DEVELOPMENT AND IMPLEMENTATION OF AN ATTENUATION CORRECTION ALGORITHM FOR CASA OFF THE GRID X-BAND RADAR NETWORK

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ABSTRACT

The Collaborative Adaptive Sensing of the Atmosphere (CASA) Engineering Research Center (ERC) at UPRM developed an Off-The-Grid (OTG) X-band single polarized radar network deployed in the Puerto Rico west coast. With this kind of radar it is possible to observe some meteorological events that might not be detected by NEXRAD radar due to earth curvature. The main goal of this research is to break with the paradigm and limitations of using X-band OTG radars as a reliable forecast system, where the principal issue is the attenuation due to rain along the path. To overcome this problem the attenuated signal could be rectified through a correction algorithm based on reflectivity and also an ideal polarization (vertical or horizontal) will be identified to certain effects of rain attenuation. To correct for attenuation a hybrid between Hitschfeld – Bordan (HB) method and a Surface Reference Technique (SRT) would be used where the reference signal is the NEXRAD radar data because is considered negligible to attenuation.

1. INTRODUCTION

Weather radars as part of forecasting systems, are useful tools for meteorology and hydrology purposes. Meteorological trends and patterns can be analyzed with the highest precision possible provided by these types of radars. In particular X-band weather radars have various advantages such as high temporal and spatial resolution and low cost as compared to S-band systems. Yet the main X-band radar limitation is the attenuation caused by rain and others hydrometeors. Several attenuation correction algorithms have been proposed for both single and dual-polarized X-band radars. Here we present the development and validation of a modified algorithm to correct for atmospheric attenuation for low-cost single-pol X-band weather radars, which will greatly improve the data provided by these systems.

Previous studies have focused on the limitation (attenuation) of X-band weather radars and possible solutions to this limitation. These studies were the motivation from the NSF CASA-ERC at UPRM to develop and implement an attenuation correction algorithm for Off-The-Grid (OTG) X-band radar network installed in the western region of Puerto Rico. This paper describes the process of the development of this attenuation correction algorithm as well as validation of such.

This algorithm is then implemented to the data provided by the CASA OTG X-band radar. The method applied to estimate and correct the attenuation caused mainly by rain was based on a hybrid between Hitschfeld – Bordan (HB) method and Surface Reference Technique (SRT). A similar method was first adapted and tested by Colorado State University (CSU) with CASA radars but for wet ice attenuation correction. The method was refered to as the SRT-modified correction method.

This mentioned method uses the measured reflectivity (Z_v) to estimate true reflectivity and specific attenuation (A_v) at each range gate based on a power law A_v-Z_v relationship. The coefficient β is fixed, and α is adjusted so that the path – integrated attenuation estimated with Hitschfeld – Bordan (HB) method matches with the path – integrated attenuation (PIA) estimated with Surface Reference Technique method as specified in the SRT modified method. SRT modified method requires computing ∆Z value that is the difference between the un-attenuated S-band reflectivity (WSR-88D S-band NEXRAD located at Puerto Rico) and X-band measured reflectivity (OTG X-band radar data).

The corrected radar reflectivity data was finally compared and the method validated using X-band TropiNet radar data, an NSF funded network of dual-pol, Doppler weather radars also located at UPRM.

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Before applying the attenuation correction algorithm, some aspects were taken into consideration such as: radar calibration, theoretical analysis of atmospheric attenuation and the effect of radar polarization.

2. METHODOLOGY

The attenuation correction procedure followed was divided into four stages. The Figure 1 presents the methodology flow diagram to reach the objectives of this work.

Before the application of the SRT-MODIFIED method to the OTG X-band data, it is necessary to compute the input variables required by the algorithm and the most important aspects which affect the final algorithm results.

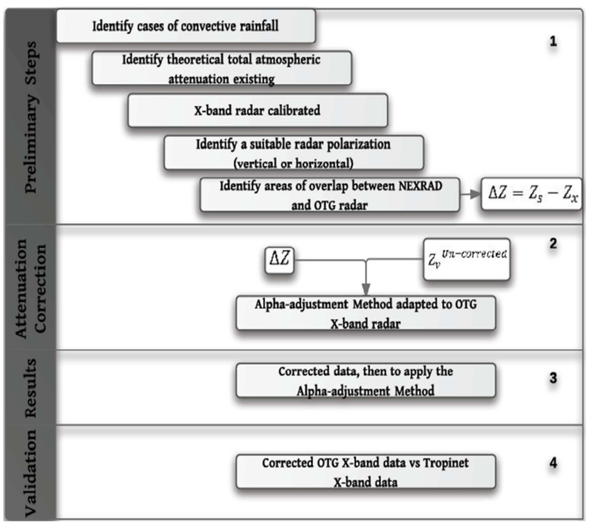

Figure 1. Methodology flow diagram.

2.1 Identify Cases of Convective Rainfall

The first stage is to select a convective rain event. Usually, these types of rain events are characterized by high rainfall rate, indicating that the radar data has the highest rate of attenuation along the propagation path.

2.2 Atmospheric Attenuation Correction

The SRT-modified method does not take into account other atmospheric factors and is useful only for attenuation due to rain, not atmospheric gases. For this reason, the effects due to other atmospheric factors of the rain event taken into account (or corrected for) using the improved atmospheric absorption model proposed by *(Cruz-Pol, 1998)* and presented in *(Ulaby et al., 1981)*.

2.3 Radar Calibration

A suitable radar calibration is another fundamental aspect to avoid undesired variability in the system because would lead to mistakes and overestimation of the radar data in the attenuation correction procedure. In order to verify the radar calibration, a characterization process proposed by the OTG X-band radar developer was implemented *(Pablos, 2010)* to all electronic circuits of the radar with the purpose to determine the radar constant by solving the weather radar equation using the new parameters obtained through this process. In addition, as a result of this characterization process we achieved to expand the radar coverage from 15.36 km to 20.48 km.

2.4 Horizontal and Vertical Polarization Alignment

Previous studies have shown that horizontal radar polarization may lead to increase the attenuation levels of the detected data, in particular when measuring convective rain, because there are greater numbers of prolate rain drops *(Sogo, 2010).* In this research an experiment was developed to identify the presence of prolate and oblate particles in the western region of Puerto Rico. Figure 2 summarizes the procedure used to identify the prolate and oblate raindrops in the western region of Puerto Rico.

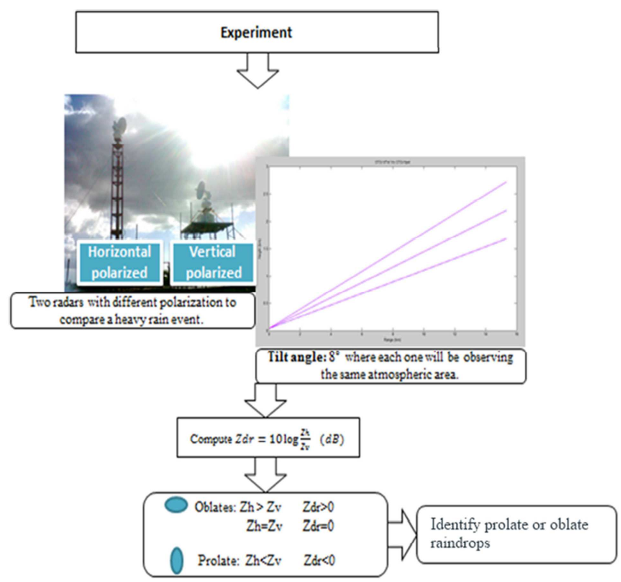

Figure 2. Procedure to identify prolate or oblate raindrops.

2.5 Attenuation Correction Algorithm

After analyzing several attenuation correction techniques for single polarized X-band radars, the advantages and disadvantages of each method, we concluded that a hybrid between HB and SRT would work under the circumstances of lacking the dual polarization.

A flow chart of the attenuation correction method applied to OTG-X band radars is shown in Figure 3. The input variables are: OTG X-band reflectivity data at each azimuth $Z_{m_V}^{X}$ (dBZ), NEXRAD S-band reflectivity data at each azimuth $Z_{m_H}^{S}$ (dBZ), the coefficient α_{inital} and β_{fixed} of the $k - Z_{V_{Corrected}}^{X}$ relationship, k is the specific attenuation.

First of all, each gate of the azimuth is tested for the purpose of identifying if it contains rain data. If there are not rain data in the gate, it means that there is not any $Z_{m_V}^{X}$ (measured reflectivity) value in the gate to which estimate k (specific attenuation). The next step is to implement the attenuation correction method for rain induced attenuation is computed ΔZ value, one of the input variables. Within the algorithm, this value represents the reflectivity difference between an un-attenuated S-band signal (known as a reference signal) and the X-band attenuated signal at the end of the beam, to be more precise, this value is equivalent to $\Delta\sigma°$water cross-section was used in the Tropical Measuring Mission (TRMM) standard algorithm *(Iguchi et al., 2000)*. This value is defined as:

$$\Delta Z = Zh(S - band) - Zh(X - band) \quad \mathbf{1}$$

The reflectivity correction is applied for each azimuth, and the ΔZ value is also computed for each azimuth. An algorithm was developed in this research with the purpose to obtain the ΔZ values.

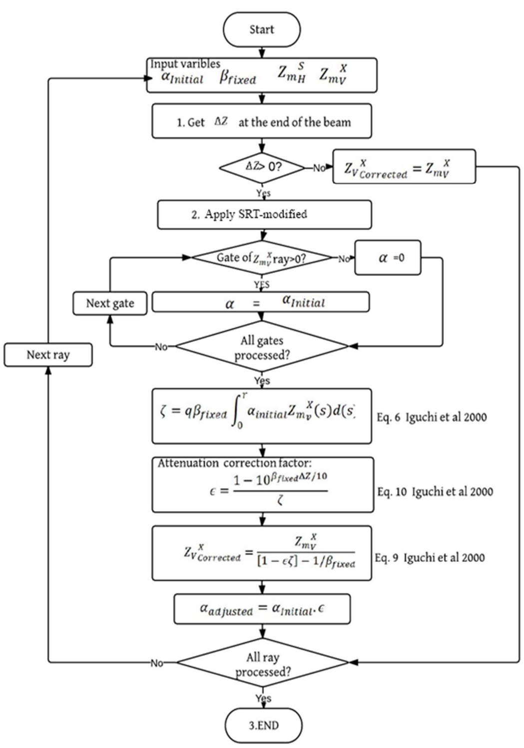

Figure 3. Flowchart of the OTG X-band radars attenuation correction algorithm.

2.5.1 SRT-modified method

The SRT-modified method is based on rain–profiling algorithm for TRMM precipitation radar *(Iguchi et al., 2000)* that is a hybrid of the Hitschfeld-Bordan method and a surface reference method, therefore the SRT-modified method also assumes has a power relationship $k = \alpha Z^{\beta}$, that relates the specific attenuation with the un-attenuated reflectivity.

Within the power relationship, the α value is adjusted while α value remains unchanged. In this research, the initial α value was set as 0.00048 and β fixed to 0.6, as suggested by *(Tuttle & Rinehart, 1983)*. Where the α adjusted by each azimuth is given by

$$\alpha_{adjusted} = \alpha\epsilon \quad \mathbf{2}$$

where: ϵ is the attenuation correction factor and is defined as

$$\epsilon = \frac{1 - 10^{\beta\Delta Z/10}}{\zeta} \quad \mathbf{3}$$

The quantity ζ was defined by *(Iguchi et al., 2000)* as

$$\zeta = q\beta\int_0^r \alpha(s) Z_m{}^{\beta}(s)ds \quad \mathbf{4}$$

where,q=0.2 ln (10).

The corrected reflectivity for OTG X-band radars is computed using the contribution of *(Hitschfeld & Bordan, 1954)* in cooperation with the surface reference technique, which enters changes to the coefficient α with the α –adjustment method. The corrected reflectivity is defined by

$$Z_{V_{Corrected}}^{X} = \frac{Z_{m_V}^{X}}{[1 - \epsilon\zeta] - 1/\beta_{fixed}} \quad \mathbf{5}$$

where, $Z_{m_V}^{X}$ is the OTG X-band measured reflectivity [dBZ].

3. VALIDATION AND RESULTS

First, the validation of the attenuation correction process is discussed in order to evaluate how well the SRT-modified method estimates the true reflectivity.

The selected convective rain event was *June 28th, 2012 Event at 19:41:26 UTC*. A strong attenuation was detected when was compared with the un-attenuated S-band dataset obtained from the WSR-88D NEXRAD Doppler radar, used as reference. Figure 4 and Figure 5 shows the reflectivity data provided by the OTG X-band radar and NEXRAD S-band radar observing the same volume of the atmosphere.

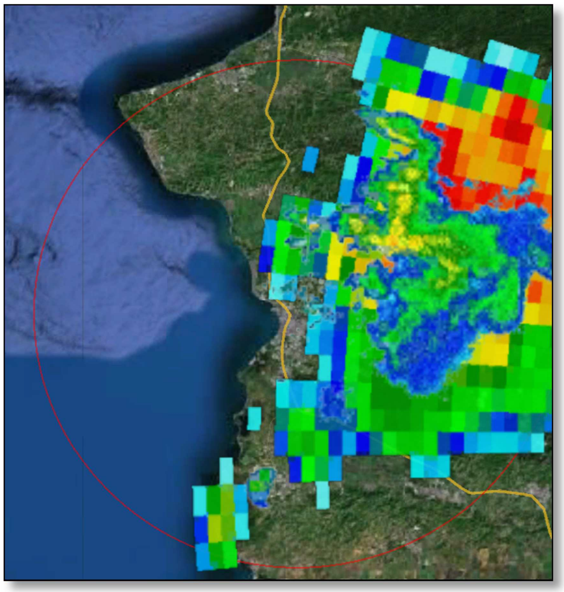

Figure 4. A PPI scan of the OTG X-band measured reflectivity at the elevation angle of 13° and WSR-88D NEXRAD S-band measured reflectivity at 1.3°, June 28, 2012-19:41:26 UTC.

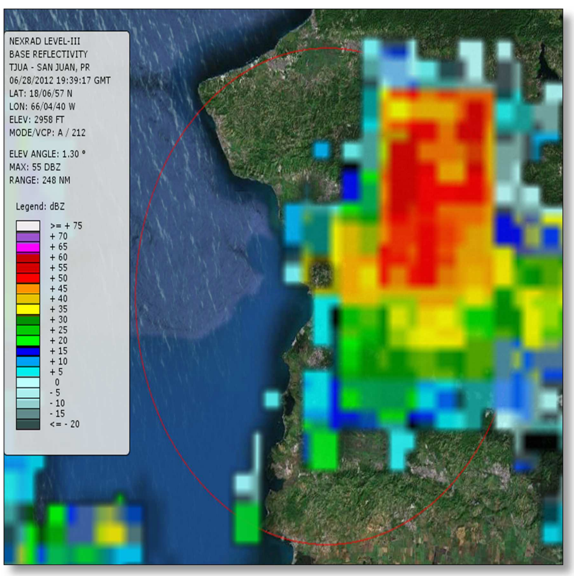

Figure 5. A PPI scan of the WSR-88D NEXRAD S-band measured reflectivity at 1.3°, June 28, 2012-19:41:26 UTC.

In order to test the OTG corrected reflectivity, the reflectivity obtained from TropiNet was used as a reference. This test was conducted to identify if the OTG X-band reflectivity was properly corrected.

Figure 6 shows the attenuation correction from the reflectivity values of rain inside the radar ray selected at 13° in elevation and 287.475° in azimuth. It is evident that the SRT-modified correction implemented for OTG X-band radar performed well. For this case, the ΔZ value retrieved was 19.476 dBZ at the end of the beam. In other words, the ΔZ value is showed attenuation along the path.

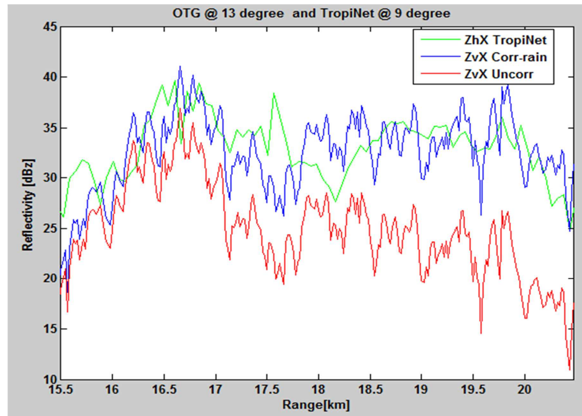

Figure 6. Range profiles of the corrected and uncorrected OTG X-band reflectivity at 13° in elevation and TropiNet X-band reflectivity at 9° in elevation, June 28th, 2012 event at 19:41:26 UTC.

The OTG X-band radar azimuth chosen to be analyzed was 287.4754°, and TropiNet was 287.13° for comparison purposes. The mentioned azimuths were considered because both radars have some gates observing the same rain volume in this area. To identify the overlapping zone between both radars, a beam propagation model was analyzed taking into account the OTG X-band elevation 13° and the TropiNet elevation angle 9°. Figure 7 illustrates how the OTG and TropiNet X-band radars beams propagate through the atmosphere considering the effects due to the curvature of the earth.

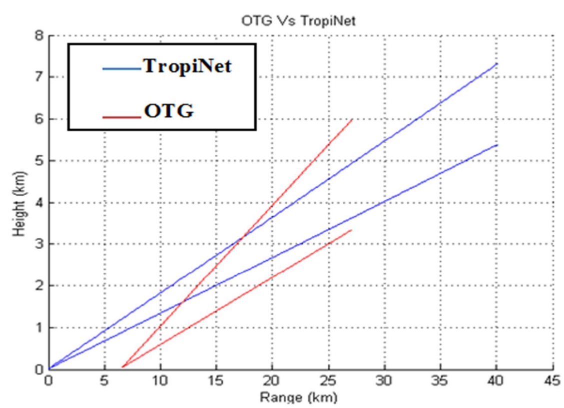

Figure 7. OTG X-band radar beam path at 13° in elevation versus TropiNet X-band radar beam path at 9° in elevation, June 28th, 2012 event at 19:41:26 UTC.

The attenuation correction method was validated for this rain event and proved that is working properly. Therefore, we proceeded to implement the attenuation correction procedure proposed in this research following the steps specified in Figure 1.

Before applying the attenuation correction algorithm, it is required to verify whether the OTG X-band radar signal is attenuated by atmospheric constituents other than rain.

For this purpose, the absorption model summarized by *(Ulaby et al., 1981)* and the improved atmospheric absorption model developed by *(Cruz-Pol, 1998)* at the 3.19cm of the OTG X-band radar were used. Figure 8 shows the results of this modeling for different heights. For this analysis, a sounding dataset from Puerto Rico was used. The observation time was June 28, 2012 at 1200 UTC. As a result, we reaffirm that the attenuation due to gases for the OTG X-band radar operating frequency 9.41GHz is negligible here, as shown Figure 8.

Inside the preliminary steps applying the attenuation correction algorithm to OTG X-band radars, we propose to develop a test in order to determine an appropriate radar polarization (vertical or horizontal) that does not increase the radar signal attenuation. For this purpose, two OTG X-band radars were located in a sites nearby and observing the same atmosphere volume and thus, to compute the differential reflectivity Z_{DR}.

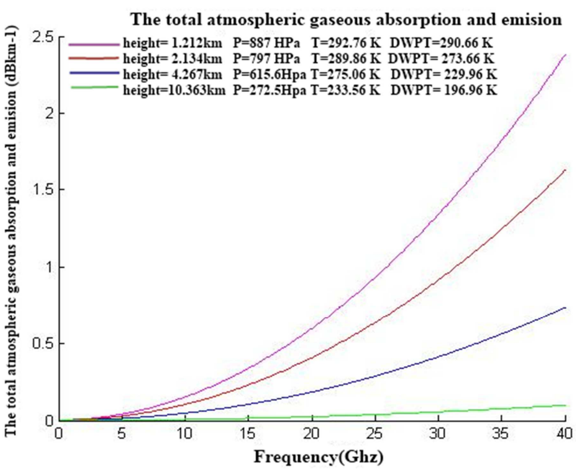

Figure 8. Theoretical total atmospheric gaseous attenuation versus frequency for various heights, June 28th, 2012 event at 19:41:26 UTC.

The differential reflectivity is defined as

$$Z_{DR}(dB) = 10\log\frac{Z_h}{Z_v} \qquad (6)$$

The retrieved differential reflectivity Z_{DR} is plotted in Figure 9. The Z_{DR} value was obtained with the radar reflectivity provided by two OTG X-band radars that have been set up with the two different polarizations.

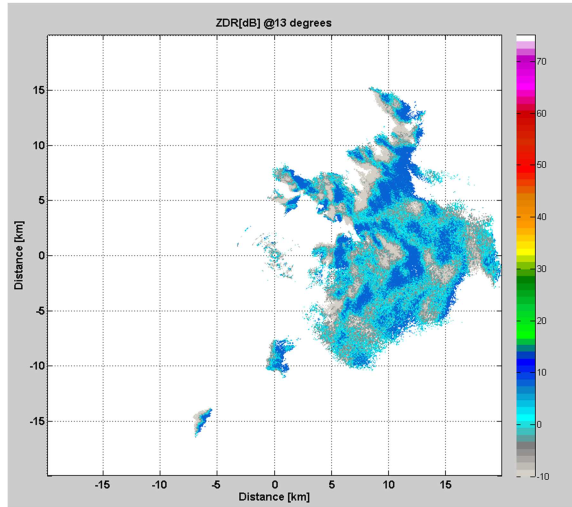

Figure 9. PPI scan of the differential reflectivity Z_{DR} (dB) at 13° in elevation, June 28th, 2012 event at 19:41:26 UTC.

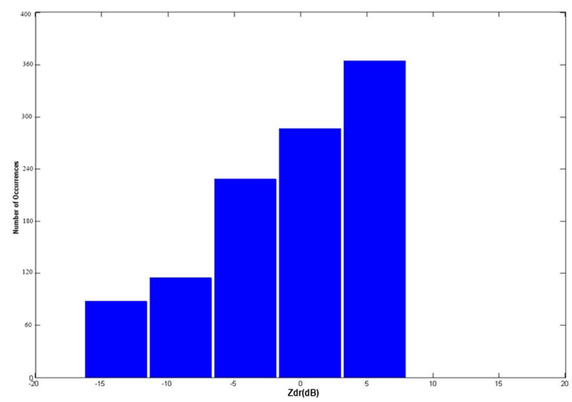

Figure 10. Histogram of the Z_{DR} (dB) for the on June 28th 2012 at 19:41 UTC event, June 28th, 2012 event at 19:41:26 UTC.

Figure 10 shows the histogram of Z_{DR} obtained from the developed test. This histogram's results indicate more occurrences from oblate raindrops than prolate raindrops. In theory, Z_{DR} is positive for oblate raindrops, negative for prolate raindrops and approximately 0 for spherical shape raindrops *(Doviak & Zrnic, 1993)*.

Therefore, to prevent possible errors due to the radar polarization (vertical or horizontal) in the attenuation correction process, we decided to use vertical polarization for OTG X-band radars. These results have confirmed, like other studies, that horizontal radar polarization tends to increase the attenuation effects along the propagation path *(Sogo, 2010)*.

The last step of the methodology flow diagram is to identify the possible tilt angle to which both radar data should collocated for data comparison, specifically for reflectivity data at the end on the beam, where each one is observing the same atmospheric volume in the OTG's last gates.

For this purpose, the effective Earth model for refraction given in *(Peebles, 1998)* was used. Figure 11 was generated as a result of the applied model, which shows the radar beam propagation through the atmosphere. The NEXRAD radar is located in Cayey, Puerto Rico on the coordinate; 18.1155998°N, 66.0780644°W separated 112.853km from the OTG–Stefani located in Mayagüez, Puerto Rico on the coordinate: 18.20955 °N - 67.140033 °W.

The dataset obtained from NEXRAD S-band radar used for the analysis was retrieved at 1.5° elevation angle in such a way as to make a good match between S-band reflectivity and OTG X-band reflectivity at 13° elevation angle at the end of the beam.

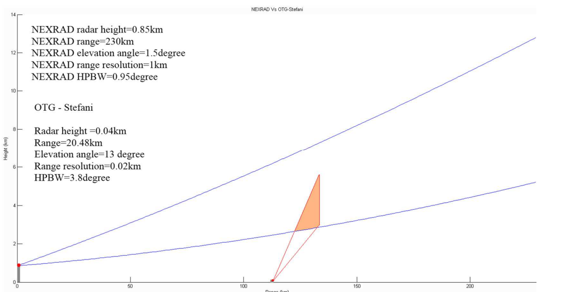

Figure 11. NEXRAD S-band radar versus OTG-Stefani radar propagation beam through the atmosphere.

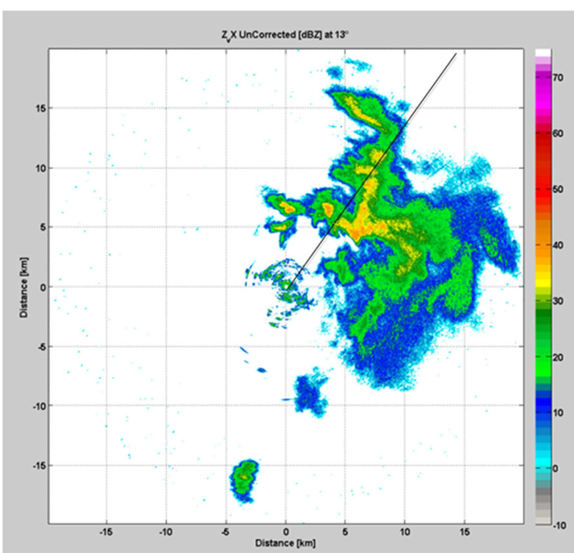

Figure 12. A PPI scan of the OTG X-band measured reflectivity at the elevation angle of 13°, June 28th, 2012 event at 19:41:26 UTC.

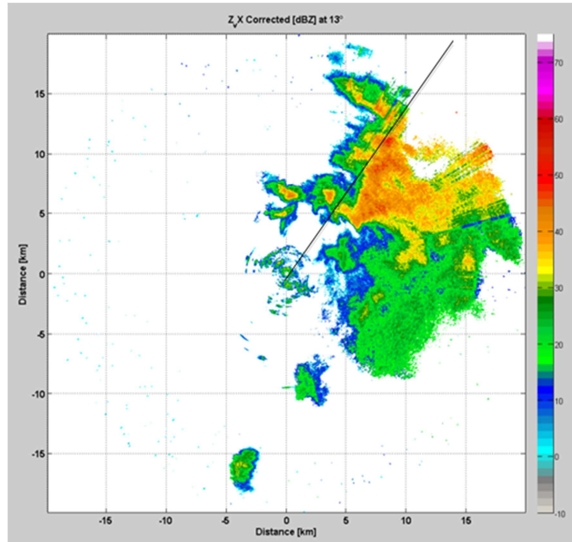

Figure 13. A PPI scan of the OTG X-band corrected reflectivity at the elevation angle of 13°, June 28th, 2012 event at 19:41:26 UTC.

Figure 13 shows a plan position indicator (PPI) scan image of the corrected reflectivity obtained from OTG X-band using the SRT modified method where an α_{adj} is obtained by each azimuth. Comparing the measured (uncorrected) reflectivity data obtained from OTG X-band radar illustrated in the Figure 13 with the corrected reflectivity is visible the highest attenuation correction occurs in far away areas from the radar center because it is a cumulative process along the propagation path.

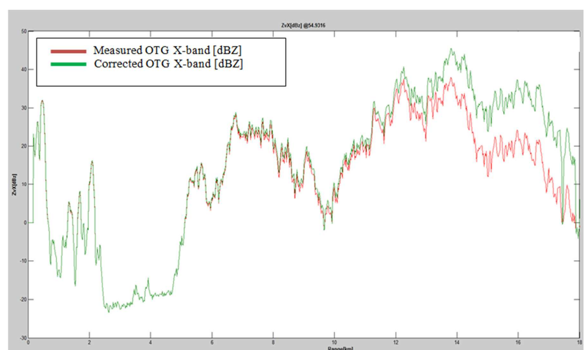

Figure 14. Range profiles of the measured OTG X-band reflectivity along the azimuth angle of 54.9316° and the corrected OTG X-band reflectivity along the azimuth of 54.9316°, June 28th, 2012 event at 19:41:26 UTC.

Figure 14 shows reflectivity range profiles at 13° elevation angle of the OTG X-band signal corrected and the measured reflectivities, both at the same 54.9316° with a ΔZ of 15.2355dB at the maximum range of the beam.

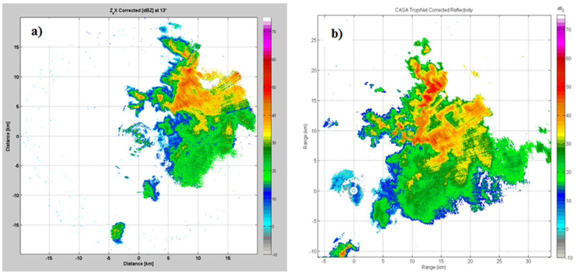

Figure 15. A PPI scan of (a) the OTG X-band corrected reflectivity at the elevation angle of 13^o (b) the TropiNet X-band corrected reflectivity at the elevation angle of 9^o, June 28th, 2012 event at 19:41:26 UTC.

Figure 15 illustrates the PPI scan with the estimated or corrected reflectivity at elevation angle 13^o and PPI scan obtained from the TropiNet X-band radar of the same rain event at an elevation angle 9^o. It is noted the measured reflectivity from OTG X-band radar have been improved and is comparable with reflectivity provided by the TropiNet X-band radar. The α_{adj} (used in the A-Z power law relationship) retrieved by the algorithm ranges from 0.0027 to 0.2027.

4. CONCLUSIONS

Before applying the attenuation correction method, the radar was calibrated and the attenuation caused by atmospheric factors was proven to be negligible. Also, it was identified that in the tropic, rain events are prone to have more prolate raindrops than oblate ones. Then it was decided that vertical polarization was to be used in the OTGs if installed in PR to avoid attenuation.

The SRT-modified algorithm applied to OTG X-band radars was validated with real data provided from TropiNet X-band radar. As a final result, the statistical results and the reflectivity data comparison realized with respect TropiNet X-band radar show us the algorithm is properly estimating the true reflectivity.

5. REFERENCES

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