A Review of the First Year of Operations of ARM's 8-mm Cloud Profiling Radar at the SGP CART Site

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Introduction

The U.S. Department of Energy's (DOE's) Atmospheric Radiation Measurement (ARM) Program designed the Cloud and Radiation Testbed (CART) sites to provide researchers with a set of measurements of the state of the atmosphere for monitoring the radiative aspects of climate (Stokes and Schwartz 1994). Recently, a millimeter-wavelength cloud radar (MMCR) was developed for ARM to provide continuous unattended measurements of the clouds over CART sites. Nearly two decades of atmospheric cloud research showed the value of using millimeter-wavelength radars to probe clouds (Kropfli and Kelly 1996; Sekelsky and MacIntosh 1996). However, existing research radars were less suitable for continuous operations due to the short lifetime of the transmitters (2000 hours, typically), the complex designs that often included scanning platforms with dual polarization receivers, and the need for a scientist/engineer operator. In the fall of 1996 the first of five in a new series of operational MMCRs was installed at the Southern Great Plains (SGP) field site near Lamont, Oklahoma. Unlike its research counterparts, this radar uses a low power transmitter [traveling wave tube amplifier (TWTA)] for extended life and continuous unattended operations, a fixed vertical beam high-gain antenna for excellent sensitivity, a single polarization receiver, a high-duty-cycle transmitter for improved average power, and a versatile program controller. This new instrument (Moran et al. 1998) is providing a unique set of continuous observations of the clouds over the CART sites.

Operating Characteristics

The MMCR provides measurements of cloud reflectivity as well as the mean vertical velocity and the width of the velocity spectrum, for heights up to 15 km. It has operated with a remarkably high degree of reliability, providing continuous data records more than 97% of the time. Four operating modes provide a wide degree of flexibility in adjusting the altitude coverage, velocity range, height sample spacing, sensitivity and averaging time for a variety of cloud conditions. Adjustment of the parameters leads to some tradeoffs in the range, velocity, sensitivity and other measurement parameters. Careful selection of the operating parameters was needed to optimize the tradeoffs and to reduce the range and velocity ambiguities common to pulsed radar systems (Clothiaux et al. 1998). To observe low-reflectivity clouds, two modes were selected that have high sensitivity and a small velocity range for the expected low particle fall speeds. One of the modes was set for high altitude cirrus while a slightly less sensitive mode was selected for low altitude stratus. There is also a mode for general purpose use, which encompasses commonly encountered conditions, while the fourth "robust" mode was selected to minimize the various radar ambiguities.

The radar's sensitivity is greatly improved by using a pulse compression technique known as pulse coding, which transmits a very long pulse made up of a series of short coding "chips." The long pulse increases the average transmitted power therefore improving the ability of the MMCR to detect low-reflectivity clouds such as the cirrus and stratus modes discussed above. Figure 1 shows the sensitivity plots for the robust mode (uncoded) and the most sensitive "cirrus" mode (coded), using the present operating parameters. The large difference is due to the 15-dB improvement obtained by using a 32-bit code in the most sensitive mode. Note also, that the minimum range has increased to 3 km for the coded mode due to the effects of using a long coded pulse.

The pulse coding technique is best suited for observing weak clouds. Often the presence of high-reflectivity clouds has a drawback in that some of the strong signal leaks into adjacent weak signal regions. This leakage of adjacent range information is termed a range sidelobe artifact and is not present if pulse coding is turned off. The use of pulse

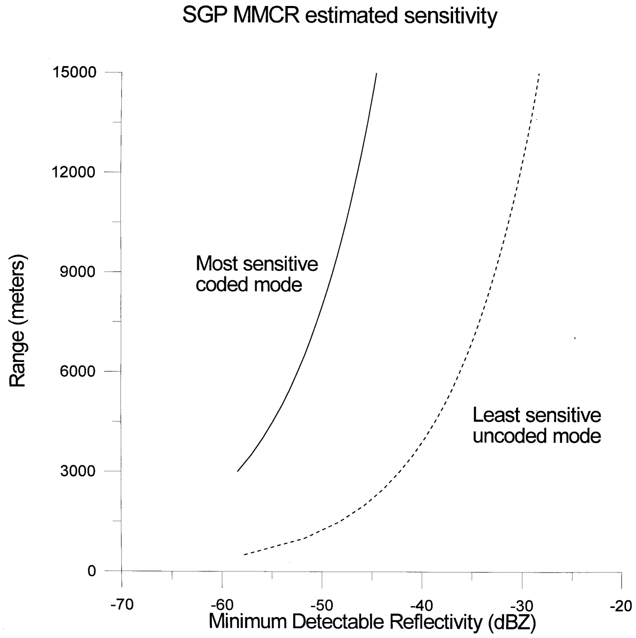

Figure 1. Estimated minimum detectable reflectivity for two operating modes for the MMCR. The most sensitive mode uses a long coded pulse, which increases the average power and raises the minimum range.

coding with its improved sensitivity needed to observe the very weak reflectivity clouds, such as cirrus, would be limited by the range sidelobe artifacts if observation of the same regions were not made with coding turned off. The routine operations contain both coded and uncoded modes to maximize useful measurement combinations of range, velocity, and sensitivity as well as to minimize artifacts. The artifacts present in the coded reflectivity data can be edited out using a simple threshold algorithm (Moran et al. 1998; Clothiaux et al. 1998). Other techniques (E. E. Clothiaux, personal communications) have been used to combine the data from all four modes to provide a single edited data set. The first year of observations has shown the ability of the radar to observe most nonprecipitating and weakly precipitating clouds and to detect all but the very weakest cirrus and stratus clouds.

Millimeter-wavelength radars experience significant atmospheric losses during rainfall. The MMCR also experiences some additional loss when rain water collects on the antenna radome. The radome is tilted about 5°, which allows water to run off, but small puddles still collect on the surface and can add 10 dB or more to the system losses. During rain, the combination of the atmospheric path losses and the wet radome loss makes accurate reflectivity measurements much more uncertain than during dry conditions. At present, there is no detector to indicate the presence of rain water, however the radar's signal can indicate when the precipitation reaches the surface.

Most radar systems have a an minimum operating range well outside the antenna near-field region. The large diameter (D=3 m or 350 wavelengths) of the SGP antenna results in a near-field region ($\approx D^2/\lambda$) that extends past 1000 m. Inside the near-field region, range losses are described by a near-field range formula from Lataitis et al. (1998). Because stratus clouds are often observed at this altitude or below, the formula was applied to the MMCR data sets at the beginning of the Spring 1997 Intensive Observation Period (IOP). Evaluation of the near field data through comparisons with other instruments colocated with the MMCR is presently under way to verify the theory.

Spring 1997 IOP

The Environmental Technology Laboratory's (ETL's) 35-GHz research cloud radar, NOAA/K, was collocated with the MMCR during the Spring 1997 IOP in April to compare measurements of range, reflectivity, vertical velocity and sensitivity. A 90-minute series of observations on April 16, 1997, of a fairly uniform altostratus cloud deck provided a good record for comparing data from the two radars. Un-averaged time series plots of reflectivity and vertical velocity in the cloud from a single height at an altitude of 4 km above ground level (AGL) and the corresponding reflectivity scatter plot are shown in Figure 2a, b, and c. NOAA/K data is shown as solid lines (Figure 2a, b) while the MMCR data is plotted as points. The offset in the radar's reflectivities (Figure 2c) has been explained by the omission of 2.3 dB in the MMCR's initial calibration. After applying the offset, the reflectivity and velocity comparisons show excellent agreement. Another comparison used the height of the melting layer on April 21, 1997, and showed that the two radars' height data agree to within one range bin (45 m). Over the length of the 3-week IOP comparison, the sensitivity of MMCR with its pulse-compressed modes regularly exceeded that of the more powerful NOAA/K, thus enabling it to detect very weak cirrus. The radars were separated by 270 m.

The MMCR can easily detect large suspended particles such as insects, seeds and ash in addition to the cloud hyrdometeors for which they can be mistaken. Several techniques are being explored to identify these echoes from the atmospheric "plankton" and distinguish them from stratus cloud droplets. Wavelet transformations can provide a means of identifying and removing large sinusoidal signals from other statistically different signal types (Jordan et al. 1997). Dual-polarization radar can distinguish spherical droplets from

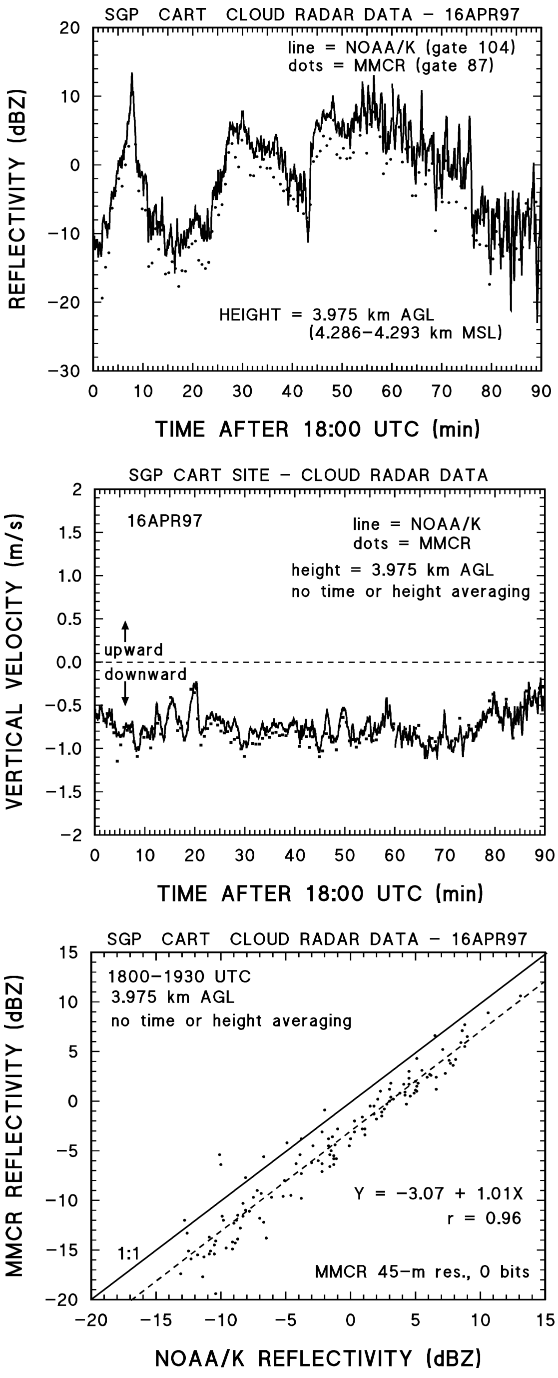

Figure 2. Intercomparison of reflectivity and vertical velocity measurements from the MMCR and the NOAA/K radar during the 1997 Spring IOP. (a) Time series of reflectivity measurements from the NOAA/K radar (line) and the MMCR (dots). (b) Time series of vertical velocity measurements: NOAA/K radar (line) and MMCR (dots). (c) Scatter plot of reflectivity measurements from Figure 2a. Measurement data came from a uniform cloud deck at a range of 4 km AGL.

other particles, by computing the linear depolarization ratio (LDR) of the signals. The NOAA/K radar is equipped with a dual polarization receiver and on April 10, 1997, during the Spring 1997 IOP, a 2.3-hour record of reflectivity showed a complex mix of atmospheric echoes (Figure 3, upper panel). The computed LDR (Figure 3, lower panel) revealed the low-altitude echoes to be primarily non-spherical particles, most probably insects. The remaining regions can be identified as stratus and strato-cumulus clouds. The addition of a dual polarization receiver to the MMCR would aid in distinguishing these "plankton" from the cloud particles.

Summary

The SGP MMCR has operated nearly continuously for over a year providing high quality measurements of reflectivity, vertical particle velocity, and width of the velocity distribution. During this time, several key features of the radar's operating characteristics have been explored and improved upon to provide better performance. The system operating

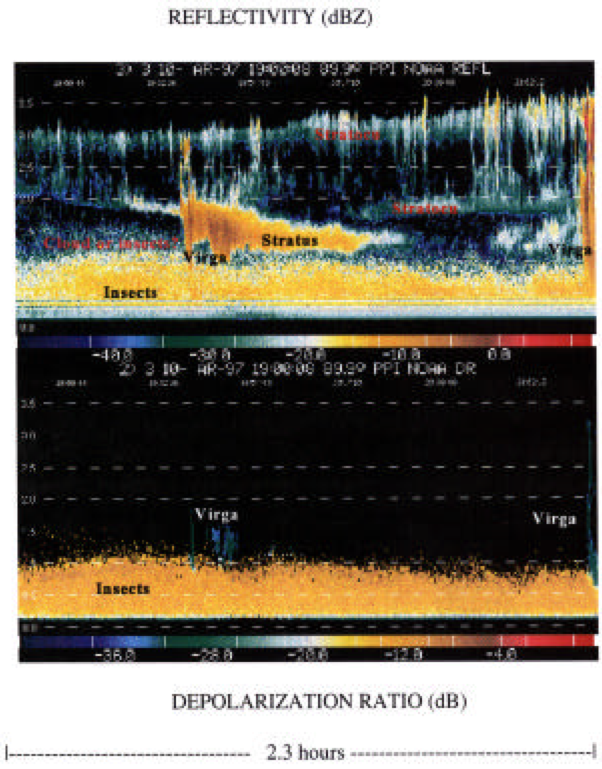

Figure 3. Example of polarization discrimination between insects and cloud from the NOAA/K radar for April 10, 1997. (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/moran-98.pdf*.)

parameters have been refined to provide an improved coverage for a variety of cloud conditions. A near-field antenna formula has been implemented that will provide more accurate low-altitude reflectivity measurements, once it has been verified. An editing algorithm has been implemented that provides a way to combine the four operating modes and reduce the effects of range sidelobe artifacts in the pulse-coded data. Simultaneous comparisons of the radar's observations with those of the NOAA/K radar have verified its measurement accuracies. The use of dual-polarization capability on NOAA/K was demonstrated to aid in distinguishing between insects and cloud particle echoes.

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