Severe Hail Detection: Hydrometeor Classification for Polarimetric C-band Radars Using Fuzzy-Logic and T-matrix Scattering Simulations

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1. Introduction

Detecting and discriminating hail size is done operationally for S-band radars *e.g.* in the US using published and discussed algorithms (e.g. Ryzhkov et al. (2013a), Ortega et al. (2016)). However, these algorithms were designed for S band and may require different approaches or at least adjustment to work at C band. During summertime convective events large hail is frequently reported in the growing European severe weather database (ESWD) and can cause severe damage. Therefore, a hail discrimination algorithm needs to be developed for utilization on operational weather radar networks in Europe, including Germany, which consist mainly of C-band radars.

C-band radars are more affected by attenuation especially in hail cases. The usability to detect hail due to attenuation and methods to mitigate attenuation in C band have been discussed Schmidt et al. (2017). Furthermore, current operational algorithms were designed for S band and do not consider specific attenuation A_h at all for the classification. Modifications to operational algorithms, like the hydrometeor classification algorithm (HCA) from Park et al. (2009) and the hail size discrimination algorithm (HSDA), described in Ryzhkov et al. (2013a) and Ortega et al. (2016), to include A_h and use proper parameter ranges for C band are possible. We present here an approach to determine proper parameters for C-band radars using backscattering simulation.

2. Data and Model

2.1. Radar Data

For the development and as a testbed of the algorithms, we use the German polarimetric radar network of the German Weather Service (DWD) covering an area of more than $357\,000\,\mathrm{km}^2$ as primary radar data source. To compare the performance on S-band and C-band data, same radar volumes should be collected by both type of systems. For the comparison of S band and C band we use data of two quasi-collocated radar sites in Alabama, KEOX (S band) and EEC (C band). The sites are approximately $40\,\mathrm{km}$ apart from each other.

2.2. Scattering Model

We use a two-layer T-matrix scattering model to obtain backscattering amplitudes of dry and wet hail. For rain or dry hail a single-layer T-matrix scattering would be sufficient, but to cope with the scattering properties of water coated, wet hail, a two-layer model performs better Ryzhkov et al. (2010). The code for the model used here is the same as in Ryzhkov et al. (2013b). To calculate scattering, temperature dependent dielectric constants of the simulated medium are necessary. These are calculated using the equations from Cole and Cole (1941).

Also, scattering is not only dependent on the material, but on the shape as well. Two-layered spheroids are assumed, but the outer axis-ratio of the shape is variable. Here the axis-ratio γ for rain droplets with diameter D (in mm) is assumed to follow Ryzhkov et al. (2010):

$$\gamma = 0.9951 + 0.02510 \cdot D - 0.03644 \cdot D^2 + 0.005303 \cdot D^3 - 0.0002492 \cdot D^4 \; . \tag{2.1}$$

For dry, small hail/graupel with Diameter D the axis-ratio γ is assumed to follow Ryzhkov et al. (2010)

$$\gamma = \begin{cases} 1 - 0.02 \cdot D & if\ D < 10\,\mathrm{mm}, \\ 0.8 & if\ D \geq 10\,\mathrm{mm} \end{cases} \tag{2.2}$$

Tumbling of hydrometeors is considered with a “two-dimensional axissymmetric gaussian distribution of orientations” Ryzhkov et al. (2010). By providing a standard deviation of the canting angle, angular moments can be calculated. The polarimetric variables are then calculated using the scattering amplitudes obtained by the T-matrix and the angular moments as described in Ryzhkov et al. (2010).

3. Hydrometeor Classification

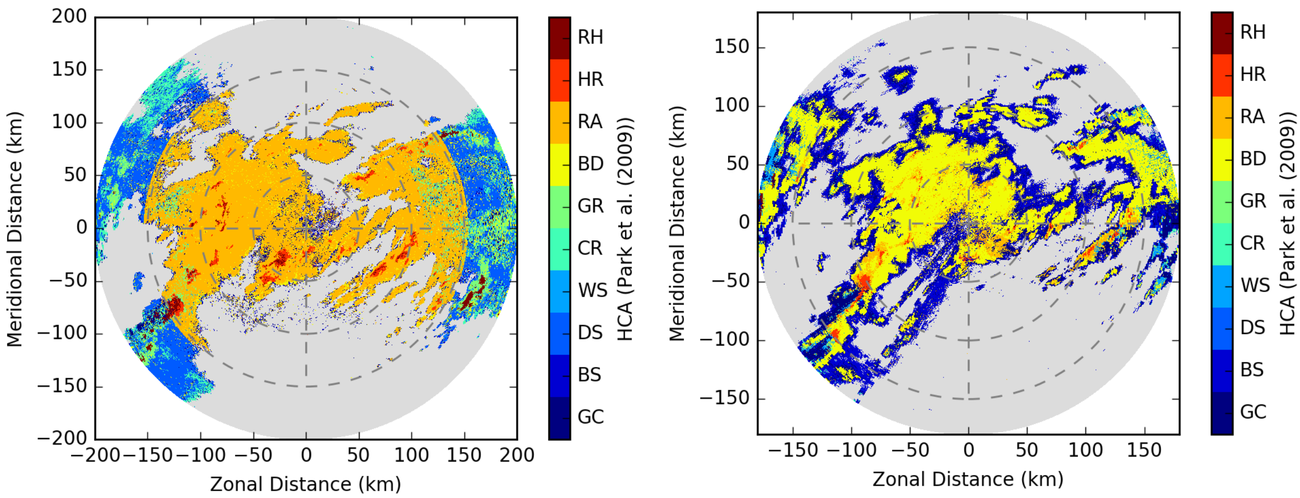
3.1. Performance of unmodified algorithm

Reference Park et al. (2009) presented a well working hydrometeor-classification algorithm (HCA). It is used operationally and was extended to discriminate between small, large and giant hail (see Ortega et al. (2016)). But with the parameters provided, the algorithm does not work well at C band. This is shown exemplarily in Fig. 1, where we compare the application of HCA to S-band data and C-band data of two quasi-colocated radars.

For the S-band data, shown in Fig. 1a, most of the area is detected to contain rain with some cells bearing heavy rain and hail. Further away only snow is detected as the melting layer is passed. The classification seems to be quite plausible for this example at S band.

For the same date and time the closeby C-band radar captured the same storm. Using the same algorithms as before, the resulting classification, shown in Fig. 1b, appears to be quite different. First of all, the C-band radar suffers from strong attenuation at locations where hail was detected with S-band data. This is not a shortcoming of the applied algorithm as this problem is related to wavelength properties. However, for a successful hydrometeor classification and hail detection at C band, attenuation is highly recommended being monitored and included in the algorithm (compare with Schmidt et al. (2017)).

Secondly, most of the area is classified to contain big drops instead of rain. This is a clear indication, that the parameters provided by Park et al. (2009) do not fit for C band. Also, almost no hail was clearly classified. One obvious reason might be, that the reflectively for hail at C band is generally lower than at S band (see *e.g.* Fig. 8 and 15 in Ryzhkov et al. (2013b)).



(a) S band (KEOX) *(b) C band (EEC)*

Figure 1: The hydrometeor classification algorithm (HCA) as in Park et al. (2009) for two quasi-colocated radar sites (KEOX and EEC) in Alabama, USA. The ordinate shows the meridional and the abscissa the zonal distance from the radar site in km. The gray color marks areas without classifiable echoes inside the radar range. According to the colorbar the different determined hydrometeor classes are given by color. Here stands RH for rain and hail mixture, HR for heavy rain, RA for rain, BD for big drops, GR for graupel, CR for ice crystals, WS for wet snow, DS for dry snow, BS for biological scatter and GC for ground clutter (compare with Park et al. (2009)). The data used has been measured on Jan., 21th 2017 16:43 (local time).

3.2. Simulation Setups

To obtain useful parameters for the fuzzy-logic, a broad variety of hydrometeors needs to be simulated. Most crucial is the distinction between rain and hail. Therefore, we will focus on those two (main-)classes here.

To simulate all possible rain drops, which could appear in the radar volume, a variety of different settings has to be considered in the simulations. The following specifications of simulation parameters should cope with all probable kind of rain drops to some extent:

- Medium (inner and outer) is liquid water
- Dielectric constants for 30 °C, 20 °C, 10 °C and 0 °C

- Drop diameters from $0.1\,\mathrm{mm}$ and up to $50\,\mathrm{mm}$ with step size of $0.1\,\mathrm{mm}$
- Tumbling: Canting angle distributions have standard deviations of $7°$, $20°$ or $45°$.
- Axis-ratio of droplets depends on drop diameter and follows (2.1).

For hail - in general - other specifications are important. Not only can hail be dry and wet, but also appear in various combinations of size, shape and density. Later on three size categories for hail will be used: small hail ($D < 2.5\,\mathrm{cm}$), large hail ($2.5\,\mathrm{cm} \geq D < 5\,\mathrm{cm}$) or giant hail ($D \geq 5\,\mathrm{cm}$). Therefore, the simulation results will be split into these three groups as well. In certain heights only dry hail appears and in lower heights only wet hail may appear. Therefore, in the later classification additionally discrimination for range gates in dependency on the temperature of the radar volume has to take place (compare with Ortega et al. (2016)). Following specifications will be considered in the simulations:

- Inner medium is ice (with variable density) and outer medium is either ice (with same density as inner medium) or liquid water.
- If outer medium is liquid, the water coat will be simulated to be $0.5\,\mathrm{mm}$ thick.
- Dielectric constants at $20\,°\mathrm{C}$, $0\,°\mathrm{C}$ and $-10\,°\mathrm{C}$ for each medium (*i.e.* various combinations of different temperature are possible with mixed media)
- Particle diameters from $1\,\mathrm{mm}$ up to $25\,\mathrm{mm}$ (small hail), $26\,\mathrm{mm}$ up to $50\,\mathrm{mm}$ (large hail) and $51\,\mathrm{mm}$ up to $100\,\mathrm{mm}$ (giant hail). Each with $1\,\mathrm{mm}$ step-size.
- Axis-ratio for small hail will follow (2.2). For large and giant hail it will be set to 0.5, 0.6, 0.7, 0.8, 0.85, 0.9, 0.95, 1.0.

With the simulation results trapezoidal membership functions can be defined. E.g. for differential reflectivity Z_{DR} for rain we obtain values as shown in Fig. 2. The probability shown (blue histogram) is determined by the occurrence of the respective value and the total number of simulations for this class (here rain). The edges of the trapezoidal function are here determined by the 5, 25, 75 and 95 percentiles of all simulated values of this class. Most values are found to be around $+0.2\,\mathrm{dB}$. With these values a fuzzy-logic algorithm (*e.g.* as in Park et al. (2009)) could be fed to consider Z_{DR} at C band. With this approach, parameters based on simulations instead of empirical values can be set for all polarimetric values. However, the simulations reflect every variation of a simulated hydrometeor alike. This does not necessarily mean, that all variations appear in observation equally. But no polarimetric signal of any variation is hereby missed or underestimated by probability assumptions of appearance (*e.g.* by a drop-size distribution).

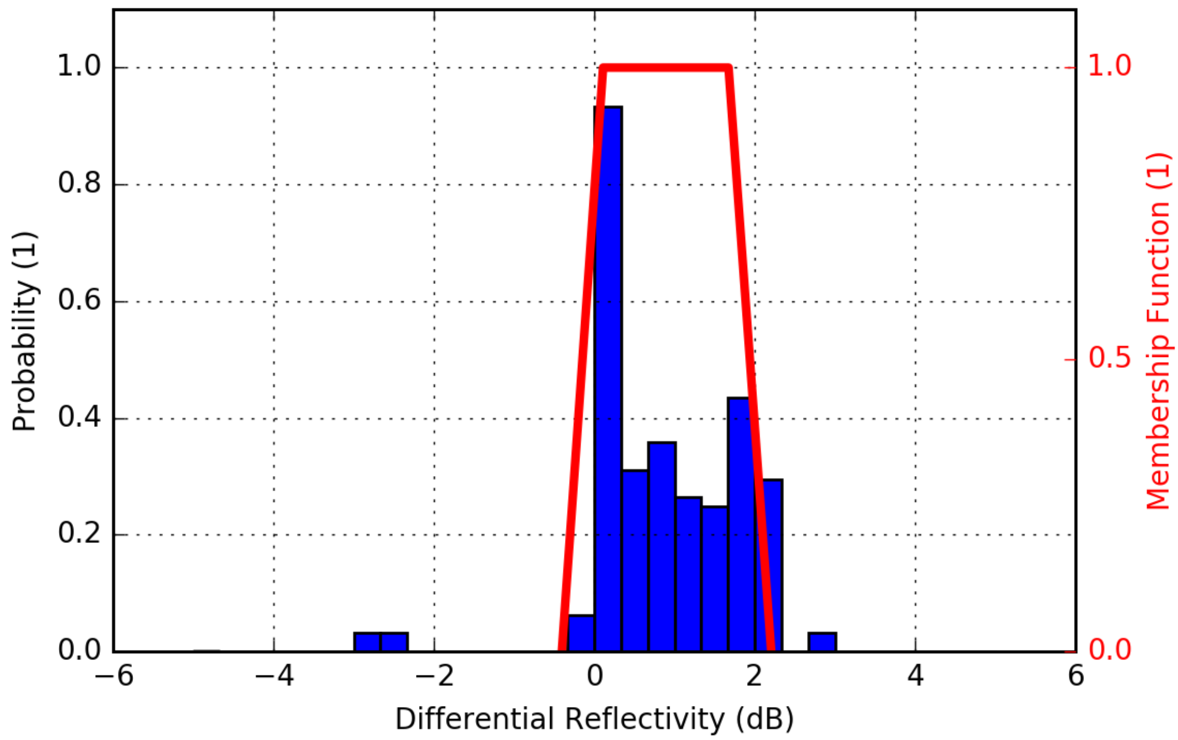


Figure 2: Probability of occurrence of differential reflectivity in T-matrix backscattering simulation for rain shown as histogram in blue. See text for simulation specifications. Trapezoidal membership function in red is obtained by 5, 25, 75 and 95 percentiles of simulated values.

4. Limits of this approach

Some assumptions have been made during developing the proposed method. Therefore, limits and drawbacks of the approach are mentioned here. Without making claims of being a complete list of all flaws, here are some of which should be kept in mind:

- the used scattering model may not be able to correctly model ice crystals and biological scatter. For these two classes empirical values may be much more accurate.
- all possible kind of hail variations were meant to be thought of and realized in the simulations. However, some hail variations are missing. *E.g.* only regular shapes are possible to be simulated and non-regular shapes (*e.g.* spiky hailstones) could not be simulated.
- every simulation is weighted to be equally important as every other simulation. In nature, some "simulations" may appear more often than others and lead to different polarimetric observations.
- each simulation considers currently only a single set of hydrometeors (*e.g.* large rain drops). In nature all kind of different hydrometeors could appear in the same radar volume and lead to different scattering results.

5. Conclusion and Current Work

We have shown that the unmodified HCA with default parameters is not suitable for the application on C-band radars. Adjustments to the parameters used for the fuzzy-logic are required. This could be done reliably by scattering simulations - although with limits - as proposed here.

As concluded in former work, the specific attenuation A_h is a unique polarimetric variable for hail size discrimination as it is the only polarimetric variable known so far, which monotonically increases with size diameter at C band (see Schmidt et al. (2017)). Therefore, we highly recommend including A_h in hydrometeor classification algorithms.

Lastly, a third modification is recommended: different hail classes for differently sized hail, since scattering behavior of hail varies with size. Not only provides a separation of hail into sized subclasses (e.g. small, large and giant hail) more information, it may improve the reliability to detect hail too.

The current approach being tested is well suited for nowcasting in operational systems. With the required radar data loaded, the discrimination algorithm yields hydrometeor classes and hail size classes for a given set of fuzzy-logic parameters in less than a few seconds on a modern Linux PC. With multiprocessing this can be reduced even further.

At the time being not all simulations are finished and not all results are available yet. However, work is in progress and further results (*e.g.* parameters range for fuzzy-logic) are currently being produced. Once testing and evaluation is done, these parameters will be published separately.

Once all parameters have been determined, the modified algorithm will be applied to the German polarimetric radar network. Using the hail size reports of the growing European Severe Weather Database (ESWD), the hail classification and discrimination will be evaluated.

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