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POLARIMETRIC RADAR RAINFALL ESTIMATION AT X-BAND: EVALUATION OF ATTENUATION CORRECTION

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1. INTRODUCTION

The most commonly used polarimetric radar measurements in rainfall estimation are the reflectivity factor, usually at horizontal polarization (Z_h), differential reflectivity (Z_{dr}) and specific differential propagation phase (K_{dp}). Based on the above three measurements, a number of algorithms have been derived in the literature to estimate rainfall (see Bringi and Chandrasekar, 2001 for a summary of references). These algorithms have been derived assuming a particular shape size relation for raindrops. The mean shape versus size relation is crucial for deriving algorithms that use Z_{dr} and K_{dp}. At low rainfall rates, the radar rainfall algorithms that use K_{dp} at S-band have relatively large measurement error. However K_{dp} directly scales with frequency, and has a higher dynamic range at X band. This feature makes K_{dp} at X band more useful at low rainrates (Matrosov et al., 2002). Along with the advantages, X band measurements come with their own problems; the significant ones being, attenuation, differential attenuation and phase shift on backscatter. Testud et al. (2000) extended the attenuation correction method used in space borne radars to ground polarimetric radars. The “rain profiling” technique uses parameterization of the specific attenuation with respect to reflectivity of the form $A = aZ_h^b$ where A is specific attenuation at horizontal polarization, Z_h is the reflectivity and a, b are the parameters. The parameter b was fixed whereas the parameter a is changed for each path. Assuming a constant a along a propagation path is equivalent to assuming a constant intercept parameter N_w in the drop size distribution. Chandrasekar et al. (2002) compared S band and X band estimate of rainfall and showed that (in presence of measurement errors) for a given accuracy that can be achieved at S band, the same can be achieved at about 1/3 the rainfall rate at X-band, which is a direct result of frequency scaling. This paper investigates the attenuation correction aspect of rainfall estimation at X-band specifically the attenuation correction process and accuracies.

2. POLARIMETRIC RADAR MEASUREMENTS AND RAINFALL ALGORITHMS

The distribution of raindrop sizes and shapes determines the electromagnetic scattering properties of rain-filled media. These effects, in turn, are embodied in radar measurements such as, reflectivity factors ($Z_{h,v}$) at h and v polarization states, differential reflectivity (Z_{dr}), which is the ratio of reflectivities at the two polarization states, and specific differential phase (K_{dp}) which is due to the propagation phase difference between the two polarizations. The raindrop size distribution (RSD) can be expressed as (Chandrasekar and Bringi, 1987)

$$N(D) = n_c f(D) \qquad (\mathrm{mm^{-1}m^{-3}}) \tag{1}$$

where $N(D)$ is the number of the raindrops per unit volume per unit size interval (D to $D+\Delta D$), n_c is the concentration and $f(D)$ is a probability density function. Theoretical, experimental studies as well as dual-polarization radar measurements show that the raindrop shapes can be approximated by an oblate spheroid with the axis ratio r (ratio of minor axis to major axis) given as

$$r \approx 1.03 - \beta D \tag{2}$$

where D is the equivolumetric spherical diameter (typically in units of mm). The radar observables namely, $Z_{h,v}$, Z_{dr}, and K_{dp} can be expressed in terms of the RSD as follows:

$$Z_{h,v} = \frac{\lambda^4}{\pi^5 |k|^2} \int \sigma_{h,v}(D) N(D) dD \qquad (\mathrm{mm^6m^{-3}}) \tag{3}$$

where $\sigma_{h,v}$ represent the radar cross sections at horizontal and vertical polarizations, respectively; λ the wavelength, and $k=(\varepsilon_r-1)/(\varepsilon_r+2)$ where ε_r is the dielectric constant of water

$$Z_{dr} = 10\log_{10}\left(Z_h / Z_v\right) \qquad (\mathrm{dB}) \tag{4}$$

$$K_{dp} = \frac{180\lambda}{\pi} \Re \int \left[f_h(D) - f_v(D)\right] N(D) dD \qquad (\mathrm{deg\ km^{-1}}) \tag{5}$$

where $\Re$ refers to real part of a complex number and f_h and f_v are the forward-scatter amplitudes at h and v polarization, respectively. The specific attenuation A can be explained in terms of extinction cross section as

$$A = 4.343 \times 10^3 \int \sigma_{ext}(D) N(D) dD \qquad (\mathrm{dB\ km^{-1}}) \tag{6}$$

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At X band the extinction cross section versus size power law can be approximated as $\sigma_{ext}=C_\lambda D^{4.1}$,for $0.1 \le D \le 8\,\text{mm}$. However for large drops the exponent can be as much as 4.9. If A and Z_h are two moments of the RSD, then the two moments can be related using the theory of normalized RSD as

$$\frac{A}{N_w} = C\left(\frac{Z}{N_w}\right)^b \tag{7}$$

Therefore the attenuation and reflectivity parameterization can be expressed as $A = CN_w^{(1-b)}Z_h^b$, where $b \approx 0.72$.

Under Rayleigh scattering approximation the reflectivity factor is independent of frequency and can be approximated as

$$Z = \int D^6 N(D)dD \tag{8}$$

Chandrasekar et al. (2002) showed that above 40 dBz, there is a difference in reflectivity larger than 1dB. Similarly Z_{dr} values differ due to non-Rayleigh scattering for values above 1 dB. K_{dp} scales directly with frequency (valid upto 13 GHz). Observing the variability in the dynamic range of measurements, the error structure of rainfall algorithm that use Z_h and Z_{dr} are likely to remain similar between S and X bands if corrected for attenuation properly. However algorithms that use K_{dp} are likely to be very different. K_{dp} is noisy at low rainrates and therefore, there is a lower limit on the rainfall rate at which it is useful (for a given path length) at X band. However since K_{dp} scales with frequency this lower limit also moves down with frequency. Chandrasekar et al. (2002) showed that at X band the same measurement accuracy can be achieved at one third the rainfall rate compared to S band. Attenuation induced effects will affect Z_h and Z_{dr}, but not K_{dp}. However K_{dp} will be contaminated by the phase shift on backscatter, which can be of the order of 8-12 degrees at X band. This needs to be dealt with at regions of radial gradients, where a radial change of δ could be interpreted as differential propagation phase.

3. EVALUATION OF ATTENUATION CORRECTION

Attenuation correction is important at X band for quantitative applications. The extent of attenuation can be estimated from the amount of cumulative ϕ_{dp} in rain. Using a simple linear approximation between the specific attenuation, specific differential attenuation (A_{dp}) and K_{dp}, estimates of cumulative attenuation and cumulative differential attenuation can be obtained as

$$\int_0^r A_h(s)ds = \alpha_A \phi_{dp} = CA_h \tag{9}$$

and

$$\int_0^r A_{DP}(s)ds = \alpha_{dp} \phi_{dp} = CA_{DP} \tag{10}$$

where the values α_A and α_{dp} takes values of 0.2 and 0.035 approximately at X band for equilibrium shapes (Pruppacher and Beard, 1970). There are more detailed procedures available for attenuation correction (see Bringi and Chandrasekar, 2001 for a summary and the references contained therein). There are three classes of algorithms to correct for attenuation namely a) iterative Z-A method commonly known as Hitschfeld Bordan (HB) algorithm (Hitschfeld and Bordan, 1954) b) differential phase based method (for a summary see Bringi and Chandrasekar, 2001) and c) the constrained Z-A based method (Testud et al, 2000). The iterative method is however not accurate enough for rainfall applications. The space borne radars bounded the solution of the HB algorithm using surface reference. The ground radar attenuation was bounded using ϕ_{dp} based cumulative attenuation constraint. This was suggested as an alternative to simple ϕ_{dp} based correction in order to be able to distribute attenuation through the path better (Le Bouar et al., 2002). The success of the Z-ϕ method depends on two factors, namely i) the relation between ϕ_{dp} and cumulative attenuation is well defined (indicating that the prevailing β is known, Gorgucci et al., 2000) and ii) the constant N_w assumption can be used through the full rainpath. The same CA_h-ϕ_{dp} relation can also be applied throughout the range for comparison. This section presents evaluation of this procedure using profiles of observed radar measurements and simulations. In the following a data based simulation of radar range profiles is discussed.

Simulations are always powerful tools to evaluate the various assumptions in analysis and algorithms. Simulations of radar observations Z_h, Z_{dr} and K_{dp} have been developed in the past based on simulation of RSD parameters. However simulation of full range profiles of typical radar observations are complicated. These simulations involve proper representation of the spatial distribution of the RSD parameters. The simulations of range profiles of radar observations and RSD parameters are fairly detailed and skipped here for brevity, however available at the conference. The basic principle is to use observed profiles of Z_h, Z_{dr} and ϕ_{dp} at S band to generate realistic profiles of X band observations to test the various attenuation correction procedures.

4. ANALYSIS AND DISCUSSION

This section presents results from profiles of simulated X band data. These profiles are simulated from S band dual polarization observations.

Fig. 1 shows the plot of unattenuated reflectivity (Z_h), attenuated (Z_h^m) and corrected reflectivities with Z-ϕ and ϕ_{dp} methods (Z_h^T and Z_h^ϕ, respectively). These profiles were simulated using the procedure described on the previous section from S band observations. The attenuation correction was done using the Z-ϕ algorithm as well as the simple ϕ_{dp} based algorithm. The underlying raindrop shape model for Fig. 2 and 3 is the one by Andsager et al., 1999, Z_h is the true reflectivity and Z_h^m is the attenuated measured reflectivity. Fig. 1.b. shows the corresponding Z_{dr}, and ϕ_{dp} plot at S-band. Fig. 2 shows the error in the attenuation correction whereas Fig. 3 shows plots of cumulative attenuation and the two estimates along the range. The purpose of Fig. 3 is to quantitatively evaluate the performance of the attenuation correction algorithm to study the usefulness for rainfall estimation.

The next aspect is the drop size model. Fig. 4 shows the profiles of true reflectivity, and the corresponding attenuation corrected reflectivities when the underlying shape model is equilibrium (Pruppacher and Beard, 1970) whereas the attenuation correction model is that given by Andsager et al. (1999). Fig. 4 provides an estimate of the sensitivity to drop size model for attenuation correction purposes.

Rainfall estimate using X band radars is gaining momentum recently for various applications. This paper is a continuation of the previous study by Chandrasekar et al. (2002) looking at various aspects of rainfall estimation from X band measurements. The attenuation correction algorithms are quantitatively evaluated using "data based simulations". The results of the paper should be considered preliminary, which indicate that the attenuation correction procedures have to be further examined carefully for quantitative applications.

5. ACKNOWLEDGMENT

This research is supported by the National Group for Defense from Hydrological Hazard (CNR, Italy), the Italian Space Agency (ASI), and the NASA TRMM program.

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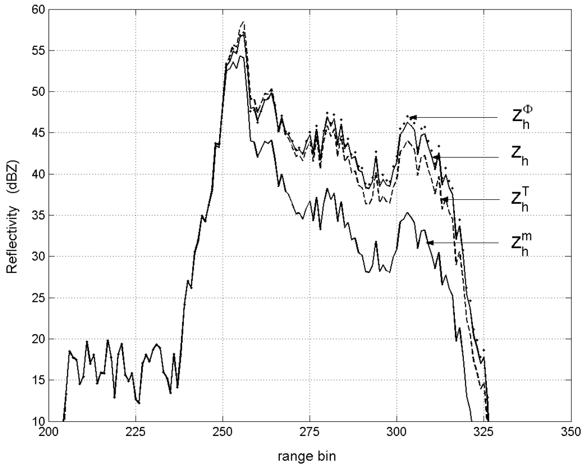

Fig. 1a. Range profile of unattenuated reflectivity (Z_h), attenuated (Z_h^m) and corrected reflectivities with Z-ϕ and ϕ_{dp} methods (Z_h^T and Z_h^ϕ) as a function of the path. The model assumes raindrop shape model of Andsagar et al (1999). The range bin spacing is 150m.

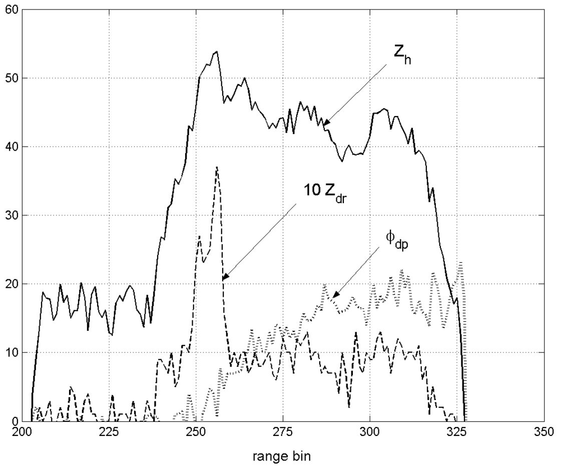

Fig. 1b. Range profile of Z_h^m, Z_{dr}^m and ϕ_{dp} corresponding to Fig. 1a. Data were collected by SPOL on 1998-09-15 during Teflun B campaign.

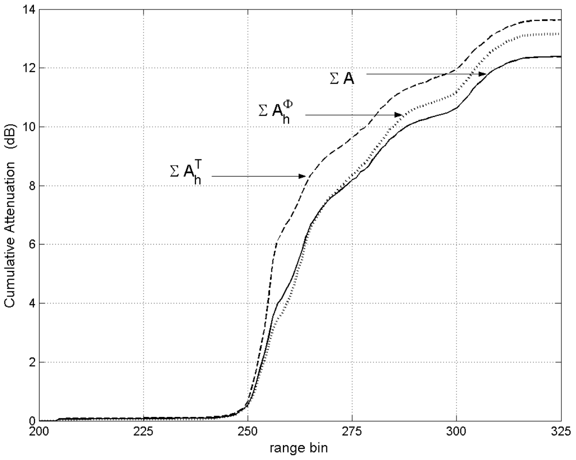

Fig. 3. Plot of true and estimated cumulative attenuation and differential attenuation by Z-ϕ and ϕ_{dp} algorithms (ΣA_h^T and ΣA_h^ϕ, respectively) as a function of the path.

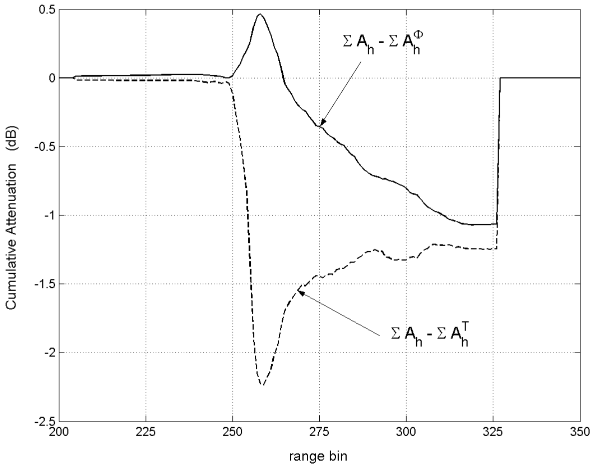

Fig. 2. Error in attenuation correction for Z-ϕ and ϕ_{dp} algorithms ($\Sigma A_h - \Sigma A_h^T$ and $\Sigma A_h - \Sigma A_h^\phi$, respectively) as a function of the path.

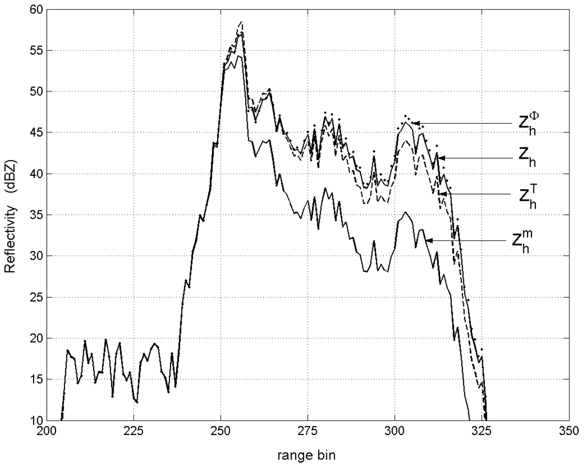

Fig. 4. Same as Fig. 1a except the prevailing raindrop shape model is based on Andsager et. (1999), while attenuation correction model is based on equilibrium drop shape model.