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KA-BAND ARM ZENITH PROFILING RADAR NETWORK FOR CLIMATE STUDY

Nitin Bharadwaj[1]*, Andrei Lindenmaier[1], Kevin Widener[1], Karen Johnson[2], and Vijay Venkatesh[1]
1 Pacific Northwest National Laboratory, Richland, WA.
2 Brookhaven National Laboratory, Upton, NY.

1 INTRODUCTION

The Atmospheric Radiation Measurement (ARM) Climate Research Facility is a U.S. Department of Energy's (DOE) atmospheric measurements and observations facility. The facility is DOE's user facility for the study of global and regional climate. The scientific motivation for global and regional climate study is to better understand the atmospheric processes that govern global climate and to develop accurate representative global climate models. Cloud and precipitation systems play a significant role in the energy and hydrological cycles of the atmosphere. One

Figure 1: Photograph of KAZR deployed at ARM's Southern Great Plains site in northern Oklahoma.

of key goals for ARM is to improve the treatment of clouds and precipitation in global climate models (Stokes and Schwartz, 1994; ARM, 1996; ASR, 2010). Recently, ARM climate research facility augmented their observational capability with many new instruments. Mather and Voyles (2013) describe the current state of ARM facility with the addition on many new instruments. ARM replaced its vertically pointing millimeter wave radar (MMCR) (Moran et al., 1998; Widener and Johnson, 2005) with KAZR (see Fig. 1). The KAZR systems deployed reuses the antenna and transmitter from MMCR and operate at 34.86 GHz. ARM operates three versions of KAZRs deployed in different parts of the world. The five KAZRs deployed around the world are at Barrow in Alaska (NSA), Billings in Oklahoma (SGP), Darwin in Australia (TWP), Manus Island in Papua New Guinea (TWP) and AMF2 respectively. Two of the KAZRs deployed at SGP and NSA provide co-polarized observations along with cross-polarized observations while the third version only provides single polarization observations.

KAZR plays a crucial role in providing long-term observation of cloud systems for climate research. The system design must include robust RF design, waveform, processing, and internal calibration loops for remote operations. In addition, it is critical to perform routine end-to-end system evaluation to assess the performance of the radar. The system must be designed to allow remote monitoring of all the sub-systems and measure parameters used in the calibration of the radar. Calibration of the zenith pointing radar with very narrow beam widths has always been a very difficult task. In addition to the narrow vertical beam the use of frequency diversity pulse compression waveform with the newly deployed KAZR makes it even more challenging to calibrate the radar. The addition of a co-located Ka-SACR with short pulse and pulse compression capability provides an invaluable tool to cross-calibrate the KAZR with Ka-SACR. Both, SACR and KAZR can be calibrated with the traditional radar equation for volume target. However, the use of corner reflector calibration with SACR provides an additional constraint to verify the calibration state of KAZR. One of the main design goals with KAZR was that it be deployed as an unmanned operational system. In this paper, we present the salient features of KAZR system design and demonstrate the cross-calibration of the zenith pointing cloud radar with co-located scanning cloud radar.

2 KAZR SYSTEM DESIGN

KAZR system design is driven by observational needs of high sensitivity and robust operations for long term deployment. A simplified block diagram of the system is shown in Fig. 2. The system shown is for dual-polarization system which operates in depolarization mode. The ARM program currently operates two of its five KAZR systems with polarization diversity, specifically, depolarization mode. In KAZR's depolarization mode of operation horizontally polarized signals are transmitted and the receiver is switched between co-polar signal and cross-polar returns. The operations and processing of co-polar and cross-polar signals is described in Section 3. The specifications of the three versions of KAZR are listed in Table 1. The polarization

*Corresponding author address: Nitin Bharadwaj, 902 Battelle Blvd, MSIN K9-38 , Richland, WA-99352. Email: nitin@pnnl.gov

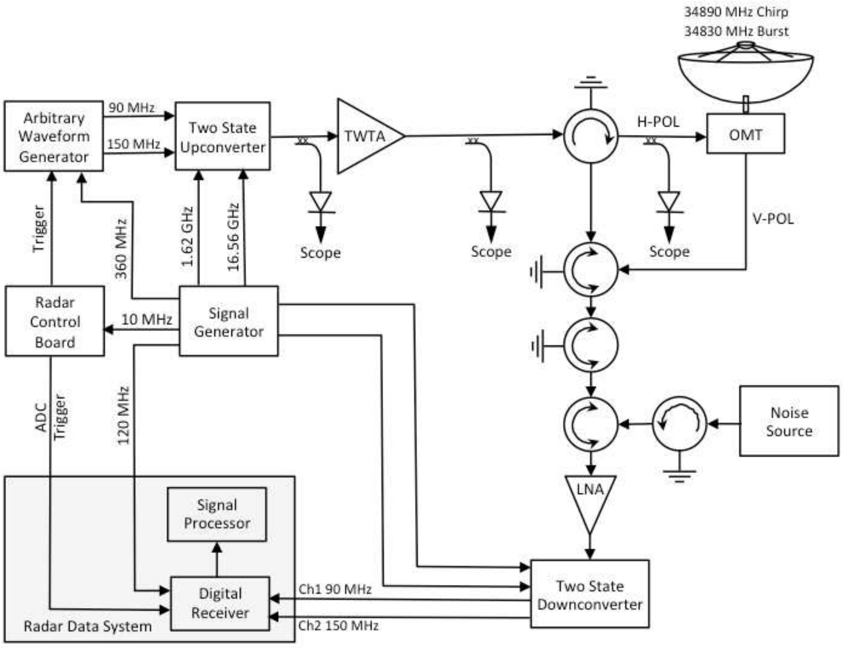

Figure 2: A simplified block diagram of KAZR.

and antenna parameters vary depending on the deployment site. A traveling wave tube amplifier (TWTA) with 150 W peak-power is used to transmit a frequency diversity pulse compression waveform. Pulse compression waveform is used to achieve good sensitivity with low-powered transmitters. The transmit chain consists of a arbitrary waveform generator that creates a complex waveform at 90 MHz and 150 MHz intermediate frequency (IF). The transmit waveform is upconverted by a two stage upconverter to drive the TWTA. The two IF channels are used for the burst and chirp pulse. The transmitted power is monitored at many stages with a scope card. The scope card provides digitized outputs of detectors located at the output of the TWTA and at the antenna reference plane. Such a internal setup enables remote monitoring of the transmitter. The cloud systems are often observed at numerous spatial scales and it is not uncommon for clouds to be broken instead of a continuum of clouds spread over a large area. KAZR uses a relatively large antenna with a narrow beam to provide high spatial resolution. The nominal beamwidth for all KAZR is 0.31° except for the radar deployed at SGP central facility which has a 0.18° beam.

A single receiver is used to process the co-polar and cross-polar returns. The receiver alternates between the co-polar and cross-polar channels to facilitate depolarization mode of operation. The received signal is split into two IF channels at 90 MHz and 150 MHz to simultaneously down convert both the chirp and burst pulse. The down converted IFs are digitized using a 16 bit A/D converter operating at 120 MHz. The receiver also has a separate path used for monitoring the receiver calibration by using a noise source. The noise source is used to estimate the receiver gain and noise figure of the receiver. The noise source is turned on during each pulsing cycle. The signal generated is positioned at the end of the range gates. This is done so that the noise injected is well beyond any atmospheric echo. The receiver gain, noise figure and sky brightness noise is estimated for every dwell or profile.

Figure 3 shows an illustration of KAZR sub-system assembly. The whole transceiver is rack mounted close to the antenna which is mounted on the roof of the shelter. Such an assembly minimizes the waveguide loss by keeping the waveguide runs short. The waveguide losses can be significant at higher frequencies such as Ka-band.The RF unit is housed in a temperature stabilized enclosure, supported in a ceiling-mounted equipment rack inside the equipment shelter below the antenna access port. A dehydrator keeps a constant flow of dry air inside the antenna radome to ensure no buildup of water due to condensation. The mission control computer (MCC) maintains the system health and status of all the subsystems. The health and status information includes monitoring power supplies, temperatures, level of the antenna, humidity inside the antenna, transmitter and local clock status. The radar data acquisition (RDS) houses the digital receiver and also performs the signal processing to generate the moments and spectra.

3 WAVEFORM AND SIGNAL PROCESSING

KAZR uses a low peak-power and high duty cycle TWTA transmitter for reliability with a high gain antenna. However, the sensitivity of the system is still not adequate to observe cloud systems in spite of using a high gain antenna. Pulse compression waveform is used to improve the sensitivity

Table 1: Specification of Ka-Band ARM Zenith profiling radar (KAZR)

Parameter	KAZR[1]	KAZR[2]	KAZR[3]
Transmitter			
Type	TWTA	TWTA	TWTA
Center frequency (MHz)	34860	34860	34860
Peak power output (W)	150	150	150
Duty cycle (%)	25.0	25.0	25.0
Max pulse width (μs)	12.0	12.0	12.0
Transmit polarization	H	H	H
Max PRF (kHz)	20.0	20.0	20.0
Antenna			
Antenna size (m)	3.0	2.0	2.0
3-dB Beam width (Deg)	0.19	0.31	0.31
Gain (dB)	57.48	53.37	52.73
Receiver			
A/D (bits)	16	16	16
Receive polarization	H,V	H,V	H
Noise figure (dB)	2.4	2.4	2.4
Sampling rate (MHz)	120	120	120
Decimation factor	Adj	Adj	Adj
Video Bandwidth	Adj	Adj	Adj

H,V= Alternate co-and-cross polarization, 1=SGP, 2=NSA, 3=TWP and AMF2

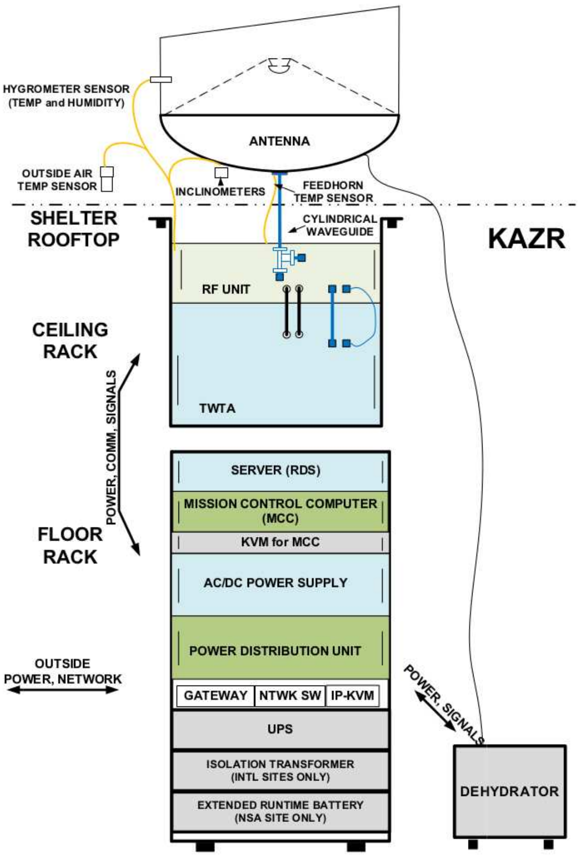

Figure 3: Illustration of the KAZR sub-system assembly.

of the radar. The inherent limitation of blind range that accompanies pulse compression waveforms is mitigated by using a lagging burst pulse. Frequency diversity is employed to keep the burst pulse and chirp pulse orthogonal (Bharadwaj and Chandrasekar, 2012). The arbitrary waveform generator is used to generate the chirp at 90 MHz and burst pulse at 150 MHz. In order to mitigate the blind range the burst pulse lags the chirp pulse on transmission. The leakage transmit pulse is stored and used to compute the compression filter. Figure 4 shows a linear FM pulse with $T_2 = 12\ \mu s$ and chirp pf 3.33 MHz implemented at Manus Island. The compression filter is computed with a constraint to minimize the integrated side-lobe levels.The compression filter designed provides very good side-lobe levels (in excess of 60 dB).

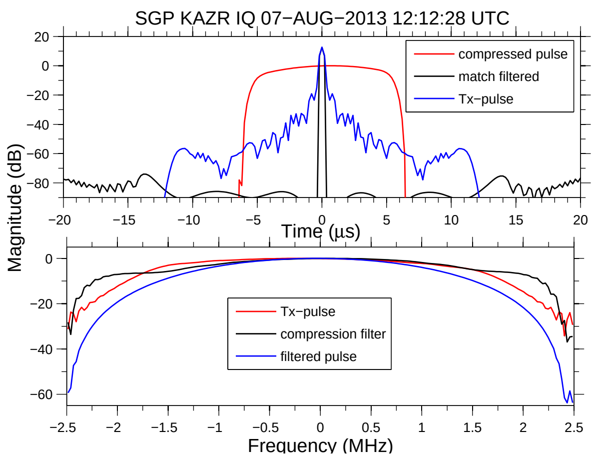

Figure 4: Use of $T_2 = 12\ \mu s$ pulse compression waveform at Manus and the response of the compression filter.

KAZR employs a single receiver to receive both co-polarized and cross-polarized back scattered returns. A horizontally polarized wave is transmitted and the receiver alternates between co-polarized and cross-polarized returns. Therefore, the depolarization ratio can be estimated from the received power in the co-polar and cross-polar channels. However, because profiling radars use longer dwell time waveform must be designed to keep the co-polar and cross-polar observations inter-leaved. Profiling radars use longer dwell times when compared to scanning radars. Longer dwell times are used to improve sensitivity through spectral processing. An inter-leaved reception scheme is implemented on KAZR to ensure that both co-polar and cross-polar signals are integrated over identical dwell times. This will ensure there is no time lag between the co-polar and cross-polar power profiles. Figure 5 shows the reception scheme used in KAZR which transmits horizontally polarized pulses. The received signals shown in Fig. 5 are for both the burst and chirp pulses. N pulses are received for each polarization channel to constitute one block of received signal.Each block of received signal is transformed to the spectral domain. Each profile is estimated from M blocks of received signal that are within the dwell time. The spectral coefficients of received signals in the p^{th} block is given by

$$S^p_{hh}(k) = \sum_{n=0}^{N-1} w(n) v_{hh}(n) e^{-j\frac{2\pi nk}{N}} \quad (1)$$

$$S^p_{vh}(k) = \sum_{n=0}^{N-1} w(n) v_{vh}(n) e^{-j\frac{2\pi nk}{N}}, \quad (2)$$

where $w(n)$ is the window function used for computing the spectral coefficients. The spectral coefficients from the M blocks are averaged to produce the Bartlett estimate of the spectral coefficients and is given by

$$S_{hh}(k) = \frac{1}{M} \sum_{p=0}^{M-1} S^p_{hh}(k) \quad (3)$$

$$S_{vh}(k) = \frac{1}{M} \sum_{p=0}^{M-1} S^p_{vh}(k). \quad (4)$$

The averaged power spectral density is used to compute the spectral moments and averaged spectral coefficients are used to obtain the polarimetric variables as shown in Fig. 6. The averaging of the spectra reduces the variance of the power spectral coefficients which enhances the noise subtraction process thereby increasing the sensitivity.

4 EXAMPLE

KAZR is deployed at four fixed sites and one mobile facility for 24/7 operations. The radar constantly records the Doppler spectra data for archival. The large volumes of Doppler spectra data is available from the ARM archive. The operating parameters for KAZR are remote configurable. The nominal parameters for typical operations are listed in Table 2. Figure 7 shows simultaneous observations of reflectivity from a burst pulse and long pulse using linear FM. The long pulse has a blind range close to 2 km while the burst pulse provides reflectivity without any significant blind range. The burst pulse covers the blind range with adequate sensitivity while the long pulse provides good sensitivity at far ranges. The improved sensitivity of the long pulse is observed for cirrus clouds around 12 km range. The $12\ \mu s$ long pulse provides 12.5 dB improvement in sensitivity when compared to the burst pulse.

Table 2: Operating parameters for KAZR operations

Parameter	
PRF (kHz)	2.77
Nyquist velocity (ms^{-1})	6.0
Pulses per FFT operation	256
No. of spectral averages	20
Burst pulse (ns)	300-333
Chirp pulse width (μs)	4 or 12
Chirp bandwidth (MHz)	3.33
Gate spacing (m)	30
Maximum range (km)	15-20

A side-by-side comparison of observation from KAZR's long pulse data was made with data collected with Ka-band ARM scanning cloud radar (Ka-SACR). SACR uses a 1.7 kW peak-power extended interaction klystron amplifier (EIKA) compared to the 150 W TWTA used by KAZR. Figure 8 shows the reflectivity observed by KAZR with a long pulse ($4\mu s$))and by SACR with a burst pulse ($300ns$)). It can be observed that the structural features are very similar from both SACR and KAZR without any significant range sidelobe effects. The compression filter is able to suppress the range sidelobe. The calibration constants for KAZR was computed using the traditional approach of characterizing each sub-systems in the transmit and receive chain. The calibration constant for SACR was ob-

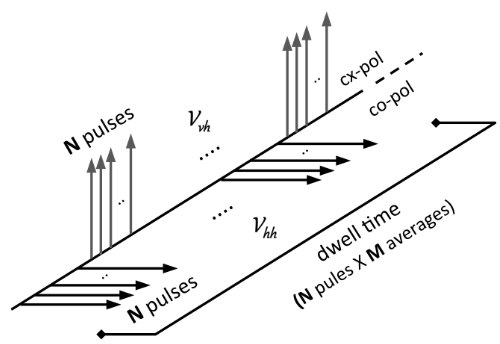

Figure 5: Reception scheme for KAZR which transmits horizontally polarized pulses.

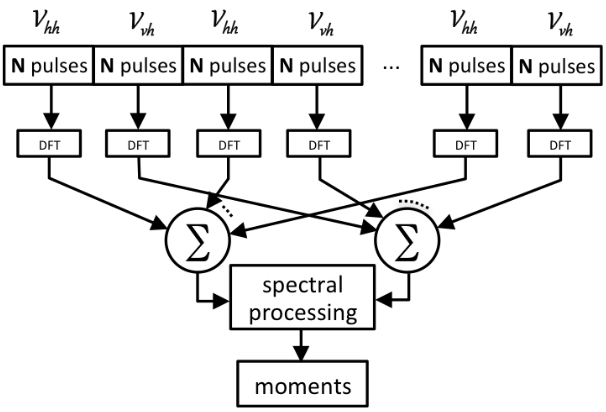

Figure 6: Diagram illustrating the processing of co-polar and cross-polar returns to estimate the moments.

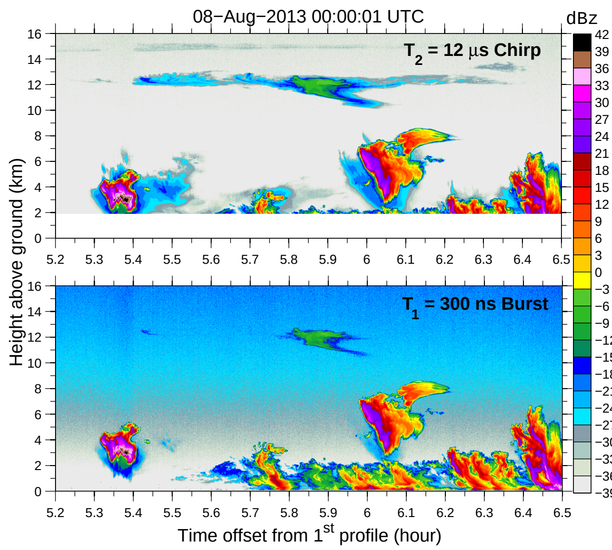

Figure 7: Reflectivity observed on Manus on August 08, 2013. The data shown is from 5.2 hours to 6.5 hours Z with observations from a burst pulse ans a long pulse with pulse compression.

tained by using a corner reflector to provide an end-to-end calibration of the radar. A scatter plot of observation from KAZR is plotted with respect to observations from SACR in Fig 9. The scatter plot of reflectivity is shown for both burst pulse and chirp pulse. The reflectivity of burst pulse and chirp pulse are within 0.5 dB of each other showing very good agreement between chirp pulse and burst pulse observations. KAZR and SACR observations are within 1.5 dB of each other indicatign good agreement between KAZR and SACR. The SACR observations with end-to-end calibration with corner reflector can be used to further fine tune the calibration constants of KAZR.

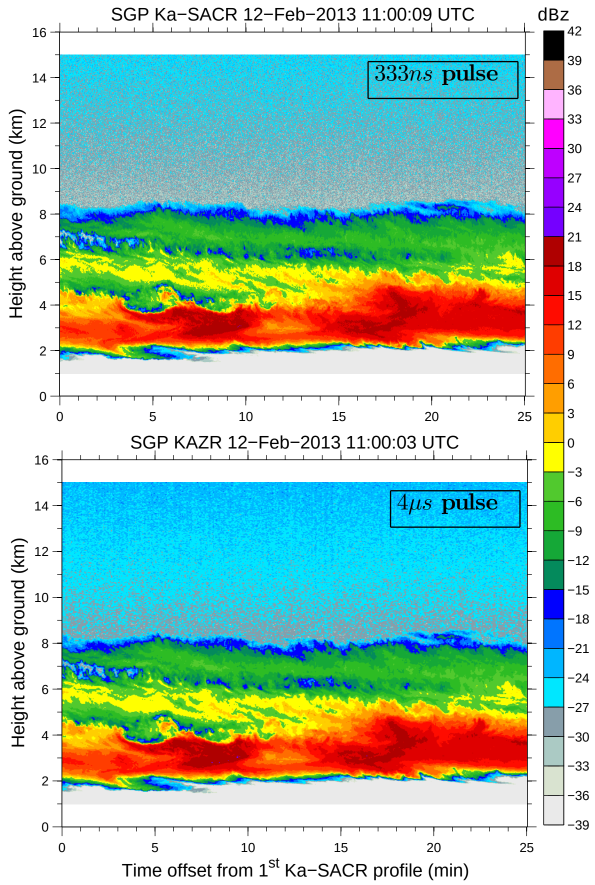

Figure 8: Side-by-side operations of SACR and KAZR. Time-height plots of reflectivity observed by SACR with a burst pulse and reflectivity observed by KAZR using a $4\,\mu s$ chirp pulse.

5 SUMMARY

The ARM climate research facility has deployed a global radar network of Ka-band zenith profiling radars to facilitate the observation of clouds systems under different climatic regimes. The main objective of the global radar network is to improve the treatment of cloud in climate models. This paper provided an overview of the salient features of KAZR's system design and operations. A new profiling radar design was deployed with improved capabilities to observe clouds. The systems was designed for remote operations with built-in calibration loop that is actively used in every integration cycle. Frequency diversity pulse compression waveform operations have increased the temporal and range resolution of the observations with minimal effects of range side-lobes. A side-by-side comparison with a co-located high power scanning radar has shown good calibration of the observed reflectivity. A robust implementation of waveform diversity and advanced spectral processing has provided 24/7 data in an operational environment.

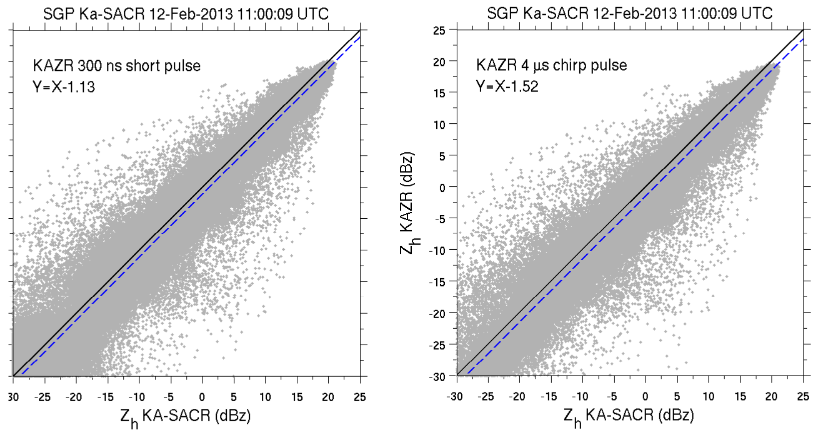

Figure 9: Scatter plot of KAZR reflectivity versus SACR reflectivity for both burst and chirp pulses.

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References

ARM, 1996: Science plan for the atmospheric radiation measurement program. Technical report, US Department of Energy, Washington, D. C.

ASR, 2010: Atmospheric system research (ASR) science and program plan. Technical report, US Department of Energy, Washington, D. C.

Bharadwaj, N. and V. Chandrasekar, 2012: Wideband waveform design principles for solid-state weather radars. *J. Atmos. Oceanic Technol.*, **29**, 14–31.

Mather, J. H. and J. W. Voyles, 2013: The ARM climate research facility. *Bull. Amer. Meteor. Soc.*, **94**, 374–392.

Moran, K. P., B. E. Martner, M. J. Post, R. A. Kropfli, D. C. Wesh, and K. B. Widener, 1998: An unattended cloud-profiling radar for use in climate research. *Bull. Amer. Meteor. Soc.*, **79**, 443–455.

Stokes, G. M. and S. E. Schwartz, 1994: The atmospheric radiation measurement (ARM) program:programmatic background and design of the cloud and radiation testbed. *Bull. Amer. Meteor. Soc.*, **75**, 1201–1221.

Widener, K. B. and K. Johnson, 2005: Millimeter wave cloud radar (MMCR) handbook. Technical report, ARM Climate Research Facility.