Validation of rainfall estimation at S band

Summary of the R(A) algorithm performance for notable flash flood events during 2010 - 2013

Versions 1 and 2

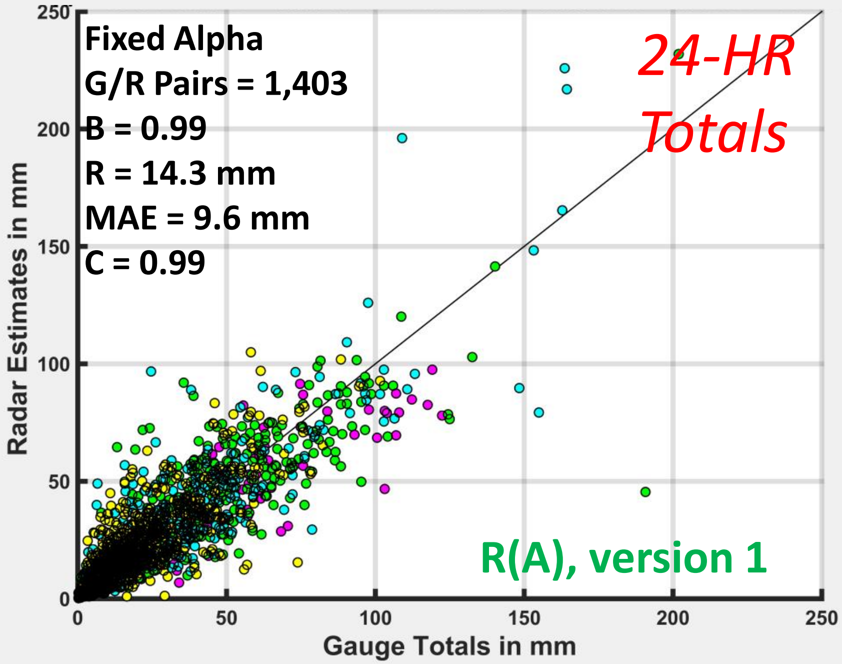
	Date	Storm	Radar	Duration, hr	$\alpha = A/K_{DP}$, dB/deg	Bias ratio R/G
1.	14 June 2010	OKC flash flood	KTLX	3	0.015	1.08
2.	20 May 2011	MCS in Oklahoma	KVNX	6	0.015	0.96
3.	26 – 28 August 2011	Hurricane Irene	KMHX	45	0.015 / adaptive	0.53/**1.16**
4.	30 – 31 May 2012	Severe hailstorm	KICT	6	0.015	0.98
5.	30 June 2012	Duluth flash flood	KDLX	24	0.015	1.09
6.	28 – 29 October 2012	Hurricane Sandy	KDOX	24	0.015 / adaptive	0.81/**0.95**
7.	4 -5 July 2013	Nashville flash flood	KOHX	12	0.015 / adaptive	0.86/**1.01**
8.	11 – 12 September 2013	Boulder flash flood	KFTG	24	0.015 / adaptive	0.43/**0.96**
9.	26 November 2013	Florida	KJAX	24	0.015 / adaptive	0.47/**0.93**

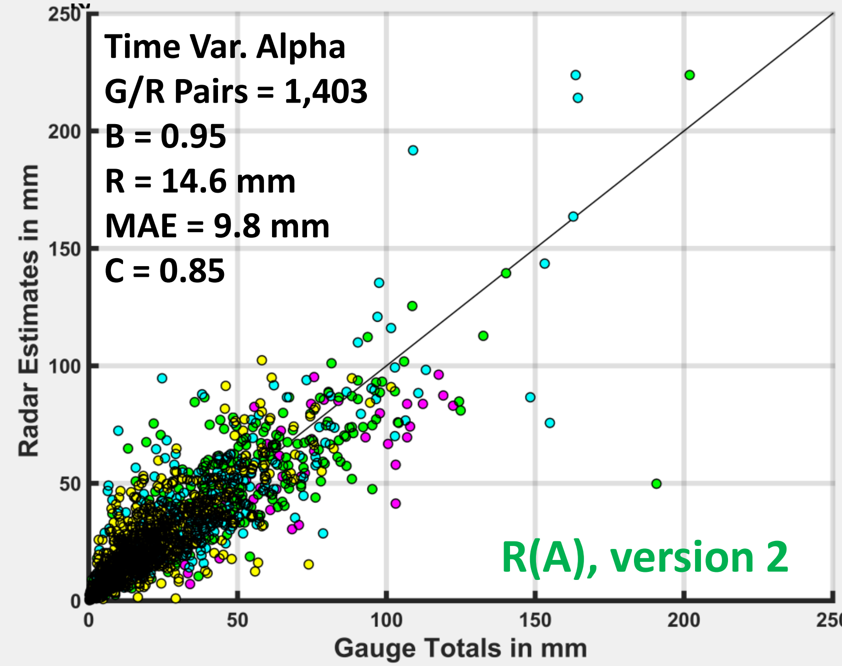
Using adaptive factor α improves the performance of R(A) dramatically

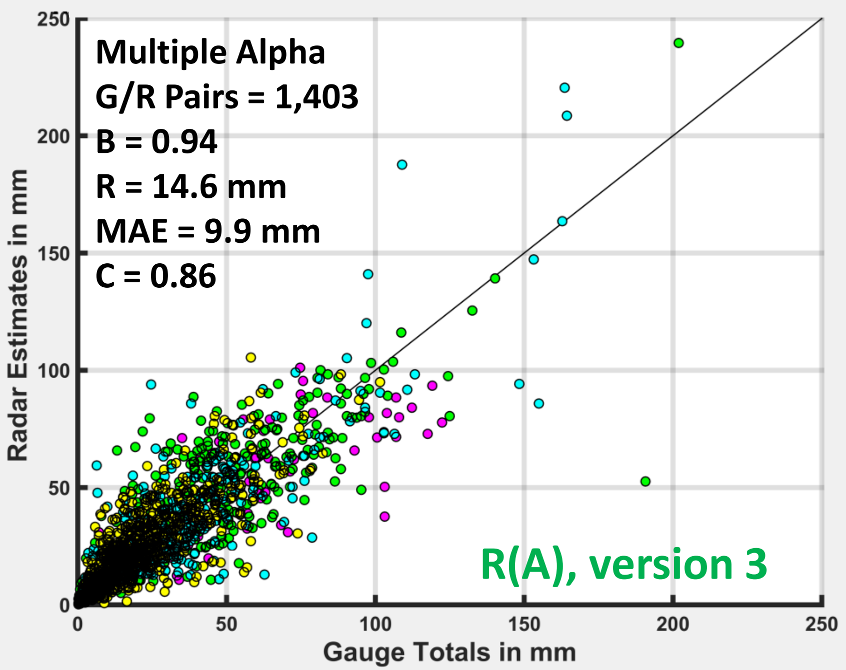
Latest validation dataset
(2014 – 2015 season)

21 precipitation – radar events

- 11 continental
- 6 tropical
- 4 US west



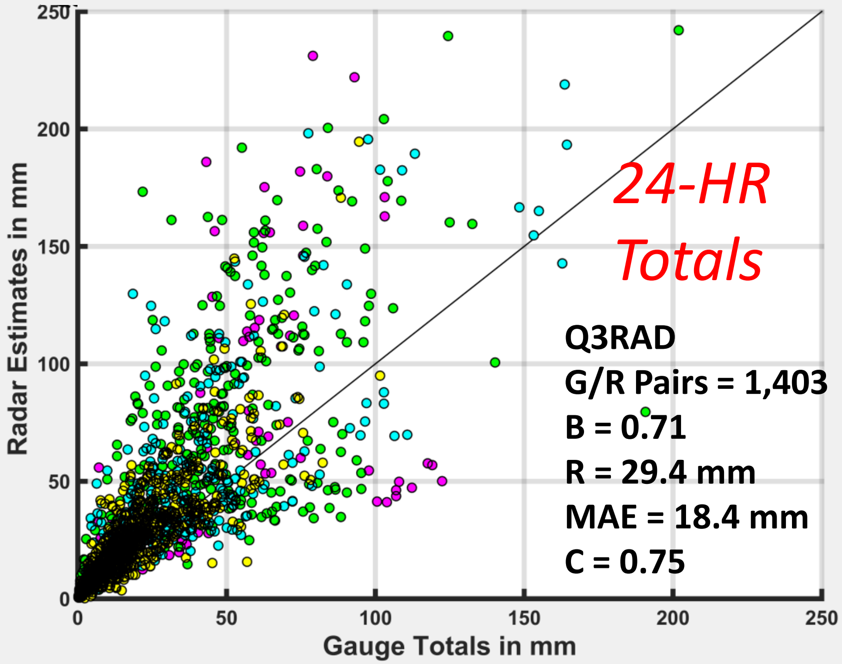


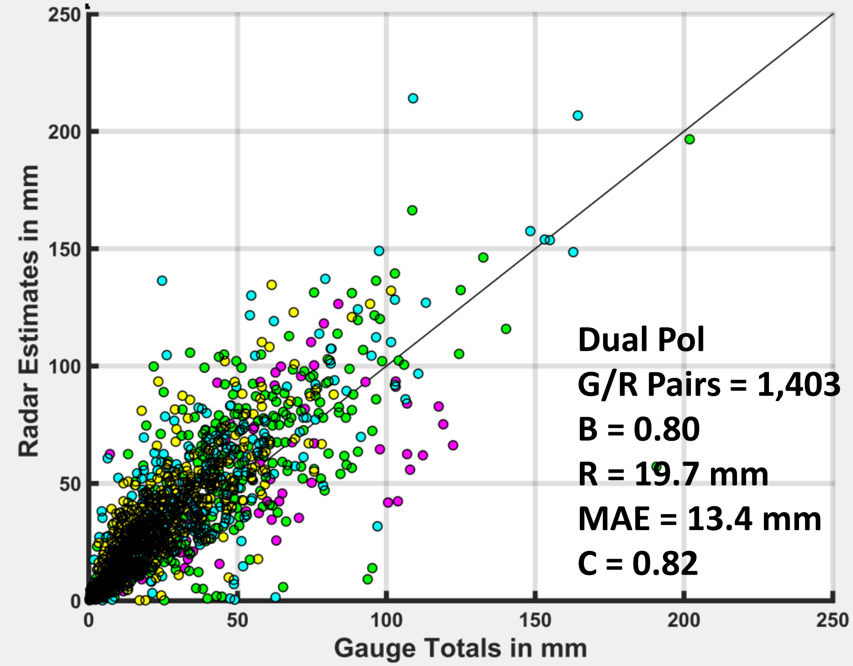


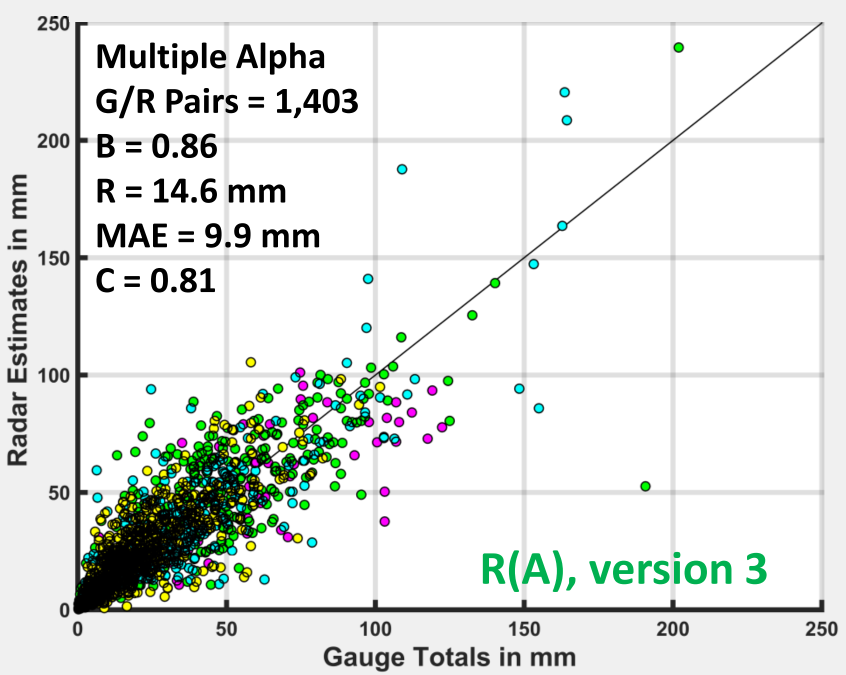
11 continental cases

G/R ... Gauge/Radar Bias Ratio
R .... RMSE
MAE....Mean Absolute Error
C....Correlation Coefficient

Maroon **- Dist (D) ≤ 25 km**
Green **- 25 km < D ≤ 100 km**
Blue **- 100 km < D ≤ 150 km**
Yellow **- 150 km < D ≤ 200 km**



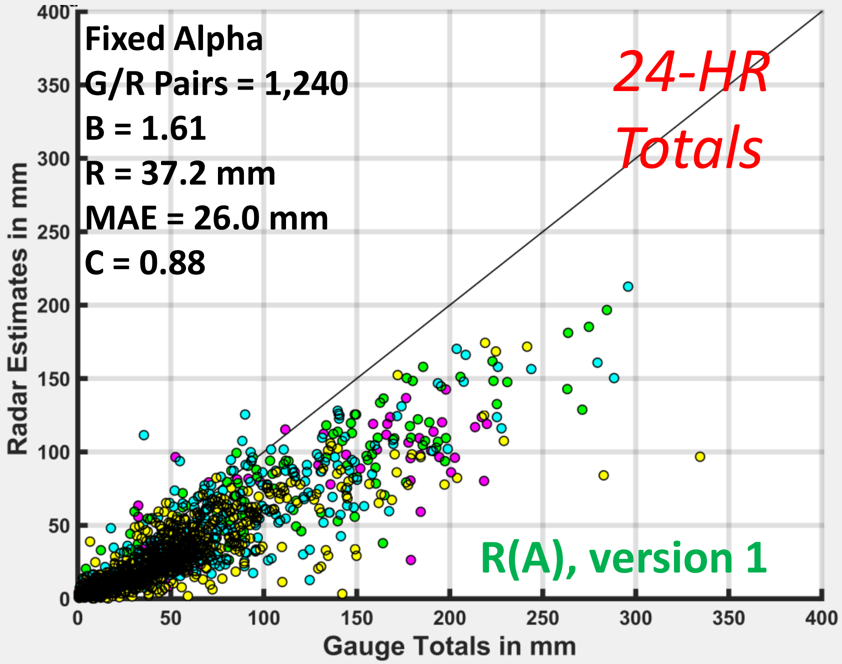


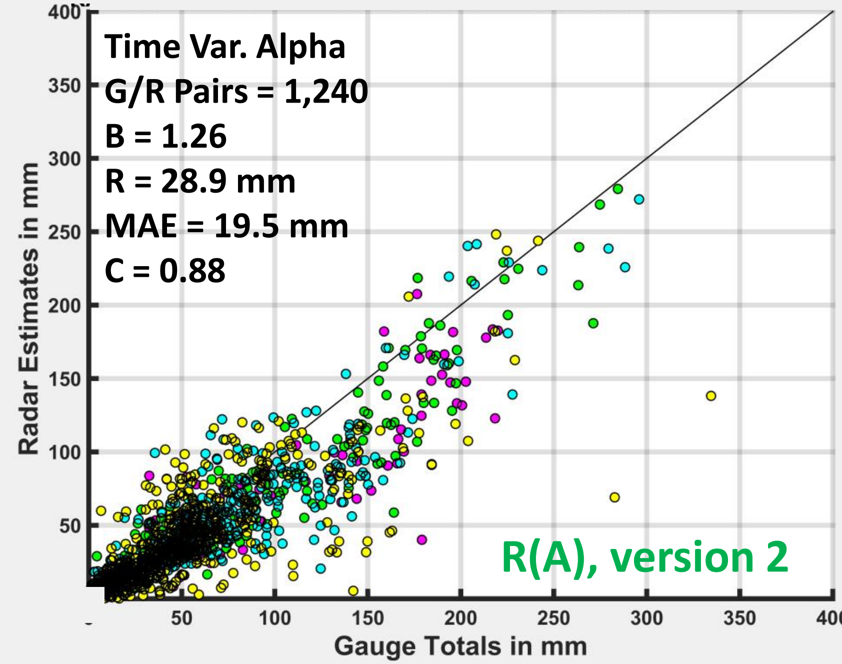


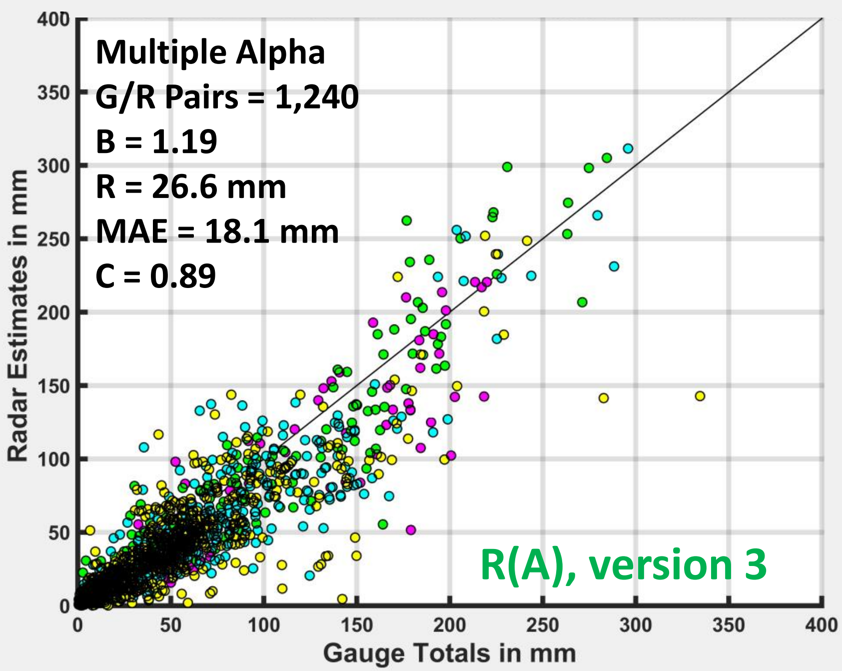
11 continental cases

- **Q3RAD (top left), Dual Pol (top right) and Multiple Alpha (bottom left) estimates vs. *24-hr acc.* for eleven *continental* events**

- *Results include five cases where Q3RAD had significant_ difficulty correctly identifying tropical precipitation*

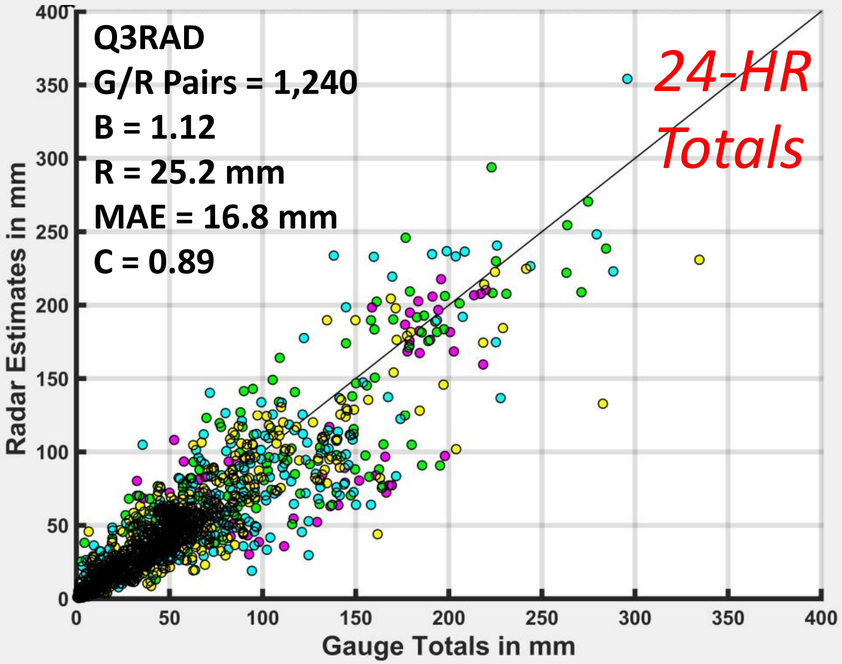


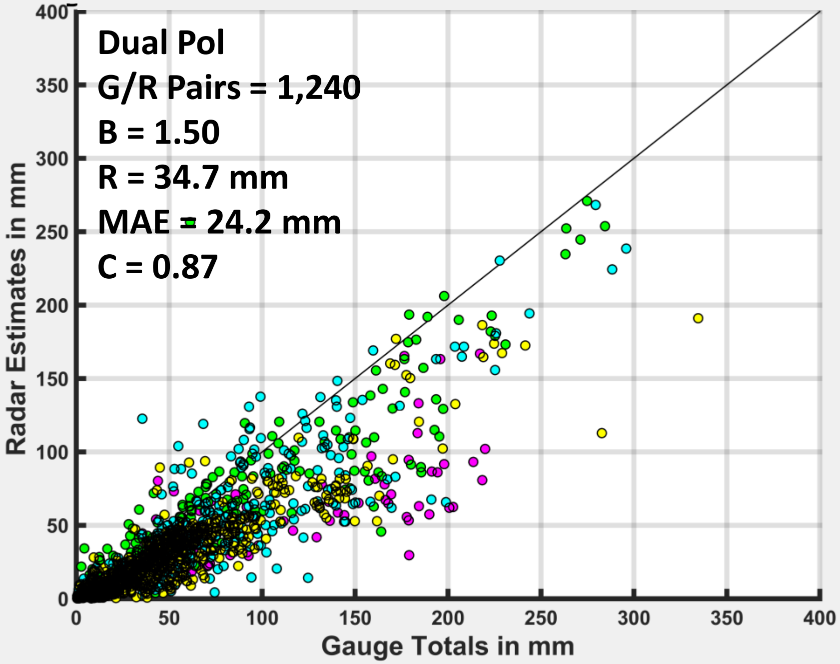


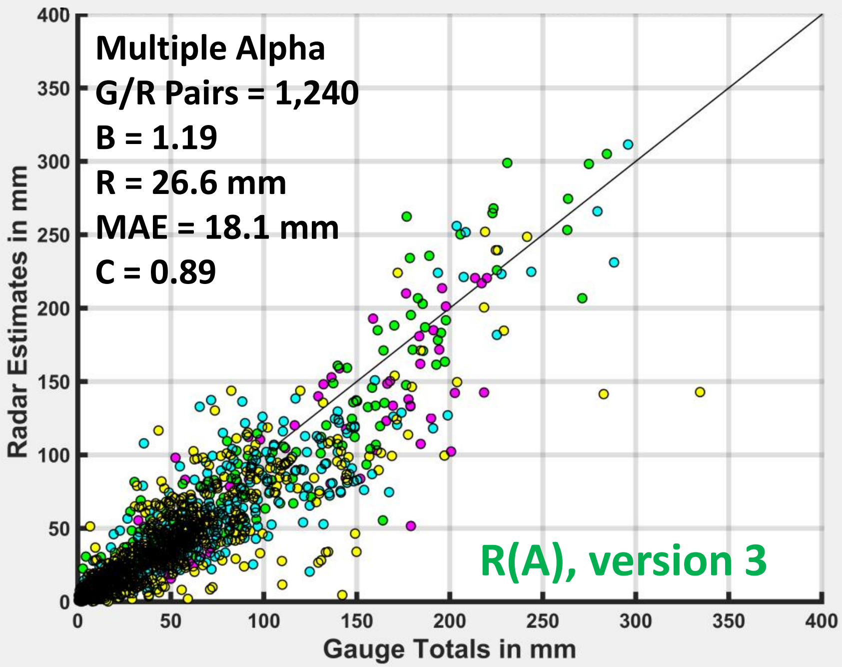


6 tropical cases

- **For tropical rain, the use of fixed α results in persistent underestimation of rainfall (R(A) version 1)**
- **The bias is practically eliminated if the optimal value of α is used**





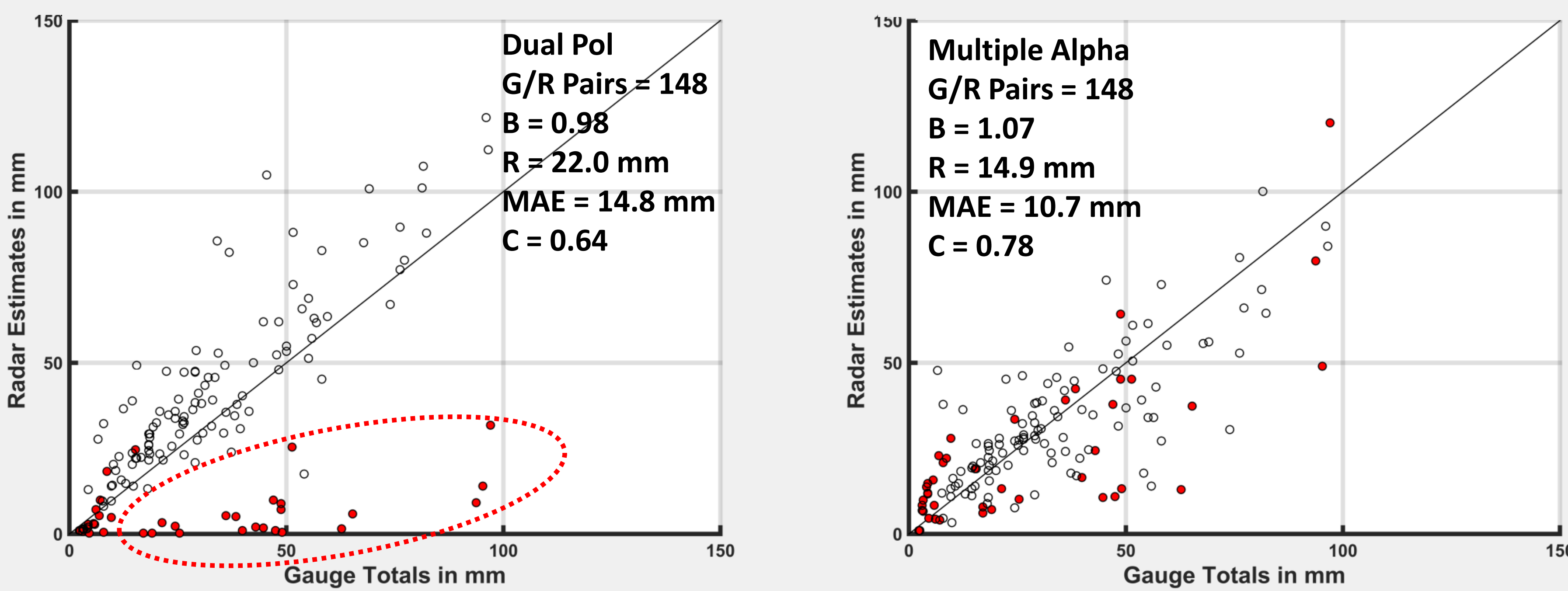


6 tropical cases

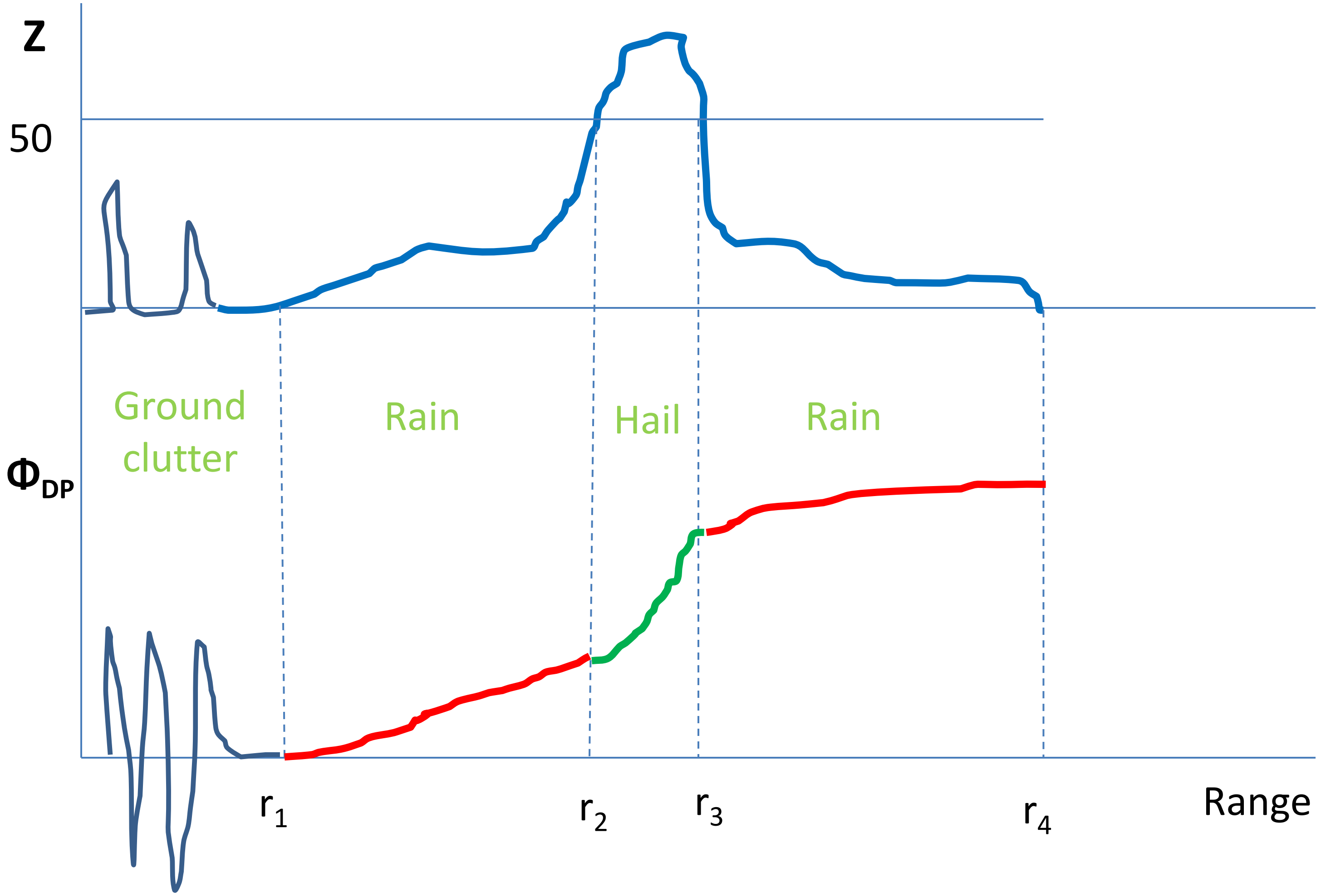
- **Q3RAD (top left), Dual Pol (top right) and multiple Alpha (bottom left) estimates vs. *24-hr accumulations* for six *Tropical* like precipitation events with limited severe weather**

Mitigation of the partial beam blockage impact

Red dots are G/R pairs associated with areas of partial beam blockage where the R(A) algorithm did much better job (right panel) than the DualPol algorithm currently implemented on WSR-88Ds (left panel)



Segmentation of the beam

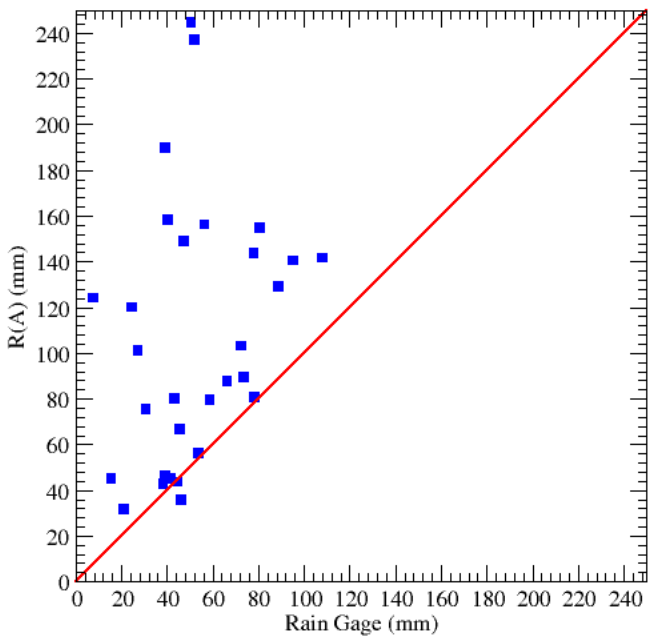


$$\Delta\Phi_{DP} = [\Phi_{DP}(r_4) - \Phi_{DP}(r_1)] - [\Phi_{DP}(r_3) - \Phi_{DP}(r_2)]$$

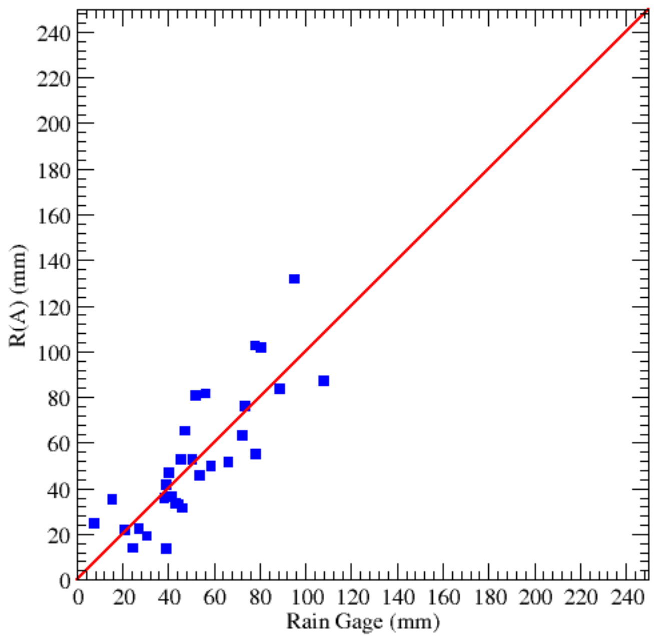
Hail contribution

Rain storm totals for the 2014/04/28 – 29 event estimated by the R(A) algorithm before and after contamination from ground clutter and hail was removed by segmentation of the beam

Before



After



Summary

- The R(A) algorithm with fixed α = 0.015 dB/deg yields unbiased estimates of 1-hr and 24-hr rain totals in the cases of continental rain but tends to underestimate tropical rain

- The R(A) algorithm with adaptable α produces unbiased estimates of rainfall for both continental and tropical rain and generally outperforms DualPol QPE algorithm (DPR) currently implemented on WSR-88D

- The R(A) also outperformed MRMS Q3RAD for warm season MCSs in the Northern Interior of the US where Q3RAD had “wet” bias due to inaccurate classification of tropical rain and the use of the “high-yield” R(Z) relation. The R(A) performed similar to MRMS Q3RAD for evaluated cases in the Southern US

- Further refinement may be needed to mitigate possible contamination from hail, ground clutter, and biota and for the smooth integration with R(Z) estimates in and beyond the melting layer for operational applications

Backup slides

Impact of temperature and radar frequency on the R(A) performance

$$R(A) = \gamma A^{d}$$

$$\gamma = c_1(t)c_2(\lambda)$$

$$c_1(t) = (2.23 + 0.078t + 0.00085t^2)10^3$$

$$c_2(\lambda) = 1 - 0.26(11.0 - \lambda)$$

S band

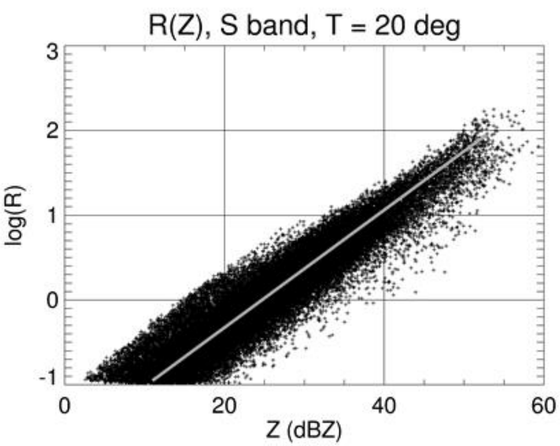
$\alpha \propto \gamma^{-1}$ and $R(A) \propto \gamma\alpha$ for low PIA (S band)

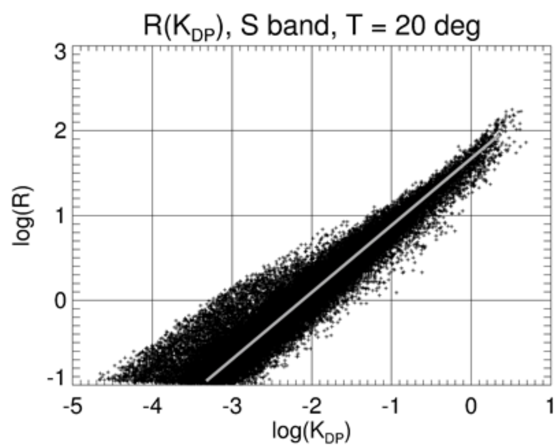
Because the temperature and wavelength dependencies of γ and α tend to cancel each other, it is possible to ignore these dependencies and use a fixed R(A) relation at all temperatures and radar frequencies within S band

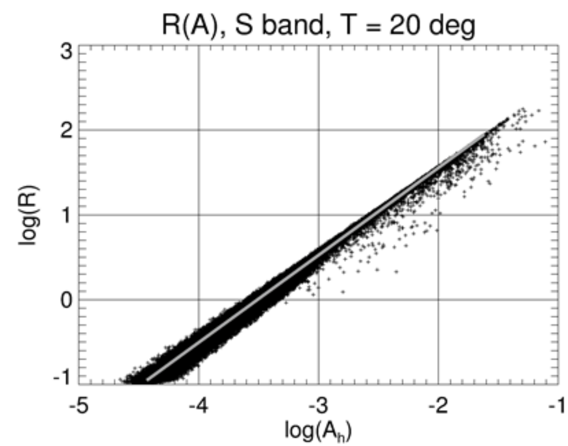
This may not always be the case at C and X bands

Although the intercept γ is fixed, the dependence of α on rain type has to be taken into account

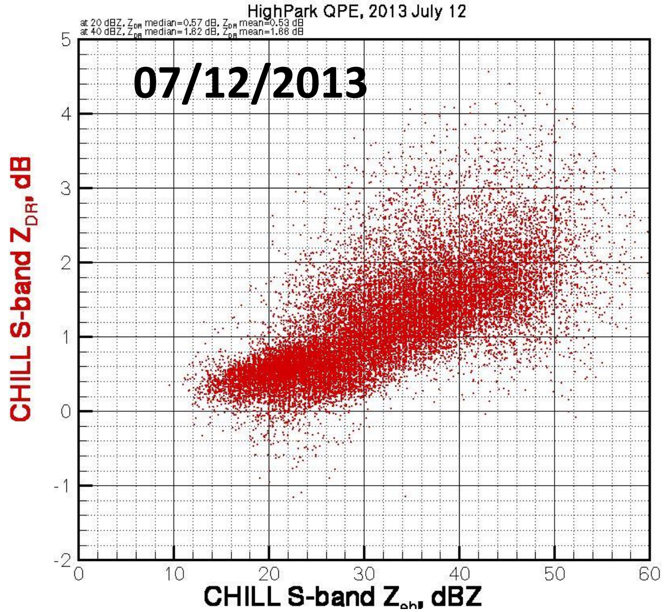
Sensitivity of the R(Z), R(K_{DP}), and R(A) estimates to the DSD variability at S band

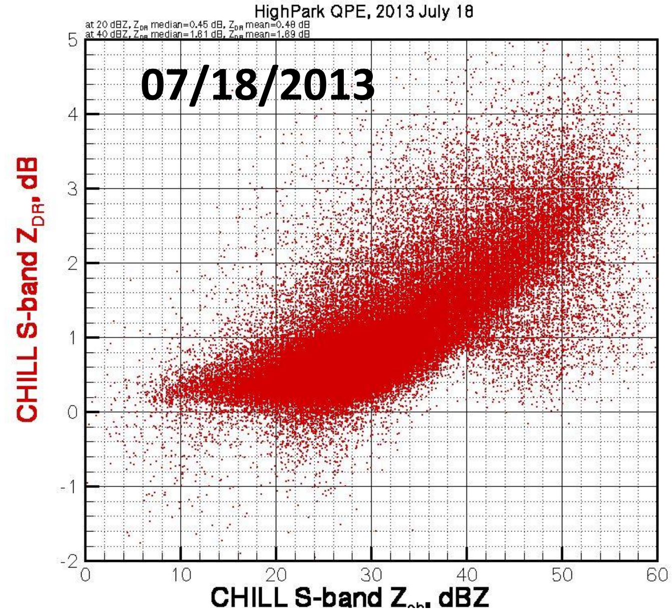


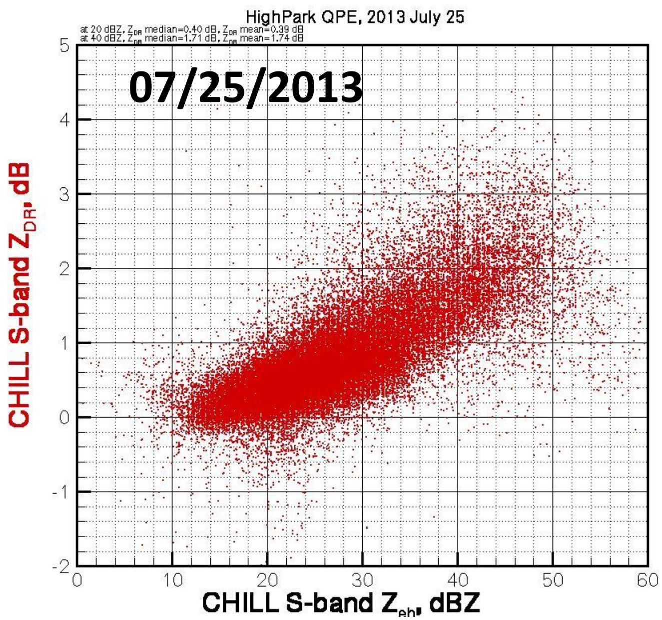


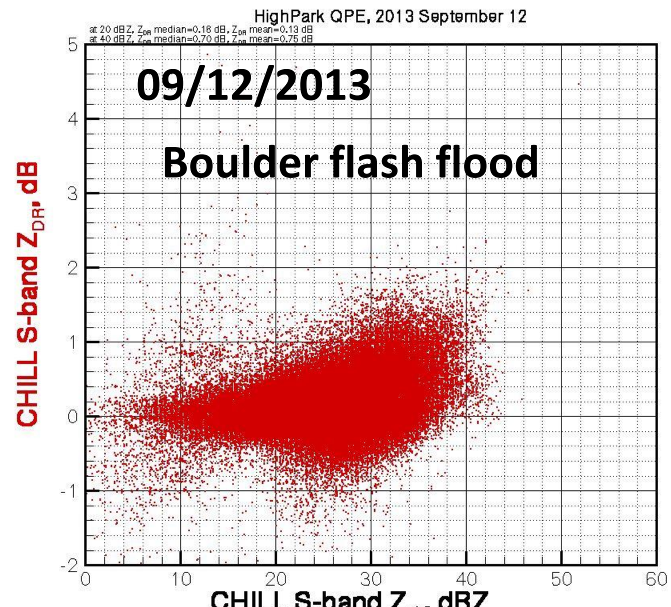


CSU – CHILL data









Courtesy of Sergey Matrosov