Comparison of Millimeter-Wave Cloud Radar Measurements for the Fall 1997 Cloud IOP

S. M. Sekelsky, L. Li, J. Calloway, and R. E. McIntosh
University of Massachusetts
Amherst, Massachusetts

M. A. Miller
Brookhaven National Laboratory
Upton, New York

E. E. Clothiaux
The Pennsylvania State University
University Park, Pennsylvania

S. Haimov
University of Wyoming
Laramie, Wyoming

G. G. Mace and K. Sassen
University of Utah
Salt Lake City, Utah

Introduction

One of the primary objectives of the fall 1997 intensive observation period (IOP) was to intercompare Ka-band (35 GHz) and W-band (95 GHz) cloud radar observations and verify system calibrations. During September 1997, several cloud radars were deployed at the Southern Great Plains (SGP) Cloud and Radiation Testbed (CART) site, including the full time operation 35-GHz CART millimeter-wave cloud radar (MMCR) (Moran et al. 1998), the University of Massachusetts (UMass) single antenna 33-GHz/95-GHz Cloud Profiling Radar System (CPRS) (Sekelsky and McIntosh 1995), the 95-GHz Wyoming Cloud Radar (WCR) flown on the University of Wyoming King Air (Galloway et al. 1996), the University of Utah 95-GHz radar and the dual-antenna Pennsylvania State University 94-GHz radar (Clothiaux et al. 1995). In this paper, we discuss several issues relevant to comparison of ground-based radars, including the detection and filtering of insect returns. Preliminary comparisons of ground-based Ka-band radar reflectivity data and comparisons with airborne radar reflectivity measurements are also presented.

Polarimetric Filtering of Insect Returns

Radar returns from insects and from other non-hydrometer targets, often referred to as “angels” or “atmospheric plankton,” complicate comparison of radar observations because radar systems operating at different frequencies or having different beamwidths observe different concentrations of these scatterers and report different reflectivity values. This is due to the fact that these targets are typically not beam filling and often produce non-Rayleigh scattering, which is frequency-dependent. Although insects are probably the principal contaminants because of their large size and large dielectric constant, spiders, spider webs, and other organic materials have been collected high in the atmosphere using nets and other means. These targets must somehow be filtered or otherwise accounted for when comparing liquid cloud measurements. One possible method for removing atmospheric plankton returns is the use of polarization diversity in the radar transmitter or receiver.

Numerous references in the existing body of literature describe observations of insects using variable polarization and multiple frequency radars operating below 30 GHz (Hajovsky et al. 1966, Hardy et al. 1966). Polarimetric observations of atmospheric plankton collected by the University of Massachusetts (UMass) CPRS show that linear depolarization measured at millimeter-wavelengths can also identify non-hydrometer returns. Linear depolarization ratio is defined as:

$$LDR = 10\log(P_{vh}/P_{hh}),$$

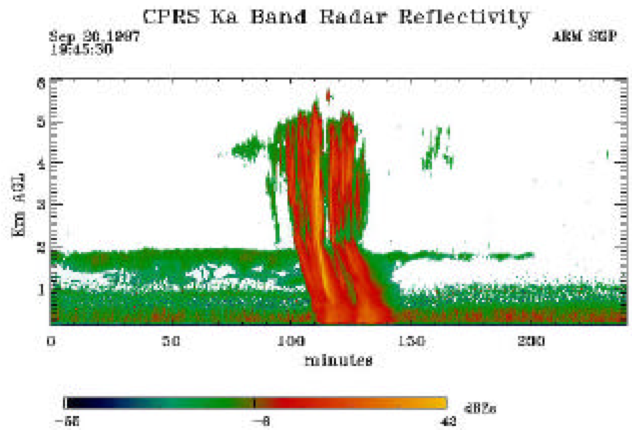
$$= 10\log(P_{hv}/P_{vv}),$$

where P represents received power measured by radar. The first subscript denotes the transmit polarization and the second subscript denotes the receiver polarization. Therefore, a dual-polarized receiver is required to measure linear depolarization ratio (LDR). A fraction of the energy in the radar pulse incident on an insect or other irregularly shaped particle is scattered in other polarization planes. LDR is simply the ratio of the power scattered in the orthogonal plane to that scattered in the parallel plane with respect to the transmit polarization.

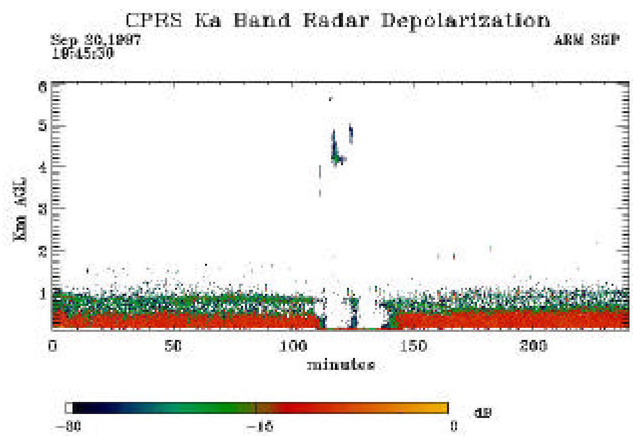
Figures 1a-c illustrate how LDR can be used to identify and remove contaminated radar samples. Figure 1a shows a time-height image of CPRS reflectivity and Figure 1b shows LDR. Liquid clouds and precipitation are not depolarizing when viewed at zenith incidence. Insect returns are highly depolarizing. Therefore, all pixels below the freezing level that contain significant depolarization are flagged as non-hydrometer contaminants and masked from the reflectivity image. A second algorithm searches for insect contaminated pixels removed from liquid clouds and interpolates across these pixels estimating their reflectivity from adjacent, non-contaminated pixels. A filtered version of the data in Figure 1a is shown in Figure 1c.

Comparison of CPRS and MMCR Ka-Band Reflectivity Data

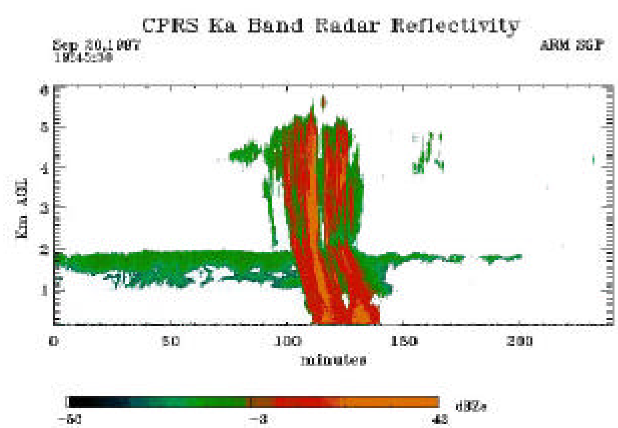
Given that contaminants can be identified using depolarization, we can compare liquid cloud data with confidence that we are not mistakenly comparing insect returns. Several discrepancies between CPRS Ka-band and MMCR reflectivity and Doppler moments have been observed in measurements collected during the fall 1997 IOP. For the moment, we concentrate on reflectivity comparisons because Doppler comparisons are complicated by the use of spectral processing in the MMCR and pulse-pair processing



(a)



(b)



(c)

Figure 1. Results of LDR insect filter. Original reflectivity image (a) is difficult to interpret. LDR image (b) identifies pixels containing insects and other depolarizing material. Most insect returns are eliminated in the filtered image (c). (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/sekelsky-98.pdf*.)

in CPRS. Below, Ka-band reflectivity values from CPRS and the MMCR are compared in high clouds under non-precipitating conditions, and in low clouds before, during, and after precipitation.

High Clouds

A nearly constant offset of 6.5 dB was observed for high clouds during precipitation-free periods. 2.3 dB has been accounted for thus far in the MMCR calibration. The radars also assume a different index of refraction for water. This accounts for an additional 0.57 dB, which leaves a residual discrepancy with MMCR reflectivity values 3.65 dB lower than those measured by CPRS.

Low Clouds and Precipitation

Comparison between MMCR and CPRS reflectivity for low clouds and precipitation shows a large spread of values with MMCR data falling between 6.5 dB and 20 dB lower than that observed by CPRS. The 6.5 dB offset for low clouds is identical to that seen in high clouds when no precipitation is present. The larger differences in low clouds may be explained both by rainwater sheeting on the MMCR radome, and saturation of the MMCR receiver in precipitation. Figure 2 shows a time series of reflectivity at 1.7 km above ground level measured by CPRS and the MMCR. This data corresponds to that shown in Figure 1a. This displays the constant offset of 6.5 dB in the stratus cloud prior to precipitation. When precipitation passed over the radars, the peak reflectivity values measured by CPRS were substantially larger than those measured by the MMCR. In fact, for this particular precipitation event, the peak reflectivity for CPRS was 20 dB larger than that measured by the MMCR. This corresponds approximately to the difference in the dynamic range of the CPRS and MMCR receivers as reported by Sekelsky and McIntosh (1995) and Moran et al. (1998).

Figure 2 also shows that when liquid contacted the radar antennas there was a sudden and large difference in MMCR and CPRS reflectivity. In this case, MMCR reflectivity drops below that measured by CPRS. The CPRS antenna is a 1-meter-diameter plano-convex dielectric lens with the curved face pointing outward. The lens is waxed and water tends to bead and run off the curved lens surface. The MMCR antenna is a 3-meter-diameter cassegrain dish with a cylindrical shroud and a tilted fabric radome. McGill University has reported (personal communication) that a similar antenna with a 2-foot diameter operating at X-band (10 GHz) produces approximately 4 dB of attenuation when rain strikes its radome. Given these facts, the large differences observed at Ka-band are not surprising.

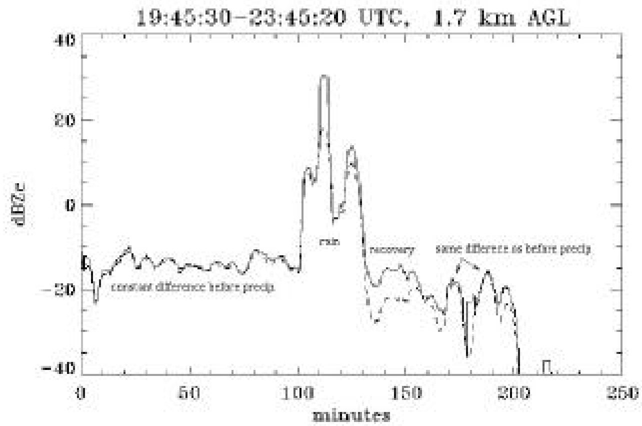


Figure 2. Attenuating effects of rain on MMCR radome.

The 3.65-dB difference observed in non-precipitating clouds remains unexplained. One method for evaluating a system calibration is to measure the radar cross-section of a known target. While the MMCR antenna is fixed in the zenith direction, the CPRS antenna is scannable. During the fall 1997 IOP observations of 3-inch and 5-inch trihedral reflectors were used to calculate CPRS calibration coefficients. A consistency check at both CPRS frequencies showed good agreement in reflectivity values when the calibration coefficients were applied to measurements of liquid clouds and differences due to water vapor absorption were removed. However, independent confirmation of cloud reflectivity values measured by CPRS and the MMCR using airborne radar and in situ data might help to resolve the discrepancies observed between the CPRS and the MMCR.

Comparison of Airborne and Ground-Based Radar Reflectivity Measurements

Airborne radar and in situ data are being analyzed as independent measurements to corroborate the accuracy of the ground-based radar calibrations. The University of Wyoming King Air aircraft carries a full suite of microphysical probes and the 95-GHz WCR radar that can be configured to point vertically or horizontally. Initial comparisons of in situ probe measurements are incomplete. However, initial comparison of WCR data and ground-based CPRS data are promising. Figures 3a and 3b compare average vertical profiles of 95-GHz airborne and CPRS Ka-band ground-based radar measurements over two averaging periods. The aircraft data are averaged spatially

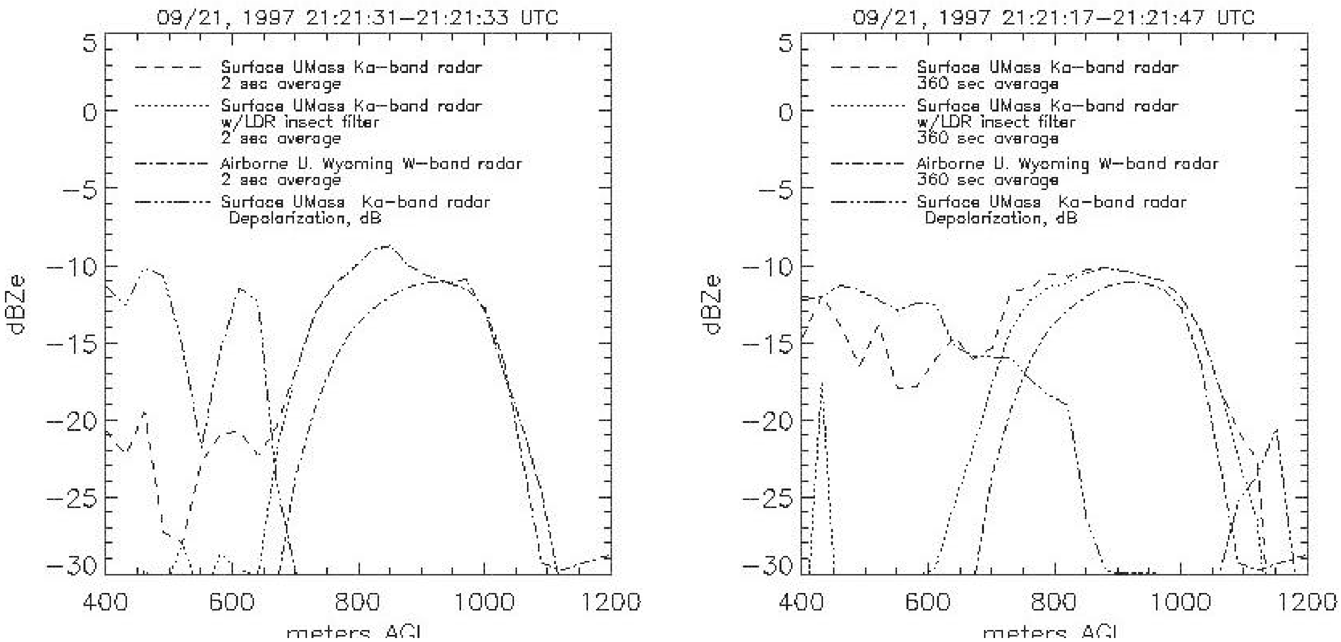


Figure 3. Comparison of UMass ground-based 33-GHz radar and University of Wyoming airborne 95-GHz radar data. (a) 2-second average and (b) 360-second average of ground-based data. Airborne radar averaging is discussed in the text.

such that the averaging distance corresponds to the distance over which the cloud advects during the ground-based radar averaging time. Horizontal wind measurements before and after the cloud observations showed a consistent wind speed and direction.

Comparisons of ground-based and airborne radar measurements are complicated and, therefore, the following results should be regarded as preliminary. Radar reflectivity observations of a stratus cloud deck measured on September 21, 1997, show flattened cloud tops and a more ragged bottom. CPRS depolarization data also showed many insect returns below the cloud and some insects in and above the cloud. The number concentration of insects tended to decrease with height. Therefore, it is not surprising that Figure 3b shows agreement between CPRS and King Air radar reflectivity in the upper portion of the cloud. Agreement in the lower portion of the cloud improves as insects are filtered from the ground-based data but is still worse than at cloud top. The scatter in agreement near cloud top ranged between -1 dB and +1 dB for September 21, 1997.

Conclusions

The results presented reflect progress to date in the comparison of ground-based and airborne radar data collected during the fall 1997 IOP. While there are many factors complicating the comparison, such as insect returns, progress has been made in explaining discrepancies between Ka-band radar reflectivity values for precipitating clouds. For non-precipitating clouds, a residual difference of approximately 3.6 dB between Ka-band reflectivity measurements remains. Continued analysis of King Air aircraft in situ and radar observations should help to resolve the ground-based radar reflectivity offsets.

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