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The atmospheric radiation measurements millimeter wavelength cloud radars new operational modes and the new cloud and climate physics value added product

P. Kollias[1], E. E. Clothiaux[2], M. A. Miller[3], K. L. Johnson[3], K. B. Widener[4], K. P. Moran[5], and B. A. Albrecht[6]

[1]CIRES/ETL, Univ. of Colorado
[2]Pennsylvania State University
[3]Brookhaven National Laboratory
[4]Pacific Northwest National Laboratory
[5]NOAA, Environmental Technology Laboratory
[6]RSMAS/MPO, Univ. of Miami

Abstract. The United States (US) Department of Energy (DOE) Atmospheric Radiation Measurements (ARM) Program operates several MilliMeter-wavelength Cloud Radars (MMCRs) in several climatological regimes. Recently, the MMCRs Digital Signal Processing (DSP) units were upgraded. The capabilities of the new DSP, the significant improvement of the temporal resolution and the recording of Doppler spectra provided the potential for changes in the operational modes and parameters of the MMCR. Furthermore a recent evaluation of the MMCR signal processing performance with respect the range of cloud dynamical and microphysical conditions provided some indications for potential improvements (e.g. wider Nyquist velocities, de-aliasing, and ARSCL merged product). Here, the new set of MMCR operational modes is presented. The new operational modes have wider Nyquist velocities, removal of pulse compression from the Boundary Layer sensitive mode, 2 s temporal resolution and continuous recording of the Doppler spectra. A significant change is the introduction of an uneven mode sequence with 50 percent of the sampling time dedicated to the lower atmosphere that allows for a more detail sampling of the Boundary Layer (BL) clouds. The changes in the MMCR operational modes have a substantial impact in the design and merge strategy of the Active Remote Sensing of Clouds (ARSCL) Value Added Product (VAP). A microphysical ARSCL VAP product based on the new superior temporal resolution of the ARM MMCRs is presented along with MMCR Doppler moments uncertainty estimates. Furthermore the climate ARSCL VAP, a coarse temporally product that includes variance estimates of the MMCR measurements that are applicable to the microphysical and dynamical variability of the cloud field is described.

1 Introduction

Clothiaux et al. (1999) described the operational parameters currently installed on the ARM program MMCRs (Moran et al., 1998). These operational modes were designed for maximum sensitivity, given the receiver signal processor on which they were run, while attempting to maintain accurate estimates of hydrometeor reflectivities and atmospheric motions. Recently, the Environmental Technology Laboratory (ETL) of the National Oceanic and Atmospheric Administration (NOAA) completed an upgrade of the ARM MMCR digital signal processors (DSPs), vastly improving the signal processing efficiency of the MMCRs (Widener et al., 2004). As a consequence of the upgrade, a four-mode sequence that takes 36 s on the old DSPs can be completed in 11 s on the new DSPs. Installation of the new DSP in the MMCRs at the ARM Southern Great Plains (SGP) and North Slope of Alaska (NSA) sites has already been completed, with installation of the new processor at the remaining Tropical Western Pacific (TWP) sites slated for the year 2005. A recent evaluation of MMCR signal processing performance by Kollias et al. (2004) using samples of MMCR data from the ARM sites, as well as high temporal resolution data from the University of Miami (UM) 94-GHz Doppler radar (e.g. Kollias et al., 2001), has identified both problems and limitations in the current processing paradigm of Clothiaux et al. (1999; 2000) and potential improvements that should be implemented on the new DSP-generated data, including wider Nyquist velocities, removal of pulse coding in the boundary layer and a reduction in the number of coherently integrated pulses.

Correspondence to: P. Kollias
(pavlos.kollias@noaa.gov)

2 Limitations of Current Operational Modes of the ARM MMCRs

The four current operational modes of the ARM MMCRs are a "Boundary Layer" (BL) mode, a "Cirrus" (CI) mode, a "General" (GE) mode and a "Precipitation" (PR) mode. The parameters of the current operational modes that influence MMCR signal dwell and processing (SDP) and mode sensitivity are listed in Table 1. Kollias et al. (2004) identified several problems in the parameters listed in Table 1, including 1) the sampling interval of 9 s being much too coarse to resolve boundary layer cloud motions, 2) unambiguous, or Nyquist, velocities that are too small for the BL, CI and GE modes under a variety of cloud conditions, leading to deleterious filtering of received power as a result of coherent averaging, 3) velocity resolutions for the BL, CI and GE modes that are too coarse, often placing the Doppler spectrum power from boundary layer clouds into a single Doppler spectrum velocity bin, 4) treatment of noise in the processing of the Doppler spectra to Doppler moments that produces spurious moments for low signal-to-noise ratio returns, and 5) nonlinear compression of voltages at the top of the PR mode dynamic range (receiver saturation) that leads to reflectivities of questionable accuracy. Inspection of MMCR BL mode returns from low-level clouds has indicated subtle problems with pulse coding of this mode, leading to biases in the cloud-top heights of 100–200 m.

While 32-bit coding of the cirrus mode, with a 15 dB enhancement of system sensitivity, has proven to be valuable in detecting high-level clouds, the problems inherent in the 8-bit coding of the BL mode may outweigh the advantages of the 9 dB gain in system sensitivity. Analysis of the ARSCL data product also indicates relatively weak information content of boundary layer clouds in this data product, which is attributable to the shallow and broken nature of boundary layer clouds, especially at the TWP-Nauru site, and the presence of bugs and other clutter at the SGP site. Furthermore, the 9 s dwell and processing time for the BL mode smears in time the cloud reflectivity and Doppler velocity fields and contaminates the Doppler moments with undesired contributions from gradients of reflectivity and wind shear that pass through the radar sample volume during this period.

Overall, the MMCR modes have 9 s temporal spacing with dwell times varying from 0.4–3.0 s. Thus, current DSP efficiency, defined as the ratio of the dwell time to sample temporal spacing, i.e. the sum of the dwell and processing times, varies from 5–30%. The new DSP substantially improves processing efficiency of the ARM MMCRs, leading to efficiencies of 50–70% for the current modes.

3 New Operational Parameters of the ARM SGP MMCR

The number N_{bits} of coded pulses in the current operational modes is 8 for the boundary layer mode and 32 for the cirrus mode. We propose eliminating the pulse coding for the boundary layer mode, while keeping the 32-pulse coding in place for the cirrus mode. We propose reducing the number of coherent integrations for each of the three modes that uses this approach. We often encounter high magnitude Doppler velocities with corresponding wide Doppler spectral widths in non-precipitating cloud conditions. Wider velocity Nyquist boundaries that accommodate these wide Doppler spectra will reduce the deleterious effects of coherent integration (Kollias et al., 2004), allowing observations of such features with greater fidelity and better noise floor estimates. By reducing the number of coherent integrations, we lose a few dB of sensitivity. However, Kollias et al. (2004) have used simulations of Doppler radar signals to demonstrate that the apparent loss of sensitivity as a result of fewer coherent integrations is actually compensated by a real gain in sensitivity by keeping the receiver bandwidth large compared to the signal bandwidth of some turbulent clouds. The changes for the MMCR operating at the ARM SGP site are shown in Table 1. By increasing the 64-point BL, CI and GE spectra to 256-point FFTs and the 128-point PR mode spectra to 256-point FFTs, the Doppler spectra velocity resolution of the modes increases to approximately 5–6 cm s^{-1}. Furthermore, the four-mode cycle repetition time of 10–12 s, which is down by factor of four from the current repeat time of 36 s. For the new ARM MMCR signal processing in this configuration the ARSCL product would have a true 10 s resolution, as opposed to an interpolated resolution of 10 s with a true temporal resolution somewhere between 9–36 s.

In the MMCR mode cycling that we are proposing the main objectives are a cycling between the modes that is as fast is practicable, a repeating BL mode sequence with approximately sampling period of 4 s and Nyquist velocity boundaries sufficiently wide to accommodate turbulent clouds. All of the signal dwell times in Table 1 are less than approximately 1 s. Moreover, the proposed fast repetition of the BL mode will compensate for the apparent loss in sensitivity and detection of boundary clouds with reflectivities of −40 dBZ at 1 km will remain possible over 4 s time periods. While general mode sensitivity is also reduced by a smaller number of samples, there is no overall loss of sensitivity because of overlapping BL and CI mode data with GE mode data. The precipitation mode is not affected by the proposed scheme, but it will lose 20–25 dB of sensitivity with the switch of one of the four MMCR receiver T/R circulators into the closed position during activation of the PR mode. The received atmospheric signal is attenuated at the front of the MMCR receiver, before the mixer and pre amplifier in order to preserve the receiver noise level and maintain the same MMCR receiver calibration procedure. This change in the PR mode, while leading to a loss of sensitivity, will prevent the PR mode from saturating in light to moderate drizzle and precipitation.

Table 1. New operational parameters of the SGP MMCR (old parameters in parenthesis).

Mode	1	2	3	4	5
Name of the mode	**BL**	**CI**	**GE**	**PR**	**PO**
Interpulse Period (μs)	68	126	106	106	**106**
Number Coded Bits	**0 (8)**	32	0	0	**0**
Coherent Averages	**6 (10)**	**4 (6)**	**4 (6)**	1	**1**
Number FFT points	**256 (64)**	**128 (64)**	**128 (64)**	**256 (128)**	**128**
Minimum Range (m)	**105 (465)**	2985	105	105	**105**
Unambiguous Range (m)	10200	18900	15900	15900	**15900**
Sampling Rate (Hz)	14706	7936	9433	9433	**9433**
Number of Samples	**15360 (40960)**	**6144 (8064)**	**8192 (23040)**	3712	**8192**
Signal Dwell Time (s)	**1.04 (2.78)**	**0.77 (1.02)**	**0.87 (2.44)**	0.39	**0.87**
Nyquist Velocity (ms^{-1})	**5.27 (3.16)**	**4.26 (2.84)**	**5.07 (3.38)**	20.28	**10.14**
Velocity Resolution (cm^{-1})	**4.11 (9.87)**	**6.65 (8.88)**	**7.92 (10.6)**	**15.8 (31.7)**	**15.8**
Temporal Resolution (s)	**2 (9)**	**2 (9)**	**2 (9)**	**2 (9)**	**2**

4 ARM MMCR Mode Sequence

The use of different modes is still dictated by the firm objectives of observing most clouds at all altitudes, including clouds with low reflectivities in the range of −45 dBZ to −40 dBZ, and producing accurate Doppler moment estimates for them. As a result, we propose keeping all four modes since they serve different purposes. We could adopt the same exact sequence of modes with implementation of the new DSPs, decreasing the temporal spacing between modes to 2.5 s with an overall cycle time of 10 s. In this paradigm all four modes would be used to determine the best Doppler moments profile at the 10 s resolution for the ARSCL product, thereby substantially improving the quality of this product by eliminating the need to interpolate to 10 s resolution and limiting smearing to approximately 2.5 s intervals.

Another approach, and the one that we actually are proposing, is to weight differently the modes. Given the four modes, we propose the following sequence:

BL GE BL CI BL GE BL PR PO

with an approximately 2 s signal dwell and processing period for each mode. The above eight-mode sequence (Uneven MMCR mode cycle scheme) will be a complete operating modes cycle. There are 4 BL mode repetitions within the mode cycle, 2 GE repetitions and 1 CI and PR/PO repetition. The different weighting is proposed given the difficulty to observe BL clouds. This eight-mode sequence cycle could fit within 16 s. The important modification will not be the reduction of the temporal spacing of the ARSCL profiles but rather a change in the merge philosophy. This proposed scheme accounts for turbulent and fast changing clouds in the boundary layer and our desire to use the non pulse coded modes as much as is possible. Analysis of ARSCL data reveals that the GE mode is the most frequently used even for boundary layer or cirrus clouds. Thus we decided to cycle the GE mode more frequently that the CI mode and use the CI mode for thin cirrus clouds detection. Furthermore, the new BL mode, without pulse compression is very similar to the GE mode.

5 New ARSCL VAP

The design of the new ARSCL product is based on analysis of the current ARSCL product from the various sites and the upgrades of the MMCRs (Widener et al., 2004). One new proposed ARSCL, the Cloud Physics ARSCL VAP will contain the original high temporal resolution mode data with flags and uncertainty estimates on the Doppler moments that characterize the quality of the data from each mode. A second proposed ARSCL product, the Climate Physics ARSCL VAP will incorporate a change in philosophy for merging the mode data to 64-s resolution that should make the product of more interest to the modeling community.

The advantages of the new operational modes and processing strategies are severalfold. Rather than a four-mode merge product, this new approach is single mode product. This should provide better merging of the radar data, since the BL and CI/GE modes will be used for the cloud composites at the low and high altitudes respectively. In the boundary layer, the BL mode (repeated every 4 s) will be used for BL cloud detection. In the old modes, the BL mode had pulse compression and the GE mode data in the boundary layer were used to recover BL reflectivities and remove BL mode range side-lobes induced by imperfect pulse decoding in the MMCR receiver. Since the new BL mode has no pulse compression there will be no need to use GE mode data in the boundary layer. In the presence of very weak clouds, several fast repeating BL estimates can be used for Doppler moments consistency and could be averaged to provide a better estimate (less variance) for the low troposphere. In the case of stronger echoes, the BL mode can form the basis for a separate high-resolution product (4 s) in the PBL that could improve our capability to detect broken cloud fields. The GE mode will be repeated every 8 s (twice in an ARSCL estimate) and will be use for the cloud composite in the upper troposphere (5–16 km). The CI mode is the most sensitive mode in the upper troposphere (5-16 km) and the CI will be used for the detection of thin cirrus clouds especially at the ARM TWP sites. The GE as a non-coded mode will be used as a reference mode for the CI modes. Thus, the ARSCL merge strategy at the upper troposphere will be similar to the one used before, however, the CI mode will repeat every 16 s (36 s before) and the GE mode every 8 s (36 s before). The scheme is based on 2 BL, 1 GE and another mode (CI or PR). If needed additional supportive modes (e.g. PO (polarization)) could be added. In this case we will have 12 modes cycle 3×(BL,GE,BL,Y) where Y = [CI, PR, PO]. The PR mode will be used for accurate reflectivity (addition of 20–25 dB attenuation in the MMCR receiver) and Doppler velocities (no coherent integration) in precipitation.

The ARSCL Climate Physics VAP will have a temporal resolution of 64 s (4 complete cycles of the new ARSCL mode sequence) and will include time mean reflectivity, mean Doppler velocity and Doppler spectrum width at each range gate. Variance estimates of cloud reflectivity (indicator of cloud homogeneity), and mean Doppler velocity (indicator of cloud turbulence) will be included in the VAP along with appropriate flags to characterize the cloud conditions (e.g. broken cloud field, number of cloud detections within the 64 s).

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