Tropical Rainfall Rate Relations Assessments from Dual Polarized X-band Weather Radars

Carlos R. Wah González, José G. Colom Ustáriz, Leyda V. León Colón

Department of Electrical and Computer Engineering
University of Puerto Rico at Mayagüez
Mayagüez, Puerto Rico

***Abstract*—** Rainfall rate estimation has become one of the main priorities in radar meteorology measurements to help understand the climate change effects. Accurate estimation and prediction of the rainfall rate it is important to safe home, properties, and most important lives. This project consists in the developing of a code, which calculates the relation of Rainfall Rate using the Dual Polarized X-band radar network, localized at the west coast of Puerto Rico. This program will be validated with the ground-based disdrometers network, installed at UPR-Mayagüez and UPR-Aguadilla. To complete the validation of the data collected by the 3 Dual Polarized X-band radars, a minimum of 10 events of moderate to heavy rain has been identified, where two of them are the effects of the near pass of the Tropical Storm Bertha and Tropical Depression Cristobal. To achieve the validation of the data, the program under development uses the polarimetric products such as Reflectivity, Differential Reflectivity and Specific Phase and compares it with the data obtained from a Ground-Based Disdrometers. This type of disdrometer provides data such as: Radar Reflectivity, Precipitation Intensity, diameter, velocity and classification of the hydrometeors. To the develop the code and base on the parameters *a* and *b* from the disdrometer, a relation between Reflectivity and Rainfall rate has been calculated as follows, $Z_h = aR^b$, where Z is the reflectivity in $mm^6 \cdot m^{-3}$ and R is the rainfall rate in $mm \cdot hr^{-}1$. Using polarimetric Variables we can use similar relationships such as R= c1 K_{DP}^{b1}, R (Z_h, Z_{DR}) = a $Z_h^b Z_{DR}^c$, R (K_{DP}, Z_{DR}) = a $K_{DP}^b Z_{DR}^c$, where Z_{DR} is the differential reflectivity in linear form, and K_{DP} is the specific differential phase in $deg \cdot km^{-1}$. From the algorithm developed with reflectivity and from the data obtained from the disdrometer, the event from May 08, 2014 at 19:19:35 UTC was analyzed. It is observed that for this specific time mention, the disdrometer record a Rainfall Rate of 42.49 $mm \cdot hr^{-1}$ and a radar reflectivity of 47.6 dBZ. A rainfall rate for the event of about 40 to 45 $mm \cdot hr^{-1}$ was calculated. The reflectivity obtained from the Dual-Pol X-band radar at Cabo Rojo (Fig. 2a) shows values of 40-50 dBZ, which tell that the measurements from the radar are near the values that the disdrometer calculates.. Over the disdrometer it is observed that there is a rain intensity of 42.49 $mm \cdot hr^{-1,}$ and looking the figure 3, it is evident that there is also an intensity of 45 to 50 $mm \cdot hr^{-1}$. It is then apparent that the estimation with this relationship has an excellent match. It is expected to compare the different algorithms to determine which one results is a better estimation.

Keywords- Polarimetric Variables, Disdrometers, Rainfall Rate, Reflectivity,Differential Reflectivity

I. INTRODUCTION

The Puerto Rico Weather Radar Network (PRWRN) consists of an infrastructure of several X-band Weather Radars working in a networked configuration; which aids in the forecast of lower atmosphere severe weather events at the west coast of Puerto Rico. Each node of the network consist of a dual polarized X-band radar (TropiNet Radar), that is capable of providing different products such as reflectivity (Z_h), differential reflectivity (Z_{DR}), specific differential phase (K_{DP}) velocity, propagation differential phase shift, among others (Galvez et al., 2013). A long term goal of the PRWRN is to consistently provide in a daily basis an accurate forecast to protect the life and property of the people of the west coast of the island. The network will monitor and study the different atmospheric events which are developed at the lower atmosphere of the island's west coast.

In the present day, Dual Polarized Weather Radars are known to provide valuable information for hydrological and meteorological studies such as, improved rainfall estimation, retrieval of drop size distribution (DSD), hydrometeors classification, and interpretation of microphysical processes of precipitation systems. The west area of Puerto Rico is subject to sudden flooding, due the extreme rainfall events, some of which the National Oceanic and Atmospheric Administration (NOAA) National Weather Service (NWS) NEXRAD (Next-generation Radar) radar fails to detect (Torres et. al, 2013). Most of X-band radars offer good spatial resolution and less problematic ground clutter with relatively small size, which makes them a preferable tool for polarimetric radar applications compared to longer wavelength radars. Not only does using shorter wavelengths allow easy detection of the polarimetric product, propagation differential phase shift (K_{DP}), which is proportional to the reciprocal of the wavelength, but also increases the sensitivity of detecting weak targets.

II. CASE STUDIES, INSTRUMENTS AND DATA COLLECTION

A. Cases Selection

Data from radar and disdrometers were obtained from around 40 convective storms capture by the PRWRN, during the wet season of the island from May thru November. For this study the following criteria were used for the case selection: 1) storm data above the disdrometers sites, and 2) radar intensity observed Z > 25dBz (approximate threshold between light rain and heavy rain). Based on these criteria, we consider data from five convective storms, where two of them were associated to Tropical Storm Bertha and Cristobal, from the 2014 Hurricane Season.

B. Disdrometer measurements

A disdrometer is an instrument which primarily measures the DSD. These instruments such as the Parsivel's, 2DVD disdrometers, or similar, provide valuable datasets such as radar reflectivity, different types of rainfall hydrometeors, velocity fall of the particles, and rainfall rate between 0 to 150 mm · hr $^{-1}$ (see Fig. 1). But as Lee et al. (2006) points out, most of conventional disdrometers have difficulty in measuring big drops because of the small sampling volume. As for the rain gauges, they record the precipitation quantity of any of the rain event in their location, which is a single data point in the measurement of the whole rainfall region. But still, they serve as a good instrument to validate the prediction or estimation made by any of the algorithm that will be used in this work. As Cifelli et al. (2011) indicates, it is complicated to make a comparison with rain gauges because of a combination of difference in sampling geometry, DSD, subcloud drop evaporation or breakup, advection of drops in or out of the gauge, and temporal sampling. It is also known that at windy conditions rain gauges tends to underestimate the rainfall rate.

C. Radar measurements

Radar data were obtained from the PRWRN X-band dual-polarized weather radars. Table 1 provides a summary of the radar configuration during each of the storms. For the cases considered in the research, the disdrometer is 6.5 km from the radar location. The dual-polarized radars provide high resolution data which significantly improves the information related to the weather. With the dual-pol radars there is additional information besides the radar reflectivity, such as the velocity, the Z_{DR}, K_{DP}, among other variables. With these variables, more information of the tornados debris, hail storms, flooding, among other weather phenomena are obtained.

III. DATA PROCESSING

Rainfall Rate estimation is one of the most important parameters in radar meteorology that helps understand climate change (Matrosov et. al., 2002). The estimation and prediction of the rainfall rate are application products that are important to help to save, properties, and most importantly lives. In the literature is common to use a polarimetric radar measurement to make the rainfall rate estimation, this has been a well-known research topic for the last 4 decades. The most common polarimetric parameters to develop an estimation algorithm are Z_h, Z_{DR}, and the K_{DP} (Gorgucci et. al., 2001).These polarimetric products and algorithm are influenced by deviation from the equilibrium of the raindrop shapes. It would be important to derive an algorithm to estimate rainfall rate that is immune to variability in the mean raindrop shape-size relationship.

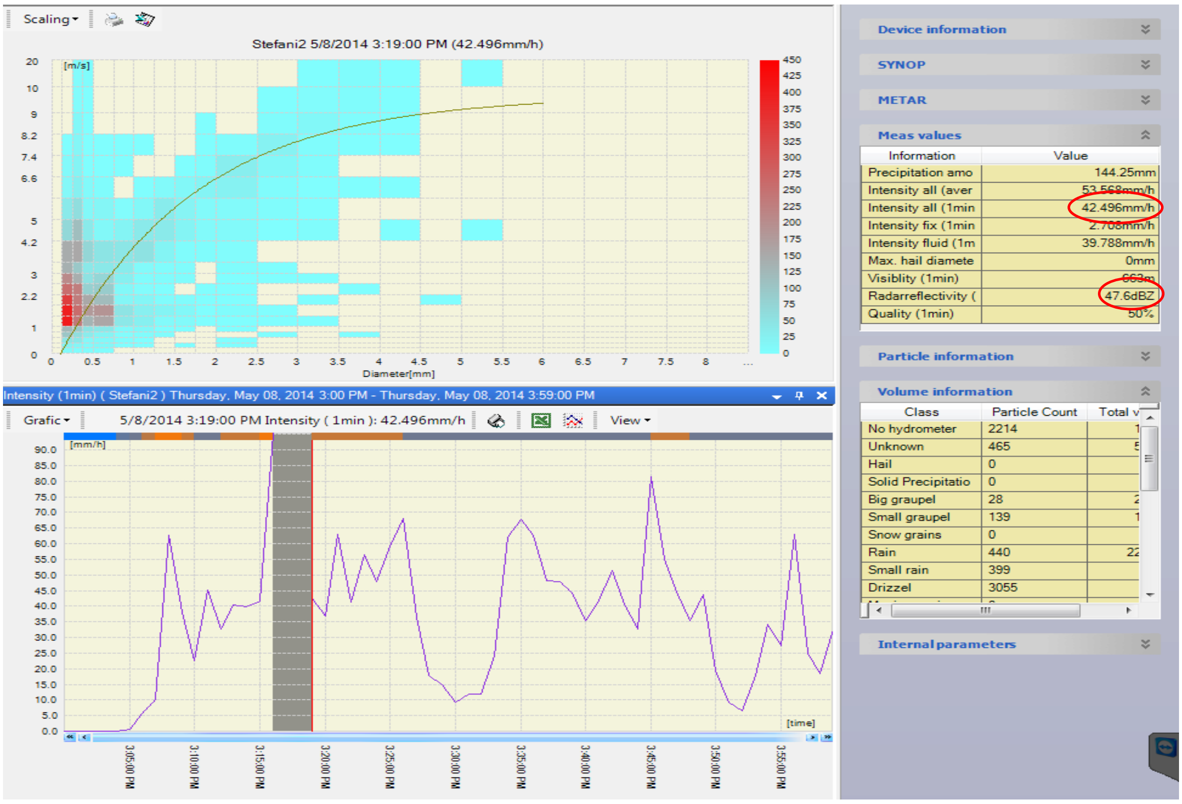

Figure 1: Disdrometer data for May 8, 2015 at local time 3:19 pm. Red circles shows us the Intensity and the Reflectivity. Main screen of the Disdrometer showing principal parameters such as, the Volume Information, quantification of Drops Diameters and Fall Velocity, and Radar Reflectivity and Rain Intensity.

A. Rainfall Rate with Reflectivity

Most of the scientists look for accurate rainfall estimation for short flash flood forecast; but with conventional single polarized radar, a simple power-law relationship is used:

$$Z_h = aR^b, \quad (1)$$

where Z_h is the horizontal reflectivity, R is the rainfall rate, and *a* and *b* are calculated parameter. This simple relationship can lead to rainfall rate errors, which can be overcome using polarimetric products. In the literature wit is found that the most common and practical relationship is derived from NEXRAD with, default for convection (a= 300, b = 1.4), and the Marshall-Palmer (a = 200, b = 1.6) (Cataneo, 1969) (Hong & Gourley, 2014b). Marshall-Palmer distributions come from an exponential DSD with fixed slope and intercept parameters (see Fig. 1). Jones et al. (1956) said, these relationships change with the intensity of the rain. For example for a continuous rain the variables of the equation 1 change to $Z_h = 313R^{1.25,}$ for thundershowers $Z_h = 486R^{1.37,}$ and for rain showers $Z_h = 380R^{1.24}$. From the equation 1 it can be obtained the relation of rainfall rate and reflectivity for the case under observation. The relationship from eq. 1 is found to be accurate, but inherent of the variations in the size distributions of the drops (Hogan, 2007). For example, single polarized radar has difficulty distinguish hail from heavy rain, and it has limitations when correcting for attenuation. In Hong et. al. (2014) it is shown that, Z alone is insufficient to reveal the natural variability of precipitation.

B. Rainfall Rate with Differential Reflectivity

The most commonly used polarimetric variables is the reflectivity ($Z_{h,v}$), which refers to horizontal and vertical polarizations. With this technology new variables to estimate the rainfall rate such as Z_{DR} are introduced, which is the ratio of the reflectivity at the two polarization states. The Z_{DR} is an important parameter as Hong et al. (2014) explains, is directly related to the median size of observed hydrometeors, which is use to describe the DSD. Also the parameter is used to measure the reflectivity-weighted mean axis ratio of different hydrometeors in the radar sampling volume. Also Maki et al. (2005) shows that for X-band radars, the polarimetric value of Z_{DR} exhibit a positive value, which shows the effect of the Mie scattering by large drops. The Z_{DR} is also used with other polarimetric parameters, to achieve a more accurate result with the rainfall algorithm.

C. Rainfall Rate with Specific Differential Phase

K_{DP} can also be measured; this is defined as the propagation phase difference between the two polarizations. Positive values of K_{DP} result from a phase lag in horizontal polarized wave, when is compared to the vertical one. Oblate raindrop basically cause a slight phase delay, which is more pronounced at horizontal polarization. A limitation that the radar meteorologist has with K_{DP} parameter is that at lower rainfall rates, the parameter is very low and noisy. K_{DP} is dependent of the raindrops number concentration but is less sensitive to the size distribution than Z_h. As Maki et. al. (2005) stated K_{DP} is the simplest estimator to calculate the rainfall rate. For K_{DP} we can also calculate the power-law regression like the equation 1, which will change due the intensity and type of the rain as show in Table 1. Using K_{DP} as an estimator, errors of 14% have been reported in Maki et. al. (2005), which is more accurate than the rainfall algorithm of Z_h.

$$R = c_1 K_{DP}^{b1} \quad (2)$$

Table 1: Coefficients for $R= c1K_{DP}^{b1}$ rainfall algorithm at X band.

Rain Type	*c_1*	*b_1*
Convective	20.2	0.809
Stratiform	14.5	0.811
All	18.9	0.856

D. Rainfall Rate with a combination of variables

It is possible to construct rainfall rate estimators using combinations of the polarimetric variables. The most commons combinations to estimate rainfall rate with the polarimetric variables are: R (Z_{DR}, Z_h), R (Z_{DR}, K_{DP}) and a non-linear regression using the three polarimetric variables. These combinations have also power-law relations, similar to the relations of K_{DP} (eq. 2) and Z_h (eq.1), which are as follow:

$$R(Z_h, Z_{DR}) = a\, Z_h^b\, Z_{DR}^c \quad (3)$$

$$R(K_{DP}, Z_{DR}) = a\, K_{DP}^b\, Z_{DR}^c \quad (4)$$

where R is in $mm \cdot hr^{-1}$, Z_h is in $mm^6 \cdot m^{-3}$, K_{DP} is in $deg \cdot km^{-1}$, and Z_{DR} is a dimensionless linear ratio. Table 2 shows the values of the variables for the rainfall estimators. These parameters may change due to different raindrop model assumptions. With these relations, an accuracy of 9% of error results for R (K_{DP}, Z_{DR}) and 10% of error for R (Z_H, Z_{DR}) (Maki et al., 2005).

Table 2: Parameters for Polarimetric Radar Rainfall Estimators

	a	*b*	*c*
R (Z_h,Z_{DR})	3.9 e -3	1.07	-5.97
R (K_{DP},Z_{DR})	28.6	0.95	-1.37

Gorgucci et al. (2001) show in his study that for S-band polarimetric radar measurements, raindrops shapes can be approximated by oblate spheroids with the axis ratio given by

$$r = \frac{b}{a} = 1.03 - mD, \quad (5)$$

where D is the spherical diameter in mm; *a* and *b* are the major and minor axes of the spheroid, and m is the slope given by

$$m = -\frac{dr}{dD} \quad (6)$$

On the other hand, Matrasov et al. (2002) show us that the Gorgucci study can be applied to X-band radars using the following nonlinear regression,

$$m = 12\, Z_h^{-0.36}\, K_{DP}^{0.4}\, Z_{DR}^{1.02} \quad (7)$$

The parameter K_{DP} is dependent of the raindrops concentration and to make estimation between the rainfall and the slope factor (2) can be expressed as

$$R\,(K_{DP}) = 8.2\, m^{-0.82}\, K_{DP}^{0.81}. \quad (8)$$

Substituting (7) into (8) a nonlinear algorithm is obtained to estimate the rainfall rate with the three polarimetric parameters

$$R\,(Z_h, K_{DP}, Z_{DR}) = 1.0624\, Z_h^{0.3}\, K_{DP}^{0.5}\, Z_{DR}^{-0.84} \quad (9)$$

This relation is very stable due the low sensitivity that K_{DP} has due to variations of the DSD. (Matrosov et al., 2002)

X-band radars have a great number of advantages, such as finer resolution, easy mobility and low cost system. A great limitation with the X-band radar, though, is that the radar signals have a partial attenuation for quantitative measurements of rainfall. The only rainfall rate relation that is immune to the partial attenuation is the equation (2), since K_{DP} is phase derived and is not affected. For equation (9), which depends on the variables of Z_{DR} and Z_h, these are subject to attenuation and partial attenuation. The result of this attenuation as Park et al. (2005) states it could cause a significant decrease of the power received by the radar, affecting the variables like Z_h and Z_{DR}. If this problem is not corrected, the quantitative application, such as estimation of rainfall will affect the accuracy of this estimation.

IV. Results and Discussion

A. Radar comparison with disdrometer

From Figure 2a, it is observed a convective storm over the west side of Puerto Rico. One of the disdrometers is installed at the UPRM campus, at 6.5km from the radar. Observing the data of the reflectivity, there is a rain shower around the 45 to 50 dBZ. Doing the conversion of the reflectivity to the rainfall rate with the equation 1, Figure 2b shows that there is a rainfall rate over the disdrometer around the 40 to 45 mm/hr. By observing the images, only an estimation of what is falling over the disdrometer is made, since is a point in the entire image of the radar.

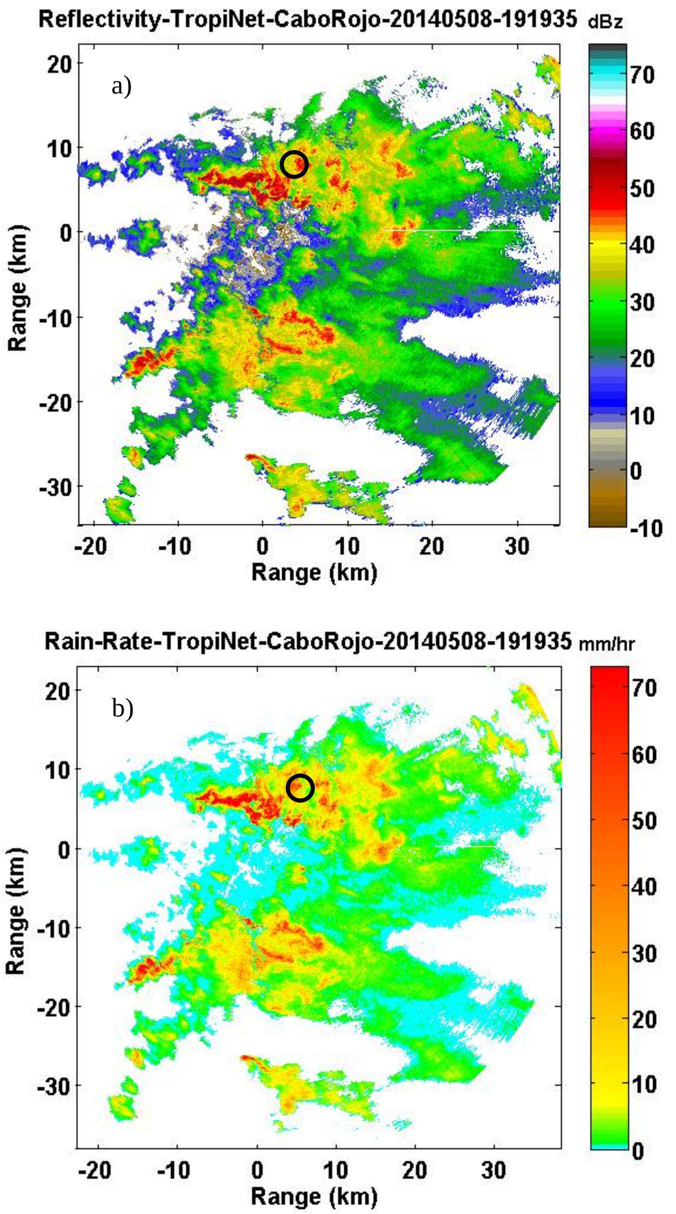

Figure 2: Convective storm over west side of Puerto Rico and the circle showing the location of the UPRM disdrometer. a) Reflectivity b) Rainfall Rate using Reflectivity ($Z_h = aR^b$)

Comparing Figure 2b results, with the information of the disdrometer in Figure 1 below, it can be can noticed that there is a good match. It is known that the disdrometer will show the exact value, since is an instrument designed to measure the rain intensity and it also provides other parameters of the rain drop such as the diameters and fall velocity. Two important parameter values that be obtained from the disdrometer are the *a* and *b* values, which are used in the equation 1. With the disdrometer, a correction of data of the radar for that location is made, and more accurate rainfall estimation is obtained

B. Comparison with Z_{DR} and Reflectivity

Theoretically Z_{DR} can provide information about the shape of the drops. For example, for elongated drops negative values of the Z_{DR} are observed. This variable is good to detect heavy rains and hail, which will help in obtaining a good estimation of the rainfall rate. Converting the reflectivity data of the radar to rainfall rate using equation 3 the data from Figure 3 is obtained. Observing the figure and comparing it with the Figure 2b, it is observed that the algorithm is more accurate than results with the equation 1.

As stated before, two ground-based disdrometer were installed and served as ground reference of the rainfall. These disdrometers measure the rain drop diameters and fall velocity and also provides the rainfall intensity and calculates the radar reflectivity. From Figure 1, for the case on May 8, 2014 at 19:19:35 UTC, over the disdrometer the rain was falling with an intensity of 42.49 mm/hr, and calculates a reflectivity of 47.6 dBZ. Comparing these results with the Figures 2b and 3, it is observed that the results are very similar. The algorithm used to obtain the data of the Figure 3 yields results between 45 to 55 mm/hr, which is slightly overestimating the rainfall. This led us to introduce other polarimetric variables in the analysis.

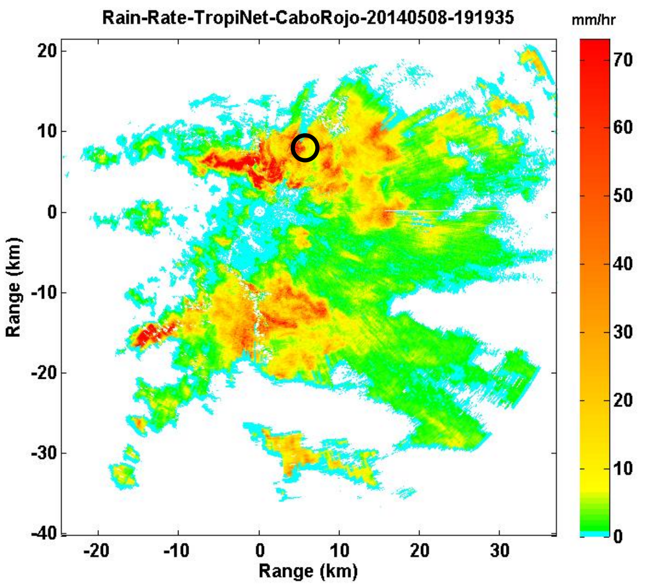

Figure 3: Rainfall Rate algorithm using Differential Reflectivity and Reflectivity ($R(Z_h, Z_{DR}) = a Z_h^b Z_{DR}^c$)

C. Comparison with Z_{DR} and K_{DP}

The specific differential phase is a very useful parameter, but has the limitation that at lower reflectivities, K_{DP} is low and noisy. But for severe storms, it is useful to detect heavy rains.

Similar to other algorithm, using the polarimetric products of the radar, a rainfall algorithm is obtained introducing K_{DP} and Z_{DR} is used to generate (Fig. 4). Comparing it with the disdrometers values, it is evident that for this algorithm there is also a range of rainfall intensity of 45 to 50 mm/hr. As mentioned above, for low reflectivities the K_{DP} variable is very low, which result in the low values in intensity in Figure 4.

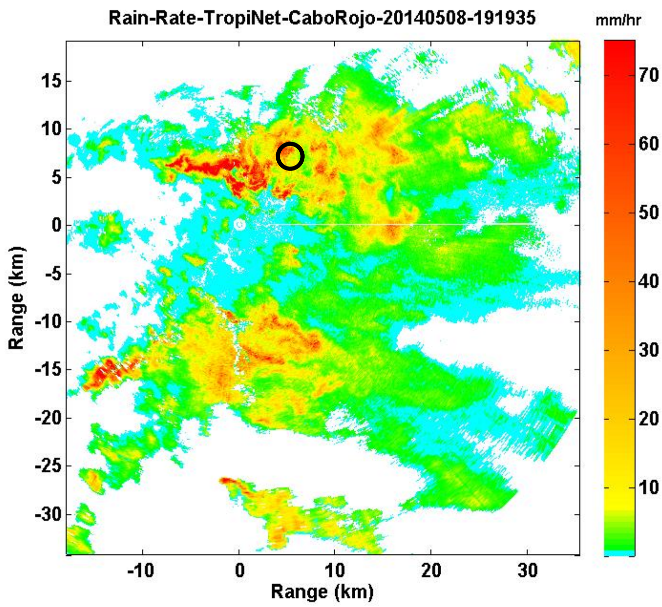

Figure 4: Rainfall Rate algorithm using Differential Reflectivity and Specific Differential Phase ($R(K_{DP}, Z_{DR}) = a K_{DP}^b Z_{DR}^c$)

D. Comparison with Z_{DR}, K_{DP} and Reflectivty

Knowing that the rainfall rate estimation, only with the reflectivity is underestimated; and that with the Z_{DR} is overestimated and in addition that K_{DP} is very noisy and low for low reflectivity, it is desired a combination of the variables, to make a better estimation of the rainfall intensity. This algorithm from equation 9, combines the three polarimetric variables, it would integrate the reflectivity and ground parameters, and the shapes of the hydrometeors. Looking into Figure 5, it is observed that the image almost match with the data from figure 2b. It is observed that over the disdrometer is falling a rainfall intensity around the 45 to 50 mm/hr, which almost match with the data capture by the disdrometer (Fig.1). This algorithm had less estimation error than the other two, which will help to improve the rainfall estimations over the western Puerto Rico.

V. CONCLUSION

Due the topography and location of Puerto Rico, during the wet season of the island and in the afternoons, the west side of the island receives most of the precipitation. Since NEXRAD is around 100 km from the west side, and scan high altitudes, accurate estimation is not possible. Many cases of different rainfall algorithms help us to improve the estimation of the precipitation quantity, and help prevention of property and life loss. With the 3 dual X-band weather radars, we are looking to improve the rainfall estimations, to alert the population on the west side of the island of major flooding event. Due to the introduction of the polarimetric variables, rainfall rate estimations are improved. Usually the rainfall rate algorithm is calculated with the reflectivity but with the variables as the differential reflectivity and the specific differential phase, we have more information about the diameters and shape of the hydrometeors.

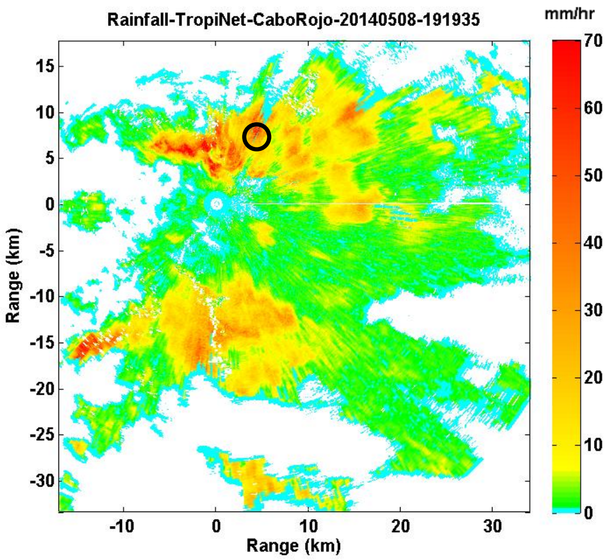

Figure 5: Rainfall Rate algorithm using the three polarimetric variables $R(Z_h, K_{DP}, Z_{DR}) = 1.0624\, Z_h^{0.3} K_{DP}^{0.5} Z_{DR}^{-0.84}$ ($R(Z_h, K_{DP}, Z_{DR}) = 1.0624\, Z_h^{0.3} K_{DP}^{0.5} Z_{DR}^{-0.84}$)

It is observed that with these algorithms are sensitive to low values of K_{DP} which is very noisy and the Z_{DR} overestimate the rainfall algorithm. With the combination of the three variables is expected that these problems will be mitigated, but from Figure 5, we can see that for lower values of the rainfall algorithm, that the algorithm almost match with the rainfall estimation from Figure 2b. But knowing that with the K_{DP} and Z_{DR} are parameter that are used to detect the hydrometers shapes, diameter and velocity, it is concluded from figure 4, that the best algorithm is from equation 4, which use the K_{DP} and the Z_{DR} variables to estimate the rainfall algorithm. If we compare it with the Figure 2, we can conclude that the estimation has a better result and the data can be validated for this day with the disdrometer. These ground truth references are necessary to make changes in the estimation, for example looking only at the image, a range of values is provided, but with the disdrometers exact values are obtained. Looking into the different data, we saw that the rainfall estimation is around the 45-55 mm/hr, which is almost what the UPRM disdrometer capture, with 42.49 mm/hr. It is also recommended to install around the entire coverage of the radars, rain gauges to make a good estimation and make improvements in the estimations of the rainfall rate.

Acknowledgements; This work was supported by the MRI program of the NSF under award number 0821331.

REFERENCES

Cataneo, R. (1969). A Method for Estimating Rainfall Rate-Radar Reflectivity Relationships. *Journal of Applied Meteorology*. http://doi.org/10.1175/1520-0450(1969)008<0815:AMFERR>2.0.CO;2

Cifelli, R., Chandrasekar, V., Lim, S., Kennedy, P. C., Wang, Y., & Rutledge, S. A. (2011). A new dual-polarization radar rainfall algorithm: Application in Colorado precipitation events. *Journal of Atmospheric and Oceanic Technology*. http://doi.org/10.1175/2010JTECHA1488.1

Galvez, M. B., Colom, J. G., Chandrasekar, V., Junyent, F., Cruz-Pol, S., Rodriguez Solis, R. A., … Mora Navarro, K. M. (2013). First observations of the initial radar node in the Puerto Rico TropiNet X-band polarimetric Doppler weather testbed. In *International Geoscience and Remote Sensing Symposium (IGARSS)*. http://doi.org/10.1109/IGARSS.2013.6723287

Gorgucci, E., Scarchilli, G., Chandrasekar, V., & Bringi, V. N. (2001). Rainfall estimation from polarimetric radar measurements: Composite algorithms immune to variability in raindrop shape-size relation. *Journal of Atmospheric and Oceanic Technology*. http://doi.org/10.1175/1520-0426(2001)018<1773:REFPRM>2.0.CO;2

Hogan, R. J. (2007). A variational scheme for retrieving rainfall rate and hail reflectivity fraction from polarization radar. *Journal of Applied Meteorology and Climatology*, *46*(10), 1544–1564. http://doi.org/10.1175/JAM2550.1

Hong, Y., & Gourley, J. J. (2014a). Polarimetric Radar Quantitative Precipitation Estimation. In *Radar Hydrology* (pp. 41–66). CRC Press. http://doi.org/doi:10.1201/b17921-4

Hong, Y., & Gourley, J. J. (2014b). Radar Quantitative Precipitation Estimation. In *Radar Hydrology* (pp. 17–40). CRC Press. http://doi.org/doi:10.1201/b17921-3

Jones, D. M. a. (1956). Rainfall drop size-distribution and radar reflectivity, (D), 3 – 9. Retrieved from http://www.isws.uiuc.edu/pubdoc/CR/ISWSCR-9.pdf

Lee, G. W. (2006). Sources of errors in rainfall measurements by polarimetric radar: Variability of drop size distributions, observational noise, and variation of relationships between R and polarimetric parameters. *Journal of Atmospheric and Oceanic Technology*. http://doi.org/10.1175/JTECH1899.1

Maki, M., Park, S.-G., & Bringi, V. N. (2005). Effect of Natural Variations in Rain Drop Size Distributions on Rain Rate Estimators of 3 cm Wavelength Polarimetric Radar. *Journal of the Meteorological Society of Japan*, *83*(5), 871–893. http://doi.org/10.2151/jmsj.83.871

Matrosov, S. Y., Clark, K. A., Martner, B. E., & Tokay, A. (2002). X-Band Polarimetric Radar Measurements of Rainfall. *Journal of Applied Meteorology*. http://doi.org/10.1175/1520-0450(2002)041<0941:XBPRMO>2.0.CO;2

Park, S. G., Bringi, V. N., Chandrasekar, V., Maki, M., & Iwanami, K. (2005). Correction of radar reflectivity and differential reflectivity for rain attenuation at X band. Part I: Theoretical and empirical basis. *Journal of Atmospheric and Oceanic Technology*. http://doi.org/10.1175/JTECH1803.1

Torres Molina, L. S., Harmsen, E. W., & Cruz-Pol, S. (2013). Flood alert system using rainfall forecast data in Western Puerto Rico. In *International Geoscience and Remote Sensing Symposium (IGARSS)*. http://doi.org/10.1109/IGARSS.2013.6721221