Active rain-gauge concept for liquid clouds using W-band and S-band Doppler radars

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ABSTRACT

The use of multi-frequency radar's Doppler Spectrum to study different aspects of precipitation has demonstrated its utility as an accurate profiling rain-gauge method. Recent studies used this concept to retrieve the drop-size distribution and vertical air motion in rain using dual-frequency Cloud Profiling Radar System, which operates at 33GHz (Ka-band) and 95GHz (W-band). This study was performed for low to moderate rain-rates because the use of the Ka-band frequency limited the accuracy of the measurements for high rain-rates due to the attenuation this signal suffers while it passes through the cloud. The use of a non-attenuating frequency, such as 2.8GHz, instead of the Ka-band, can provide measurements over a wider dynamic range of rain conditions, extending the active rain-gauge concept to heavier rain-rates. The W-band signal provides accurate measurement of the vertical air motion in rain. The actual drop's shapes must be corrected for heavy rain in which case large non-spherical raindrops exist. Data will be processed as suggested by *Firda et al., 1999*[1] considering the drop's shape corrections. This research's goal is to develop IDL codes to align, process, and analyze the collected data to retrieve several cloud characterization parameters, such as drop size distribution and vertical air motion that would be used to study the inner processes of rain. Rain-rate approximations and the vertical air motion retrieval will be presented.

Keywords: Active Rain Gauge, Drop Size Distribution, Vertical Air Motion, Rain-Rate

1 INTRODUCTION

The drop size distribution is the most fundamental component in microwave rainfall estimation techniques since it governs all the microwave and rainfall integral relations. It is characterized by a high temporal and spatial variability that affects both microwave measurements and ground validation. Therefore, an accurate estimation of the drop size distribution for all rain-rates is necessary in order to develop and validate rainfall retrieval algorithm[2].

The knowledge about the inner processes of rain development can be examined by studying the drop-size distribution of rain. In the past, several research studies have been conducted about this matter including the use of ground-base vertically oriented Doppler radar spectra[3-4]. The Doppler radar spectra method relates the drop-size distribution to the terminal velocity, but the vertical air motion introduces errors by shifting the Doppler spectra along the velocity axis. This makes it difficult to measure the terminal velocity independently from the vertical air motion.

The first approach to remove the vertical air motion was the lower bound method. This method assumes the existence of a large number of drops with a minimum detectable size associated to a minimum detectable velocity[1]. This velocity was compared to the measured values to extract the vertical air motion effect, but this method has several complications including the assumption of a large number of drops, the noise effect, the limitation of dynamic range and that the turbulence was not taken into account. These limitations lead to a second approach using measured reflectivity to predict the drops' correspondent velocities, but errors of about one magnitude mislead to the correct distribution retrieval[1]. A third approach, known as the 3P (three parameters) approach used three parameters to get the drop-size distribution. The problem with this approach was that it only functioned when turbulence

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was negligible[1]. Another study used the wind profilers approach was tried to get the drop-size distribution, but was limited to low rain rates and uniform wind fields[1]. All of the approaches named above, as can be observed, were limited to negligible turbulence effects and uniform wind fields.

Millimeter-wave radars have the potential to estimate vertical winds in rain where complex wind fields exist, even in convective situation where changes in wind and drop size distribution occur rapidly[3]. The Mie scattering effect observed in precipitation using millimeter-waves extracts information of the particles of varied sizes and the distribution as well. In 1988, Lhermitte proposed a method using the Mie backscattering null observed in the 94GHz Doppler spectra to determine the vertical air motion[1]. This algorithm uses correlation analyses between the measured and simulated spectra to remove the vertical air motion and the turbulent broadening even where complex wind fields and turbulence are present, different from the previous four approaches.

In 1999, Lhermitte's proposed algorithm was applied to measurements collected by dual-frequency CPRS (with 35GHz and 95GHz channels) to obtain the Doppler spectra. This approach to retrieve the drop-size distribution was successful but was limited for low-rain rates because of the Ka-band attenuation through the precipitation cloud[3].

Extending our study to all rain rates will require the use of a lower frequency, S-band non-attenuating radar and take into account the real drop's shape. For heavy rain, the drop sphericity is not hold because the change in shape due of its weight and collisions with other drops while falling. This situation will be tackled using Green's model, which approximates the drop shape as a more realistic oblate spheroid[5].

The goal of this research is to retrieve the rainfall rate from the reflectivities obtained in the Doppler Spectra by comparing the measurements with simulation. This way attenuation can be corrected and the vertical air motion and turbulence be removed from the collected data, in order to get the drop size distribution. In order to accomplish this, collocated data from the two radars must be aligned and the drop-size distribution retrieved by an iterative method explained below.

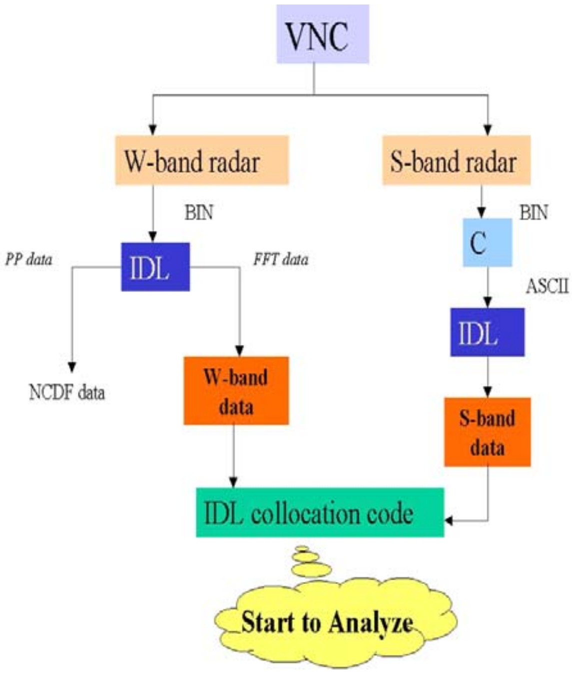


Figure 1: Flowchart depicting steps needed to align data from both radars.

Precipitation data are one of the important inputs to global hydrological cycle and climate models. The dataset obtained from the rain-gauge measurements consist of monthly gridded area-mean rainfall totals for a period of time (January 1986 through March 1999). This work could potentially be used as a basis for verification of climate model simulations, investigations of the global hydrological or as validation for missions such as the NASA Global Precipitation Climatology Project (GPCP). NASA

GPCP aims to derive gridded data sets of monthly precipitation totals covering the entire globe based on all available observation technologies and data[6].

2 METHODOLOGY

Doppler Radars have an important role in the field of meteorology. These sensors send out electromagnetic pulses that interact with objects in the path of the signal, such as water droplets, that scatter the electromagnetic energy. For monostatic (single antenna) radars, this signal provides the backscattered radiation providing valuable information about the target's velocity and reflectivity, which in advanced Doppler radar technology, provides these parameters with high resolution, being vital to short-term forecasting and severe weather prediction.

2.1 Doppler Spectra

In this work two different profilers[†] are used; the University of Massachusetts (UMASS) W-band cloud profiling radar and the National Oceanographic and Atmospheric Administration (NOAA) S-band profiler. Both were deployed at the Cloud and Radiation Testbed (CART) site in Lamont, Oklahoma for a period of 6 months, starting on June 2001, during which weather was monitored and rain data was collected (http://abyss.ecs.umass.edu/Wband2001).

The Pulse-Pair technique estimates the first and second moments of the Doppler Spectra by calculating the auto-correlation function at a time delay of T=VPRF (pulse repetition frequency)[7]. The Fast Fourier technique estimates the full Doppler Spectrum by computing the Fast Fourier transforms (FFT) to the auto-correlation function. The Pulse-Pair mode produces less information because it calculates an average reflectivity for one cell of the profile, while the FFT mode produces a large volume of data because it saves the whole Doppler spectrum for each range cell.

The Doppler spectrum data collected by both profilers using the FFT mode is obtained from the power spectrum created by the backscattered energy and the velocity. This provides information about the drop size distribution with the terminal velocity of the hydrometeors. This relation with the Doppler spectra[4] is as follows,

$$S(v) = N(D)\sigma(D)(dD/dv) \qquad [\mathrm{mm^2 m^{-3}/m{*}s^{-1}}] \tag{1}$$

where v is the velocity of the drop, $S(v)$ is the Doppler spectra, which quantifies how much power from each velocity range is received, $N(D)$ is the drop size distribution (how many drops exist of each size), $\sigma(D)$ is the backscatter cross section of a drop of diameter D, and dD/dv is the relationship between the drops' diameter and terminal velocity.

For rain, the drop-size distribution can be described as a special case of the gamma distribution where μ=0[4]. This is known as the exponential distribution and can be described as,

$$N(D) = N_o e^{-aR^b D} \tag{2}$$

According to the Marshall-Palmer drop-size distribution, a and b, determine the distribution's slope and are given by 4.1 and –0.21 respectively, and N_o=8000[7].

Gunn and Kinzer (1949) empirically determined the relationship between a water drop's velocity and its diameter. This velocity-diameter relationship is given as,

$$v(D) = 9.25\left[1\text{-}e^{(-6.8D^2+4.88D\ )}\right] \qquad [\mathrm{m/s}] \tag{3}$$

[†] A profiler is a vertically oriented Doppler radar.

This formula must be corrected to account for the air density (which decreases with the increasing altitude). This is done by multiplying this equation by a factor of $(\rho_o/\rho)^{0.4}$, for which radiosonde data will be used[8].

2.2 Vertical Air Motion

Vertical air motion (updrafts and downdrafts) and turbulence, all bias the measured signal. These effects must be removed from the radar data to obtain the true drop-size distribution. The dual-frequency method uses the Mie scattering null-effect observed at microwave frequencies to remove biases due to vertical air motion. Lhermitte work showed that the Doppler spectrum depends on frequency; however the drop-size distribution does not. Plotting both frequency spectra (at 95GHz and 33GHz), it follows that the K_a-band has a Gaussian shape and the W-band has several peaks and nulls that later will be used to calculate the vertical air motion[8].

2.3 Raindrops Shape

Another factor to considerate when processing the data, is the actual shape of the hydrometeors. The sphericity of the drops must be corrected using Green's model as described in[5]. This model explains how the drop deviates from sphericity as the drops collide with other drops increasing in size and changing from spheres to oblate drops. We relate the sphere diameter D and the minor and major axis a and b of the equivalent volume ellipsoid (a represents the diameter obtained) (See equation 4 and Figure 2).

$$\left(\frac{a}{ao}\right)^2 - 1 = \frac{4}{17}\left(\sqrt{\frac{17B}{4}+1}-1\right) \tag{4}$$

where $B=\rho a_o^2 g'\sigma^{-1}$ is the Bond number, which is the ratio of the drag and surface forces at terminal speed. The surface tension σ=72.75 g/s^2, the effective gravity g'=980 cm/s^2, and the water density ρ=0.998 g/cm^3 are used in the Bond number calculation.

Figure 2: Side views of an ellipsoid and the equivalent sphere used in Greens model for large rain drops found in heavy rain.

The radar measures the backscatter energy received from the volume of raindrops, which for W band frequencies, lie on the Mie region. Mie scattering theory describes how particles scatter the incident wave, thus this measurement give an estimate of the particle's size with the backscattering coefficient $\sigma_b \propto f^4$ [9].

2.4 Dual-Wavelength Ratio And Attenuation

The radar reflectivities for both radars are determined from,

$$Z_e = \frac{\lambda^4}{|K_w|^2 \pi^5} \int_0^\infty S(v)dv \tag{5}$$

where K_w is calculated from the refraction index of water and λ is the wavelength of the radar in free space[2]. The dual-wavelength ratio, DWR, is calculated using both radar reflectivities by,

$$DWR = 10 \log_{10} \left(\frac{Z_{e2.8}}{Z_{e95}} \right) \tag{6}$$

The one-way attenuation can be calculated as,

$$K = 4.34 * 10^3 \int_0^\infty N(D) \sigma_e (D) dD \qquad \text{[dB/km]} \tag{7}$$

where σ_e is the extinction cross section[7].

2.5 Data Analysis

The proposed data analysis is based upon Firda's work[2]. It uses an iterative method that starts with simulated values and ends up with a rain drop distribution independent from the starting values.

This method starts from a single range cell, moving up to the next higher cell until the whole profile is done and then it moves up to the next time profile as shown in Figure 3. The flow diagram is shown in Figure 4. It starts up simulating reflectivity, the attenuation, the spectrum and the scattering cross section at both frequencies. This is done by using the Mie theory (to obtain the Mie scatter and backscatter coefficient) and radiosonde data. Radiosonde data takes into account the temperature at that cell. The simulations have shown that is temperature dependent[1]. With these values the simulated *DWR* is calculated and compared to the measured one. This step is repeated adding different rain-rates until both quantities are the same, indicating the real rain-rate. Next, attenuation is corrected and once we estimate the rain rate, the spectra can be plotted. To extract the vertical air motion, the velocity axis is moved until the first nulls of the actual and simulated spectra coincide. Turbulence is then estimated by convolving $\sigma(D)$ with simulated turbulence and calculating *N(D)* until the quantity at both frequencies are alike. This is because there is only one drop-size distribution, which is frequency independent [4]. The new spectrum is then calculated using this unique distribution and this is repeated several times to make the spectrum independent from the first simulation. This is the spectrum calculated for just one cell. The next cell's spectrum is then calculated using the latest drop-size distribution calculated as initial guess. This process continues until the first profile is completed; then the next profile is calculated too. These next profiles work with the *N(D)* adjacent to each cell of the past profile as shown in Figure 3.

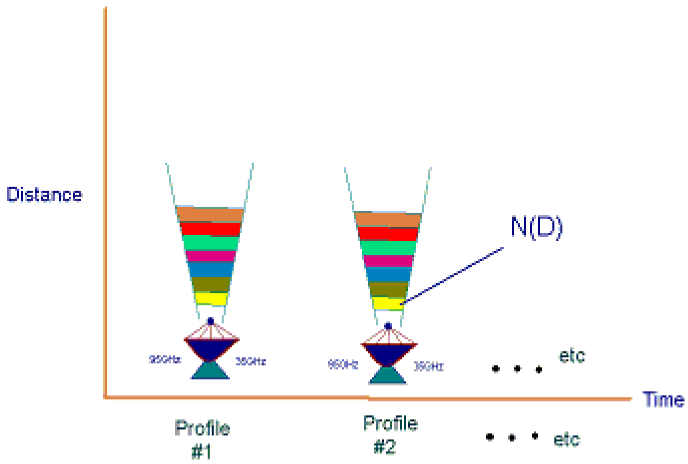


Figure 3: Diagram depicting the calculation order for the drop size distribution, *N(D)*.

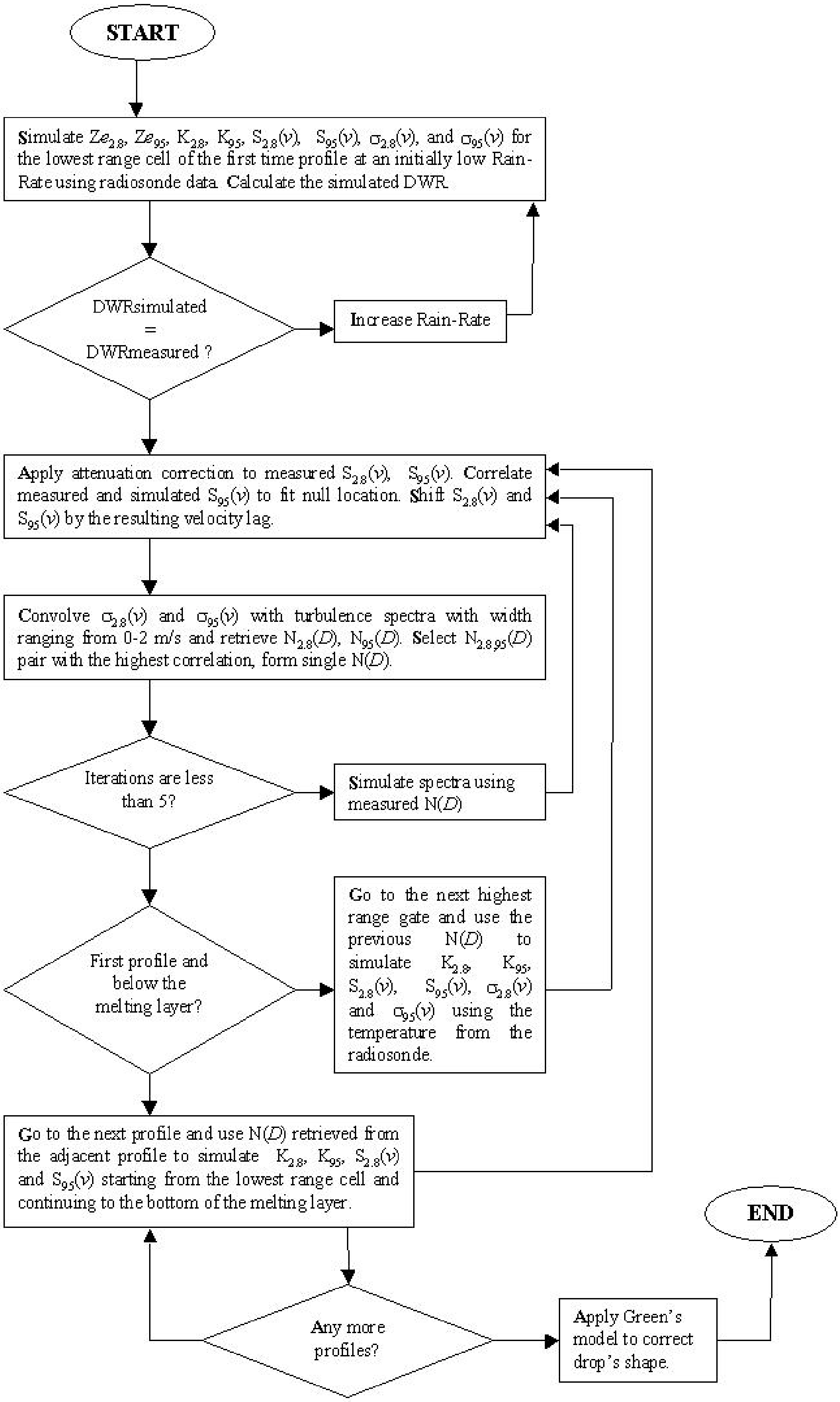
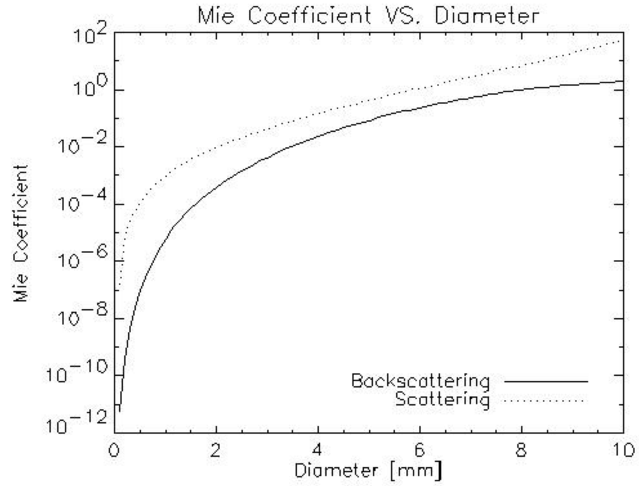


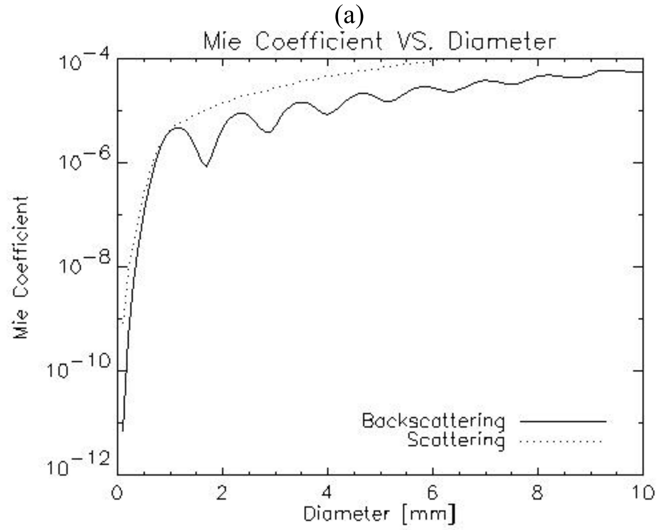
Figure 4: Flowchart for the iterative method to be followed for data processing.

3 RESULTS

As seen in Figure 4, the first step was to simulate reflectivities and spectra for both frequencies, for the first range cell of the first profile. These simulations depend upon the Mie scattering and backscattering coefficients and the radiosonde data (see equations 1 and 5). For the first range cell of the first profile, it was found from the radiosonde data that the temperature was 16.3°C. This temperature was used for the Mie coefficient calculation and results are shown in Figure 5. This Figure shows the Mie scattering and backscattering coefficients obtained for the S-band and W-band as a function of the particle diameter.



(a)



(b)

Figure 5: Mie scattering and backscattering coefficients as a function of the particle diameter (a) Mie Coefficient for 2.8GHz (b) Mie Coefficient for 95GHz

Once the Mie coefficients are obtained, $Z_{e2.8}$ and Z_{e95} were simulated. The two-way attenuation was calculated with equation 7 and then removed from the retrieved reflectivities. Figure 6 shows the attenuation obtained for rain-rates from 0.1 mm/hr to 100 mm/hr. It can be observed that frequency of 95GHz suffers more attenuation than the 2.8GHz.

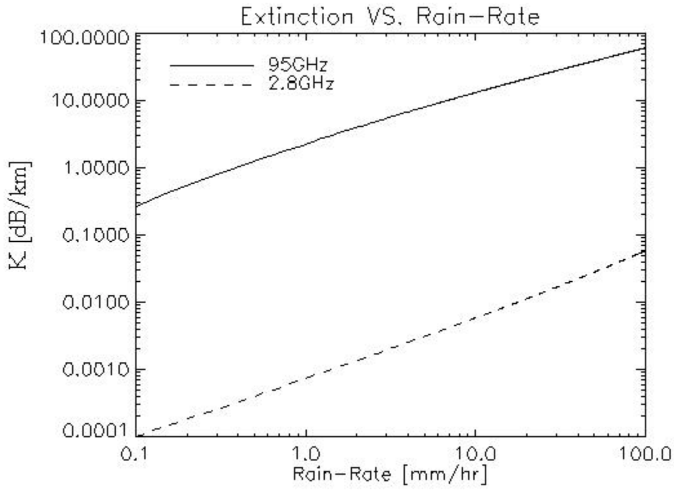


Figure 6: Attenuation for 2.8 GHz and 95 GHz for rain-rates up to 100 mm/hr

After removing 1 km of attenuation from both reflectivities, the simulated DWR was calculated (see Figure 7) and compared to the real DWR, which was found to be 15.14dB for the first range cell of the first profile. After iterating, we found that the simulated and measured values were equivalent when the rain-rate was 10.3514 mm/hr assuming the Marshall-Palmer drop size distribution *N(D)* (equation 2).

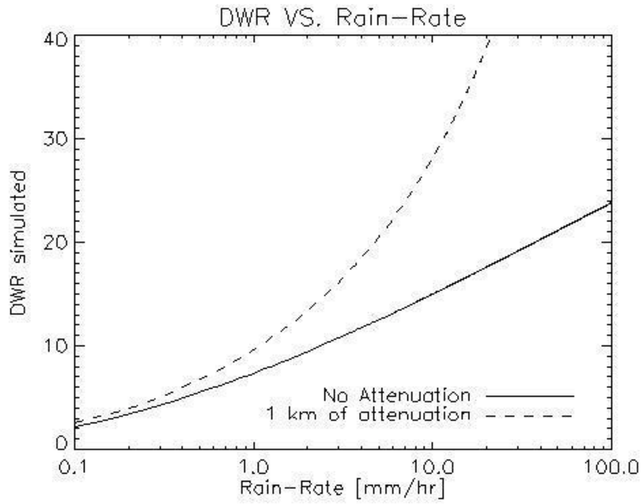


Figure 7: Simulated DWR VS. Rain-Rate with and without removing attenuation

Using the rain-rate equal to 10.3514 mm/hr, the spectrum was simulated and attenuation was calculated for this obtained drop size distribution. The attenuation for the W-band was found to be K_W=13.4879 dB. Once it was removed from the simulated data, both spectra (simulated and measured) were plotted to see the shifting in the velocity axis caused by the vertical air motion. This is shown in Figure 8.

The vertical air motion (VAM) was calculated by subtracting the first Mie null from both, the simulated and the measured spectra. In the simulated spectra the first Mie null is located at approximately 1.5 m/s while the measured first null is found at 6.75 m/s. This gives a difference of 5.25 m/s of velocity lag. This velocity lag is due to downdrafts within the rain.

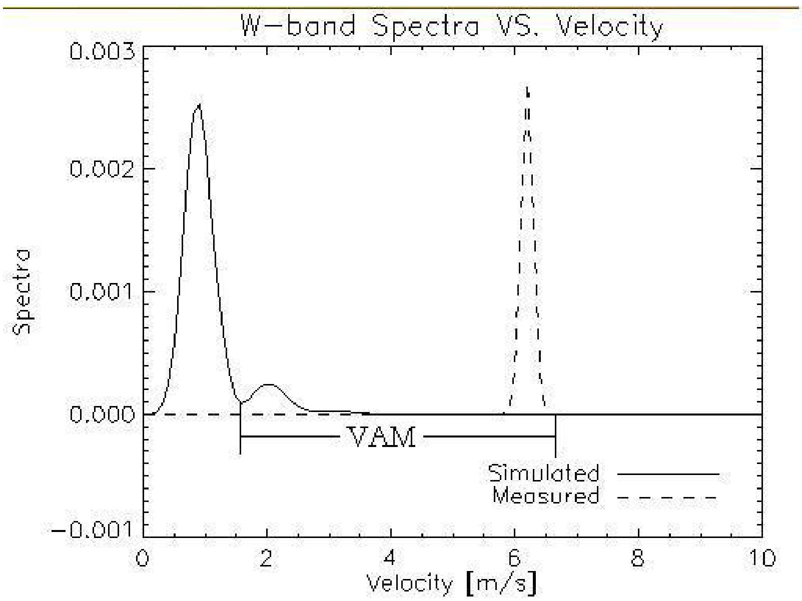


Figure 8: Simulated and Measured Spectra VS. Velocity for 10.3514 mm/hr assuming Marshall-Palmer drop size distribution.

4 CONCLUSIONS

The attenuation and dual-wavelength ratio were computed in order to retrieve the vertical air motion. The rain-rate for the first range cell of the first profile was found to be approximately 10.3514 mm/hr. The Marshall-Palmer drop size distribution was used as an initial guess to compute the simulated spectra for this rain rate value. The 1-km attenuation found for this case, 13.4879 dB, was removed from the simulated and measured spectra. They both were plotted and it was demonstrated the spectra shifting caused by the downdrafts (vertical air motion). This velocity lag was found to be of 5.25 m/s. We have therefore developed the required process to compute the rain rate and the vertical air motion from S and W band Doppler radar data.

Future work will focus on the retrieval of the exact drop size distribution from low- to heavy rain. To do this, the next step is to subtract the velocity lag from the measured data for both frequencies. This way the vertical air motion corrected for. The other factor that biases the spectrum by broadening it, is the turbulence. This will be adjusted as shown in Figure 4, by convolving the backscattered coefficient with a turbulence of different widths. This iteration will be done several times to obtain a drop size distribution that will be independent from the simulation results and from the initial guess.

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