Proceedings of ERAD 2006

The prevailing raindrop shape obtained by polarimetric radar measurements

Eugenio Gorgucci [1], Luca Baldini [1], V. Chandrasekar [2]

[1] Institute of Atmospheric Sciences and Climate – CNR, Roma (Italy).

[2] Colorado State University, Fort Collins CO (USA).

1 Introduction

Polarimetric radar measurements are used to retrieve properties of raindrop distributions. While there has been extensive research conducted on microphysical retrievals such as hydrometeor classification or hail detection, there has not been much research into polarimetric radar based deduction of raindrop shape even though the shape of raindrops plays a critical role in rainfall estimation from polarimetric radars. Equilibrium shape of raindrops as the result of a balance of surface tension, aerodynamic forces, and hydrostatic and internal pressures has been assumed in earlier studies, although it was observed that the average shape departs significantly from that of the equilibrium. There has been considerable discussion about the deviation of the drop axis ratio from its equilibrium value (Goddard et al. 1982; Beard and Chuang 1987; Chandrasekar et al. 1988; Bringi et al. 1998; Andsager et al. 1999; Gorgucci et al. 2000; Keenan et al. 2001; Brandes et al. 2002; Thurai and Bringi 2005). Studies have produced different models emphasizing that a nonlinear relationship should be better than a linear one. Using the self-consistency of the polarimetric radar measurements, Gorgucci et al. (2000) proposed a shape-size model in terms of the linear slope (β) approximating the implied shape-size function as

$$\frac{b}{a} = r = 1.03 - \beta D \tag{1}$$

In (1), a/b = 1 if $D < 0.03/\beta$. For β=0.062 mm^{-1}, (1) is close to the equilibrium shape-size relation of Pruppacher and Beard (1970), and therefore such value is denoted by β_e. A $\beta > \beta_e$ indicates that raindrops are more oblate than at equilibrium, whereas $\beta < \beta_e$ indicates raindrops are less oblate (or closer to spherical) than at equilibrium.

Correspondence to: Eugenio Gorgucci

e.gorgucci@isac.cnr.it

In this work, the retrieval of the drop shape directly from polarimetric radar measurements is presented and evaluated. using radar data collected in regions with different climatological regimes (here, Florida and Italy).

2 Polarimetric radar measurement: DSD and drop-shape relation

Raindrop size distribution and drop shapes are of central importance in determining the electromagnetic scattering properties of rain-filled media. Their effects are embodied in the radar parameters of interest such as reflectivity factor ($Z_{h,v}$), differential reflectivity (Z_{dr}), and specific differential phase (K_{dp}).

Assuming a normalized gamma DSD model Rayleigh scattering, and the linear raindrop shape model (1), it can be shown that

$$\frac{K_{dp}}{Z_h} = g(\mu)\frac{\left(1 - r_m\right)}{\left[\frac{1}{\beta}\left(1 - Z_{dr}\right)^{-3/7}\right]^3} \tag{2}$$

where r_m is the mass weighted raindrop axis ratio (Bringi and Chandrasekar 2001) and $g(\mu)$ combines all the constants as well as functions of the DSD shape parameter μ. It should be noted that $g(\mu)$ is nearly constant and does not vary too much with μ yielding the relation between (K_{dp}/Z_h) and Z_{dr} is dependent only on the shape model (Gorgucci et al., 2006). Though the above expression was derived assuming a linear model for raindrop shape-size relation, it is a general result that the relation between (K_{dp}/Z_h) and Z_{dr} is completely dependent on the raindrop shape model, and nearly independent of the DSD parameters.

3 Data sources

3.1 Radar measurements

The radar polarimetric data used in this paper were collected by the NCAR S-POL S-band dual-polarized radar during two campaigns in different climatological regions: i) Central Florida (TEFLUN-B campaign of the Ground Validation component of TRMM, 1998) and ii) North Italy (Mesoscale Alpine Programme MAP, September 1999). The TEFLUN-B profiles were selected from the entire campaign while the MAP profiles refer only to the Intense Observation Period IOP 02 (September 19-21, 1999) characterized by the passing of a frontal cloud system with embedded convective elements that yielded heavy rainfall throughout the region. The chosen rain radar profiles are all paths containing 100 range bins distanced 0.150 m apart with an increasing differential phase along the path greater than 10 degrees. The data used were carefully selected to avoid contamination of the rain radar profile from ground clutter, bright band and anomalous propagation effects, etc. Here 4982 and 1280 profiles are considered for Florida and Italy, respectively.

3.2 Simulation of radar measurements for various drop-shape models

Assuming the DSD parameters varying in a wide range ($0.5 \le D_0 \le 3.5$mm,$3 \le \log_{10} N_w \le 5$, and $-1 < \mu < 5$), for each drop-shape relation, radar measurements Z_h, Z_{dr}, and K_{dp} are simulated at S-band (3 GHz) using the constraints of $10\log_{10}Z_h < 55$ dBZ at for S-band and R < 300 mm h^{-1}. It is assumed that the drops are canted with the mean canting angle equal to zero and the width of the canting angle distribution 10°. In conclusion, for a wide range of DSD triplets (100000) a data set of simulated radar measurements was built for each of drop-shape models. The following axis ratio relationships are here chosen among those commonly used in the literature:

- the experimental linear relation of Pruppacher and Beard (1970) [PB]
- the equilibrium relation of Beard and Chuang (1987) [BC]
- the experimental relation of Andsager et al. (1999) [ABL] for 1<D<4; outside this interval the BC relation was taken
- the cubic-polynomial fit by Keenan et al. (2001) [KCZM]
- the linear relation with the slope β=0.04 mm^{-1} [β4]
- the linear relation with the slope β=0.05 mm^{-1} [β5]
- the linear shape with the slope β=0.07 mm^{-1} [β7]

3.3 Reconstructed S-band rain profiles

The selected profiles of Z_h and Z_{dr} obtained from TEFLUN-B and MAP were used to generate realistic profiles of DSD parameters (Chandrasekar et al. (2006). It was shown by Scarchilli et al. (1996) that triplets of Z_h, Z_{dr}, and K_{dp} nearly lie on a three-dimensional surface when the drop-shape model is fixed. Therefore, once Z_h and Z_{dr} are specified, the choice of possible K_{dp} values falls in a narrow range. For each (Z_h, Z_{dr}) pair in the S-POL profiles, a search in each data set of the simulated radar measurements corresponding to the drop-shape models listed above provides a possible choice of DSDs that satisfy the observations. One is randomly chosen to establish the reconstructed S-band rain observation profile corresponding to a fixed drop-shape model.

4 Drop-shape retrieval methodology

The previous discussion has demonstrated that K_{dp}/Z_h versus Z_{dr} curves depend on the drop shape. Fig. 1 shows the scatter plot of K_{dp}/Z_h as a function of Z_{dr} for widely varying DSDs and for different drop-shape relations. The DSD variability results in points along the tight curve and any change in drop-shape model moves the curve up and down. This figure can be considered as two dimensional manifestation of the self consistency principle of polarimetric measurements in rain, cast in a way that the variability in drop-shape model is enhanced while suppressing DSD variability.

4.1 Practical considerations

The radar measurements Z_h, Z_{dr} and K_{dp} are affected by measurement errors that will directly translate into an error of the parameter that must be estimated. These radar measurements have completely different error structures; in addition, these errors are nearly independent. The main difference is that K_{dp} refers to the path over which it is estimated whereas Z_h and Z_{dr} are point measurements referred to the radar resolution volume. To make them comparable, all the measurements are related to a fixed path. In this way, Z_h represents the mean power along the path in logarithm scale, Z_{dr} the ratio between the average power at h and v polarization expressed in dB, and K_{dp} the mean value obtained from the finite difference between the end and the beginning of the differential propagation phase profile. The

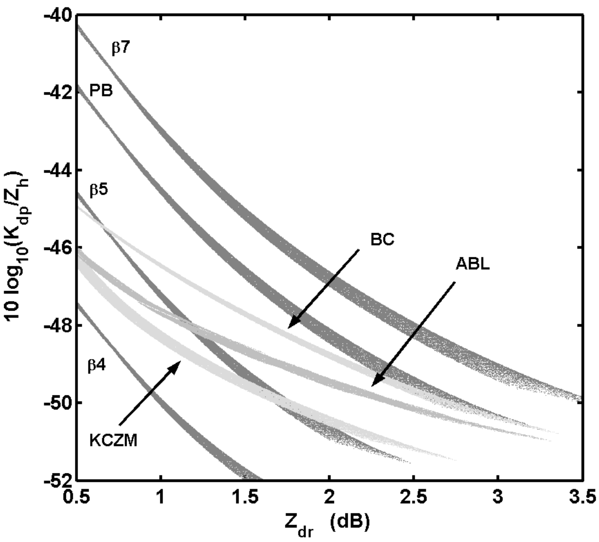

Fig. 1. – Scatter plot of K_{dp}/Z_h ratio for widely varying DSD as a function of Z_{dr} for the nonlinear relations BC, ABL, KCZM and for the linear relations PB, β4, β5, β7.

impact of the path integration on the parameters K_{dp}/Z_h and Z_{dr} was evaluated through simulation. The two quantities K_{dp}/Z_h and Z_{dr} are computed both from point-wise and path-wise measurements. It was seen that also in the occurrence of the DSD variability along the path revealed by the presence of a Z_h gradient, the difference between point- and path-wise values of K_{dp}/Z_h and Z_{dr} is negligible (Gorgucci et al. 2006). Therefore, in the hypothesis of a rain filled medium following a fixed drop-shape model, the model can be retrieved using path-wise Z_h, Z_{dr}, and K_{dp} measurements.

Another aspect regarding the sensitivity of K_{dp}/Z_h versus Z_{dr} relation is the bias on Z_h and Z_{dr} estimates. Z_{dr} is a relative measurement and the bias can be easily removed by several techniques available in the literature (Gorgucci et al. 1999). However, absolute bias on Z_h cannot be removed easily. Any bias on Z_h is directly converted into a shift of the relationship between K_{dp}/Z_h and Z_{dr}.

5 Applications of the methodology

The methodology developed in this paper was applied to retrieve drop shape from polarimetric radar measurements from the Florida and Italy data sets. Figs. 2a and 2b show scatter plots between the ratio K_{dp}/Z_h as a function of Z_{dr} for data collected in Florida on August 8 and September 14 1998, respectively. For the August 8 case (K_{dp}/Z_h, Z_{dr}) points are essentially located around the PB model, while points of September 20 are limited in the space bordered by $\beta5$ and the PB model, showing a drop shape less oblate than the equilibrium.

Figs. 3a and 3b show the distribution of the K_{dp}/Z_h and Z_{dr} values for the two data sets of Florida and Italy, respectively. Fig. 3a shows that the different contours are centred around a parallel line to the PB curve, denoting a linear relation as in the PB model, except that the droplets are more spherical. The same argument can be made for the distribution for the Italy data set, except that the droplets appear more oblate that the PB equilibrium model.

It should be emphasized here that, in the plane defined by the quantities K_{dp}/Z_h and Z_{dr}, these values for the entire data sets are mostly located within the region bordered by the BC and β7 models. It should be noted that in both data sets the underlying drop-shape model approaches the PB model and that the BC model is a border for the sphericity of the drop shape. This means the data set used in this study did not produce any mean raindrop axis ratios less than the axis ratios of BC shape model.

More precisely, for the Florida data set, the distribution shows that 95,9% of the measurements are placed in that surface whereas 3.9% and 0.2% present axis ratios greater than β7 and less than of BC model, respectively. For the Italian data set the values are 93.2%, 6.7% and 0.1%, respectively. However, the two different behaviours are not strictly comparable because the Florida data set refers to measurements distributed over three months whereas the Italy data set is composed by a single convective event.

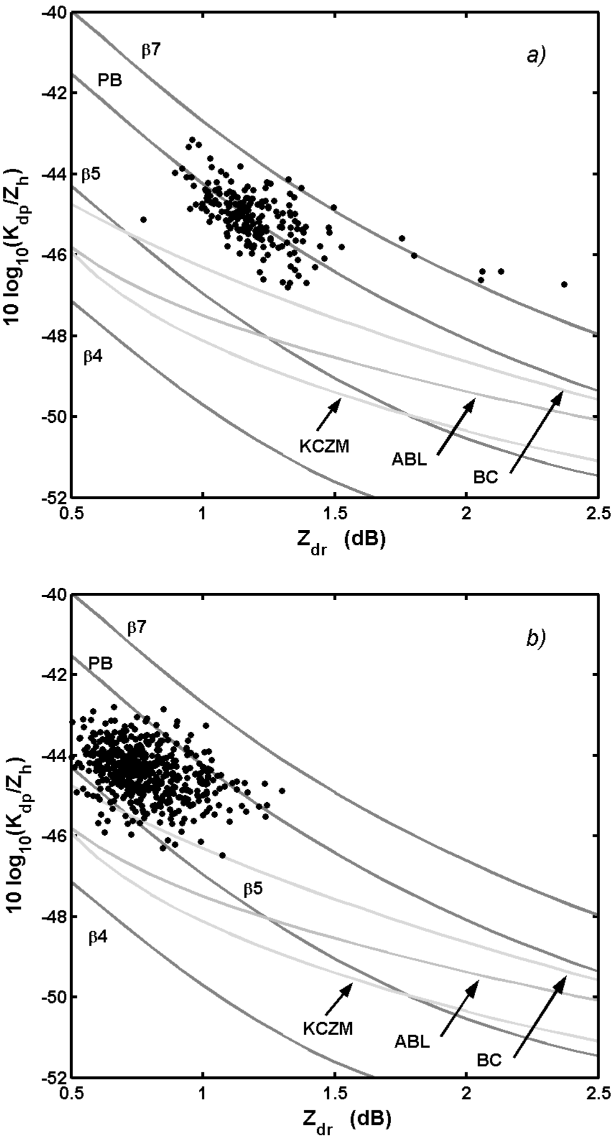

Fig. 2. – Scatter plot between the ratio K_{dp}/Z_h as a function of Z_{dr} for TEFLUN-B data collected: a) on August 8, 1998 and, b) on September 20, 1998. Averaged values for widely varying DSD obtained from the nonlinear relations BC, ABL, KCZM and from the linear relations PB, β4, β5, β7 are also shown.

6 Summary and conclusion

The paper presents a technique by which it is possible to reveal information about the mean actual axis ratio underlying the polarimetric radar measurements. This technique follows the methodology introduced by Gorgucci et al. (1992): to use in synergy mode the radar polarimetric measurements Z_h, Z_{dr}, and K_{dp} and taking into account the generalization operated by Scarchilli et al. (1996) with the self-consistency principle of the polarimetric radar measurements in relation to the weight covered by the microphysical model in the interpretation of polarimetric measurements for quantitative estimation. The methodology presented in this paper is a two dimensional manifestation of the 3D self-consistency principle developed to examine rain drop-shape achieved by considering a two-dimensional

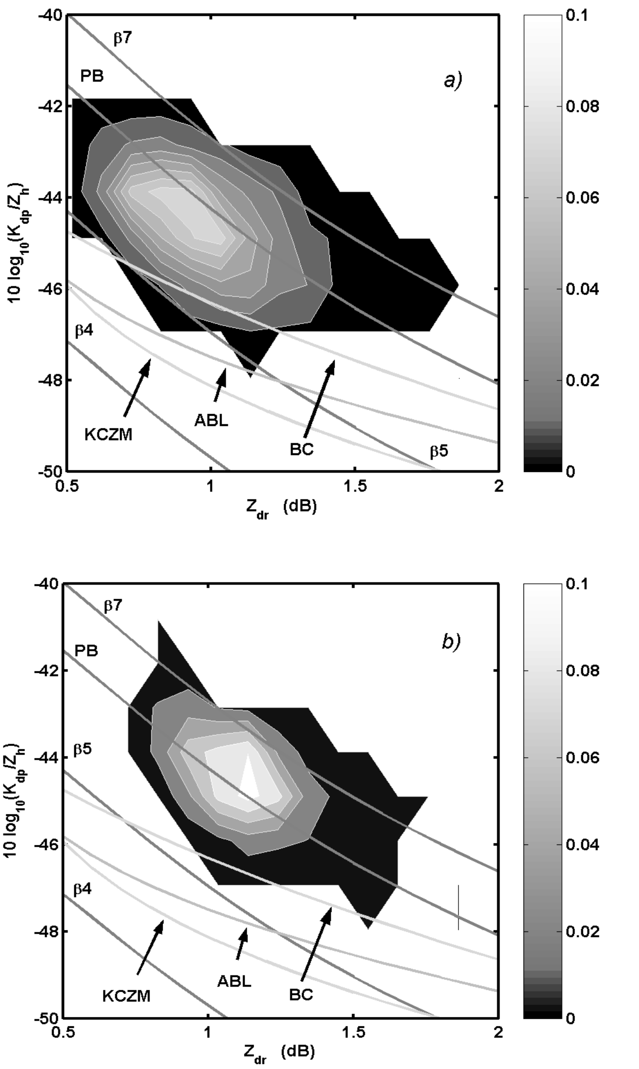

Fig. 3. – Contours of occurrence frequency of the ratio K_{dp}/Z_h as a function of Z_{dr} for Florida a) and Italy data set. Averaged values for widely varying DSD obtained from the nonlinear relations BC, ABL, KCZM and from the linear relations PB, β4, β5, β7 are also shown.

domain defined by the two variables K_{dp}/Z_h and Z_{dr}. Using simulation, it can be seen that for fixed drop-shape models the different K_{dp}/Z_h and Z_{dr} pairs, obtained widely varying DSD are constrained over a well-defined curve. As a result, any changes from the curve depend on variability of the drop shapes. Plotting on this domain the curves relative to the different drop-shape models considered in this study, it is possible to examine the prevailing drop shape related to Z_h, Z_{dr} and K_{dp} measurements.

Acknowledgements: This research was conducted as part of the NASA Precipitation Measurement Mission (TRMM/GPM) program. The research was partially supported by the National Group by Defence from Hydrological Hazard (CNR, Italy) and by the European Commission through the Interreg IIIB CADSES "RISK-AWARE" (3B064) project.

References

Andsager, K., K. V. Beard, and N. F. Laird, 1999: Laboratory measurements of axis ratios for large raindrops. *J. Atmos. Sci.*, **56**, 2673–2683.

Beard K. V., and C. Chuang, 1987: A New Model for the Equilibrium Shape of Raindrops. *J. Atmos. Sci.*, **44**, 1509–1524.

Brandes, E. A., G. Zhang, and J. Vivekanandan, 2002: Experiments in rainfall estimation with a polarimetric radar in a subtropical environment. *J. Appl. Meteor.*, **41**, 674-685.

Bringi, V. N., V. Chandrasekar, and R. Xiao, 1998: Raindrop axis ratio and size distribution in Florida rainshaft: An assessment of multiparameter radar algoritms. *IEEE Trans. Geosci. Remote Sens.*, **36**, 703–715.

Bringi, V. N., and V. Chandrasekar, 2001: Polarimetric Doppler Weather Radar: principles and applications. Cambridge University Press, 648 pp.

Chandrasekar, V., William A. Cooper and V.N. Bringi. 1988: Axis Ratios and Oscillations of Raindrops. *J. Atmos. Sci.*, **45**, 1323–1333.

Chandrasekar, V., S. Lim, and E. Gorgucci, 2006: Simulation of X-band rainfall observations from S-band radar data *J. Atmos. Oceanic Technol.*, (in print)

Goddard, J. W. F., S. M. Cherry, and V. N. Bringi, 1982: Comparison of dual-polarization radar measurements of rain with ground-based disdrometer measurements. *J. Appl. Meteor.*, **21**, 252–256.

Gorgucci, E., G. Scarchilli, and V. Chandrasekar, 1992: Calibration of radars using polarimetric techniques. *IEEE Trans. Geosci. Remote Sens.*, **30**, 853–858.

Gorgucci, E.; Scarchilli, G.; and V. Chandrasekar, V., 1999: A procedure to calibrate multiparameter weather radar using properties of the rain medium. *IEEE Trans. Geosci. Remote Sens.*, **37**, 269 - 276.

Gorgucci, E., L. Baldini, and V. Chandrasekar, 2006: What is the Shape of Raindrops?. *J. Atmos. Sci.*,(in print).

Gorgucci, E., G. Scarchilli, V. Chandrasekar, and V. N. Bringi. 2000: Measurement of mean raindrop shape from polarimetric radar observations. J. Atmos. Sci., **57**, 3406–3413.

Keenan, T. D., L. D. Carey, D. S. Zrnić and P. T. May. 2001: Sensitivity of 5-cm wavelength polarimetric radar variables to raindrop axial ratio and drop size distribution. *J. Appl. Meteor.*, **40**, 526–545.

Pruppacher, H. R. and K.V. Beard, 1970: A wind tunnel investigation of the internal circulation and shape of water drops falling at terminal velocity in air. *Quart. J. Roy. Meteor. Soc.*, **96**, 247-256.

Scarchilli, G., E. Gorgucci, V. Chandrasekar, and A. Dobaie, 1996: Self-consistency of polarization diversity measurement of rainfall. *IEEE Trans. Geosci. Remote Sensing*, **34**, 22–26.

Thurai, M., and V. N. Bringi, 2005: Drop axis ratios from 2D video disdrometer. *J. Atmos. Oceanic Technol.,* **22**, 966–978.