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Enhancing the Membership Functions of a Fuzzy Hydrometeor Classifier in a C-Band Weather Radar System

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Dual-polarization precipitation radars (operating in S, C, and X bands) can effectively differentiate between meteorological and non-meteorological scatterers, as well as identify various types of hydrometeors, including rain, hail, graupel, and different forms of snow. Hydrometeor classification plays a crucial role in enhancing weather predictions, identifying severe weather events, and providing accurate measurements of precipitation. These measurements are essential in the fields of meteorology, aviation safety, agriculture, and water resource management. Additionally, hydrometeor classification improves the interpretation of radar data and supports climate studies by offering detailed insights into precipitation patterns and changes.

Several techniques can be utilized for hydrometeor classification based on dual-polarization radar signatures: (i) the decision tree method, (ii) classical statistical decision theory, (iii) neural network techniques, and (iv) fuzzy logic. Among these techniques, the fuzzy logic method is particularly suitable for addressing the current problem due to the non-mutually exclusive and non-unique radar signatures of different hydrometeors. The principles of fuzzy logic were initially investigated by Straka and Zrnic (1993) and Straka (1996). Since then, they have been further refined and developed into more sophisticated classification routines by Zrnic and Ryzhkov (1999), Vivekanandan et al. (1999), Liu and Chandrasekar (2000), Zrnic et al. (2001), Schuur et al. (2003), Keenan (2003), Lim et al. (2005), and Marzano et al. (2008), among others.

C-band dual-polarization radar is deployed by Indian Institute of Tropical Meteorology (IITM) at its Atmospheric Research Testbed (ART) Facility in Silkheda, located in the monsoon core zone. Since June 2021, this radar has been collecting the Doppler and polarimetric observations of precipitating cloud systems over the region. In this study, we have used polarimetric measurements to adjust and improve the parameters of membership functions for C-band fuzzy logic-based hydrometeor classification, as the parameters of the membership function depend on the frequency band used by the radar.

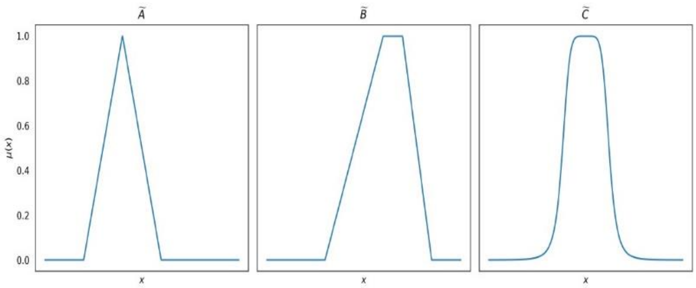

Figure 1. Example of different fuzzy sets

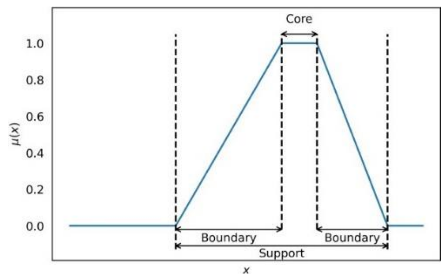

Figure 2. membership function with core, support and boundary

Figure 1 depicts several common examples of shapes that are often utilized as fuzzy membership functions for hydrometeor classification. These shapes include the triangular, trapezoidal, and Gaussian membership function. Figure 2 depicts the different segments of a standard membership function. The core signifies the area where membership is fully established, while the support represents the region where membership exists to some degree, although not complete. On the other hand, the boundary indicates the region where membership is not fully established, but still present to some extent. As a result, the support encompasses both the core and boundary regions. Figure 3 shows a scatter plot between differential reflectivity (Zdr) and reflectivity (Zh) measurements from 1.5^0 elevation and 360^0 azimuths where the SNR is more than 10 dB during a rain even. The simple regression analysis reveals a slight upward trend, indicating a positive correlation between Zh and Zdr. Specifically, as Zh increases, Zdr tends to increase, which is commonly associated with the presence of larger raindrops or a greater volume of liquid precipitation. This weak positive correlation suggests that an increase in the size or concentration of hydrometeors is accompanied by corresponding changes in their morphological characteristics and composition. The one-dimensional trapezoidal membership functions for various precipitation types have been plotted for both Zh and Zdr using a C-band weather radar data (Fig 4 & 5). The modified trapezoid vertices have been estimated by taking the minimum, 25th percentile, 75th percentile, and maximum values, respectively, for reflectivity and differential reflectivity. Furthermore, an enhanced two-dimensional membership function has been derived and plotted, as illustrated in Figure 6. This figure depicts the variation of differential reflectivity with respect to reflectivity parameters for all the considered precipitation types, providing a comprehensive overview of their interdependencies. Different precipitation types (e.g., rain, snow, hail) do not exhibit clearly distinct relationships between Zh and Zdr. Typically, liquid precipitation displays higher ZDR values than ice or mixed-phase precipitation at equivalent reflectivity levels. Dry snow and wet snow have similar characteristics, but the presence of liquid particles in wet snow results in higher Zdr and Zh values compared to dry snow. Hail exhibits very high reflectivity (around 60 dB) but has a lower ZDR than heavy rain. By refining membership functions to better capture the nuances in reflectivity and differential reflectivity values, such as the distinct characteristics of dry and wet snow or the unique signature of hail, we can more accurately classify different precipitation types. This leads to more precise radar-based precipitation analysis and forecasting.

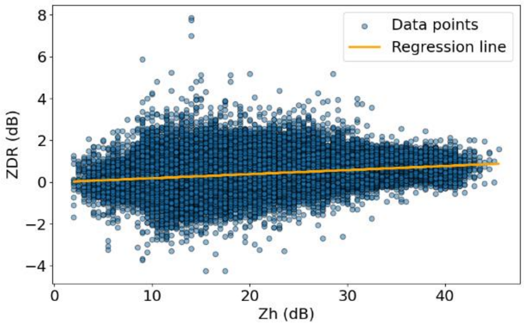

Figure 3. Scatter plot Zdr vs Zh

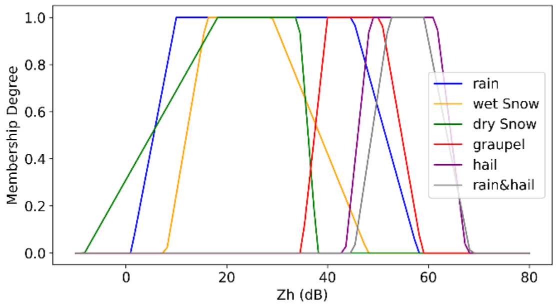

Figure 4. 1D membership functions (Zh)

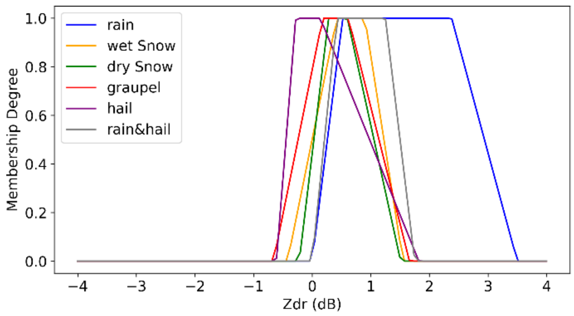

Figure 5. 1D membership functions (Zdr)

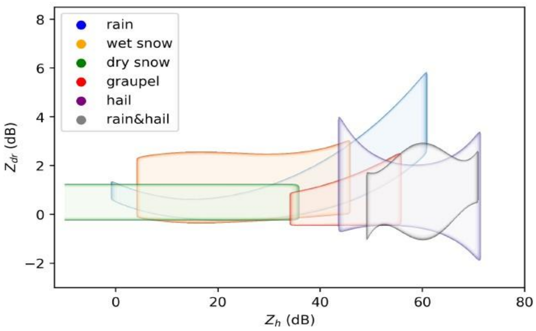

Figure 6. 2D membership functions (Zdr, Zh)

The fuzzy logic membership functions for various hydrometeors observed by a C-band weather radar have been improved using a statistical approach. The breakpoints of the membership functions have been determined based on the minimum, 25th percentile, 75th percentile, and maximum values of the radar variables. By applying a statistical method to optimize the breakpoints of the fuzzy trapezoidal membership functions, the overall two-dimensional fuzzy membership functions have been enhanced, as shown in Figure 6. This approach establishes clear classification boundaries among hydrometeors, even in a noisy and non-mutually exclusive dataset that lacks distinct thresholds for hydrometeor identification. This will enable better discrimination between hydrometeor types such as rain, dry snow, wet snow, and others. By utilizing these refined membership functions, the radar can more accurately classify the different hydrometeors present in the observed data.

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