Authors' Response to Interactive comment from Anonymous Referee # 2 on "Dual-Wavelength Radar Technique Development for Snow Rate Estimation: A Case Study from GCPEx" by Gwo-Jong Huang et al., Atmos. Meas. Tech. Discuss.,
doi:10.5194/amt-2018-211, 2018.

A method is proposed to estimate snowfall rates from the D3R dual-frequency radar measurements. The method is developed and assessed during a snowfall event in 2012. 2D-video disdrometer and gauge data are used to link observed radar reflectivity and particles physical properties. The dual-frequency estimator is shown to estimate snowfall rates with more accuracy than the conventional single frequency Z-S approach.

The paper is well written. The detailed discussion on the assumptions, methodology and techniques is appreciated. Dual-frequency estimation of snowfall rates addresses the critical need for improved snow estimation from ground- and space-based remote sensing. The work presented is worthy of publication after some minor aspects have been addressed.

Our Response:

We would like to thank the reviewer for the positive general comments, as well as the corrections, suggestions, and questions regarding minor aspects. We have responded below to all of the comments (except those that are entirely complimentary) and included changes in the revised manuscript.

1. This study relies on a set of observations that is unique. This is probably the reason why it is applied on a single event. It is recommended to discuss the representativeness of the results, i.e. to what extend the Z-S and DWR-S relations developed in this study can be applied to other precipitation events, regions, or environmental conditions.

Response:

The case we have analyzed during GCPEx is a common synoptic snowfall event (large scale forcing is described in brief in Section 3) that occurs in the area surrounding the CARE site and is not unique per se, but dual-wavelength scanning radar observations combined with measuring instruments sited inside a DFIR wind shield are somewhat unique. The Z-SR power law derived for this event is expected to be applicable to similar synoptic forced snowfall in similar climatology under similar environmental conditions (eg Temperature and RH profiles from sounding) but not for example to lake effect snowfall as the microphysics are quite different. Regarding the DWR-SR relations, they should be considered for now as 'condition' specific and analysis of more events are needed before any firm conclusions can be drawn as to applicability to other regions or environmental conditions.

We have added some sentences in the conclusions at the very end as the ending para.

“The snow rate estimation algorithms developed here are expected to be applicable to similar synoptic forced snowfall under similar environmental conditions (e.g., temperature and relative humidity) but not for example to lake effect snowfall as the microphysics are quite different. However, analysis of more events are needed before any firm conclusions can be drawn as to applicability to other regions or environmental conditions.”

2. What are the perspectives in terms of implementing such approach to other instruments on the ground or in space (i.e. GPM dual-frequency radar)?

Response:

Substantial work exists and is on-going using airborne particle size distribution probes and downward pointing radars to develop Z-SR relations stratified by temperature, for example. Multiple-wavelength downward pointing airborne radars at the GPM frequencies (Ku, Ka-bands) have been used in many field programs including comparisons with GPM overpasses. The GPM dual-wavelength technique for measuring snowfall near the surface is an active area of research. As such our experience using scanning dual-wavelength radar (D3R) is bound to be useful as ground-validation for GPM-based algorithms.

3. P.2 ll.10-11: “it is shown that a physically consistent representation of the geometric, microphysical, and scattering properties needed for radar-based QPE can be achieved” and following discussion on Ze-SR relations. For information this has been also been shown in a recent contribution involving dual-polarization ground-based radars: Bukovci ˇ c, P., A. Ryzhkov, D. Zrni ´ c, and G. Zhang, 2018: Polarimetric Radar ´Relations for Quantification of Snow Based on Disdrometer Data. J. Appl. Meteor. Climatol., 57,103–120, https://doi.org/10.1175/JAMC-D-17-0090.1.

Response:

We are aware of this paper which uses dual-polarization radar to estimate snowfall with algorithms developed using 2DVD. To the best of our knowledge, the derived algorithms were not tested with independent snow gage measurements. We have cited this reference in our revised version on page 2, lines 10-11.

4. P.3 ll.8&10: Dm is not measured; it is actually estimated from measurements.

Response:

We have changed “measurements” to “estimation”.

5. p.3 ll.1-11: this paragraph seems too technical in the introduction section. You can consider including it in the methodology section.

Response:

After much consideration we feel that keeping the paragraph the same i.e., in the Introduction, is reasonable.

6. Please correct Skolfronik-Jackson et al. (2015) to Skofronick-Jackson et al. (2015) throughout the paper.

Response:

This typo has been corrected throughout the paper.

7. p.13 ll.20 – p.14 l.10: Fig. 13 that there is considerable scatter at Ku-band for all three methods with the normalized standard deviation (NSTD) ranging from 55- 70%". Are the errors in table 3 assumed to be normally distributed? Kirstetter et al. (2015) proposed a probabilistic Z-S QPE approach showing that uncertainty is characterized by non-symmetric distributions: Kirstetter, P.E., J.J. Gourley, Y. Hong, J. Zhang, S. Moazamigoodarzi, C. Langston, A. Arthur, 2015: Probabilistic Precipitation Rate C2 Estimates with Ground-based Radar Networks. Water Resources Research, 51, 1422-1442. doi:10.1002/2014WR015672 "To reduce error, we may take the geometric ´ mean of these two estimators": do you mean to reduce the bias? Does the non- ´ linear least square fitting approaches assumes normally distributed uncertainty? Can this assumption be discussed?

Response:

As stated in the text the Z-SR power law prefactor and exponent are determined using weighted total least squares method where Z is in mm^{6}m^{-3} and SR in mm/h. We do not fit a straight line in log-log space. As in all least squares methods the residual errors are assumed to be normally distributed. Also, the estimated NSTD values reflect the parameterization errors only (see Chapter 7 of Bringi and Chandrasekar 2001) in an additive error model. We use the geometric mean to show the central tendency and avoid giving too much weight to the outliers. It is not intended for reducing the bias. We do not believe that it is necessary to include this in the revised text.

We have read the article by Kirstetter et al. which is based on mapping the radar measurement of Z to measured snow rate at the ground; thus their uncertainty is due to various error sources such as radar bias in Z as well as errors in snow gage measurements due to horizontal wind etc. They find 50% bias (underestimate) when using the climatological Z-SR relationship and the relative uncertainty expressed in terms of the interquartile range normalized by the mean of 50-75%. We agree that the errors (bias+random) can be unsymmetric and interquartile ranges are more appropriate. We have added a few sentences from Kirstetter et al. in our revised manuscript just before Section 4 on Summary and Conclusions.

"Note that the error model used here is additive with the parameterization and measurement errors modeled as zero mean and uncorrelated with the corresponding error variances estimated either from data or via simulations (as described in Chapter 7 of Bringi and Chandrasekar 2001). This is a simplified error model since it assumes that radar Z and snow gage measurements are unbiased based on accurate calibration. A

more elaborate approach of quantifying uncertainty in precipitation rates is described by Kirstetter et al. (2015).”

8. p.14 l.4: “the SR (ZKu ,DWR) using LM method has the smallest NSTD (28.49%) but the other two methods have similar values of NSTD (≈30%)”. Is this difference in NSTD significant?

Response:

The differences in NSTD are not statistically different. That sentence has been modified to:

“*As can also be seen from Fig. 14 and Table 4, the SR(ZKu,DWR) using LM method results in the lowest NSTD of 28.49%, but the other two methods have similar values of NSTD (≈30%) and, as such, these differences are not statistically significant.”*