DOE/SC-ARM/TR-117

ARM
CLIMATE RESEARCH FACILITY

X-Band Scanning ARM Precipitation Radar (X-SAPR) HANDBOOK

October 2012

U.S. DEPARTMENT OF ENERGY | Office of Science

Work Supported by the U.S. Department of Energy
Office of Science, Office of Biological and Environmental Research

DISCLAIMER

DOE/SC-ARM/TR-117

X-band Scanning ARM Precipitation Radar (X-SAPR)

K Widener
N Bharadwaj

October 2012

Work supported by the U.S. Department of Energy,
Office of Science, Office of Biological and Environmental Research

Acronyms and Abbreviations

ϕ_{DP}	differential phase
ϕ_{HH}	horizontal signal
ϕ_{VV}	vertical signal
ρ_{HV}	dual-polarization correlation magnitude
3D	three-dimensional
ARM	Atmospheric Radiation Measurement (Climate Research Facility)
BIT	built-in-test (messages)
CCDB	Common Calibration Database
dB	decibel
dBi	antenna gain referenced to isotropic radiator
dBm	decibel referenced to 1 mW
dBZ	reflectivity
GHz	gigahertz (10^9 Hz)
Hz	hertz
Ka band	frequencies between 26.5 GHz and 40 GHz
K_{DP}	specific differential phase
kW	kilowatt
m	meter
MHz	megahertz (10^6 Hz)
mW	milliwatt
PPI	Plan Position Indicator
PRF	pulse repetition frequency
RHI	Range Height Indicator
SGP	Southern Great Plains
SQI	signal quality index
V	linear channel Doppler mean velocity
W	linear channel Doppler spectrum width
W band	frequencies between 75 GHz and 110 GHz
X band	frequencies between 8 GHz and 12 GHz
X-SAPR	X-band scanning ARM precipitation radar
Z	log channel reflectivity corrected for clutter
Z_{DR}	differential reflectivity
Z_H	horizontal reflectivity
Z_T	log channel total reflectivity including clutter
Z_Y	vertical reflectivity

Contents

Figures

Tables

1.0 General Overview

1.1 Introduction

Figure 1. X-SAPR installation near Lamont, Oklahoma.

The X-band scanning ARM cloud radar (X-SAPR) (Figure 1) is a full-hemispherical scanning polarimetric Doppler radar transmitting simultaneously in both H and V polarizations. With a 200 kW magnetron transmitter, this puts 100 kW of transmitted power for each polarization. The receiver for the X-SAPR is a Vaisala Sigmet RVP-900 operating in a coherent-on-receive mode.

Three X-SAPRs are deployed around the Southern Great Plains (SGP) Central Facility (Figure 2) in a triangular array. A fourth X-SAPR is deployed near Barrow, Alaska (Figure 3 and Figure 4) on top of the Barrow Arctic Research Center.

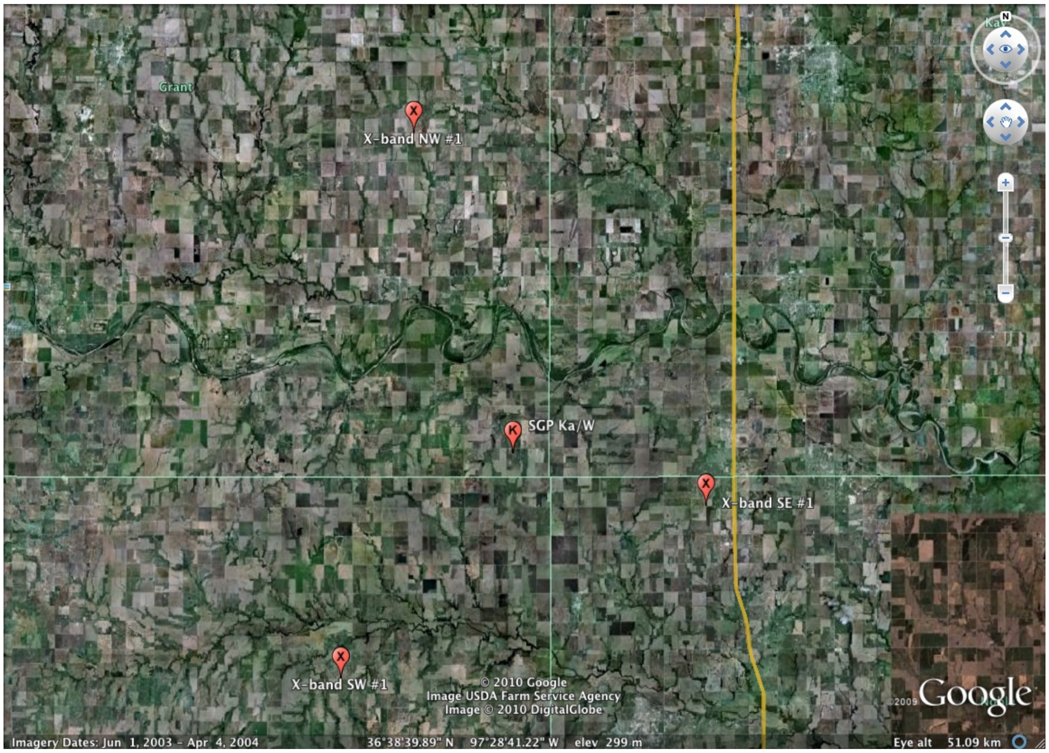

Figure 2. X-SAPR locations at SGP.

Figure 3. X-SAPR at Barrow, Alaska.

Figure 4. Barrow X-SAPR location.

1.2 Specifications

1.2.1 Transmitter

Type:	Magnetron
Center frequency:	9.35–9.45 GHz
Peak power output:	200 kW
Pulse width:	200 ns–2 μs
Polarization:	dual-polarization, simultaneous H and V
Maximum duty cycle:	0.1%
PRF:	200 Hz–2.7 kHz
Manufacturer:	Radtec

1.2.2 Receiver

Type:	coherent-on-receive, dual channel digital Vaisala RVP-900
Dynamic range:	> 80 dB
Noise figure:	3.0 dB
Sampling rate:	80 MHz
Decimation factor:	Adjustable
Video bandwidth:	Adjustable
Processing software:	IRIS
Manufacturer:	Vaisala

1.2.3 Antenna/pedestal

Antenna Type:	offset feed parabolic reflector
Diameter:	2.4 m
3 dB beam width:	1.0°
Gain:	45.0 dBi
Cross polarization isolation:	-32 dB
2-way radome loss:	<1.0 dB
Pedestal Type:	azimuth over elevation
Azimuth scan rate:	up to 36°/s
Elevation scan rate:	up to 30°/s
Pedestal manufacturer:	Radtec

2.0 Contacts

2.1 Mentor

Kevin Widener
Pacific Northwest National Laboratory
412 Hale Drive
Underwood, WA 98651
Phone: 509-375-2487
Fax: 509-375-6736
Email: kevin.widener@pnnl.gov

Nitin Bharadwaj
Pacific Northwest National Laboratory
P.O. Box 999
Richland, WA 99352
Phone: 509-372-4267
Fax: 509-375-6736
Email: nitin@pnnl.gov

2.2 Vendor/Instrument Developer

Radtec Engineering, Inc.
2150 W. 6th Ave.
Broomfield, CO 80020
Website: http://www.radar-sales.com

3.0 Deployment Locations and History

Table 1. Deployment locations and history.

Location	Direction from Central Facility	Site Designation	Date Installed	Date Removed	Status
Billings, Oklahoma	SE	SGP/I4	12/10/2010		
Garber, Oklahoma	SW	SGP/I5	04/20/2011		
Lamont, Oklahoma	NW	SGP/I6	04/20/2011		
Barrow, Alaska	WNW	NSA/C1	06/26/2011		

4.0 Near-Real-Time Data Plots

See http://radar.arm.gov.

5.0 Data Description and Examples

There are many different types of scans that the X-SAPR can perform. Scan strategies are defined for each site that alternate between the following types of scans:

- **RHI** (Range Height Indicator) scans are scans in which the azimuth axis is held constant while the elevation axis is changed. An RHI scan can go horizon-to-horizon over 180 degrees of elevation or a subset of that. Figure 5 shows one type of RHI scanning scenario that ARM currently uses, which is also known as a "Hemispherical Sky RHI." It is a series of horizon-to-horizon RHIs in which the azimuth is incremented. This type of scan provides a good indication of the 3D cloud field.

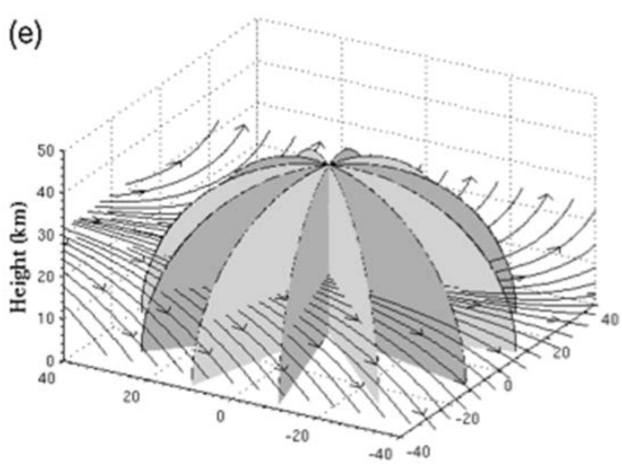

Figure 5. RHI "Domer" scan.

- **PPI** (Plan Position Indicator) scans are what are typically thought of when thinking about weather radars. These are scans in which the elevation is scanned for 360 degrees, and then the elevation is incremented. Figure 6 shows a scan with four different elevations.

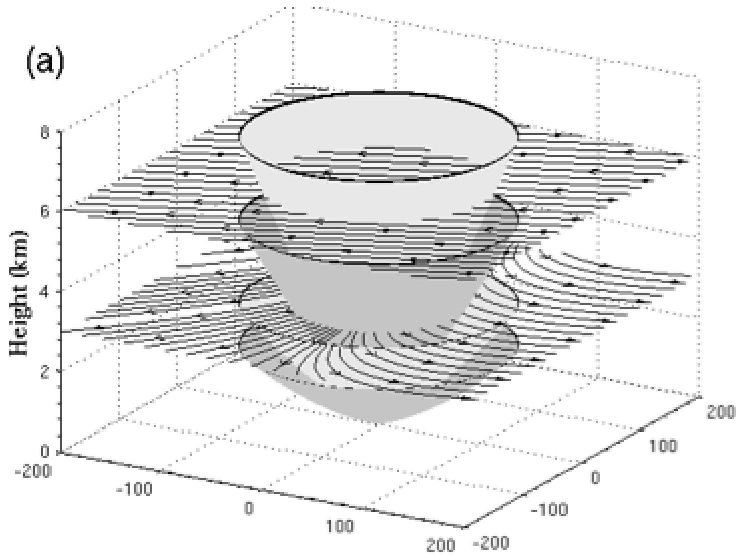

Figure 6. PPI scan.

- **Vertical pointing** – during part of the measurement period, ARM plans on operating the X-SAPR in a vertical-pointing mode to obtain zenith cloud profiles similar to those obtained by the Ka-band ARM zenith radar and W-band ARM cloud radar. Figure 7 shows an example of this type of scan.

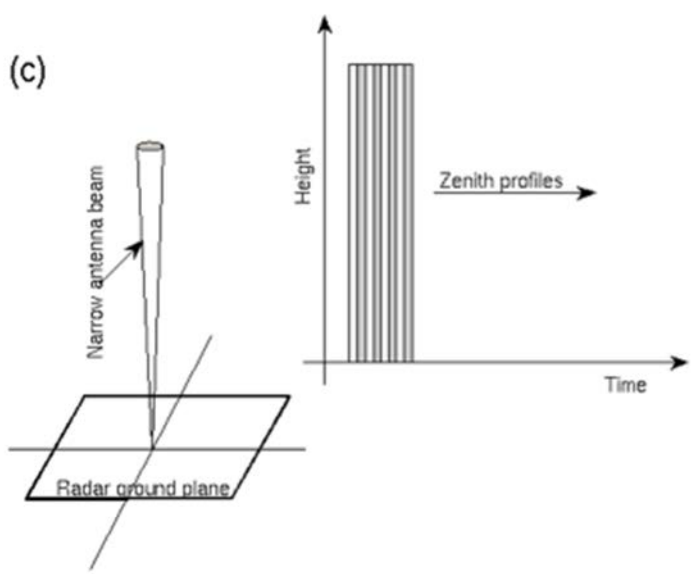

Figure 7. Vertical pointing mode.

- **Sector Scan** – elevation scans along a particular azimuth have proven to be desirable among researchers. Typically, these are sector scans are perpendicular to the prevailing wind direction as shown in Figure 8. However, there are times when it is desired to perform sector scans in parallel with the wind direction. These sector scans must be set up manually by the radar instrument mentor.

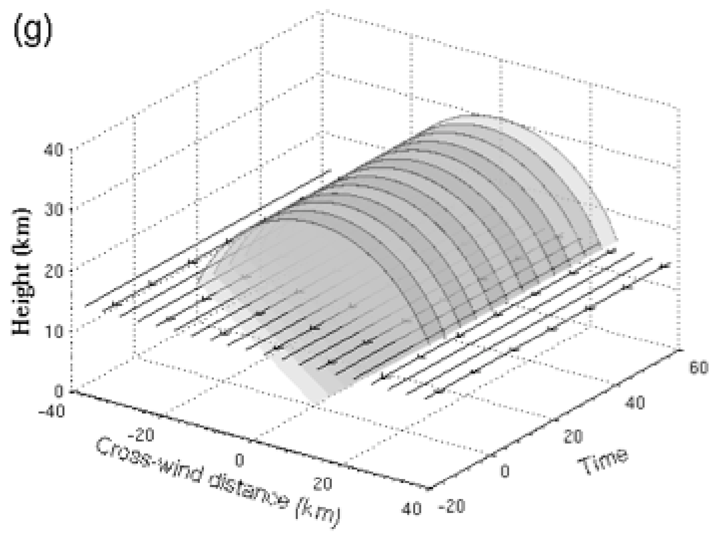

Figure 8. Sector scan.

- **Calibration** – one of the great benefits of having a scanning radar with a relatively narrow beamwidth is the ability to look at a fixed target of known radar cross-section to provide an absolute calibration point for the X-SAPR. In this mode, the X-SAPR points at a predetermined fixed azimuth and elevation for the corner reflector. Figure 9 shows an example of calibration.

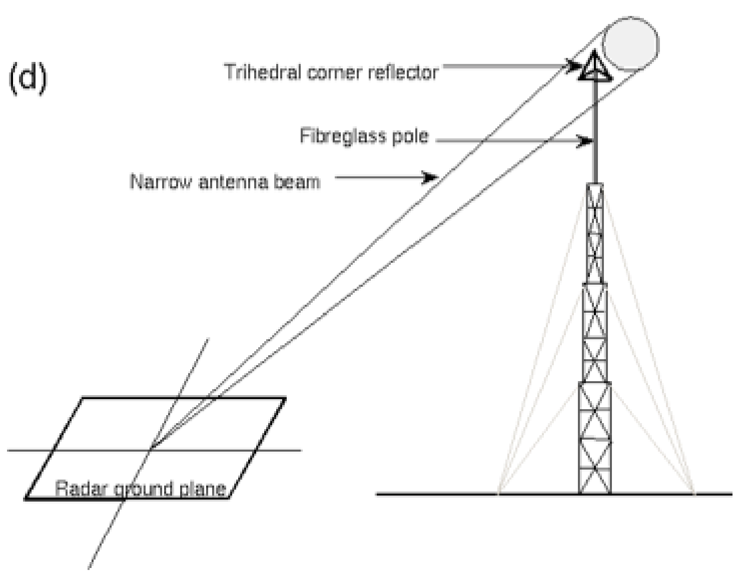

Figure 9. Calibration target.

5.1 Data File Contents

For the time being, ARM has decided to not ingest the X-SAPR data into netCDF. X-SAPR data are stored in the IRIS format developed by Vaisala (formerly Sigmet). Data file descriptions are given in Vaisala's IRIS documentation. A free version of IRIS software for viewing data is available from Vaisala at: http://www.vaisala.com/en/defense/products/weatherradar/Pages/IRIS.aspx

Click on the "Fee Display License" and fill out the form.

Below is an example of the PPI header information that is available from the IRIS file:

Site name: 'xsapr-sgpr3', Task name: 'MC3E_CNV_PPI'
Scan: PPI, Speed: 26.00 deg/sec, Resolution:0.90 deg
Description: 'MC3E Convective Volume scan '
Location: 36 34.7'N 97 21.8'W, Altitude: 346 meters, Melting height:Unknown
Volume Time: 20:06:43.967 29 MAY 2012 UTC (0 min. west) (LT: CDT 360 min.)
ZFlags: sp_t, block_zc, attn_zc, target_zc, DPATTEN_ZC, dpatten_z
VFlags: sp_v, 3lag_w, ship_v, unfold_vc, fall_vc, storm_vc
PRF: 2222Hz, PulseWidth: 0.37 usec (0)
BeamWidth: 1.18/1.02 deg.
Radar constant: 72.45/72.45 dB, Receiver bandwidth 2476 kHz.
Calibration I0: -106.13/-105.62 dBm, with noise -72.40/-72.56 dBm.
LOG-Noise: 0.3769, Lin-Noise: 0.3769, I-Off: 0.0000, Q-Off: 0.0000
SOPRM Flags: 0x3681, LOG Slope: 0.640, Z-Cal: -33.69dBZ, H/V: -2.00 dB
Filters: Dop:0, Log:0; PntClt: 0, Thresh: 0.0 dB; Samples: 90
Processing Mode: PPP, Xmt Phase: Random
T Threshold: All Pass LOG = 0.8 dB
Z Threshold: All Pass SIG = 5.0 dB
V Threshold: All Pass CSR = 18.0 dB
W Threshold: All Pass SQI = 0.40
Zdr Threshold: All Pass PMI = 0.00
Differential offset GDR = 0.00 dB De-polarization offset XDR = 0.00 dB
Available moments are: dBT2 dBZ2 V2 W2 ZDR2 Kdp2 RhoHV2 dBZc2 SQI2 PhiDP2 ZDRc2
Original moments were: dBT2 dBZ2 V2 W2 ZDR2 Kdp2 RhoHV2 SQI2 PhiDP2
Starting range 0.000 km, range bin spacing 50 meters
There are 22 sweeps, each having 400 rays and 801 bins
Angle list: 0.5 1.5 2.5 3.5 4.5 5.5 6.5 7.5 8.5 9.5 10.5 11.5 12.5
14.0 17.0 20.0 25.0 30.0 35.0 40.0 45.0 50.0

5.1.1 Primary Variables and Expected Uncertainty

V Linear channel Doppler mean velocity
W Linear channel Doppler spectrum width
Z Log channel reflectivity corrected for clutter
$\mathbf{Z_T}$ Log channel total reflectivity including clutter
$\mathbf{Z_{DR}}$ Differential reflectivity
$\boldsymbol{\phi_{DP}}$ Differential phase

K_{DP} Specific Differential phase
ρ_{HV} Dual polarization correlation magnitude
SQI Signal quality index

5.2 Annotated Examples

To be determined.

5.3 User Notes and Known Problems

To be determined.

5.4 Frequently Asked Questions

What is the meteorological radar range equation?

This is the equation to determine the reflectivity and is usually given in decibels of Z or dBZ.

$$Z = 10\log\left(\frac{1024\ln(2)\lambda^2 R^2 P_r L_a L_{sys}}{10^{-18} c\tau\pi^3 G_0^2 |K_w|^2 \theta_{3dB}^2 P_t}\right) \qquad dBZ$$

where:
Z = reflectivity (dBZ)
λ = wavelength (m)
R = range (m)
P_r = received power (watts)
L_a = two-way atmospheric loss
L_{sys} = radar system losses
c = speed of light (m/s)
τ = pulse width (s)
G_o = antenna gain
$|K_w|^2$ = index of refraction factor for liquid water at 0 C
θ_{3dB} = antenna beamwidth
P_t = transmit power (watts)

What dielectric factor for water is used to computer reflectivity in the radar range equation $/K_w/^2$?

The dielectric factor of water is a function of frequency and temperature of water drops as shown in Figure 10.

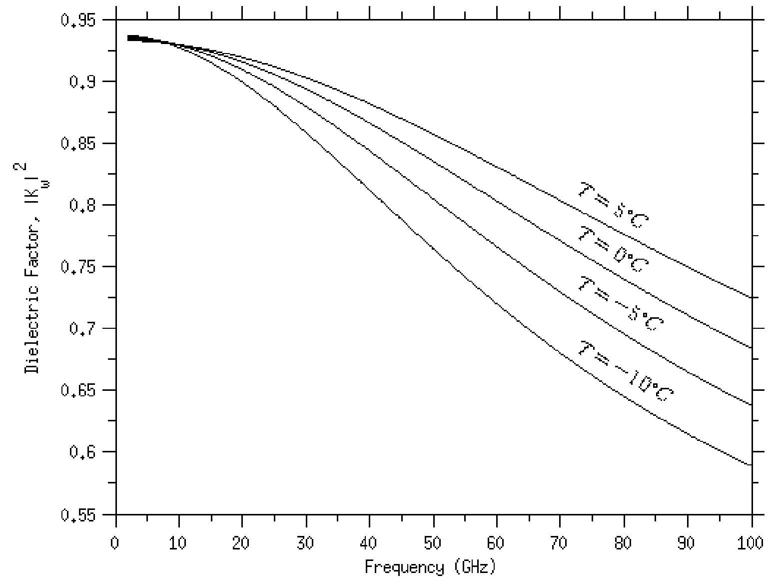

Figure 10. Dielectric function of water as a function of frequency and temperature.

The dielectric factor of water at 0°C is used for the computation of equivalent reflectivity factor. The value of dielectric factor used is 0.93 for X-SAPR.

What are measurements are made with a dual-polarization radar versus that of a single polarization radar?

All Doppler weather radars provide a measurement of equivalent radar reflectivity factor (colloquially just reflectivity). Single-polarization radars cannot distinguish much in the way of the type of hydrometeor being observed. They also have varying degrees of success in estimating rainfall rates, and they depend on empirically derived parametric models to do this. These models are different for differing climatic regimes. The promise of dual-polarization techniques is to alleviate some of these shortcomings.

To understand the role of dual-polarization radars in meteorology, it is useful to consider the shape of water droplets. They are not always spherical, nor are they shaped like the customary teardrop. Water droplets are roughly oblate spheroids for larger drops and spherical for small drops. The larger the drop, the larger the horizontal axis is with respect to the vertical axis (Figure 11). Smaller drops are much closer to being spherical (Figure 12).

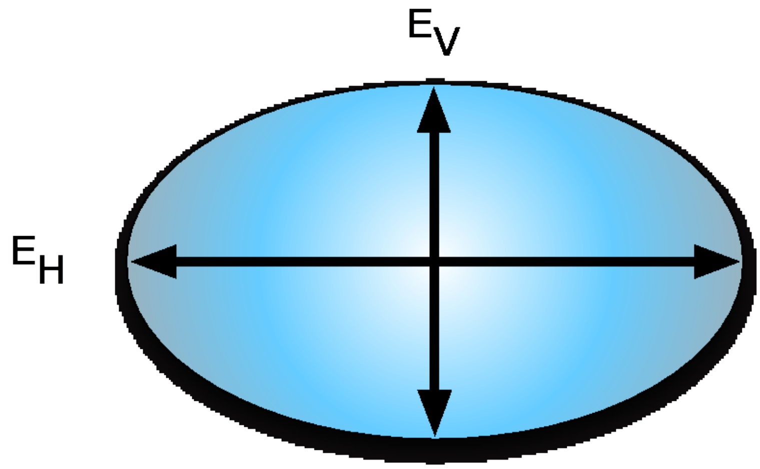

Figure 11. Large raindrop (idealized).

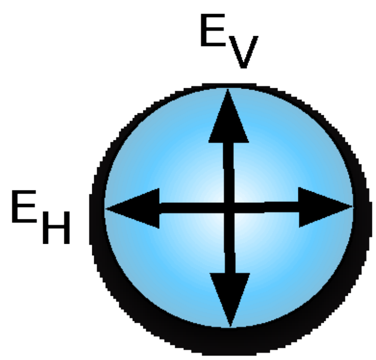

Figure 12. Small raindrop (idealized).

Keeping in mind the oblateness of raindrops, dual polarization adds the ability to measure the following variables:

- Horizontal reflectivity (Z_H) is a measurement of the reflectivity in the horizontal polarization plane. For large raindrops, the reflectivity in the horizontal axis is going to be much larger than that in the vertical axis, i.e., more oblate the larger the drop is.
- Vertical reflectivity (Z_V) is a measurement of the reflectivity in the vertical polarization plane. As the raindrop gets smaller, it becomes more like a sphere, i.e., less oblate smaller the drop is.
- Differential reflectivity (Z_{DR}) is the ratio of the horizontal reflectivity (Z_H) to the vertical reflectivity (Z_v). For large water drops, $Z_H > Z_v$ and $Z_{DR} > 0$ dB. For small drops, $Z_H \approx Z_v$ and $Z_{DR} \approx 0$ dB. What about ice in the form of hail? Although hail is irregularly shaped, as it tumbles during its rise and fall in the atmosphere, it looks close to spherical and its $Z_{DR} \approx 0$ dB. Z_{DR} is unitless and reported in dB.
- Differential propagation phase shift (ϕ_{DP}) is the measured two-way cumulative differential phase shift between the horizontal signal (ϕ_{HH}) and the vertical signal (ϕ_{VV}). As the radar signal goes through water, its speed is reduced for that period of time it is in a raindrop, inducing a phase delay in the signal. In large oblate drops, this phase delay, also called phase shift, is larger than smaller less oblate drops. ϕ_{DP} is measured in degrees.

- Specific differential phase (K_{DP}) is defined as:

$$K_{DP} = \frac{\phi_{DP}(r_2) - \phi_{DP}(r_1)}{2(r_2 - r_1)} \left(\frac{deg}{km}\right)$$

  K_{DP} is useful for estimating rainfall rates because it is not affected by spherical particles (i.e., tumbling hail). This allows the amount of liquid water in a rain-ice mixture to be estimated. Another important feature of K_{DP} is that it is a propagation variable, which means it is not dependent on the amount of received power.

- Co-polar correlation coefficient magnitude (ρ_{HV}) is a measurement of the correlation between the horizontal and vertical radar signals. ρ_{HV} can be useful in hydrometeor discrimination, e.g., differentiating between rain, hail, graupel, snow, etc.

6.0 Data Quality

6.1 Data Quality Health and Status

The Data Quality Office website has links to several tools for inspecting and assessing X-SAPR data quality:

- DQ Explorer
- DQ Plot Browser
- NCVweb: Interactive web-based tool for viewing ARM data.

Plots of reflectivity, Doppler radial velocity, and dual-polarization variables provide a good indicator of whether the system is operational or not.

6.2 Data Reviews by Instrument Mentor

Instrument mentors review X-SAPR data in the following ways:

- Routine review for nominal operation, usually daily Monday–Friday
- When requested by Site Operations
- When requested by the site scientist team
- When requested by an ARM data translator
- When requested by a data user
- When notified automatically by the X-SAPR's built-in test (BIT) email messages.

6.3 Data Assessments by Site Scientist/Data Quality Office

To be determined.

6.4 Value-Added Products

There are no value-added products for the X-SAPR at this time. There are plans to produce a “corrected moments” product, which will include velocity and range dealiasing and water vapor attenuation correction. After that, a gridded moments product with cloud boundaries will be produced.

7.0 Instrument Details

Instrument details are available in the manufacturer’s documentation. Contact the instrument mentor for information.

7.1 Detailed Description

The following figure shows the basic block diagram for the X-SAPR. There are four major functional groups: (1) Transmitter Group, (2) Receiver Group, (3) Antenna Group, and (4) Data Processing and Control Group.

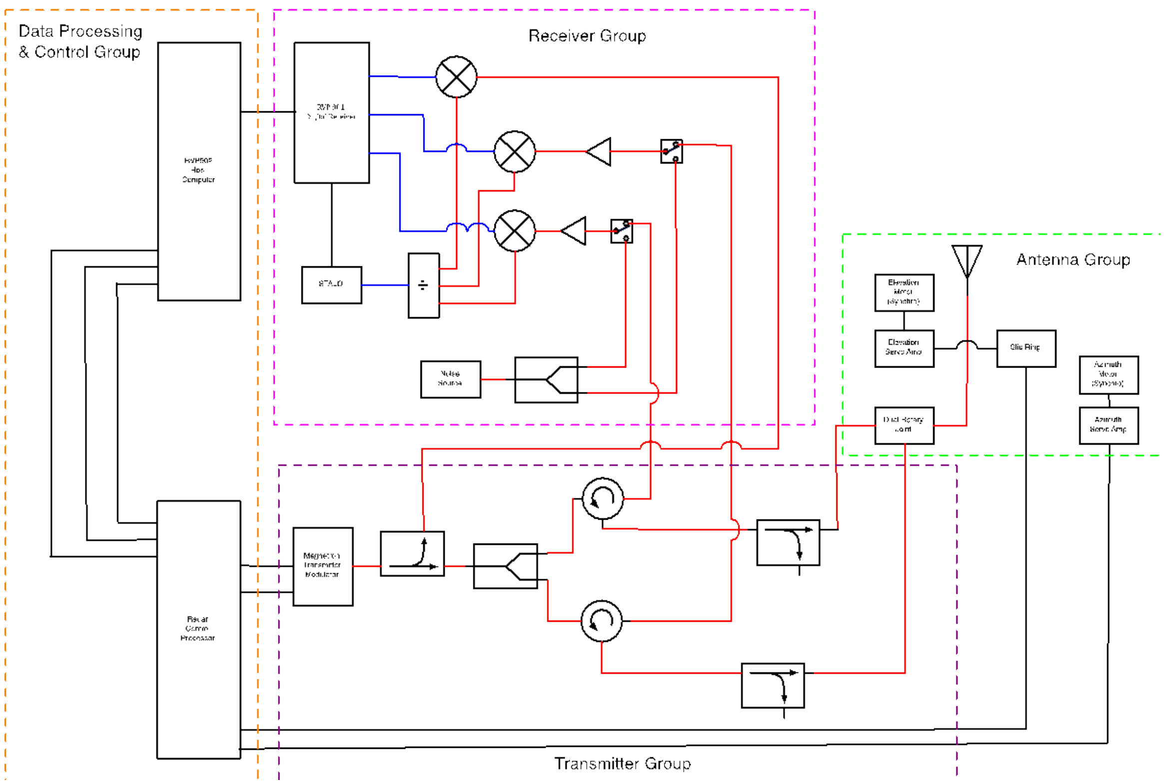

Figure 13. X-SAPR block diagram.

Transmitter Group

- Type: Magnetron
- Power: > 100 kW peak
- Frequency: ~ 9.45 GHz
- Duty Cycle: 0.1%
- Pulse Widths: 0.2–2.5 microseconds

Receiver Group

- Front End: < 3 dB noise figure for Low Noise Amplifier/Mixer
- IF: 60 MHz
- Processor: Vaisala RVP901
- Digitizer: 16-bit
- Dynamic range: >100 dB with digital signal processing

Antenna Group

- Type: 2.4 meter offset feed
- Beamwidth: ~ 1.0 degree
- Gain: 44 dB
- Control: Digital 2-axis servo with position/velocity feedback
- Motors: 400-750 W servo
- Drive: Digital torque amplifier
- Position Sense: Synchro

Data Processing & Control Group

- Operating system: Linux
- System software: Vaisala IRIS
- Control: Radtec Radar Control Processor

7.2 Theory of Operation

The theory of operation is available in the manufacturer's documentation. Contact the instrument mentor for information.

7.3 Calibration

To be included in manufacturer's documentation and the ARM Common Calibration (CCDB) database. Contact the instrument mentor for information.

7.4 Operation and Maintenance

Operation and maintenance information is available in the manufacturer's documentation. Contact the instrument mentor for information.

Citable References

Bharadwaj N, K Widener, A Koontz, and K Johnson. “Data Specification for ARM Scanning Radars.” In progress.

Bringi VN and V Chandrasekar. 2001. *Polarimetric Doppler Weather Radar*. Cambridge University Press, Cambridge, United Kingdom.

Doviak RJ and DS Zrnic. 1993. *Doppler Radar and Weather Observations*. 2nd Edition, Academic Press, San Diego, California.

CLIMATE RESEARCH FACILITY

www.arm.gov

U.S. DEPARTMENT OF ENERGY

Office of Science