16B.4 ARM RADAR INFRASTRUCTURE FOR GLOBAL AND REGIONAL CLIMATE STUDY

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1 INTRODUCTION

The Atmospheric Radiation Measurement (ARM) Climate Research Facility (ARM, 1990) is a U.S. Department of Energy (DOE) atmospheric measurements and observations facility for the study of global and regional climate by the research community. 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. The ARM facility is establishing a cloud and precipitation radar infrastructure through the American Recovery and Reinvestment Act of 2009 to enable the observation of cloud and precipitation systems under various climate regimes.

The ARM radars are deployed at four fixed sites and on two mobile facilities (AMF1 and AMF2) for regional climate studies. The four fixed sites are at Southern Great Plains (SGP) in Oklahoma, North Slope of Alaska (NSA) in Barrow, Tropical Western Pacific (TWP) Darwin in Australia and Tropical Western Pacific Manus Island in Papua New Guinea. These radars will be located with the baseline instrument suites at the ARM sites for comparative measurements. The newly added radars to the ARM radar infrastructure consist of four X-band scanning ARM precipitation radars (X-SAPRs), two C-band scanning ARM precipitation radars (C-SAPRs), three X/Ka-band scanning ARM cloud radars (X/Ka-SACRs), three Ka/W-band scanning ARM cloud radars (Ka/W-SACRs), and the replacement of the venerable MMCRs with the new Ka-band ARM zenith radars (KAZRs). In addition, ARM will continue to field the zenith-pointing W-band ARM cloud radar (WACR) and the scanning W-band cloud radar (SWACR).

There are two main objectives for the ARM radars deployed around the world. First, maintain and augment the collection of comprehensive and continuous long-term data sets that provide observations of cloud and precipitation over a wide range of environmental conditions. Second, supplement the long-term data with shorter-duration field campaigns for targeted atmospheric processes. This paper presents an overview of ARM radar infrastructure and its observational capability to facilitate the quantification of cloud and precipitation interactions to improve fundamental process-level understanding of atmospheric systems.

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2 RADAR OBSERVATIONS OF CLOUD AND PRECIPITATION

The cloud and precipitation systems are composed of a very large number of hydrometeors (different sizes and shapes). The nature of the hydrometeors in a cloud or precipitating system depends on the atmospheric conditions that govern the phase changes of atmospheric water. Atmospheric radars have been used to observe and characterize the bulk properties of hydrometeors in clouds and precipitation for over three decades. Centimeter wavelength radar systems are typically used for meteorological purposes to overcome the impact of attenuation as the waves propagate through the precipitation medium. On one hand, centimeter wavelength radars are necessary to observe precipitating clouds and on the other hand, they are lack the sensitivity and resolution to observe clouds.

A simple comparison of the sensitivity of the radars

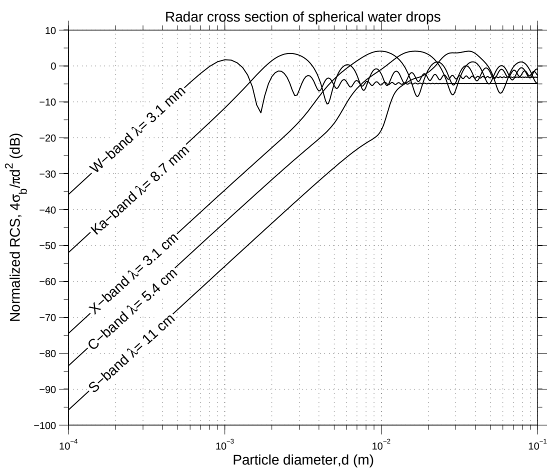

Figure 1: Normalized radar cross-section of spherical water drops as a function of drop size.

from a scattering perspective can be made by comparing the radar cross section (RCS) of spherical water drops (rain drops or cloud droplets). Spherical drops are only considered for simplicity to emphasize the sensitivity of the radar frequency to drop size. The normalized RCS (Bringi and Chandrasekar, 2001) is shown as a function of drop or particle diameter for varying radar frequencies in Fig. 1. The RCS of water drops is much larger at Ka-band and W-band and this larger RCS translates to better sensitivity due to larger received signal power. Therefore, millimeter wavelength radars are much more sensitive and suitable to observe cloud systems where the droplets are small ($10\ \mu m$). However, the extinction cross-section (not shown) are also larger at higher frequencies (Ka-band and W-band). The larger extinction cross-section at higher frequencies leads to higher attenuation of the signal as it propagates though the precipitating medium. The attenuation at Ka-band and W-band signal is severe and introduces large biases in observed cloud properties. Therefore, it is very beneficial to observe the cloud and precipitation systems with both centimeter and millimeter wavelength radars so as to improve our processes-level understanding.

One of key goals for ARM is to improve the treatment of clouds and precipitation in global climate models (ARM, 1996; ASR, 2010). To address these goals ARM climate research facility has deployed both centimeter and millimeter wavelength systems for the observations of cloud and precipitation systems. Figure 2 shows an conceptual diagram to indicate the radar frequencies required to make observations of clouds and precipitation. The diagram shows the radar frequency band that is most appropriate for a given particle size distribution in simplistic way. The diagram also shows the general range of the radars on the right hand side of the figure. The actual operational ranges varies with specifications and operational parameters of the radar but the diagram provides a good indication of the differences between centimeter and millimeter wavelength radars. The ARM climate research facility has deployed radars at C-band, X-band, Ka-band and W-band at four fixed sites and two mobile facilities around the world. The radars include zenith pointing profiling radars and scanning radars (see Fig. 3).

3 CLOUD PROFILING RADARS: KAZR AND WACR

The ARM climate research facility operates cloud profiling radars at Ka-band and W-band. The specifications of ARM's cloud profiling radars are show in Table. 1. All of ARM's cloud profiling radars are unattended 24×7 operational radars that are remotely monitored and operated via the internet.

3.1 KAZR

ARM replaced its vertically pointing millimeter wave radar (MMCR) (Moran et al., 1998; Widener and Johnson, 2005) with KAZR (see Fig. 3). 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. The main characteristics of KAZR are listed in Table. 1. 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. KAZRs employ a frequency diversity pulse compression waveform on a operational basis to provide adequate sensitivity (Bharadwaj and Chandrasekar, 2011). KAZR uses spectral processing to improve the signal-to-noise ratio, remove any side-lobe clutter and compute the Doppler spectral moments. In addition to storing Doppler spectral moments KAZR stores the Doppler spectrum for all the range gates. In dual-polarized KAZRs both the co-polar and cross-polar Doppler spectrum are stored for all range gates.

3.2 WACR

The WACR is ARMs W-band profiling radar operating at 95 GHz (Mead and Widener, 2005; Widener and Johnson, 2006) (see Fig. 3) and is deployed with AMF1. The main characteristics of WACR are listed in Table. 1. WACR is a dual polarized radar capable of observing co-polar and cross-polar signals. The single digital receiver in the WACR can alternate between co-polar and cross-polar signal on a profile-by-profile basis. The fast switching in the receiver enables WACR to provide reflectivity and depolarization ratio along with mean Doppler velocity and Doppler spectral width. Both the co-polar and cross-polar Doppler spectrum are stored for all range gates.

4 SCANNING RADARS

ARM has operated cloud profiling radars for over ten years and the data from these profiling radar has lead to the development of many retrieval techniques to characterize clouds. However, the profiling radar make observations in two dimensions:namely, height and time. The ARM climate research facility has recently deployed scanning radar to capture the three dimension spatial nature of the clouds and precipitation. The scanning radars include high powered C-band, X-band precipitation radars; and two dual-frequency scanning radars operating at X/Ka-band and Ka/W-band respectively. All

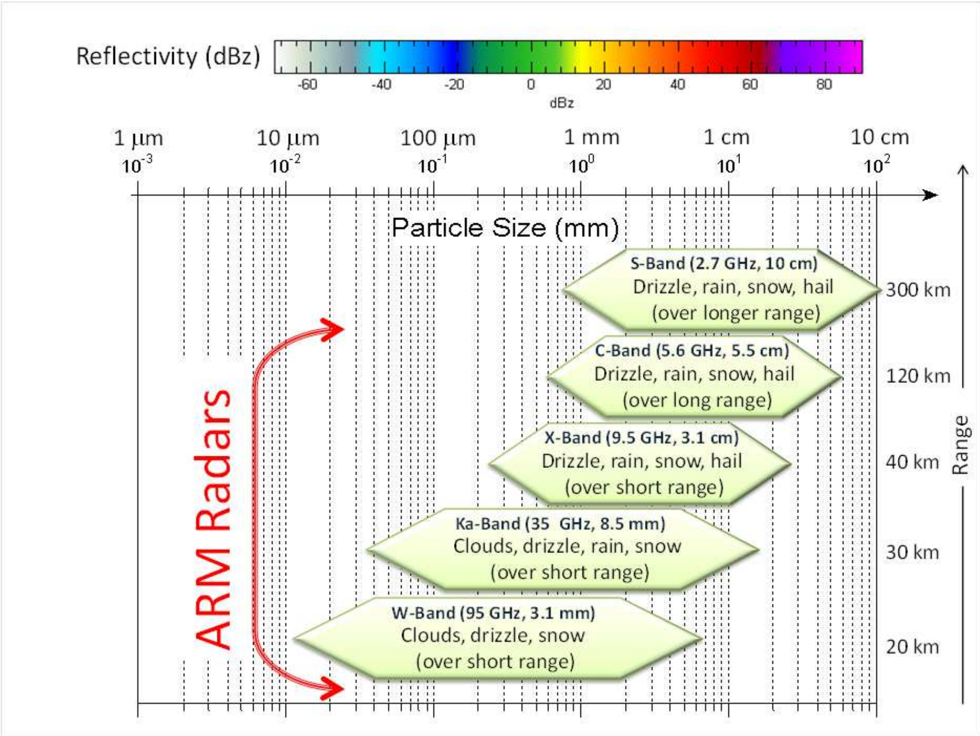

Figure 2: Diagram showing the the observational capability of ARM radars. ARM radar cover the whole range of hydrometeors ranging from small cloud droplets (W-band) to big rain drops and hail (C-band).

of ARM's scanning radars are unattended 24×7 operational radars that are remotely monitored and operated via the internet.

4.1 C-SAPR

The ARM program has deployed two C-SAPRs (5.625 GHz) to map precipitation field. One of the C-SAPRs is in the mid-latitude region at SGP and the other is in the tropics at Manus Island, Papua New Guinea. The main characteristics of the radar are listed in Table. 2. C-SAPR is dual-polarization radar that uses magnetron with a coherent on receive system to enable it to make Doppler observations. In addition for performing regular PPI volume scans the radars will perform routine RHI scans over the cloud profiling radar at SGP and Manus Island respectively. The use of dual polarization will enable hydrometeor classification and provide better estimates of rainfall.

4.2 X-SAPR

The ARM program has deployed four X-SAPRs to map precipitation field. Three of the X-SAPRs form a dense network of dual-polarized X-band radars in the mid-latitude region at SGP and the fourth X-SAPR is in the Arctic region at Barrow, Alaska. The main characteristics of the radar are listed in Table. 2. X-SAPR is dual-polarization radar that uses magnetron with a coherent on receive system to enable it to make Doppler observations.

- SGP network: The SGP X-band radar network consists three radars around the SGP central facility (CF) and are separated by about 25-30 km from each other. The three radars are 18.8 km north west, 11.3 km south east and 16.0 km south west of the central facility as shown in Fig. 4 (a). The geometry of the three radar will enable triple-Doppler retrieval in the common coverage region over the SGP central facility. The X-SAPR radar network is intended to provide wind field over the central facility. In addition, the X-SAPRs provide observation of the drizzle and rain over the cloud profiling radars. The cloud profiling radars experience signal extinction and saturation in rain events.

- Arctic deployment: The X-SAPR deployed in Barrow, Alaska is the only operational weather radar in the Arctic region and the northern most weather radar in North America (see Fig. 4 (b)). The X-SAPR deployed in NSA will provide a unique data set for the study of Arctic precipitation and clouds.

Figure 3: Images of ARM cloud and precipitation radars. Both profiling and scanning radar are shown.

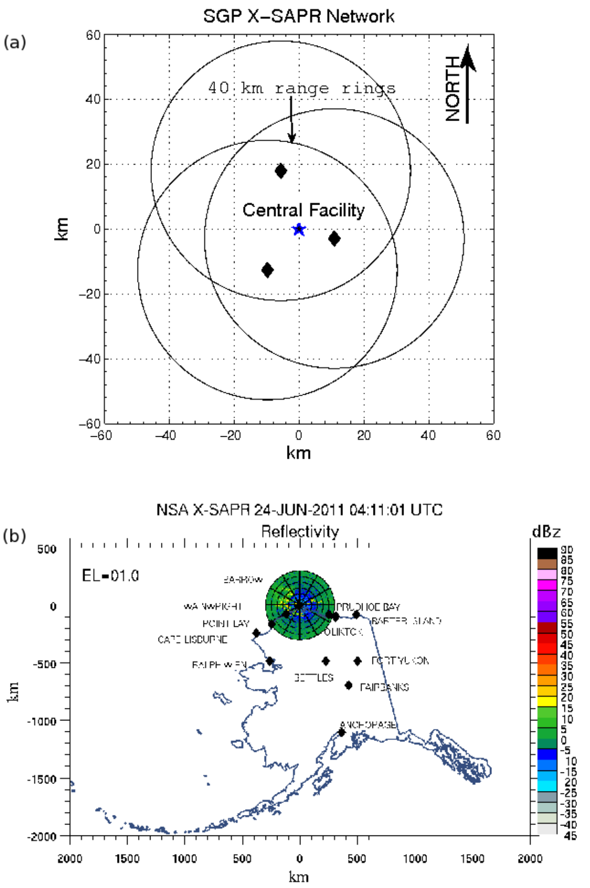

Figure 4: Coverage region of X-SAPR (a) Southern great plains. (b) Northern slopes Alaska (Barrow)

4.3 X/Ka-SACR

The X/Ka-SACR is a dual-frequency radar deployed at the two fixed tropical sites in Darwin, Australia and Manus Island. The third X/Ka-SACR is deployed with the AMF2. The X/Ka-SACR consists of an X-band and Ka-band antenna mounted on a single pedestal to make dual-frequency observation of the cloud and precipitation systems. The main characteristics of X/Ka-SACR are listed in Table. 2. It is important to note that the X-band and Ka-band system do not have matched beams; the X-band radar beam is nearly four times as wide as the Ka-band radar beam. The X/Ka-SACR at the fixed sites are co-located with the cloud profiling KAZRs at both Darwin and Manus. The location of AMF2 X/Ka-SACR can vary from deployment to deployment. The Darwin and Manus sites have permanent installation of a triangular trihedral corner reflectors towers to calibrate the radars. The scanning Ka-SACR with a nearby corner reflector tower provides an excellent opportunity to cross-calibrate KAZR at both Darwin and Manus.

The X-band system uses TWTA transmitter and Ka-band system uses EIKA. The waveforms in the X-SACR and Ka-SACR are generated by identical but independent digital waveform generator. The X/Ka-SACR is capable of using a pulse compression waveforms to provide better sensitivity. The X/Ka-SACR can store raw timeseries and spectra for all the range gates and operationally stores dual-frequency spectra for all range gates when operating in zenith pointing mode.

4.4 Ka/W-SACR

The Ka/W-SACR is a dual-frequency radar deployed at SGP and Barraw in NSA. The Ka/W-SACR consists of an Ka-band and W-band antenna mounted on a single pedestal to make dual-frequency observation of the cloud and precipitation. The main characteristics of Ka/W-SACR are listed in Table. 2. The W/Ka-SACR is co-located with the cloud profiling KAZR at both SGP and Barrow. The SGP and Barrow sites have permanent installation of a triangular trihedral corner reflectors on towers to calibrate the radars. The scanning Ka-SACR with a nearby corner reflector tower provides an excellent opportunity to cross-calibrate the KAZR at both SGP and Barrow. The Ka-band and W-band system uses EIKA transmitter. The waveforms in the Ka-SACR and W-SACR are generated by identical but independent digital waveform generator similar to X/Ka-SACR. Just as with X/Ka-SACR, Ka/W-SACR is capable of using a pulse compression waveforms to provide better sensitivity. The Ka/W-SACR can store raw timeseries and spectra for all the range gates and operationally stores dual-frequency spectra for all range gates when operating in zenith pointing mode.

5 SUMMARY

The ARM climate research facility has deployed a global radar network to facilitate the observation of clouds and precipitation. The ultimate objective of the global radar network is to improve the treatment of cloud and precipitation in global and regional climate models. The ARM climate research facility's radar infrastructure has twenty five radars deployed around the world and Table 5 shows the distribution of the cloud and precipitation radars at different ARM fixed sites and ARM mobile facilities. The ARM radar infrastructure provides an invaluable data set at different climate regimes with its multi-wavelength dual-polarization radars.

6 ACKNOWLEDGEMENT

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Table 1: Specification of ARM profiling cloud radars

Parameter	KAZR[1]	KAZR[2]	KAZR[3]	WACR[4]	WACR[5]
Transmitter					
Type	TWTA	TWTA	TWTA	EIKA	EIKA
Center frequency (MHz)	34860	34860	34860	95000	95000
Peak power output (W)	150	150	150	1600	1600
Duty cycle (%)	25.0	25.0	25.0	1.0	1.0
Max pulse width (μs)	12.0	12.0	12.0	0.600	0.600
Transmit polarization	H	H	H	H	H
Max PRF (kHz)	20.0	20.0	20.0	20.0	20.0
Antenna					
Antenna size (m)	3.0	2.0	2.0	0.6096	1.2192
3-dB Beam width (Deg)	0.19	0.31	0.31	0.34	0.18
Gain (dB)	57.48	53.37	52.73	53.5	59.5
Receiver					
A/D (bits)	16	16	16	16	16
Receive polarization	H,V	H,V	H	H,V	H,V
Noise figure (dB)	2.4	2.4	2.4	5.5	5.5
Sampling rate (MHz)	120	120	120	120	120
Decimation factor	Adj	Adj	Adj	Adj	Adj
Video Bandwidth	Adj	Adj	Adj	Adj	Adj

H,V= Alternate co-and-cross polarization, 1=SGP, 2=NSA, 3=TWP and AMF2, 4=AMF2, 5=AMF1

Table 2: Specification of ARM scanning radars

Parameter	C-SAPR	X-SAPR	W-SACR	Ka-SACR	X-SACR
Transmitter					
Type	Magnetron	Magnetron	EIKA	EIKA	TWTA
Center frequency (MHz)	6250	9450	93930	35290	9510
Peak power output (kW)	250	200	1.7	1.7	20
Duty cycle (%)	0.1	0.1	1.0	5.0	1.0
Max pulse width (μs)	2.0	2.0	1.5	13.0	40.0
Transmit polarization	H+V	H+V	H	H	H+V
Max PRF (kHz)	2.7	2.7	20.0	10.0	10.0
Antenna and Pedestal					
Antenna size (m)	4.27	2.4	0.9	1.82	1.82
3-dB Beam width (Deg)	0.90	1.00	0.30	0.33	1.20
Gain (dB)	45.1	45.0	54.5	53.5	42.3
Maximum scan rate (deg/s)	36.0	36.0	36.0	36.0	36.0
Receiver					
A/D (bits)	14	16	16	16	16
Receive polarization	H+V	H+V	H+V	H+V	H+V
Noise figure (dB)	2.8	3.0	6.0	5.0	4.5
Sampling rate (MHz)	40	80	120	120	120
Decimation factor	Adj	Adj	Adj	Adj	Adj
Video Bandwidth	Adj	Adj	Adj	Adj	Adj

H+V=Simultaneous horizontal and vertical polarization and H=Horizontal polarization

Table 3: List matching deployment sites of radars and radar type

Radar/Site	SGP	NSA	TWP-Darwin	TWP-Manus	AMF-1	AMF-2
X/Ka-SACR	☐	☐	☑	☑	☐	☑
Ka/W-SACR	☑	☑	☐	☐	☑	☐
SWACR	☐	☐	☐	☐	☐	☑
KAZR	☑	☑	☑	☑	☐	☑
WACR	☐	☐	☐	☐	☑	☐
C-SAPR	☑	☐	☐	☑	☐	☐
X-SAPR	☑	☑	☐	☐	☐	☐

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