Radar Calibration Validation for the SGP CART Summer 1998 DC-8 Cloud Radar Experiment

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Introduction

During June 1998, the National Aeronautics and Space Administration (NASA) Jet Propulsion Laboratory (JPL), the University of Massachusetts (UMass), and the Pennsylvania State University (PSU) participated in a joint field program designed to intercompare the calibrations of 95-GHz (W-band) atmospheric research radars, and to improve our understanding of 95-GHz cloud and precipitation extinction. UMass and PSU initially deployed ground-based radars at the Southern Great Plains Clouds and Radiation Testbed (SGP CART) site near Lamont, Oklahoma. The UMass radar was later deployed to New Iberia, Louisiana, to study a persistent upper-level cloud layer generated by a tropical low located in the Gulf of Mexico. A third 95-GHz radar, mounted on the NASA DC-8 aircraft, flew over the ground-based systems in both Oklahoma and Louisiana. The airborne radar, jointly developed by UMass and NASA JPL, was fixed in a nadir pointing orientation for the duration of the experiment. The ground-based radars were pointed at zenith. This geometry allows simultaneous observations of cloud and precipitation columns from the top and bottom. From this data set we calculate profiles of the true equivalent radar reflectivity, Z_e, and extinction. This method makes no assumptions about cloud and precipitation microphysics. However, it requires accurate knowledge of the absolute calibrations for the ground-based and airborne radars. This paper focuses on calibration of the three radar systems involved in the 1998 experiment. A second by paper (this proceedings) by Li et. al. (1999) details the attenuation analysis.

Radar Calibration Constant

Calibration uncertainties are increasingly significant because the use of millimeter-wave radars by the Atmospheric Radiation Measurement (ARM) Program, and by the general atmospheric science community, has grown rapidly in recent years. Researchers are focusing on quantitative analysis of cloud radar data where accurate radar reflectivity values are of critical importance in determining liquid water content and ice mass content.

Calibration accuracy is investigated by comparing side-by-side measurements of Cloud Profiling Radar System (CPRS) and active cavity radiometer (ACR) in Amherst, Massachusetts, following the summer field experiment. Calibration constants are derived from observations of a trihedral or ‘corner’ reflector. A corner reflector is a good choice for ground-based sensor calibration because of its large radar cross section and insensitivity to orientation. This allows the reflector to overcome clutter from the ground, insects, and from the supporting tower holding the reflector. Finally, calibration accuracy is verified by applying these constants to measurements collected in Louisiana during the summer field deployment.

The following relationship between Z_e and the backscattered power measured by radar is taken from various authors including Doviak and Zrnic (1984) and Smith (1986):

$$10\log(Z_e) = 10\log(\hat{P}_r) + 20\log(r) + 20\log(R_c) + 20\log(l_{atm}) \qquad (1)$$

where Z_e = equivalent radar reflectivity (mm^6m^{-3})
P_r = average received power referenced to input of IF processor (mW)
r = range to center of sample volume (km)
l_{atm} = one-way path integrated atmospheric loss.

The radar constant, R_c, is a function of various constants and system variables including frequency, receiver gain, antenna gain, transmit power, etc. Receiver gain and transmit power can be monitored using an internal calibration loop that measures their product, or using a noise diode and detector diode to measure these quantities independently.

Observations of an external target of known radar cross section measure the same quantities as an internal calibration circuit. In addition, external calibration measures antenna bore-sight gain, G_{ant}, receiver loss, l_r, and range-weighting functions that must otherwise be approximated. The power measured from a corner reflector is given by:

$$\hat{P}_{cr} = \left(\frac{P_t (G_{ant})^2 G_s \lambda^2}{l_r L_{tx} (4\pi)^3 r_{cr}^4} \right) \frac{\sigma_{cr}}{l_{atm}^2}, \qquad (2)$$

where l_{atm} = one-way path integrated atmospheric loss
σ_{cr} = corner reflector backscatter cross section (m^2)
r_{cr} = distance between radar and corner reflector.

This provides an accurate calibration of the entire radar system for point targets, including the response of the receiver to the transmitted pulse, which is commonly referred to as the finite bandwidth receiver loss, l_r. Typically, l_r is estimated. Doviak and Zrnic (1993) show that l_r = 2.3 dB for a rectangular transmit pulse and a Gaussian response receiver filter. This value is typically used for pulsed radar systems. However, Eq. (2) provides an exact measure of l_r although it is lumped together with other gains and losses.

To relate the corner reflector calibration to that for volume targets such as clouds we must also know the dimensions of the radar sample volume. Doviak and Zrnic (1993) present two approximations for the sample volume dimensions. The first approximation, from Probert-Jones (1962), accurately describes the width of the sample volume when the main lobe of the antenna has a Gaussian shape and low sidelobe levels, and when the half power antenna beamwidth is known. Comparison of this approximation with measured patterns for CPRS and ACR shows negligible errors. This is not the case however for the range-weighting approximation.

The range-weighting function, W(r), describes the radar receiver response to an echo. W(r) is a function of receiver loss, l_r, and the transmit pulse shape as shown in Eq. (3).

$$\int_0^\infty |W(r)|^2 dr = l_r c\tau/2 \tag{3}$$

We have found that due to the short pulsewidths used in cloud radars, the tails of the range-weighting function contribute significantly to the integral in Eq. (3). This is illustrated in Figure 1, which plots $|W(r)|^2$ for the CPRS W-band subsystem (solid line). The dashed line is the approximation described in Doviak and Zrnic (1993) for a rectangular transmit pulse and Gaussian filter response. The difference between the integrals of these two curves is 0.8 dB, which cannot be neglected.

Instead of assuming that l_r = 2.3 dB, W(r) should be measured. This is accomplished by observing a corner reflector, tower, or other fixed target of small range extent. To generate a weighting function, the target should be over-sampled in time, or the delay between the transmit pulse and digitizer triggers should be varied.

To account for the discrepancy between the approximated and actual value for the integral of $|W(r)|^2$, we replace τ with τ'. τ' is the effective pulse length determined from the ratio of the integral of the true range-weighting function to that of the approximation.

Important calibration variables are summarized in Eq. (4). The first term in parenthesis consists of system constants. The second term is obtained from corner reflector observations and contains all of the variables from Eq. (2). The third term is related to the sample volume where θ and ϕ are the half power beam widths of the antenna in the vertical and horizontal planes, and τ' is the effective pulse length obtained from measurements of the range-weighting function.

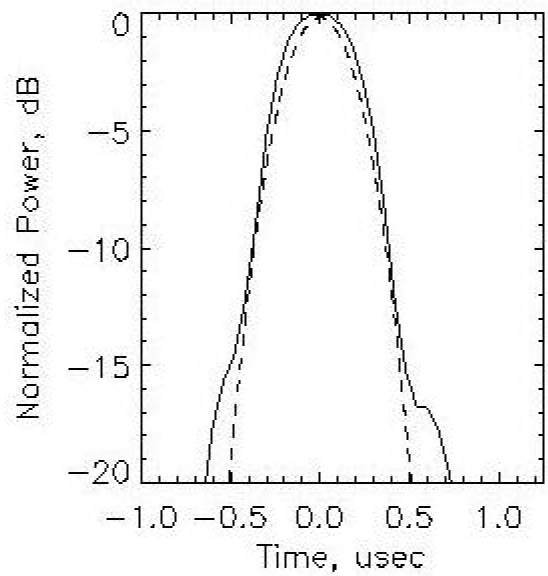

Figure 1. Plot of measured (solid) and theoretical (dashed) range weighting functions for the CPRS W-band subsystem. An error of 0.8 dB results when the theoretical curved is.

$$\hat{R}_c = \left(\frac{16\times\ln(2)10^{24}\lambda^4}{c\pi|K|^2 r_{cr}^4}\right)\left(\frac{1}{\hat{P}_{cr}}\right)\left(\frac{1}{\tau'\theta\phi}\right) \tag{4}$$

Radar Intercomparison

In the fall of 1999, ACR and CPRS were operated in Amherst such that both systems measured the same corner reflector and collected simultaneous zenith-pointing measurements. The calibration data collected in Amherst is applied to simultaneous CPRS ground-based and ACR airborne measurements collected in Louisiana. Figure 2a plots averaged profiles of deep upper-level clouds observed over New Iberia on June 27, 1998. Correlation of the up- and down-looking measurements indicates negligible signal extinction in the cloud. There is a constant difference of approximately 7 dB, however, which corresponds to water vapor and oxygen absorption from the lower atmosphere. This absorption is calculated using an extinction model from Liebe (1985) and local sounding data. Figure 2b plots the same data shown in Figure 2a with absorption corrections applied. The residual difference is approximately 0.3 dB. The results are consistent with the reflectivity differences observed for data collected in Amherst.

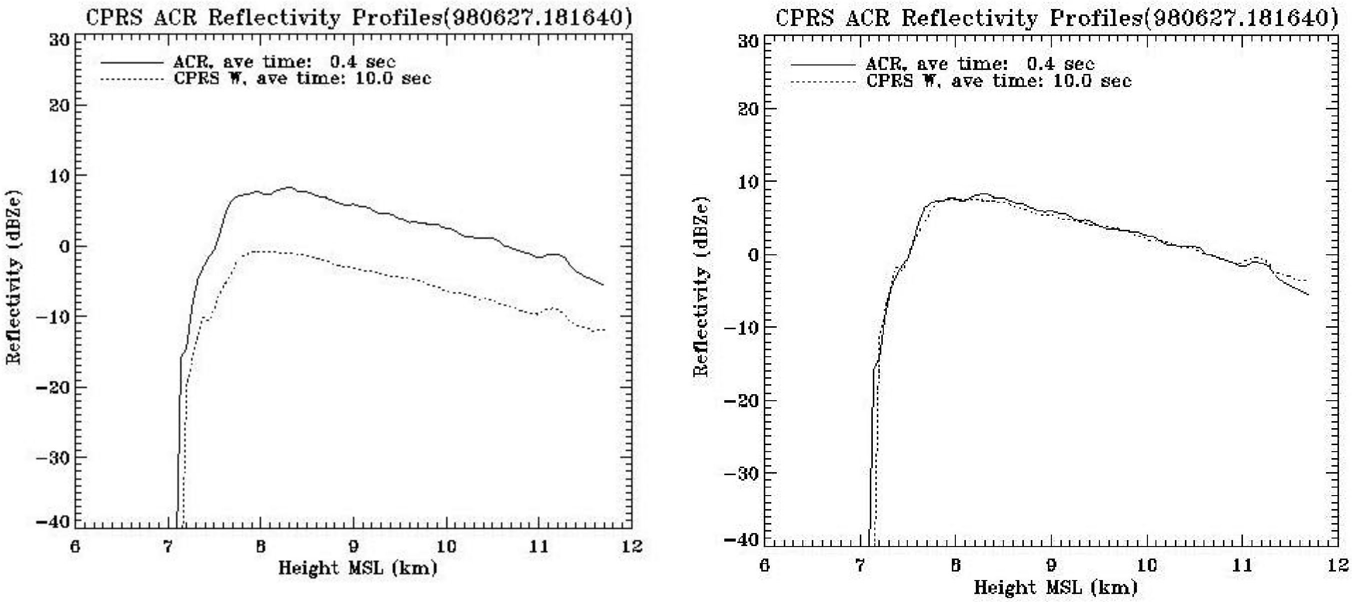

Figure 2. Collocated 95-GHz ACR airborne and CPRS ground-based measurements. (a) raw radar measurements. (b) after corrections for water vapor and oxygen are applied.

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