WET ICE SPECIFIC ATTENUATION RETRIEVAL AND CORRECTION FOR X-BAND USING A PIECE-WISE FORWARD CORRECTION METHOD

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1. INTRODUCTION

Wet ice, which is common in convective storms, can significantly contribute to attenuation in radar signals. Wet ice attenuation is usually observed at high frequencies such as 10GHz (X-band). Correcting for such signal degradation becomes very important when using X-band radars to observe atmospheric events such as severe convective storms. Current attenuation correction methods make use of the relationship between differential phase (ϕ_{dp}) and specific attenuation (A_h) in rain. Knowing that the specific attenuation $A_h = \alpha K_{dp}(r)$ (where K_{dp} is the specific differential phase and α is the coefficient) and $K_{dp} = [\phi_{dp}(r_2) - \phi_{dp}(r_1)]/2(r_2 - r_1)$ the attenuation due to rain can be corrected by simply using,

$$Z_h^{atten} = Z_h^{un-atten} - \alpha[\phi_{dp}(r) - \phi_{dp}(0)] \qquad (1)$$

However, this relationship breaks down when wet ice is present along the radar's path because it contributes little to the differential phase while highly contributing to reflectivity. This makes it difficult to correct for the contribution of wet ice to attenuation along a radar path.

To correct for such attenuation, an SRT-modified technique was explored by León et al. in [1] and [2]. However, this method requires an un-attenuated reference value (such as from S-band), which is not always available. A new technique that does not require a reference is presented here. This technique explores a piece-wise forward (PWF) Hitschfeld-Bordan (HB) [3] method applied to the rain attenuation corrected X-band profiles, where the wet-ice locations are identified using the hydrometeor identification (HID) algorithm outlined by Dolan and Rutledge in [4].

This new method intends to address the need to correct the excess attenuation induced by the wet ice without using a reference as presented in [1] and [2]. X-band radars, such as the CASA radar network, might not have a reference available. This method can be applied to such systems when the polarimetric variables needed for the HID are available making it possible to correct such attenuation independently.

2. BACKGROUND AND METHODOLOGY

A technique to estimate and correct for wet ice attenuation was presented in [1] and [2], where a variation of the TRMM Surface Reference Technique (SRT) was used. When using this technique, un-attenuated frequency reflectivity values (such as S-band) were assumed to be available at the end of each of the X-band radar beams. With this reference value the SRT-modified technique was used to adjust the alpha value in the $A_h = \alpha Z^{\beta}$ relationship (with a starting value of 0.00048, while beta was fixed to 0.6) to make the reflectivity values match at the end of the beam, calculated by $\Delta Z = Z_h^S - Z_h^X$. The adjusted alpha α_{adj} was used to calculate an estimated specific attenuation to apportion backward the reflectivity values. This technique was first tested with a 2-moment scheme Supercell simulation using the Regional Atmospheric Modeling System (RAMS) Supercell model where the attenuation due to wet ice was up to 2.5dBkm^{-1} [1]. The technique was also applied to real X-band radar data such as that from International H20 Project (IHOP), the CASA (Collaborative and Adaptive Sensing of the Atmosphere) first generation system Integrative Project 1 (IP1) radar network in Oklahoma operating at X-band and the dual-frequency CP2 radar deployed in Brisbane, Australia. During IHOP, an X-band radar (XPOL) and S-band radar (SPOL) were available to apply the SRT-like technique. Analysis of data from June 16th, 2002, where XPOL and SPOL data were matched, showed that the wet ice attenuation was as large as 1.2dBkm^{-1}. Over the X-band CASA radar network, un-attenuated reference data was provided by the NSSL Polarimetric WSR-88D (KOUN) radar. Data from a convective event on June 10th, 2007 was analyzed in [2]. The attenuation due to wet ice, which is overlaid with reflectivity shows to have maxima of 5dBkm^{-1} of attenuation in areas of wet ice (Figure 1). The retrieved specific attenuation shows good agreement with values of Z_h in wet ice regions where values are

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expected to be over 55dBZ. However, this method is limited to datasets where un-attenuated references are available, which is not always the case.

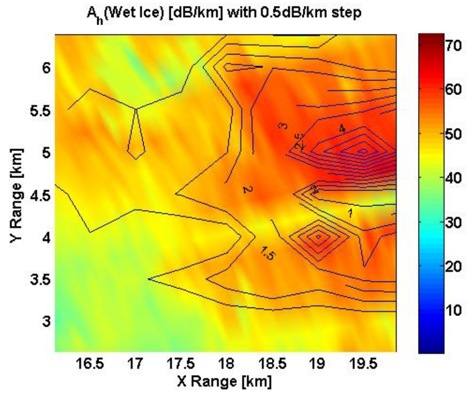

Figure 1: Contours of specific attenuation $A_h^{wet-ice}$(X) overlaid with wet ice corrected Z_h at X-band. PPI scan at 12.25° in elevation.

A new technique that does not require a reference is presented. First, rain induced attenuation in the X-band data is corrected using the $A_h - K_{dp}$ relationship. Then the relationship coefficients (α and β) between the wet ice specific attenuation A_h and X-band radar reflectivity Z_h are found using CP2 data. Here the A_h due to wet ice was calculated by subtracting the rain specific attenuation (calculated from the K_{dp}^S) from the total specific attenuation (which is estimated using the dual wavelength ratio, DWR). To determine the locations where the wet ice is in each beam, a hydrometeor identification (HID) algorithm described in [4] is used. Since the CP2 radar can only measure Z_h and LDR at X-band, the S-band polarimetric information necessary to determine the locations of wet ice (such as Z_h, Z_{dr}, ρ_{hv} and K_{dp}) are used as a proxy. Once these location ranges of wet-ice are established, a forward Hitschfeld-Bordan (HB) [3] method is applied to the rain attenuation corrected X-band profiles using,

$$Z_h^{corr}(r) = Z_h^{uncorr}(r) - A_{HB}(r) \tag{2}$$

where,

$$A_{HB}(r) = 1 - q\beta \int_{r1}^{r2} \alpha Z_h^{\beta} dS \tag{3}$$

and $q = 0.2\ln(10)$. Here the integral limits are determined by the HID results, and the coefficients from the extensive CP2 dataset. This way the HB method corrects for the excess attenuation caused by wet ice in a piece-wise forward way. The attenuation corrected results are compared to those obtained with the SRT-modified method.

3. DATASET

A convective event on 10 June 2007 passing through the CASA radar network around 23:47 UTC showed excess attenuation after being corrected for rain implying the presence of hail. The NSSL Polarimetric radar (KOUN) located in Norman, Oklahoma, provided S-band data for the same storm. Comparisons between CASA and KOUN data revealed differences between rain attenuation corrected X-band reflectivity (Figure 2) and the un-attenuated S-band reflectivity (not shown here) of up to 35dB. A hydrometeor identification algorithm at S-band was applied at a height of 6.5km, which showed the presence of high-density graupel (wet ice) aloft in the areas where the high attenuation was observed (Figure 3). A PPI scan at 12.24° in elevation of the Cyril (KCYR) radar (Figure 2) is considered to obtain the beams passing through the wet ice region aloft.

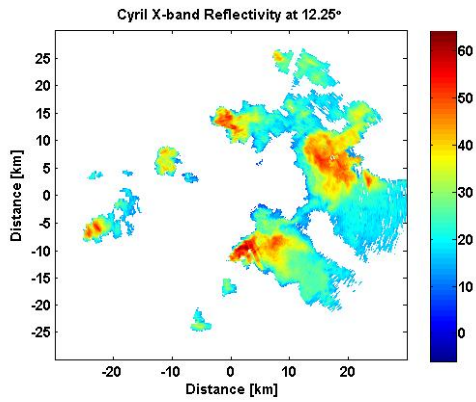

Figure 2: CASA Cyril CYR Z_h corrected for rain. PPI scan at 12.25° in elevation.

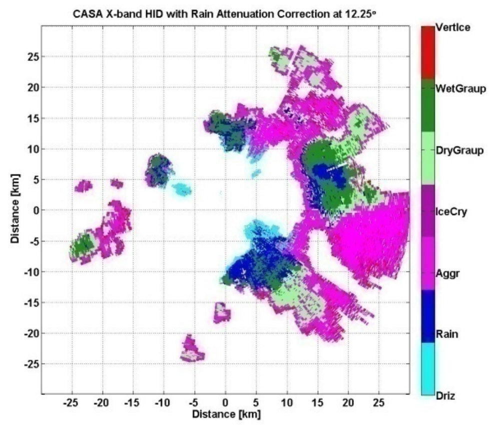

Figure 3: HID results for the event with all the classifications included. Rain induced attenuation corrected data at X-band was used here.

Also data from a large CP2 dataset from a convective event on March 26th, 2008 is used to retrieve the relationship coefficients (α and β) between the wet ice specific attenuation A_h and X-band radar reflectivity Z_h.

4. RESULTS

4.1 A_h-Z_h *Relation Coefficients Retrieval*

To be able to estimate the wet ice specific attenuation, the coefficients of the $A_h^{wet-ice}$(X)-Z_h(X) power law must be established. Table 1 shows the α and β coefficients found for this relation by analyzing two different datasets under different conditions. These values are used as reference when analyzing the datasets available for this research.

Table 1: A_h-Z_h power law relation coefficient and exponent found in different datasets. CP2 measurements correspond to the CP2 event analyzed here, and the Brisbane 2DVD disdrometer data were used for simulations.

REFERENCE	α	β	Conditions
CP2 Radar Measurements	7.0×10-4	0.5529	Z_h(S)≥35dBZ, HDR≥10dB, Hail below melting layer
From Brisbane Disdrometer Simulations	1.9038×10-4	0.7085	A_h(X)-Z_h(X) T=0°C

For the $A_h^{wet-ice}$(X) retrieval the DWR from the CP2 event from March 2008 was used. The DWR is used to estimate the total specific attenuation and the rain component is estimated using K_{dp}(S) as described in [2]. Then, $A_h^{wet-ice} = A_h^{Total} - A_h^{Rain}$, all at X-band.

Using this procedure the wet ice specific attenuation is retrieved to further relate to Z_h at S-band. In Table 1, the coefficients found from these different datasets are displayed along with which data set was used and their conditions. Although the results found in the literature review are developed under certain conditions, thresholds were applied to try to emulate these. For example, a hail detection ratio (HDR) [5] threshold of higher or equal to 10dB was applied to ensure that hail was present. Also, only values for Z_h(S) ≥ 35dB were used in the relation retrieval. Additional to these coefficients, the coefficients for the same relation in a rain environment were examined, were found to be similar with what has been found in the literature review.

Examining the relations retrieved from two different datasets (Table 1), α=7×10-4 and β=0.5529 were used to estimate the specific attenuation due to wet ice at X-band and correct for it. It has to be mentioned that these coefficients were found using Z_h(S) and not Z_h(X), but from other dataset analysis, there was not a significant difference between the coefficients in both frequencies in the absence of Mie scattering. Considering that the CP2 does not have a corrected reflectivity at X-band, the un-attenuated Z_h(S) was used instead. However, the radar data simulated from the disdrometer data does have an un-attenuated X-band reflectivity, which was used to retrieve the coefficients shown in Table 1.

4.2 *Wet*-ice *Attenuation Correction*

As shown in Figure 3 the HID results for the PPI scan at 12.25° show areas with wet ice. Is important to mention that the HID algorithm is applied to the PPI scans rather than the gridded data, since the PWF is a ray based correction method. This is why the HID results look fuzzier than gridded results, which look smoother [2]. The areas identified as wet ice with the HID algorithm are the ones corrected by the PWF correction method. But one purpose behind this correction is whether highly attenuated cells in fact affects the HID results and if the wet ice attenuation correction helps identify better a wet ice cores.

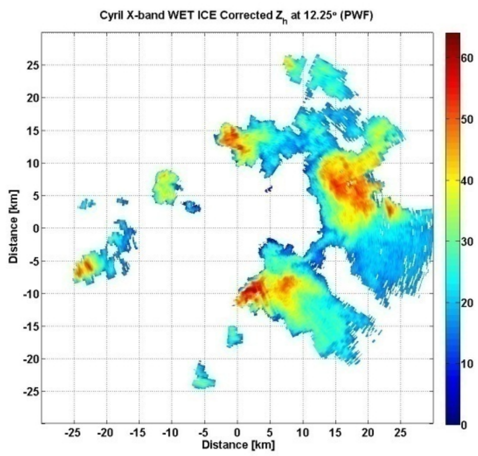

Figure 4: Wet ice attenuation corrected Z_h(X) PPI scan at 12.25°

With the PWF method, a maximum of 1dBkm^{-1} in $A_h^{wet-ice}$(X) is found. When compared with the SRT-modified method, which had a maximum of 5dBkm^{-1} [2], the PWF method shows to be underestimating the wet ice specific attenuation. It did correct some of the attenuation but not all of it given that previously with the SRT-modified method it was found that higher attenuations were affecting the reflectivity values.

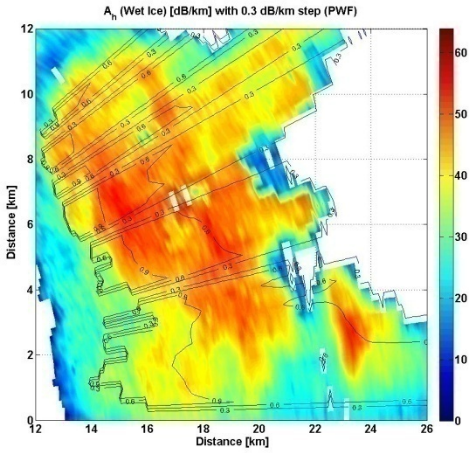

Figure 5: Z_h section from Figure 4 with the retrieved $A_h^{wet-ice}$(X) contours.

The Z_h(X) corrected profile at azimuth angle of 58° is shown in Figure 6. In this specific ray a maximum of 2 dB differences is observed. This is different that the 5dB found with the SRT-modified method for the same radar beam.

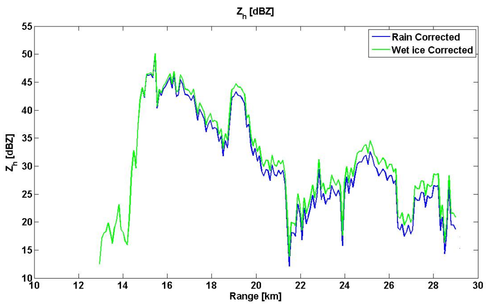

Figure 6: Z_h(X) for rain and wet ice attenuation corrected range profiles at 58° in azimuth.

With this dataset, we do not have an un-attenuated reference profile to compare with. Still, it can be compared with Figure 7 where the same CASA data is corrected using networked based (NB) attenuation correction method as described by Lim and Chandrasekar in [6] corrected the reflectivity for the same area and the SRT-modified method's result showed in [2].

When the resulting corrected data set was used to run the HID algorithm, the results (Figure 8) showed some correction in areas where wet ice is supposed to be identified. But when compared to the SRT-modified corrected results shown in Figure 9, it showed a better correction.

Figure 9 show that after using this correction method the wet ice core is better identified than using the PWF method. Even though it still looks fuzzy it looks more like a core rather than

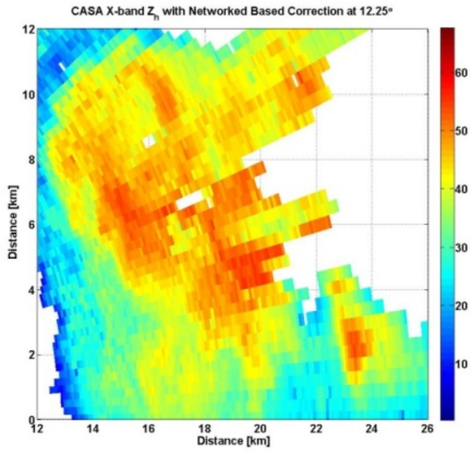

Figure 7: Network Based (NB) attenuation corrected Z_h(X) results.

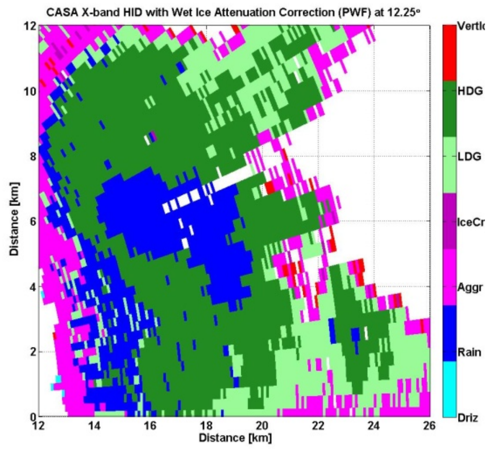

Figure 8: HID using the Z_h(X) corrected for wet ice using the PWF method.

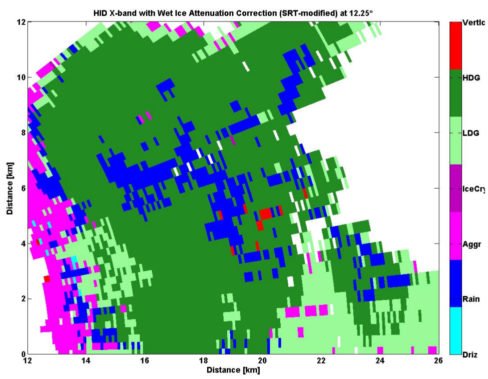

Figure 9: HID using the Z_h(X) corrected for wet

ice using the SRT-like method.

selected pixels as before the correction. It looks more 'realistic' since wet ice areas are found in a continuous way and not scattered along the beam path. These results show a better classification than the PWF results.

5. CONCLUSIONS

Given that for the CASA networked radars a reference might not always be available, a new wet ice correction method was developed. This solution is based on a combination of a hydrometeor classification to identify where the wet ice is located and a priori relation of $A_h^{wet-ice}$(X)- Z_h(X). The latter power law relation was derived from CP2 radar measurements in a severe hailstorm. With these two results, a Piece Wise Forward method based on the Hitschfeld-Bordan solution was used to correct for the estimated wet ice attenuation. This method was tested with a dataset from a CASA network radar located in Cyril, Oklahoma. With this dataset, the method showed to underestimate the wet ice attenuation compared with the SRT-modified and NB one, although some areas showed reflectivity corrections up to 7.5 dB. It was also investigated the influence of the wet ice attenuation correction in successfully identifying hydrometeors and how well it compared with other methods. This makes the methods more useful in terms of having accurate data when using HID algorithms.

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