

# Use of a fuzzy logic classification scheme with a C-band polarimetric radar: first results

P. P. Alberoni<sup>1</sup>, D. Zrnic<sup>2</sup>, A. Ryzhkov<sup>2</sup>, and L. Guerrieri<sup>3</sup>

<sup>1</sup>ARPA-SMR, Bologna, Italy

<sup>2</sup>NSSL-NOAA Norman, OK, USA

<sup>3</sup>CNR-ISAC, Bologna, Italy

**Abstract.** The correct classification of prevailing bulk hydrometeor type within a radar resolution volume should be a prerequisite of any quantitative rain-retrieving scheme. Further, the classification is also useful for warning purposes and for validation of non-hydrostatic models where the physical parameterizations is so advanced that major hydrometeor species are represented. Most of the work in this field is based on the use of S-band data that is less affected by attenuation compared to shorter wavelengths. In this paper, we utilize the scheme developed at the National Severe Storms Laboratory (USA). Briefly, the scheme uses a fuzzy logic approach to combine different polarimetric variables in order to determine the most likely type of hydrometeor present. We use a reduced set of polarimetric variables ( $Z$ ,  $Z_{DR}$ ) collected with a C-band radar over weather events ranging from convective to stratiform.

## 1 Introduction

After the scientific evidence accumulated in the last decade, it is clear and acknowledged by radar meteorologists that polarimetry will play a fundamental role in the use of weather radar. Polarimetric radar data is pertinent and has potential application to many diverse fields from improving quantitative precipitation estimates to identification of scatterers nature and type, up-to improving initial conditions and constraints in numerical models for short term forecasts. Refer to Zrnic and Ryzhkov (1999) for a summary of the state-of-the-art of polarimetry for weather surveillance radar.

A never-ending task such as the best estimation of the rain pattern will benefit from the polarimetric information. Indeed, the correct classification of prevailing bulk hydrometeor type within a radar resolution volume should be a prerequisite of any quantitative rain-retrieving scheme. Further, the classifications is also useful for warning purposes and

for validation of non-hydrostatic models where the physical parameterizations are so advanced that major hydrometeor species are represented.

Most of the work in this field is based on the use of S-band data, but the prospects of the deployment, in a near future, of polarimetric radar in Europe motivate the research community to increase research with the shorter wavelength radars. Radar data taken at C-band or X-band are affected by attenuation and resonance (see among others Holt et al., 1997; May et al., 1999; Zrnic et al., 2000). The difficulties, normally present in trying to identify the bulk hydrometeor types within a radar resolution volume, such as incomplete understanding of radar signatures, ambiguities in hydrometeor classes, occurrence of artifacts in the data, and uncertainties in radar calibration are amplified by propagation effects at C-band.

For this reason particular attention and efforts should be addressed to adapt procedures from S-band and validate these at C-band. In this paper, we utilize the scheme developed at the National Severe Storms Laboratory (USA) (hereinafter referred as NSSL scheme), with a reduced set of polarimetric variables ( $Z$ ,  $Z_{DR}$ ) collected at C-band.

## 2 Hydrometeors classification scheme

The NSSL scheme is based on fuzzy logic, the reader should refer to Straka et al. (2000) and Zrnic et al. (2001) for an exhaustive explanation of the method. Briefly it is based on a combination of weighting (membership) functions associated with a particular hydrometeor type. These functions are two-dimensional, one argument is of the polarimetric variables and the other is reflectivity factor  $Z$ . The classification is done by taking the highest value of the combination of weighting functions for each image pixel.

The original version of the NSSL scheme uses four different radar variables plus the temperature profile (to remove some ambiguities). The variables are: reflectivity ( $Z$ ), differential reflectivity ( $Z_{DR}$ ), specific differential phase (KDP)

**Table 1.** Weight coefficients

	$A_Z$	$A_{ZDR}$	$A_{KDP}$	$A_{\rho_{hv}}$	$A_T$
Original NSSL scheme	1	1	0.8	0.3	0.4
GPM 500C	1	1	0	0	1

and the cross-correlation coefficient between the horizontally and vertically polarized waves ( $\rho_{hv}$ ).

Currently, there are 11 hydrometeor classes that build on the synthesis in Straka et al. (2000); the classes are:

1. Light rain (LR);
2. Moderate rain (MR);
3. Heavy rain (HR);
4. Rain dominated by large drops (LD);
5. Rain/hail mixture (RH);
6. Graupel and/or small hail (GSH);
7. Hail (HA);
8. Dry snow (DS);
9. Wet snow (WS)
10. Horizontally oriented ice crystals (HIC);
11. Vertically oriented ice crystals (VIC).

For a fixed  $Z$  a trapezoidal membership function over a polarimetric variable describes the valid range associated with each specific bulk hydrometeor type.

Finally a weight coefficient defines the relative importance (confidence in) of each variables considered. The weight coefficients for the original NSSL scheme and for the implementation under test are indicated in Table 1.

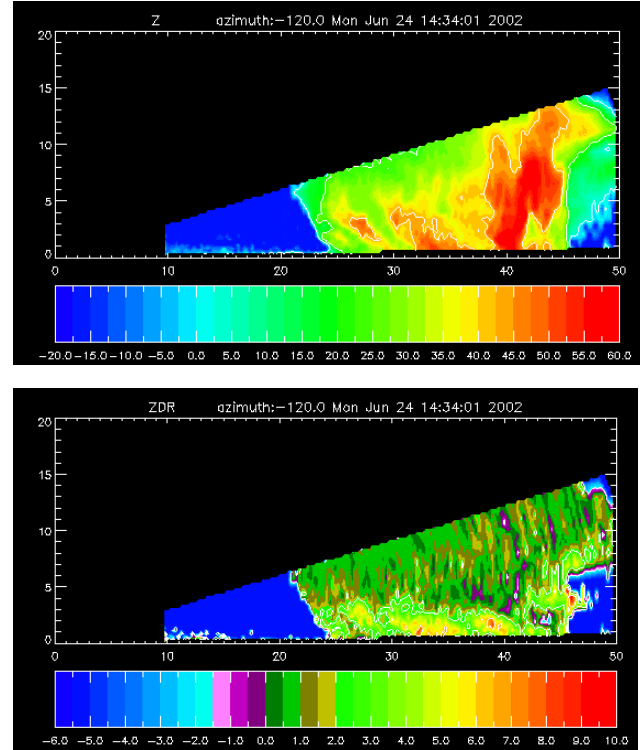
The NSSL scheme is designed to take advantages of the presence of all available polarimetric variables and also to work with a reduced set of these. As discussed in Zrníc et al. (2001), the most discriminating variables are the reflectivity factor and the differential reflectivity. Based on this fact, we expect to obtain reasonable results with our C-band polarimetric radar, which provides the two most significant variables for classification.

### 3 Radar data

Data presented here were collected with a GPM 500C radar. It is a C-band dual-linear polarized radar equipped with an offset antenna with a beam width of  $0.9^\circ$ . The antenna has a gain of 46 dB and isolation between channels of about 28 dB.

The polarization circuit uses a ferrite switch so that the differential reflectivity data are collected from alternately transmitted H and V pulses.

Data were obtained during routine operational schedule and no correction for attenuation and differential attenuation is applied.



**Fig. 1.** – 24 June 2002 14:34 GMT (a) Reflectivity data, contour lines at  $-20.$ ,  $0.$ ,  $20.$  and  $40.$  dBZ; (b) Differential reflectivity data, contour lines at  $-2.$ ,  $2.$  and  $6$  dB.

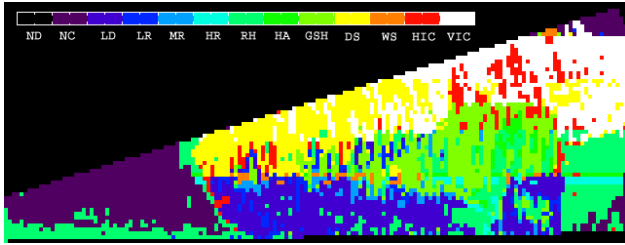
### 4 Some examples

Data presented here come from a convective event that occurred over the hills southwest of Bologna in the afternoon of 24 June 2002.

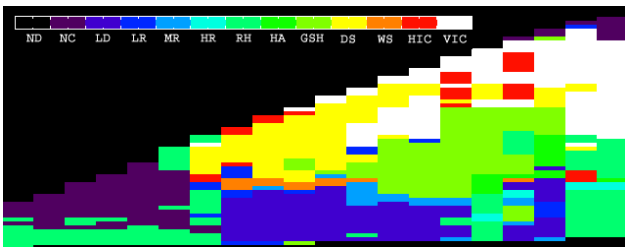
Vertical cross-section of the observed variables reveals the structure of the convective storm core at 14:34 GMT (Fig. 1). The main reflectivity storm core (Fig. 1a) is located at 40 km with another core few km behind in which the weak echo region is clearly defined. Also present in this vertical section are some developing cells close to the radar.

The vertical cross-section of differential reflectivity (Fig. 1b) indicates the presence of rain in the lowest 3 km. The presence of hail is suggested by high  $Z$  and drop of  $Z_{DR}$  at ranges between 40 and 41 km and height between 2 and 3 km. It also appears to be a three body scattering signature in the rear of the storm, where very high  $Z_{DR}$  values are detected at about 4 km altitude. The storm anvil shows values that seem to be little higher than expected, so that a possible offset problem could be present in the data.

A direct application of the NSSL scheme on this data set is shown in Fig. 2. The general pattern is quite reasonable. Light to medium rain is identified below the zero degree level and ahead and behind the main storm core. A column of hail/rain mixture with some hail pixels embedded form the core. Graupel and small hail dominate higher levels of the convective section, while in the section close to the radar, dry



**Fig. 2.** – 24 June 2002 14:34 GMT Vertical cross section of classified hydrometeors for data from Fig. 1. The letters below the color bar correspond to the hydrometeors categories as follows: ND = No data; NC = not classified; LD = large drops rain; LR = light rain; MR = moderate rain; HR = heavy rain; RH = rain/hail mixture; HA = hail; GSH = graupel small hail; DS = Dry snow; WS = wet snow; HIC = horizontally oriented ice crystals, and VIC = vertically oriented ice crystals.



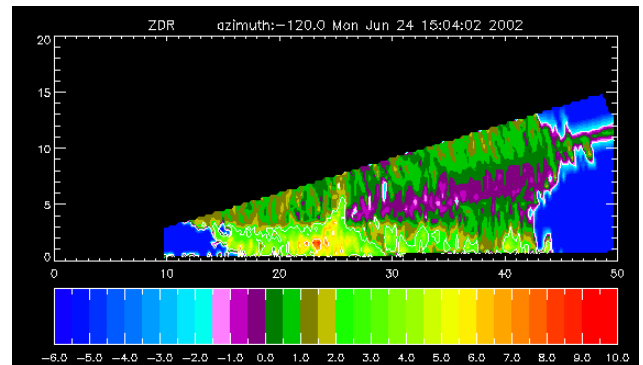
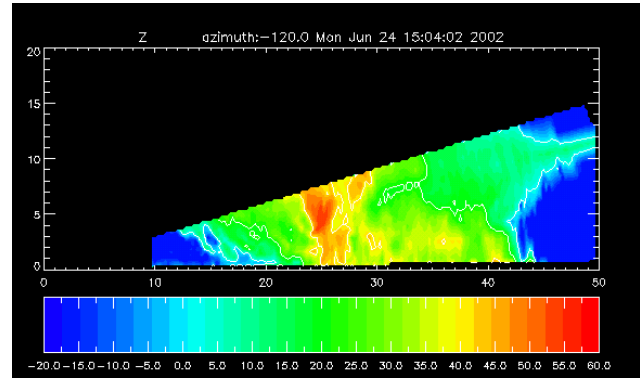
**Fig. 3.** – 24 June 2002 14:34 GMT Vertical cross section of classified hydrometeors for data from Fig. 1 resampled at 2 km horizontal resolution. The letters below the color bar correspond to the hydrometeors in Fig. 2.

snow is identified. This latter type is in accordance with the dynamics of this section of the storm; indeed, the reflectivity (Fig. 1a) clearly shows some feeder cells at about 30 km distance. Some wet snow aggregates are detected only at the melting layer. In the remaining part of the anvil vertical ice crystals are the dominant bulk hydrometeor. It is evident that this feature is unrealistic and partly caused by the temperature profile. (Note that the main discriminator of vertical crystals in the NSSL scheme is  $K_{DR}$ )

Superposed on this general picture a sort of stripe structure is present and clearly distinguishable above the melting layer. This causes a chaotic texture in the classification pattern.

To reduce the impact of this feature and following the suggestion by Zrnic et al. (2001), the  $Z$  and  $Z_{DR}$  fields are smoothed to get a resolution of 2 km in the horizontal plane. The classification obtained is shown in Fig. 3. The noisy pattern is of course reduced and conversely the overall structure of the storm is highlighted. We want to stress here that no “true” observation of the hydrometeors species are available to validate the result of the classification scheme. Thus, the way to judge the scheme is by observing that the overall picture is “physically reasonable”, in accord with conceptual models and it is compatible with output of cloud models.

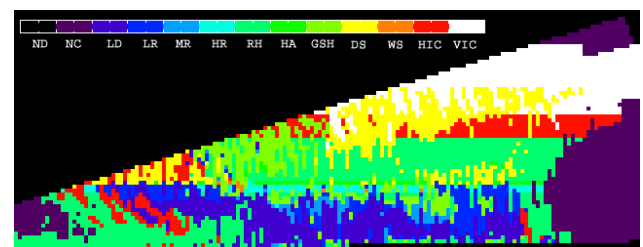
The vertical structure of the storm at 15:04 GMT is characterized by a core of high reflectivity at higher levels (Fig. 4a),



**Fig. 4.** – 24 June 2002 15:04 GMT (a) Reflectivity data, contour lines at  $-20.$ ,  $0.$ ,  $20.$  and  $40.$  dBZ; (b) Differential reflectivity data, contour lines at  $-2.$ ,  $2.$  and  $6$  dB.

with the presence of a possible three body scattering signature at the end of the system. There is a hint of attenuation behind the reflectivity core. A much more evident feature is differential attenuation in the differential reflectivity cross-section (Fig. 4b), where a strike of negative  $Z_{DR}$  values is present from 27-km distance to the end of the cloud. A positive  $Z_{DR}$  column is visible at 25-km range; it suggests presence of an updraft that feeds the reflectivity core aloft.

The vertical structure (Fig. 5) of identified bulk hydrome-



**Fig. 5.** – 24 June 2002 15:04 GMT Vertical cross section of classified hydrometeors for data from Fig. 1. The letters below the color bar correspond to the hydrometeors categories as follows: ND = No data; NC = not classified; LD = large drops rain; LR = light rain; MR = moderate rain; HR = heavy rain; RH = rain/hail mixture; HA = hail; GSH = graupel small hail; DS = Dry snow; WS = wet snow; HIC = horizontally oriented ice crystals, and VIC = vertically oriented ice crystals.

teers species is quite reasonable up to the region of significant attenuation. Further in range the attenuation and differential attenuation perturbations dominate the results of the scheme. A huge amount of hail is wrongly classified in the whole attenuation cone. As in the previous case, an unrealistic anvil of horizontal and vertical ice crystals is detected. The underlining vertical stripes are clearly due to the decrease in temperature with height.

Some minor misclassifications affect the radar bins in the front of the system. Mixture of rain and hail and horizontal ice crystals are wrongly detected there.

## 5 Conclusion

Polarimetric measurements at C-band from a convective storm that occurred on 24 June 2002 close to Bologna (Italy) were automatically interpreted with the NSSL classification scheme. The scheme originally developed for S-band polarimetric data has been tested on C-band measurements.

The major difference between the two frequencies is the effect on the data due to attenuation. At S-band the attenuation is much smaller but at the high frequency it can dominate the classification and therefore should be, at least roughly, corrected. The effect of this feature clearly and heavily affected the classification in one of the case presented.

Apart from the area corrupted by attenuation, the general behavior of the NSSL scheme is quite adequate. It gives an overall picture that is “physically reasonable”. Some minor adjustments of the weighting coefficients are needed to reduce the number of misclassified pixels.

The cross-combination between radar measurables done

within the scheme has highlighted also a possible offset problem in the polarimetric data.

Overall, we intend to proceed further with testing and evolving the NSSL scheme on C-band polarimetric radar data.

*Acknowledgement.* Partial funding of this research is provided by CARPE DIEM (contract EVG1-CT-2001-00045 a shared-cost project co-founded by the Research DG of the European Commission within the RTD activities of generic nature of the Environment and Sustainable Development sub-program 5th Framework Programme) and by the GNDCI project. One author (LG) acknowledges the CNR project Nowcasting.

## References

- Holt, A.R., Watson, R.J., Chandra, M., Nanni, S. and Alberoni, P.P., 1997: A comparison of C-band observations using different polarisation schemes. Preprints, 28th Conf. on Radar Meteorology, Austin, TX, Amer. Meteor. Soc., 15-16.
- May, P.T., Keenan, T.D., Zrnica, D.S., Carey, L.D. and Rutledge, S.A., 1999: Polarimetric radar measurements of tropical rain at a 5-cm wavelength. *J. Appl. Meteor.*, 38, 750-765.
- Straka, J.M., Zrnica, D.S., Ryzhkov, A.V., 2000: Bulk hydrometeor classification and quantification using polarimetric radar data: synthesis of relations. *J. Appl. Meteor.*, 39, 1341-1372.
- Zrnica, D.S. and Ryzhkov, A.V., 1999: Polarimetry for weather surveillance radars. *Bull. Amer. Meteor. Soc.*, 80, 389-406.
- Zrnica, D.S., Keenan, T.D., Carey, L.D. and May, P., 2000: Sensitivity analysis of polarimetric variables at a 5-cm wavelength in rain. *J. Appl. Meteor.*, 39, 1514-1526.
- Zrnica, D.S., Ryzhkov, A., Straka, J., Liu, Y. And Vivekanandan, J., 2001: Testing a procedure for automatic classification of hydrometeor types. *J. Atmos. Oceanic Technol.*, 18, 892-913.