Estimation of Cloud Droplet Size and Liquid Water Content Using Dual-Wavelength Radar Measurements

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INTRODUCTION

Several studies have demonstrated the potential of a dual-wavelength radar system for estimating liquid and ice mass contents and droplet size. Transmitted radiation at W or K_a-band is measurably attenuated by liquid water whereas at X-band is not; the range-differentiated difference between the returned signal is proportional to the amount of liquid present. The liquid water retrieval is confounded by the presence of hydrometeors, either ice or liquid, in the Mie-scattering size range (where the particle diameter is comparable to the radar wavelength). Reference [1] suggested that a dual-wavelength system consisting of X- and K_a-bands is best suited for ground-based remote sensing of mixed-phase clouds. An analysis of these radar wavelengths along with microwave radiometer observations was discussed in [2]. Factors such as Mie scattering, shallow clouds, and sensitivity of the X-band radar limited the LWC retrieval. A combination of detailed numerical simulations with radar and radiometer data demonstrated the feasibility of a dual-wavelength system for derivation of range-gated LWC along the beam path under a variety of realistic atmospheric conditions and suggested a technique for determining the presence of Mie scatterers [3].

In this study, tri-frequency radar (X, K_a, W-band) measurements collected during MWISP (Mount Washington Icing Sensors Project) were analyzed. Three different data sets exhibit distinct scattering characteristics: (a) Rayleigh scattering, (b) Mie scattering at W-band, and (c) Mie scattering at both W and K_a-bands. The liquid water path estimates along the radar beam are compared with collocated microwave radiometer measurements. In addition, spatial and temporal variations in LWC and droplet size are retrieved.

MODEL CALCULATIONS

Radar reflectivity from an ensemble of particles in a sampled volume is proportional to the incoherent sum of the power backscattered from individual particles. Attenuation through a cloudy medium can be approximated by first-order multiple scattering theory [4]. In this section, reflectivity and attenuation are computed from Mie-scattering cross sections weighted by their drop size distribution (DSD). Droplet shape is spherical and no ice is present. A Gamma DSD is assumed, given by

$$n(D) = N_0 D^{\mu} \exp(-\Lambda D) \qquad (1)$$

where N_0 is an offset parameter, μ is the shape parameter, and Λ is the slope parameter related to a characteristic particle size such as median volume diameter (MVD) and radar estimated size (RES). RES is defined as

$$\mathrm{RES} = \{\langle D^6\rangle / \langle D^3\rangle\}^{1/3} \qquad (2)$$

and can be derived from reflectivity (sixth moment) and attenuation (third moment) measurements from a dual-frequency radar system. RES is generally larger than MVD [5], this difference being greater for broader DSD. For these calculations, the droplet concentrations were varied to maintain a constant LWC of 1 g m^{-3} for all DSD; hence absorption at any given frequency is independent of DSD shape and RES for Rayleigh scattering.

As μ increases the DSD becomes narrower and more of the larger droplets are closer in size to the RES, as shown in Fig. 1. For small droplet diameters (<2000 μm), the difference in reflectivity between X and

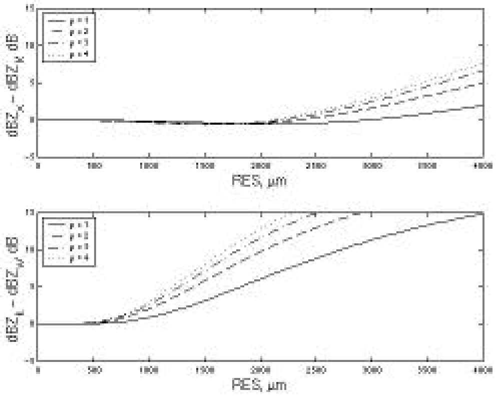

Figure 1. Model calculations of dual-frequency ratios for X,K_a and K_a,W frequency pairs as a function of RES. Liquid water contents for all DSD are 1 g m^{-3}.

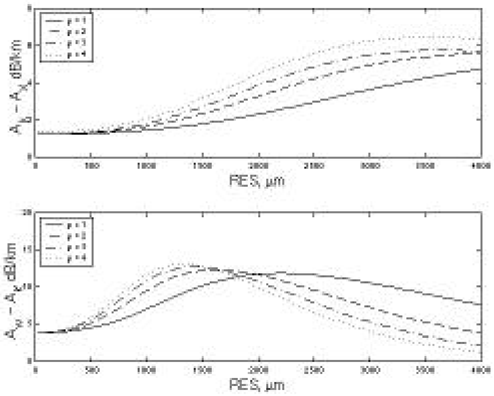

Figure 2. Model calculations of attenuation differences for X,K_a and K_a,W frequency pairs. Liquid water contents for all DSD are 1 g m^{-3}.

K_a-band is 0 dB. As the RES increases, the difference increases monotonically due to Mie scattering at RES >~2000 μm. Thus in principle the reflectivity difference, or DWR (dual reflectivity ratio), can be used to estimate RES. However, the dependence of DWR on DSD shape would introduce uncertainty in the RES estimate. Nevertheless DWR can be used to detect the presence of RES >2500 μm. Note that the DWR for the K_a,W frequency pair is larger than for the X,K_a pair for a specified RES.

For Rayleigh scattering, the difference in attenuation (Fig. 2) is independent of RES and DSD; it depends only on LWC. Attenuation is the sum of absorption (from liquid and vapor) and scattering loss. The scattering loss becomes a significant fraction of attenuation for larger RES and absorption becomes a nonlinear function of LWC. The dependency of attenuation difference on RES will lead to overestimation of LWC for DSD with larger RES. The model calculations suggest that accurate estimation of LWC is feasible only when RES is <500 μm for the X,K_a and <250 μm for the K_a,W frequency combinations. Since DWR >0 dB indicates the presence of larger RES, it can be used as a quality control parameter in LWC retrieval.

ANALYSIS

During the MWISP field program [6], remote sensors were deployed at a site ~1 km lower and ~4 km west of the Mt. Washington summit. NOAA's Environmental Technology Laboratory (ETL) operated their X and K_a-band radars. The K_a-band radar had polarization capability which proved useful for estimating particle types and sizes during the study. Quadrant Engineering, Inc. operated their dual-frequency K_a- and W- band radar. A dual-wavelength (23.8 and 31.4 GHz) tippable radiometer was also deployed by NOAA ETL at the same location. For studies of mutli-wavelength retrieval of LWC and other cloud properties, the instruments were pointed toward the mountain summit at constant elevation (18°) and azimuth angle (88°), in "stare" mode. This elevation angle was chosen to provide measurements near the summit, where in situ instruments were located for comparison, yet be high enough (~3° above the mountaintop) to minimize contamination of the radiometer data by upwelling radiation. Prior to being recorded, the radiometer brightness temperature data were averaged over 1-min intervals; for this study the radar data were averaged over the same 1-min periods.

The attenuation in the dual-frequency radar measurement is the sum of the absorption due to vapor and liquid, plus scattering loss. Attenuation due to scattering is negligible for the Rayleigh scattering regime and initially increases with RES, followed by a decrease due to the Mie scattering effect. The radiometer-retrieved vapor [7] was used to account for absorption due to vapor. The vapor profile was assumed an exponential function with a scale height of 2km, approximately the cloud top height for these studies. For comparison, the attenuation differences for the X,K_a and K_a,W frequency pairs from 1 cm of vapor are 0.25 and 0.35 dB, respectively (recall that the higher frequencies absorb more than the lower frequencies).

Rayleigh scattering

For the first example, data were collected on 22 April 1999 between 1424 and 1524 UTC. The conditions were shallow stratiform clouds with maximum K_a-band reflectivity of 15 dBZ . The K_a-band depolarization suggested the precipitation was dominated by small droplets (<250 μm diameter). Collocated LIDAR observations [8] supported the absence of large liquid droplets and ice particles in the sample volume. The DWR at the cloud top should be directly proportional to the liquid water path (LWP) and vapor attenuation, since effects from large drops are not present. For this case the radiometer and radar-retrieved LWP are in good agreement considering the small amount of liquid present. The agreement improves for times with LWP >0.5 mm. Various factors such as beam volume mismatch between K_a and W-band radars, measurement accuracy in reflectivity, and residual vapor and Mie scattering effects could introduce bias in the retrieval.

Time-series plots of along-the-beam profiles of K_a-band dBZ, X,K_a-band DWR, and retrieved LWC and RES will be shown at the conference presentation. In a medium with such small cloud droplets, DWR should increase monotonically as a function of range [3]. However, at close range, DWR changed abruptly and became negative. Fluctuations in DWR at ranges <1 km from the radar could arise from beam mismatch. The beam widths of the K_a and W-band radars differed by a factor of 2.5 which could cause significant differences in radar sampling volumes.

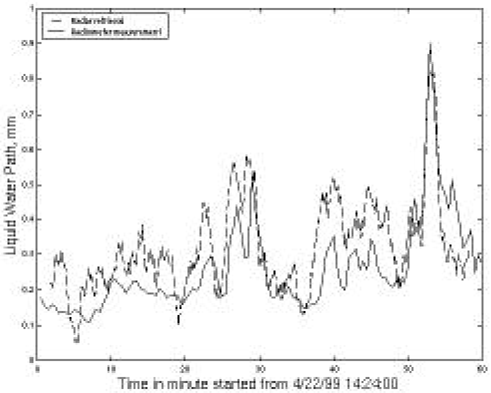

Figure 3. Comparison of liquid water path estimates from K_a,W-band radar and a radiometer for Rayleigh scattering. The data were collected on 22 April 1999 between 1424 and 1524 UTC.

Mie Scattering at W-band

Measurements taken on 13 April 1999 between 1305 and 1330 UTC exhibited Rayleigh scattering at K_a-band and Mie scattering at W-band. Fig. 4 shows X,K_a, K_a,W and radiometer LWP retrievals. Radiometer and X,K_a LWP show good agreement. The larger LWP values (~2 mm) compared to the 22 April case suggest absorption due to LWC should clearly dominate over vapor absorption. The overestimate of LWP in the K_a,W-band retrieval could be due to Mie scattering at W-band. The model calculations suggest the Mie scattering effect in attenuation precedes the Mie scattering in reflectivity. This overestimation of LWP for the K_a,W pair suggests RES is >250 μm as in Fig. 2.

Mie scattering at K_a- and W-band

Collocated X-, K_a- and W-band radar data were collected in a mixed-phase cloud on 10 April 1999 between 1605 and 1630 UTC. The depolarization data from the K_a-band radar indicated the presence of ice particles. Microwave radiometer-based LWP steadily

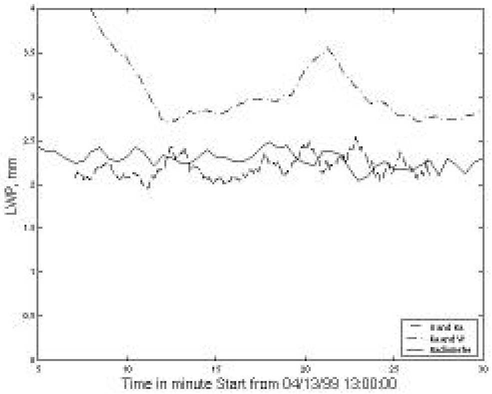

Figure 4. Liquid water path comparison between X,K_a- and K_a,W-band radar and radiometer estimates. The data were collected on 13 April 1999 between 1305 and 1330 Z.

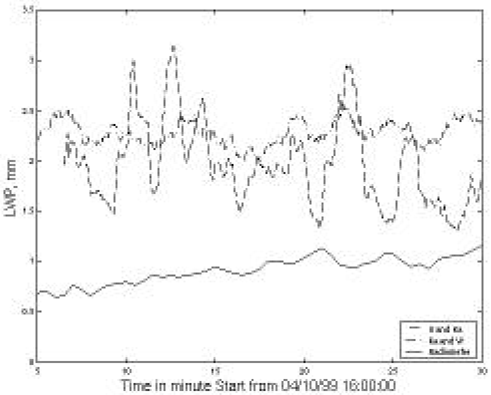

Figure 5: Same as Fig. 4 except the data were collected on 10 April 1999 between 1605 and 1630 UTC.

increased from 0.7 to 1.2 mm throughout the time period; and both X,K_a and K_a,W-band LWP are larger than these values. This overestimation of radar-based LWP is likely due to presence of Mie scatterers (particle diameter >500 µm, see Fig. 2) in the radar resolution volume.

SUMMARY

Model calculations of reflectivity and attenuation differences for X,K_a and K_a,W-band radar frequency pairs show the retrieval of liquid water content using a dual-wavelength technique is unbiased only for Rayleigh scattering conditions. Drop size distributions with RES<500 and 250 µm satisfy these conditions at K_a- and W-band respectively. Comparisons between radiometer and radar-based liquid water path reveal the effect of particle size. Generally, the Mie scattering effect results in an overestimation of liquid water content. The results of this study will be used to specify an optimal dual-frequency radar for estimating liquid water content and droplet size.

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