Research Article

Estimation of Dual Polarization Weather Radar Variables

Dalia A. Mahmood, Kais J. Al-Jumaily
Department of Atmospheric Sciences, College of Science, Mustansiriyah University, IRAQ
*Correspondent Author Email: dalia81kittyy@yahoo.com

Article Info

Received
07/11/2016

Accepted
12/06/2017

Abstract
Dual polarization weather radar has now become a widely used as instrument in meteorological offices around the world because of its capability in distinguishing different precipitation type and in improving the accuracy of quantitative precipitation estimation. The aim of this work is to estimate the polarimetry radar variables for radars of different frequency bands and study their behavior with rainfall rates.
Calculations of polarimetry radar variables were made on the basis of several assumptions. The results showed that factors at horizontal and vertical polarization, ZH,V, ranges between 20 dBz respectively, and more than 55 dBz for light rain and extreme heavy rain respectively, and radar reflectivity factor at horizontal ZH is greater than radar reflectivity factor at vertical ZV for all rainfall rates. The differential reflectivity, ZDR, also increases with increasing rainfall rates since it is the difference between ZH and Zv.
Calculations of specific differential attenuation indicated that X band radars are seriously attenuated by rain and C band radars are less affected by rain. The specific differential attenuation, S band radars is very small. In addition to this feature, the results showed that the differential phase shift between return signals of horizontal and vertical polarizations for S band radars is much less than those for C and X band radars, and also, the results showed that the co-polarization correlation coefficient for S band the radars is much higher than those of C and X bands.
In order to investigate the accuracy of the calculated polarimetric weather radar variables performed in this research, real radar measurements were used for this purpose. Results indicated that the range of values for calculated polarimetric radar variables are very consistent with range of values for measured variables.

Keywords: Polarization; Radar; Reflectivity; Rainfall.

الخلاصة
أصبح رادار الطقس مزدوج الاستقطاب جهاز شائع الاستخدام في دوائر الارصاد الجوية حول العالم بسبب قابليته في تمييز الأنواع المختلفة من الهطول وتحسين دقة التخمين الكمي للهطول. رادارات الطقس الاعتيادية ترسل وتستلم موجات ذات استقطاب افقي منفرد ويمكنها قياس معدل الهطول فقط. الرادارات المستقطبة ترسل وتستلم موجات كلا الاستقطابين الافقي والشاقولي واضافة لمعدل الهطول لها القابلية في تحديد حجم وشكل ونوع جسيمات الهطول. يهدف هذا البحث الى تخمين متغيرات الرادارات المستقطبة ذات حزم الترددات المختلفة ودراسة سلوك هذه المتغيرات مع معدلات سقوط المطر.
تم حساب متغيرات الرادار المستقطب بناءاً على عدة فرضيات. بينت النتائج بان معاملات الانعكاسية عند الاستقطاب الافقي والاستقطاب الشاقولي ZH,V، تتراوح بين 20 dBz الى أكثر من 55 dBz بالنسبة للأمطار الخفيفة والامطار الغزيرة جدا على التوالي، وان معامل الانعكاسية عند الاستقطاب الافقي ZH أكبر من معامل الانعكاسية عند الاستقطاب الشاقولي ZV لجميع معدلات الامطار. الانعكاسية التفاضلية ZDR هي أيضا تزداد مع زيادة معدل المطر كونها تمثل الفرق بين ZH و ZV.
دلت حسابات التوهين التفاضلي النوعي بأن الرادارات التي تعمل بالحزمة X تعاني بشدة من التوهين بواسطة الامطار وان الرادارات التي تعمل بالحزمة C هي أيضا تتأثر بالأمطار ولكن بشكل اقل. ان التوهين التفاضلي النوعي للرادارات التي تعمل بالحزمة S قليل جدا. إضافة لهذه الخاصية، فان النتائج أظهرت بان فرق الطور التفاضلي بين الإشارات المرتدة عند الاستقطابين الافقي والشاقولي للرادارات ذات الحزمة S اصغر بكثير من فرق الطور عند الحزم X و C، وأيضا بينت النتائج بأن معامل ارتباط اشتراك الاستقطاب لرادارات الحزمة S اعلى من معاملات الارتباط للحزم X و C.
ولغرض التأكد من دقة حسابات متغيرات رادار الاستقطاب التي تم اجراؤها في هذا البحث، فقد استخدمت قياسات رادار حقيقية لهذا الغرض. وقد دلت النتائج بان مدى قيم متغيرات رادار الاستقطاب متوافقة تماما مع مدى قيم المتغيرات المقاسة.

Introduction
Although weather radars have been in operation for more than half a century and Doppler weather radars for a few decades, polarimetric weather

radars, which retain Doppler capability, have only recently achieved operational status. Such a choice has been motivated by the capability of polarimetric variables to distinguish different hydrometeor types and to improve the accuracy of quantitative precipitation estimation [1]. The conventional meteorological radar transmits and receives a fixed single polarized wave. Meanwhile, polarimetric radar radiates and receives linear polarization waves which are polarized horizontally and vertically.

The difference of characteristics of backscattered signal due to polarizations directly depends on the shape and orientation of particles. By comparing the signals received from returns at each polarization, one can glean information about the size, shape, and orientation of targets within the radar sampling volume [2].

A large number of publications in the literature deal with theory and observations of weather radar polarimetry. Simulation of dual polarization parameters has also attracted many researchers. Otto [3] inspected the propagation effects influencing polarimetric weather radar measurements attenuation correction. Methods for weather radar measurements at linear horizontal / vertical polarization basis were compared to each other, and identifying the robustly working methods. Kumjian and Ryzhkov [4] studied the impact of size sorting on the S-band polarimetric radar variables by using two idealized bin models. They found that the size sorting produces regions of sparsely concentrated large drops with a lack of smaller drops. Thompson *et al*. [5] derived the bulk electromagnetic scattering properties of precipitation to prove that the extent to which polarimetric radar observations can be used to operate a winter hydrometeor classification algorithm. The results show that the algorithm is able to successfully discern dominant winter hydrometeor types. Jamali [6] examined the applicability of the simple models in estimation of ice mass across the microwave spectral region using three databases consisting of optical properties of some randomly oriented non-spherical ice particles and aggregates.

Materials and Methodos

Polarimetric Radar Variables

Radar echoes are combined signals backscattered by all the hydrometeors within a radar resolution volume at a given range gate. The intensity and phase of received radar echoes are determined by both scattering and propagation effects. These effects depend on the radar frequency and the size, intensity, phase, shape, structure, and orientation of the hydrometeors. The use of subscripts for polarimetric variables is quite common. In general, letters in lowercase correspond to linear units, while those in uppercase correspond to units in dB. The theoretical equations for the polarimetric radar variables are given below [7] [8] [9].

1- Radar reflectivity factors at horizontal and vertical polarizations ($Z_{h,v}$ or $Z_{H,V}$)

$$Z_{h,v}(mm^6/m^3) = \frac{4\lambda^4}{\pi^4|K|^2}\int_{D_{\min}}^{D_{\max}} \left| f_{h,v}(\pi,D)\right|^2 N(D)dD \qquad (1)$$

$$Z_{H,V}(dBz) = 10\log_{10}(Z_{h,v}) \qquad (2)$$

2- Differential reflectivity (Z_{dr} or Z_{DR})

$$Z_{dr} = Z_h / Z_v \qquad (3)$$

$$Z_{DR}(dB) = 10\log_{10}(Z_h / Z_v) = Z_H - Z_V \qquad (4)$$

3- Co-polar correlation coefficient ($\rho_{h,v}$)

$$\rho_{h,v} = \frac{\int_{D_{\min}}^{D_{\max}} f_{hh}^*(\pi,D) f_{vv}(\pi,D)N(D)dD}{\sqrt{\int_{D_{\min}}^{D_{\max}} |f_{hh}(\pi,D)|^2 N(D)dD \int_{D_{\min}}^{D_{\max}} |f_{vv}(\pi,D)|^2 N(D)dD}} \qquad (5)$$

4- Specific differential phase shift (K_{dp})

$$K_{dp}(\deg/km) = \frac{180\lambda}{\pi}\int_{D_{\min}}^{D_{\max}} Re\left[f_{hh}(0,D) - f_{vv}(0,D)\right]N(D)dD \qquad (6)$$

5- Differential phase (Φ_{dp})

$$\Phi_{dp}(r_g)(\deg) = 2\int_0^{r_g} K_{dp}(r)dr \qquad (7)$$

6- Specific attenuation at horizontal or vertical polarization (A_H or A_V)

$$A_{H,V}(dB/km) = 8.686\lambda\int_{D_{\min}}^{D_{\max}} \mathrm{Im}\left[f_{h,v}(0,D)\right]N(D)dD \qquad (8)$$

7- Specific differential attenuation (A_{DP})

$$A_{DP}(\deg/km) = A_H - A_V \qquad (9)$$

where λ is the radar wavelength; $K = (\varepsilon - 1)/(\varepsilon + 2)$, where ε is the complex dielectric constant of water; *D* denotes the effective diameter of particle (i. e. , hydrometeor); D_{max} (or D_{min}) indicates the maximum (or minimum) *D* within a radar resolution volume; and *N(D)* is the Particle Size Distribution (PSD) of all these particles; $f_{hh,vv}$ is the complex scattering amplitude at the horizontal or vertical polarization, horizontal or vertical and the parameters 0 and π for $f_{hh,vv}$ denote the forward-scattering and backward-scattering components, respectively; the notation $|\cdot|$ signifies the complex norm and Re (or Im) indicates the real (or imaginary) part of a complex number; and r denotes the range from radar and r_g is the range for a given range gate. $Z_{h,v}$ represents the energy backscattered by precipitating hydrometeors and depends on their concentration, size, and phase, which have a close connection to precipitation rate and water content. Z_{dr} is directly related to the median size of observed hydrometeors, a parameter used to describe the DSD. K_{dp} is dependent on the raindrop number concentration but is less sensitive to the size distribution than $Z_{h,v}$. Positive K_{dp} values result from a phase lag in the horizontally polarized wave compared with the vertical one. Oblate raindrops (those that have larger horizontal dimensions than vertical) basically cause a slight phase delay, which is more pronounced at horizontal polarization. These three polarimetric measurements can be directly applied for estimating rainfall. The correlation coefficient (ρ_{hv}) indicates how well the backscatter amplitudes at vertical and horizontal polarization are correlated. It is a good indicator of hydrometeor phase (homogenous vs. mixed phase) and data quality. This variable is used for classifying the hydrometeor species of the radar echo. Precipitation can cause strong attenuation (power loss) in radar measurements, depending on the frequency of the radar wave. Specific attenuation (A_H, A_V) and specific differential attenuation (A_{DP}) are two important variables to address how much power has been lost in Z_h, Z_v or Z_{dr}, though they are not directly measured. Values of A_H, A_v, and A_{DP} also have a strong correlation with precipitation rate [7][9].

Methodology

The polarimetric radar variables defined by Equations (1) through (9) were estimated under the following assumptions:

1. Air temperature of 10 ^{o}C.
2. Marshall-Palmer raindrop size distribution for raindrop diameters 0.08 to 8 mm and rainfall rates 1 to 100 mm/hr. The distribution is defined as [10]:

$$N(D) = N_o e^{-\Lambda D} \quad (10)$$

   Where D is the rain drop diameter, $N(D)dD$ is the number of drops between diameter D and $D + dD$, and N_o is the value of $N(D)$ for D=0. For this distribution it was found that $N_o = 0.08$ cm^{-4} and $\Lambda = 41R^{-0.21}$ cm^{-1} where R is the rainfall in mm/hr.
3. Rain fall speed formula proposed by Brandes et al. , [11]:

$$v(D) = -0.1021 + 4.932D - 0.9551D^2 + 0.07934D^3 - 0.002362D^4 \quad (11)$$

4. Raindrops are oblate spheroids with 0^{o} canting angle.

All computer codes used in the computations were developed in Matlab®. Calculations of polarimetric radar variables were carried for three commonly used radar frequency bands, namely X band (10 GHz), C band (5 GHz) and S band (3 GHz). To verify the theoretical computations, real polarimetric radar measurements were compared with the results of computations. The data were obtained from NOAA Weather Radar for Research and Experimentation (KOUN) in Norman, Oklahoma, USA. The data were collected for the 13 May 2005 squall-line case.

Results and Discussion

Figures 1 to 3 show the comparisons of Z_H, Z_V, and Z_{DR} for the three bands. Z_H for X band is greater than that of C band and S band has the lowest values among the three bands. Z_V values for X and S band are very comparable but they are notably greater than the values of C bands, especially for rain rates greater than 10 mm/hr. As a consequence, Z_{DR} for X band is greater than those of C and S bands for rainfall rates below 35 mm/hr. beyond this value of rainfall rate, Z_{DR} for C band becomes larger than that for X band.

Figure 4 shows the comparison of A_{DP} for the three bands. It is clear that radars operate at X band are affected seriously by rain attenuation. This leads to degradation of the radar signal as it propagates through rain medium. It is evident that even light rain affects X band radars. The C band radar waves are less attenuated than X band radar. The S band radar very less attenuated by rain medium and for this reason S band radars are widely used for detecting rain storms.

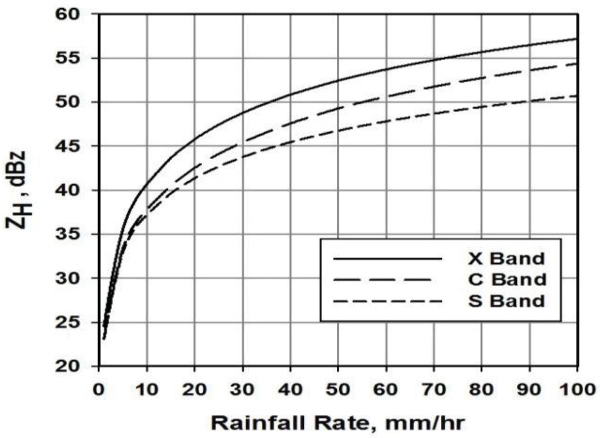

Figure 1: Reflectivity factor at horizontal polarization for X, C, and S bands versus rainfall rate.

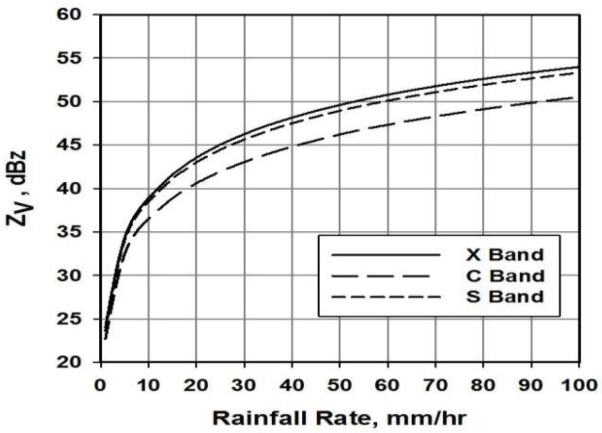

Figure 2: Reflectivity factor at vertical polarization for X, C, and S bands versus rainfall rate.

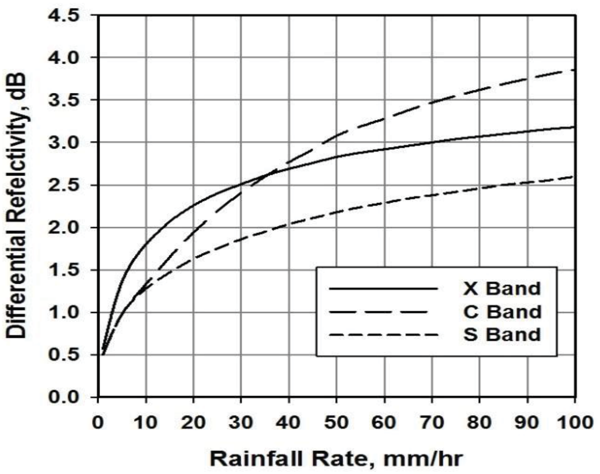

Figure (3): Differential reflectivity for X, C, and S bands versus rainfall rate.

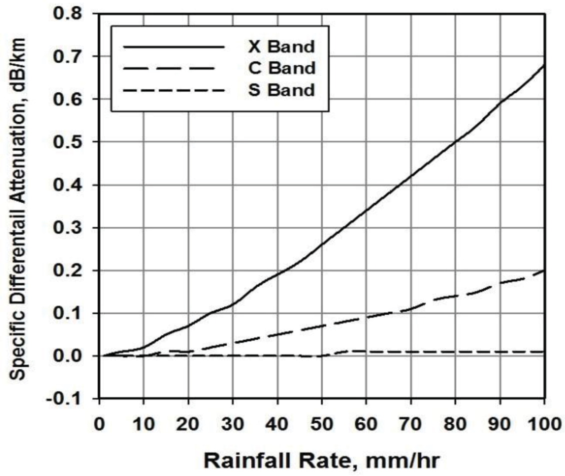

Figure 4: Specific differential attenuation for X, C, and S bands versus rainfall rate.

Figure 5 displays the results of computed specific differential phase shift, K_{DP}. It is obvious that K_{DP} increase linearly with increasing rainfall rates. Light rain produces a phase shift of less than 1 deg/km between horizontal and vertical return of the signals while heavy rainfall, 60 mm/hr for instance, can cause a phase shit of 5, 3, and 1.5 dB/km for radars operating at X, C, and S bands respectively.

Figure 6 shows the results of the calculated co-polarization coefficient, ρ_{hv}, versus rainfall for the three bands. It is seen that ρ_{hv} is more than 0.96 for rainfall rates below 10 mm/hr and that the return signals of S band radars have best ρ_{hv} it is almost constant for all rainfall rates while for radars operating at C band ρ_{hv} decreases gradually to value 0.94 at rainfall rate of 60 mm/hr and then keep constant for rainfall rates higher than this value. For X band radars, ρ_{hv} decreases sharply to less than 0.90 at rainfall rate of 50 mm/hr and then become constant for higher rainfall rates. This suggests that return signals of S band radar are best correlated than return signals of radars operating at other two bands.

In order to investigate the accuracy of the calculated polarimetric weather radar variable performed in this research, real radar measurements were used for this purpose. The measurements were obtained from the University of Oklahoma, Oklahoma, USA S band dual polarization radar (KOUN). The radar is located in Norman near Oklahoma City. The measurements were carried out during a squall-line case on 13 May 2005. Squall lines generally form along or ahead of cold fronts and drylines and can produce severe weather in the form of heavy rainfall, strong winds, large hail, and frequent lightning. Squall line appears on radar has a shape of a bow echo.

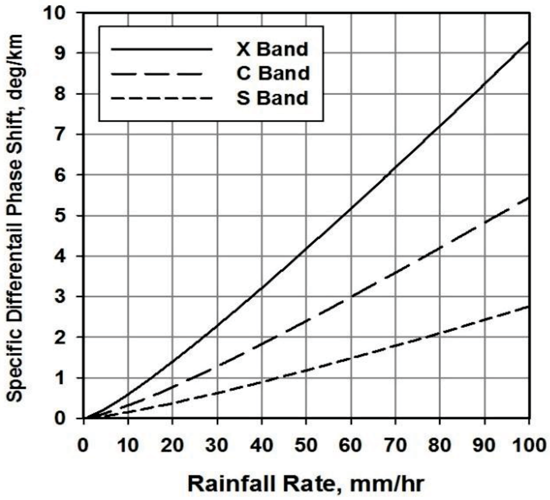

Figure 5: Specific differential phase shift for X, C, and S bands versus rainfall rate.

Figure 7 shows the PPI of Z_H, Z_{DR}, ρ_{hv}, and ϕ_{DP} for this squall-line case study, The bow echo is very apparent on Z_H, and Z_{DR} displays. The bow is located at the head of the storm, just east of the radar site and has high values of Z_H, and Z_{DR}. It is seen that the range of Z_H is between 20 and 55 and the range of Z_{DR} is between 0 and 4. ρ_{hv} is equal to unity all over the storm. ϕ_{DP} ranges between 0 and more than 50 at the edges of the storm. The ϕ_{DP} is the 2-way range integration of K_{DP}. These values of measured polarimetric weather radar are very consistent with the calculated variables obtained in this research.

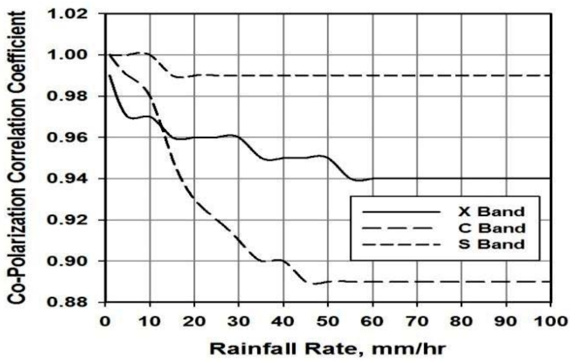

Figure 6: Co-polarization correlation coefficient for X, C, and S bands versus rainfall rate.

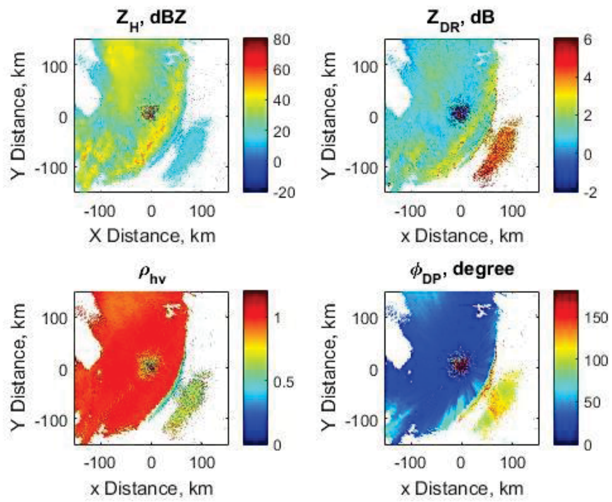

Figure (7): PPI of Z_H (top left), Z_{DR} (top right), ρ_{hv} (bottom left) and ϕ_{DP} (bottom right) for the 13 May 2005 Squall-line case observed by KOUN S band dual-polarization radar.

Conclusions

This paper presents theoretical calculations of dual polarization weather radar variables, aimed at understanding the behavior of these variables for various rainfall rates. Three common radar bands were considered, namely X, C, and S. Calculations were based on Marshall-Palmer raindrop size distribution. Results indicated that differential reflectivity for X band is greater than those of C and S bands for rainfall rates below 35 mm/hr and beyond this value of rainfall rate, ZDR for C band becomes larger than that for X band. It was found that heavy rainfall can cause a differential phase shit of 5, 3, and 1.5 dB/km for radars operating at X, C, and S bands respectively. Results also suggested that co-polarization correlation coefficient suggested that return signals at horizontal and vertical polarizations of S band radar are best correlated than return signals of radars operating at other two bands.comparisons with real radar measurements showed the calculated radar variables were very consistent with the measured ones.

References

[1] Sauvage, H. , 1992: *Radar Meteorology*. Artech House Radar Publisher, pp 384.

[2] Fukao, S. , and K. , Hamazu, 2014: *Radar*

for Meteorological and Atmospheric Observations. Springer, Dordrecht, pp 537.

[3] Otto, T. , 2011: Propagation effects influencing polarimetric weather radar measurements. Ph. D. Dissertation, der Technischen Universität Chemnitz, Germany, pp 238.

[4] Kumjian, M. R. , and A. V. Ryzhkov, 2012: The Impact of Size Sorting on the Polarimetric Radar Variables. *J. Atmos. Sci*. , **69,** 2042-2060.

[5] Thompson, E. J. , S. A. Rutledge, B. Dolan, V. Chandrasekar, and B. L. Cheong, 2014: A dual-polarization radar hydrometeor classification algorithm for winter precipitation. *J. Atmos. Oceanic Technol*. , **31(7),** 1457-1481.

[6] Jamali, M. , 2015: Soft model approximation of microwave scattering properties of ice particles. M. Sc. thesis, Department of Earth and Space Science Chalmers University of Technology, Gothenburg, Sweden. pp 87.

[7] Hong, Y. , and J. J. Gourley, 2015: *Radar Hydrology: Principles, Models, and Applications*. CRC Press, pp 191.

[8] Bringi, V. N. , and V. Chandrasekar, 2001: *Polarimetric Doppler Weather Radar Principles and Applications*. Cambridge University Press, pp 664.

[9] Zhang, G. , 2016: *Weather Radar Polarimetry*. CRC Press, pp 304.

[10] Marshall, J. S. , and W. McK. Palmer, 1948: The Distribution of Raindrops with Size. *J. Meteor*. , **5,** 165-166.

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