Performance of Scanning Millimeter-Wave Radar in a Tropical Environment

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Abstract

The minimum detectable radar reflectivity (dBZemin) is computed for the University of Massachusetts 33 GHz/95 GHz Cloud Profiling Radar System (CPRS) under humid tropical conditions. Extinction by water vapor and oxygen are calculated for a horizontally stratified atmosphere as a function of range and scan angle for both radar frequencies. Combined radiosonde and dual-frequency microwave radiometer measurements are used to model radar signal extinction for the Maritime Continent Thunderstorm Experiment (MCTEX), which was conducted in northern Australia. These data are compared with CPRS radar measurements to evaluate the performance of both frequencies for sensing clouds and precipitation versus elevation angle

1. Characterize water vapor profile

The data obtained by the radiosonde and corroborated by radiometer data show that the experiment was made under moderated humidity weather conditions with a specific humidity of 8.4 gm^{-3}, 0.48 dB of two-way total attenuation to 15 Km from zenith for the K_a band (33 GHz) with a variance of 0.016 dB. While for the *W* band (95 GHz) the total attenuation was 2.91 dB with variance of 0.37 dB.

2. Attenuation Statistics

2.1 Equations relating humidity profiles and microwave radiometer data to attenuation

Radiosonde profile of air temperature, pressure and specific humidity were used as inputs for the gaseous attenuation models. This data is necessary for atmospheric correction. Assuming a horizontally stratified atmosphere, the gaseous attenuation due to oxygen, $K_{O2}(I)$, and gaseous attenuation due to water vapor, $K_{wv}(l)$, for every height and for each radar frequency, 33 GHz and 95 GHz were calculated.
The equation for $K_{wv}(l)$ is [Cruz-Pol98]:

$$K_{wv} = 0.182\, f^{2}[T_L T_S + T_C\,];$$

where T_L, T_S, and T_C refer to the line strength, the line shape and continuum are functions of the radar frequency, *f*, the water vapor partial pressure, and the difference between total air pressure with the water vapor pressure. These terms are defined in the references.

The oxygen absorption model used is defined as: [Rosenkranz93].

$$K_{O_2} = \frac{P_{dry} c q^{3}}{p} \sum_{|n| odd = 1}^{33} S(T) \left(\frac{f}{f_n} \right)^{2} L_n(f)$$

The total gaseous attenuation in a layer is the sum of the attenuation due to water vapor plus the attenuation due to oxygen particles in that layer.

$$K_g = K_{wv} + K_{O_3}$$

After calculating the gaseous attenuation in each layer, we can obtain the absorption due to gases, where the absorption in a determined layer (A_g), is defined as the sum of the gaseous attenuation of the inferior layers, *l*, to a specific one plus the attenuation in the layer, l_0.

$$A_g(l_0) = 2\int_0^{l_0} k_g(l)\,dr \qquad \text{(Np).}$$

2.2 Zenith attenuation statistics at 33 GHz and 95 GHz

Collecting the radiosonde measurements every day during the experiment, gaseous attenuation, specific humidity and cumulative attenuation profiles were calculated for the complete experiment. Their statistics are presented here.

Statistics for specific humidity

The specific humidity average of MCTEX is 8.4 gm-3

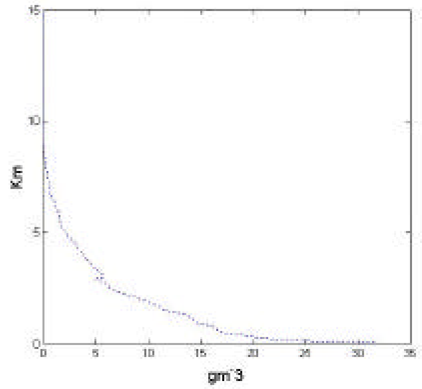

Figure 1. Mean Specific Humidity Profile

Statistics for cumulative gaseous extinction

During all the experiment an average maximum attenuation was found in the highest layer of 0.48 dB for the Ka band (33GHz) with a variability of 0.016 dB, while the W band (95 GHz) the mean was of 2.9164 dB with variability of 0.37 dB.

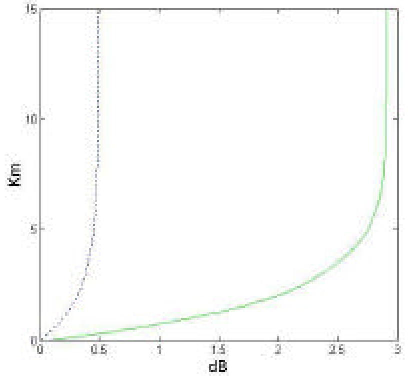

Figure 2. Mean Commutative Gaseous Extinction Profile (--33 GHz and —95 GHz)

2.3 Scan Equations

The path loss, A_g, varies depending on the frequency being used. For frequencies where the path loss degrades the signal strongly, higher power should be used to minimize this effect.

After calculating the atmospheric attenuation for every height, a projection of that attenuation was made for every radar radius at a fixed angle. A matrix of radius times angles was used to save the projected attenuation. Then the cumulative attenuation for specific angle and radius is calculated

$$A_g(q,h) = \sum_{i=0}^{n-1} k(i)\left[h(i) - h(i+1)\right]\sin(q)$$

Finally with the cumulative attenuation for every radius at a specific angle the total path loss, *l*, can be calculated. Using the path loss and the radar equation the reflectivity in dBZ can be determined [Doviak93].

$$l = e^{-A_g}$$

$$Z_e = P(r_0)\frac{6.75\times 2^{14}\, l^2 r_0^2 \ln(2)}{p^5 10^{-17} P_t g^2 g_s t q_1^2 \left|K_w\right|^2 l^2 l_r} \quad \left(mm^6/m^3\right)$$

$$dBZ_e = 10\log_{10}(Z_e)$$

For this system the radar uses the same antenna to transmit the pulses and to receive the echoes where the peak power transmitted is P_t (mW). With an antenna gain g, and one system power gain g_s, with l (m), as the wavelength of the transmitted pulse, t (s) is the duration of the pulse, the pattern of the antenna has the same beamwidth on azimuth and on elevation. The constant *ln(2)* is found in the equation because it was assumed that the antenna radiation pattern is circularly symmetric and with Gaussian [Doviak93]. q_1 (radians) is the half power beamwidth of the antenna, the range of the target is r_o (m), l^2 is the two way attenuation through the atmosphere and l_r^2 are the losses on the receiver given a finite beamwidth, and from the index of refraction of water is obtain $|K_w|$.

After this, graphics from calculations of the dBZ_{emin}, for every radio and each angle at 33 and 95 GHz are plotted

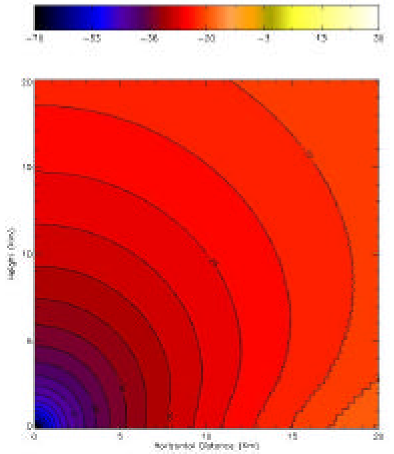

Figure 4.a. Minimum detectable dBZ for 33GHz

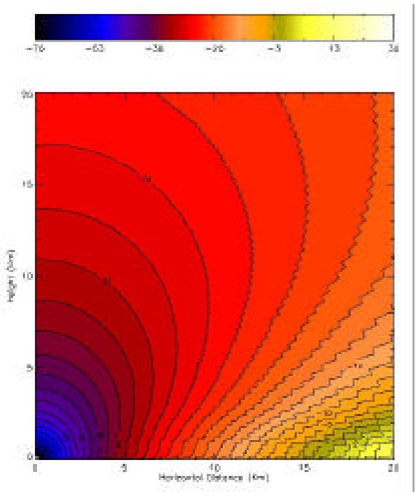

Figure 4.b. Minimum detectable dBZ for 95GHz

As can be seen in figure 4.b the 95 GHz signal is more sensitive than the 33 GHz signal (figure 4.a) to the atmospheric attenuation. This is because the higher frequency 95 GHz suffer greater attenuation due to the water vapor encountered in the lower layer of the atmosphere. As the scanning angle increases from the vertical (zenith) a higher portion of the path traveled by the signal propagates thought the lower layers (higher in water vapor concentration).

Plotting real data of the reflectivity taken November 23th of 1995 in Australia under MCTEX by CPRS in the Ka and W bands with a scanning mode from 10 to 110 degrees, measured from the horizon (Figure 5). In the same date radiosonde and radiometer data were taken, which were used to calculate the values of the Figure 4

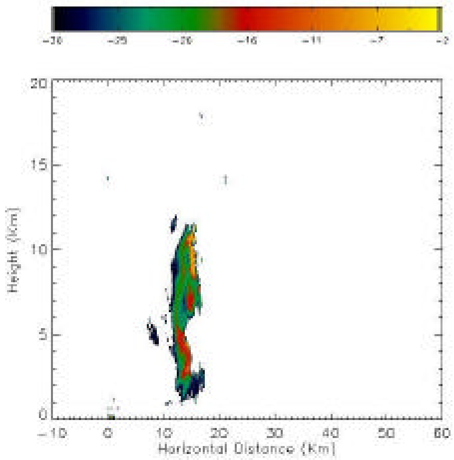

Figure 5.a Real Data of dBZ (33GHz).

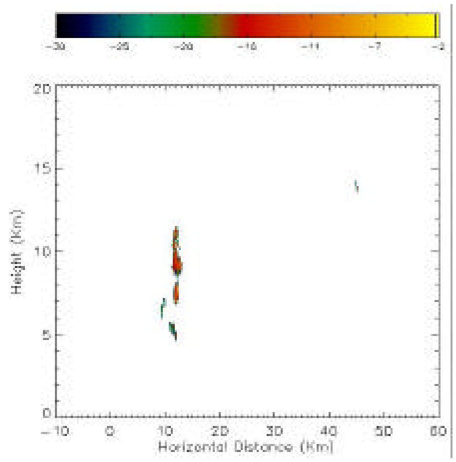

Figure 5.b Real Data of dBZ (95GHz).

The Figure 4 shows that the cloud is not behind of the radar, but some 2.3 kilometer from it along the horizon and 1 kilometers of height. Thus the radar begin to detect the cloud from a radius of 3.2 and from an angle between 15 and 36 degrees. To the W band the cloud is much smaller than the one showed by the Ka band. This data validates the simulation and confirms the effect of the attenuation of the W band in angles smaller than 50 degrees (Figure 4.b).

3. Radar System Characteristic And Mctex Experiment Layout

3.1 Maritime Continent Thuderstorm Experiment (MCTEX)

The MCTEX experiment was performed in the North Coast of Australia, and in the Bathurst and Melville Islands. The principal objective of this experiment was to understand better the physical processes, such as humidity balance over tropical islands on a maritime continent. For this reason, the experiment was realized between November 13 and December 10, 1995; season on which the transition phases occurs between the dry and wet seasons. The data of this experiment were collected with different sensors. One set was collected by means of the Cloud Profiling Radar System (CPRS). This one, collected data on the Ka frequency band (33.12 GHz) and W frequency band (94.92 GHz). Data from the W frequency band, 95 GHz, also was collected by the Airborne Cloud Radar. The NOAA radar collected data on the S frequency band, at 2.8 GHz.

3.2 Radar Hardware of Cloud Profiling Radar System (CPRS)

The CPRS is a dual-frequency polarimetric Doppler radar system that works with two sub-systems at 33 and 95 GHz. This was fully developed by the University of Massachusetts' Microwave Remote Sensing Laboratory (MIRSL).

The CPRS has a programmable structure that allows working in different modes of scanning. It has a high-speed VXI-bus-based data acquisition and digital signal processing (DSP) system. A radome protects the system from atmospheric effects. Both the 33 and 95 GHz sub-systems simultaneously transmit and receive by means of a single aperture and not producing pointing errors between both frequencies.

The CPRS measures can obtain the reflectivity (Z_e), mean fall velocity (u) linear depolarization ratio (LDR), velocity spectral width (s_v), and the full Doppler spectrum ($S(v)$) [Stephen97],[Firda97].

Conclusions

Minimum signal extinction is observed when the radar points at zenith, which corresponds to the shortest path through the moist boundary layer. For the MCTEX data, the average atmospheric two-way path extinction between the surface and tropopause (approximately 18 km) is 30.79 dB and 36.37 dB, at 33 GHz and 95 GHz, respectively and both radar channels have nearly the same minimum detectable reflectivity. However, 95 GHz signal extinction rapidly increases as the radar is scanned away from zenith. At low elevation angles (between 0° and 55° where 0° points to horizontal) the 95 GHz signal experiences significant attenuation and the minimum detectable reflectivity is severely degraded.

While pointing horizontally (0° elevation angle) the average extinction rates for the MCTEX data are 1.78 dB/km and 2.96 dB/km at 33 GHz and 95 GHz. At higher elevation angles the MCTEX data shows that the 95 GHz channel is still sufficiently sensitive to detect clouds at horizontal distances of 10 km or further. In contrast, MCTEX data shows that the 33 GHz channel detects clouds and precipitation at all elevation angles to distances in excess of 50 km. Scanning from horizon-to-horizon a swath in excess of 100 km can be covered at 33 GHz.

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