ARM Volume-Imaging Array (AVA)

A path forward for the development of 3-D ARM cloud observations

Pavlos Kollias

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1. Introduction

The success of the Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) program is partially attributed to continuous operation of vertically pointing (narrow field of view) passive and active instruments and, in particular, the vertically pointing 35-GHz millimeter-wavelength cloud radars (MMCR; Moran et al., 1998). Recent and ongoing upgrades of the MMCR's signal processors, continuous recording of their Doppler spectra and addition of 94-GHz cloud radars at the SGP and ARM Mobile Facility (AMF) have increased the value of cloud-radar observables and have led to the development of new microphysical retrieval techniques and new, higher resolution ARSCL-like data products. Synergy amongst the zenith pointing instruments at the ARM sites is the signature of the program and has led to significant improvement in our ability to retrieve cloud, aerosol and thermodynamic variables.

The ARM Volume-Imaging Array (AVA) is a proposed radar system to be deployed at the ARM Southern Great Plain (SGP) site to address the ARM program's need of mapping 3D cloud and precipitation structures at short to medium ranges (i.e., 20--75 km). The AVA system will provide time-resolved 3D precipitation fields, domain-averaged rainfall rate, cloud coverage throughout a volume, cloud-top heights, hydrometeor phase information (using polarization), horizontal and vertical variability of clouds and precipitation, and low-level convergence and divergence using dual-Doppler techniques. Outstanding scientific objectives that require 3D mapping of clouds and precipitation include the following:

1. 3D radiative transfer issues, including calculation of radiative flux profiles

As long as cloud structure must be extrapolated from vertically pointing instruments, there will always be an irreducible and unknown uncertainty in comparisons of radiation models with measurements. Thus, computation of instantaneous radiative fluxes for broken and complex cloud fields over the ARM sites would benefit from the information provided by scanning radars, assuming that scanning radars can detect cloud optical depths and cloud boundaries with accuracies approaching the vertically pointing cloud radars. Descriptions of 3D cloud structures would have a significant impact on performing realistic radiative transfer calculations. In particular, 3D cloud volume observations would provide complete information on cloud overlap conditions at any given time, providing tighter constraints on radiative transfer calculations than are derivable from soda-straw data. Even the smallest amounts of condensed water — e.g a few blobs of altocumulus — are important for radiation fluxes at the few Watt/m^2 level, hence this application requires that all clouds be detected in a domain of at least 10-km radius around the ARM SGP Central Facility.

2. Lifecycles of clouds and convective systems and cloud-aerosol interactions

The temporal and spatial scales of both Large-Eddy Simulation (LES) and Cloud Resolving Models (CRM) are suitable for studying cloud lifecycles and cloud-aerosol interactions. LES domains are typically 5-6 km with grid spacing of 50x50x50 m. CRM's have much larger spatial domain sizes (i.e., 150-200 km) with 1-2 km grid spacing. LES and CRMs provide one pathway to parameterization development and hence improvement of climate models, and ARM has invested heavily in this pathway. Scanning-radar observations over a 20-km cylinder around the ARM SGP Central Facility could play a vital role in testing and improving LES models and CRM's. Our current soda-straw observations are severely dimensionally challenged when it comes to testing and evaluating the verisimilitude of LES models and CRMs. Soda-straw observations do not allow us to follow the cradle-to-grave life cycle of individual clouds or cloud systems, and thus they provide no way to evaluate the net result of the various aerosol indirect effects, each of which operates in different stages of a cloud's lifetime. Cloud lifecycle studies require detailed observations of all phases of cloud evolution, from initiation, to development of updrafts and downdrafts, to hydrometeor evolution in time and space, to partitioning of condensate into precipitation and outflow anvils.

3. Evaluation of satellite retrievals of cloud system properties.

Surface- and satellite-based cloud products, together, are what is available today for evaluating models of all types, but clearly modelers have preferred the satellite data since it provides the 3D spatial extent and holistic view unavailable in soda-straw data. Typical satellite cloud retrievals rarely have spatial resolution better than 500 m (much worse in the microwave). The soda-straw data is very hard to compare with such satellite data because of the "beam-filling problem" -- the problem that ARM's soda-straw measurements refer to only a part, often a small part, of a satellite pixel. A scanning system would allow observing many satellite and model pixels at the same time, allowing us a coherent holistic view rather than our current peek through a keyhole. A scanning system will allow not only more honest and incisive comparisons with satellite cloud data, but also comparisons with higher statistics of the satellite data unavailable in a soda-straw view (e.g. the spatial correlations among cloud pixels that are so evident to the eye).

Note that, at the end of this document, there is a Glossary of the more obscure radar meteorology terms used.

2. Background

One of the strengths of meteorological radars is their ability to continuously probe the atmosphere over large distances and provide range-resolved information on hydrometeor location, density and velocity. With the addition of polarization, radars are able to provide additional information on particle type and phase. Scanning and polarization capabilities were first explored in radars operating at long wavelengths (5-10 cm), for the detection and monitoring of precipitation and severe weather. At such long wavelengths the atmosphere is almost completely transparent to radar waves, and hydrometeors produce very little attenuation, allowing detectable radar backscatter from ranges up to 150-200 km. The technology and signal processing for these radars is mature, and retrieval algorithms and data products based on multi-parameter estimation techniques have been published and validated.

Long wavelength (e.g., 10-cm) radars are used by the National Weather Service for the NEXRAD weather radar network and for field experiments used to evaluate CRM's (e.g., GATE, 1974; TOGA-COARE, 1992-1993; South China Monsoon Experiment, 1998; TRMM KWAJEX, 1999). Observed parameters used to evaluate CRM's include time-domain average surface rainfall deduced by the scanning radars (30-100% retrieval errors are typical), histograms of radar reflectivity by altitude, convective system echo morphology, convective system lifetimes and propagation speed. However, long wavelength radars have reduced or no sensitivity to cloud droplets and ice crystals; that is, they detect only the precipitating portion of convective clouds and thus provide little or no information on cloud microphysics, such as cirrus ice water content. Their resolution volumes are quite coarse (i.e., 250-500 m), they are difficult to transport, and they are susceptible to Bragg scattering and ground clutter which in the boundary layer will mask all returns from non-precipitating clouds.

The ARM program has a longstanding goal to observe <u>all</u> hydrometeors in the atmospheric column above the ARM sites. For this purpose ARM uses radars with much shorter wavelengths than precipitation radars: namely, the 35-GHz MMCR at all ARM sites and the recently acquired 94-GHz WACR at the SGP and AMF sites. These radars operate at the shortest wavelengths used in atmospheric research (8.6 mm and 3.2 mm) and in a zenith-pointing mode only. At such high radar frequencies, especially at 94-GHz, both atmospheric gases (water vapor and oxygen) and hydrometeors produce significant signal attenuation, motivating their use in a vertically pointing mode only. Since the early days of its existence, the ARM program has expended significant resources in algorithm development for the retrieval of cloud boundaries and microphysics from its vertically pointing radars, with additional information provided by the vertically pointing micro-pulse lidar and ceilometer.

The need to map the 3D structures of clouds and precipitation over, say, a 20-30 km cylinder around the ARM sites requires the introduction of

> *scanning radar concepts – a mode of radar operation new to the ARM program;*
>
> *new radar systems, perhaps operating at frequencies where the atmosphere is more transparent than at 35 and 94 GHz; and*
>
> *new radar observation modalities such as polarimetric and dual-Doppler.*

The success of mapping 3D cloud structures critically depends on the allocation of appropriate resources to the infrastructure and to (possibly new) ARM principal investigators for the development and optimization of scanning strategies that will mesh the vertically pointing and scanning radar observations and lead to the development of new algorithms. Equally important is the development of a useful 3D cloud Value Added Product (VAP) similar to the existing ARSCL but on a regular 3D grid. Stringent data quality control on the best estimates of cloud boundaries and radar observables will be essential in making this product of wide value. In the previous ARM 2000 Cloud IOP scanning cloud radars collected 2D cloud datasets, but these datasets were not incorporated into VAPs that could meet the needs of the modeling community, and thus received little if any use. ARM must not repeat this mistake; it must make sure that AVA leads to significant scientific VAPs. The development of such VAPs will require a strong interaction between the observation and modeling communities, and their development will certainly be the first metric of success for AVA.

Another important milestone in the effort to create AVA is the development of the “AVA Simulator”. Patterned after the well-known ISCCP Simulator, the AVA Simulator will perform forward simulations of radar observables, using as input LES model and CRM outputs of cloud properties together with the characteristics of the AVA radars. The results will be used to develop and optimize volumetric radar scanning strategies, develop and evaluate inverse retrieval techniques, and develop prototype 3D ARSCL-like VAPs for the ARM community. The AVA Simulator will be provided to the modeling community to facilitate the comparison between AVA observables and model outputs, and it may also function as an educational tool for both radar experts and modelers, allowing each group to become familiar with the issues faced by the other.

3. AVA Proposed Specifications

In its final form, the AVA radar system at the ARM SGP site will be composed of three networked scanning radars arranged in a triangle with 20-30 km legs. One of the radar systems will be a standard cloud radar operating at 35 GHz (same 8.6-mm wavelength as the MMCR) and capable of scanning the vertical region probed by the current MMCR. The other two radars will operate at 9.4 GHz (3.2-cm wavelength, so-called “X-band”). All three radars are transportable, scanning, polarimetric and Doppler

The AVA 35-GHz radar is an upgraded, scanning version of the ARM MMCR with adequate sensitivity to detect clouds at long ranges and capable of pointing vertically, as needed, to make MMCR-like observations. This radar will provide sufficient sensitivity (i.e., –40 dBZ at 10 km range) to detect low-liquid-water-content clouds, better spatial resolution than existing scanning radars (0.5° or better beamwidth and 60-m range resolution), and minimum Bragg scattering effects (see Fig. 1 for interpretation of –40 dBZ with respect to cloud types). Both a Traveling Wave Tube (TWT) amplifier with 5% duty cycle and 1.5 kW peak power and a high power (e.g., 30-80 kW) magnetron transmitter provide sufficient power for the required sensitivity at 10 km. It is critical to achieve such superb sensitivity with a scanning 35-GHz radar in order for the radar to observe both low liquid water clouds and high ice clouds. The high sensitivity of the scanning 35-GHz cloud radar will allow the mapping of the 3D cloud structures at the spatial scales of LES domains in the absence of heavy rain.

X-band radars are often called short-range (50-75 km) weather radars. They are nearly cheap enough, reliable enough, and widespread enough to be called a commodity item, perhaps because of their use as marine radars. The 9.4-GHz transmitter of the AVA versions will be based on a commercially available marine radar transmitter (25 kW peak power, 2-year lifetime and $400 replacement cost). The required sensitivity of the 9.4-GHz radars is –20 dBZ at 10 km (the requirement is different from the 35-GHz radar due to hardware limitations). At this sensitivity, the 9.4-GHz radars will be sensitive to thick cirrus and any kind of precipitation at long distances. (Note: the proposed sensitivity for the AVA radars is 20 dB better at 1 km and 6 dB worst at 20 km (R^2-term)). The radars will be capable of simultaneous horizontal and vertical (HV) polarization mode transmission that results in pairs of pulses with equal power in the horizontal and vertical polarizations. This is the same scheme recommended for future polarization upgrades to NEXRAD (Doviak et al., 2000). Polarization parameters from this mode of operation include (see Glossary for definitions): (1) differential reflectivity (Z_{DR}); (2) propagation differential phase shift (ϕ_{DP}) and (3) its range derivative; (4) specific differential phase (K_{DP}); and (5) polarization correlation magnitude at zero lag (ρ_{HV}). These polarimetric parameters are used to estimate precipitation rates and/or hydrometeor types.

X-band radars have recently received much attention due to their capability of detecting useable K_{DP} magnitudes in rain rates as low as ~2 mm/hr. K_{DP}-based precipitation estimators are thus able to perform adequately over a significantly larger portion of a raining area and extend polarimetric rain estimation capabilities lower into the rain rate distribution, leading to improvement in rain estimates relative to traditional Z-R techniques (Rutledge et al., 2005). The X-band radars will be separated by 20-30 km. When scanned together they will provide detailed precipitation mapping over a 75 km by 75 km area around the SGP site. Two such systems are required to address the need for larger areal coverage of clouds and precipitation and to provide low-level horizontal divergence and convective system kinematics using dual-Doppler radar data synthesis.

As an entity, AVA will measure all cloud particles from small droplets to precipitation-size particles in an “inner domain” of roughly 20 km by 20 km by 20 km around and above the ARM SGP Central Facility. It will map precipitation over an “outer domain” of 50-75 km radius centered on the ARM SGP Central Facility. Measurements in the inner domain will address needs of both radiative transfer and LES modelers, while measurements in the outer domain will provide precipitation (and some cloud) information within deep convection, plus surface rainfall rates and horizontal divergences as input to the dynamical forcing for Cloud Modeling and Parameterization Working Group case studies in the context of CRM evaluation and improvement of convective parameterization.

The three AVA radar nodes will be spaced to maximize the areal coverage while maintaining a sensitivity constraint over a specified volume above the ARM SGP site. Their placement will also be selected to maximize the dual-Doppler areal coverage (see Fig. 2 for suggested spacing and scanning strategies). Since the spacing of the nodes will require some tuning for maximum performance, the radars are required to be transportable on, say, a week’s notice.

4. Phased-Array Radar at SGP: A Proposed Collaboration with CIRPAS

Phased-array radar, in which scanning is done entirely electronically, or partially electronically and partially mechanically, is the wave of the future. All NEXRAD sites will have phased-array radars by 2012. The technology allows extremely fast scans (2 sec or less for a zenith to horizon scan at 1-deg increments) and research-programmable scan strategies. Thus, it behooves ARM to begin to investigate this technology. Fortuitously, an opportunity for doing so at little or no cost to ARM has appeared.

Through a collaborative effort with the Center for Interdisciplinary Remotely-Piloted Aircraft Studies (CIRPAS), a research center at the Naval Postgraduate School located in Monterey, California, we propose to deploy the CIRPAS 9.4-GHz phased-array radar at the ARM SGP site every year for 1-2 months of continuous observations. The CIRPAS radar is mounted on a Benz truck and is powered by a generator that uses the truck's fuel. As such, this 9.4-GHz radar needs no additional infrastructural provisions and operates with limited cost. In addition to its normal monitoring mode, the CIRPAS phased-array radar can be reprogrammed to address specific ARM IOP field campaign objectives, such as rapid small-sector off-zenith scanning of boundary layer clouds, or tracking cloud entities that are being sampled by aircraft.

This potential collaborative effort aims to improve our understanding of the potential of phased-array radar technology for ARM and, indirectly, for the atmospheric science community at large. ARM will team-up with CIRPAS and Prosensing Inc., the developer of the CIRPAS radar, to upgrade the CIRPAS phased-array radar, originally designed for military applications, for weather applications, including the development of scanning strategies, algorithms and any additional upgrades that will make this phased-array radar suitable for meteorological applications. The operation of the CIRPAS phased-array radar in the vicinity of the AVA presents a unique opportunity for evaluating the performance of this system and providing feedback for its further development. This collaboration offers ARM inexpensive access to phased-array radar technology without the need to acquire its own system for several years.

AVA Incremental Milestones

Summer 2006:	STEC approval of the AVA plan (Eugene Clothiaux will present)
Fall 2006:	• Complete statement of work and radar specification (Kollias) • Start development of AVA simulator (Kollias-Clothiaux-Luke)
CPWG 2006:	• 1st Meeting of the ARM-Radar Group (see Table 1) • Meeting between Navy/CIRPAS, DOE-ARM and ProSensing to develop a framework for a long-term collaboration in Phased-Array radar development for atmospheric applications
FY07:	Develop 35-GHz scanning cloud radar
STM 2007:	Complete preliminary version of the AVA simulator

Summer 2007: Deployment of CIRPAS phased-array radar during CLASIC.

FY08: Develop the two 9.4-GHz X-band radars

Spring 2008: Begin deployment of AVA at the ARM SGP site

Table 1. ARM Radar Working Group (Tentative)

Name/Affiliation	Area of expertise
Kollias (BNL/McGill) Clothiaux (PSU)	Synthesis and Coordination. New radar technologies, upgrades and their applications to ARM science. AVA Simulator and 3D-ARSCL
Mace (Utah) Marchand (PNNL)	Microphysical retrievals of ice water particles Microphysical retrievals of liquid water particles
Houze (Washington) Schumaker (TAMU)	Echo Morphology, Convective and Stratiform Classification. Domain average radar products, histograms by altitude, rainfall and convective intensity retrievals
May (BOM) Matrosov (NOAA/PSD)	Radar polarimetric-based microphysical retrievals and attenuation correction techniques in C-POL and the scanning polarimetric AVA radars.
Johnson (BNL) Luke (BNL)	Vertically pointing millimeter radars. Doppler spectra processing.
Widener (PNNL) Prosensing Inc.	Technical support and expertise on radar engineering, deployments.

Radar Meteorology Term Glossary

Dual-Doppler: The use of two Doppler radars to measure two different radial velocities; these two radial wind components can be synthesized to a spatial distribution of fully 2D (horizontal) winds. If three radars are used for the Doppler synthesis, then all three components of the wind can be retrieved.

Bragg scattering: A radar echo returned from a region of the atmosphere with no apparent cloud or precipitation scatterers. Bragg scattering is caused by spatial fluctuations of the atmospheric refractive index that are resonant with the radar wavelength. For backscattering, these fluctuations have a scale size of one-half the radar wavelength. The intensity of Bragg scattering depends on the radar wavelength (see Figure 1) and it is usually only a problem at long radar wavelengths.

Ground Clutter: A pattern of radar echoes reflecting off fixed ground targets such as buildings, the sea surface, or hills near the radar. This may hide or confuse the return echo signifying actual precipitation.

ZDR (Differential Reflectivity): A measure of the reflectivity-weighted mean axis ratio of the hydrometeors in a radar volume.

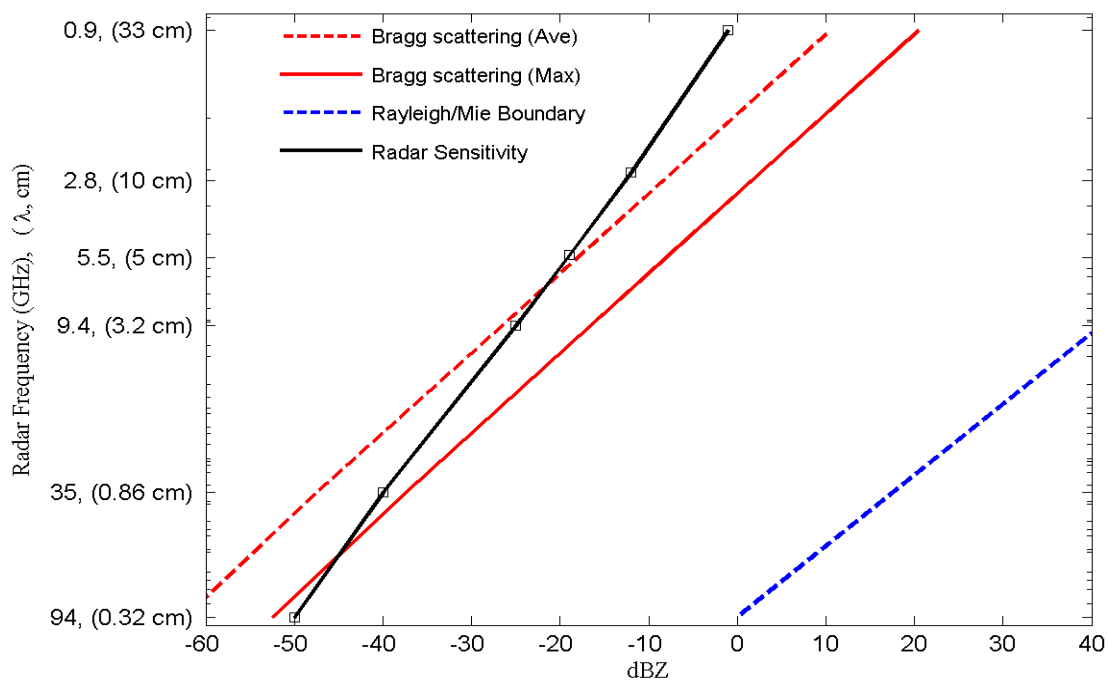
$$Z_{DR} \sim 10 \log (P_h / P_v) \text{ [dB]}$$

P_h is the returned horizontally polarized backscattered power received from the horizontally polarized transmitted pulse. P_v is the returned vertically polarized backscattered power received from the vertically polarized transmitted pulse. Z_{DR} values for meteorological echoes typically range between -2 dB and 6 dB. Values of Z_{DR} well above zero indicate the hydrometeors in the volume are horizontally oriented -- meaning their horizontal axis is longer than their vertical axis ($P_h > P_v$). Values of Z_{DR} well below zero indicate the hydrometeors in the volume are vertically oriented -- meaning their vertical axis is longer than their horizontal axis ($P_h < P_v$).

ρ_{hv} (Co-polar H,V signal correlation): Primarily useful to characterize variability of scatterer characteristics within the pulse volume. Typical values: Drizzle / light rain > ~0.98 Convective (but no ice) rain > ~0.96 Hail / rain mixtures ~0.90 Bright band mixed rain and snow ~0.75 Tornado debris ~0.50 or less.

K_{DP} (Specific Differential Phase): The specific differential phase is a comparison of the returned phase difference between the horizontal and vertical pulses. This phase difference is caused by the difference in the number of wave cycles (or wavelengths) along the propagation path for horizontal and vertically polarized waves. It should not to be confused with the Doppler fequency shift, which is caused by the motion of the cloud and precipitation particles. Unlike the differential reflectivity, correlation coefficient, and linear depolarization ratio, which are all dependent on reflected power, the specific differential phase is a "propagation effect". It is a very good estimator of rain rate.

Relationship Between Radar Reflectivity, Bragg scattering, Radar Wavelength and Cloud Type



Low :	Cumulus	Stratus	Drizzle	Heavy Drizzle		
Middle:	Alto-Cumulus	Alto-Stratus				
High:	Thin cirrus	Thick Cirrus	Precipitating cirrus			
Precipitation:					Stratiform	Convective

Fig 1. The blue line shows the transition boundary from the Rayleigh approximation to non-Rayleigh scattering as a function of the radar frequency (wavelength) and equivalent radar reflectivity. The red lines show the point where the backscattered radar signal from clouds equals the expected backscattered radar signal from Bragg for average (dashed red line) and extreme (solid red line) refractive index variations. For a given radar frequency, observed echoes on the right of the Bragg lines have mostly contribution from hydrometeors, while observed echoes on the left of the Bragg lines have mostly contribution from Bragg scattering. Thus, the dashed red lines shows on average the limit of hydrometeor detection for various radar wavelengths. For instance, at X-band (9.4-GHz), low level returns from non-precipitating fair weather cumuli will be difficult to discriminate from Bragg echoes. Note, at 9.4-GHz (the X-band frequency), Bragg scattering is present in the lowest 1.5 km of the atmosphere. In addition, the black line shows examples of operational radar sensitivity of well known radar systems: the NOAA wind profiler network at 0.915 GHz (range 5 km), the WSR-88D at 2.7-GHz (range 20 km), the Bureau of Meteorology C-Pol (5.5-GHz) scanning radar (range 20 km), the NOAA Physical Science Division 9.4-GHz radar (2 km range), the 35-GHz ARM MMCR (2 km range) and the ARM 94-GHz Mobile Facility radar (5 km).

AVA Suggested Spacing and Scanning Configuration

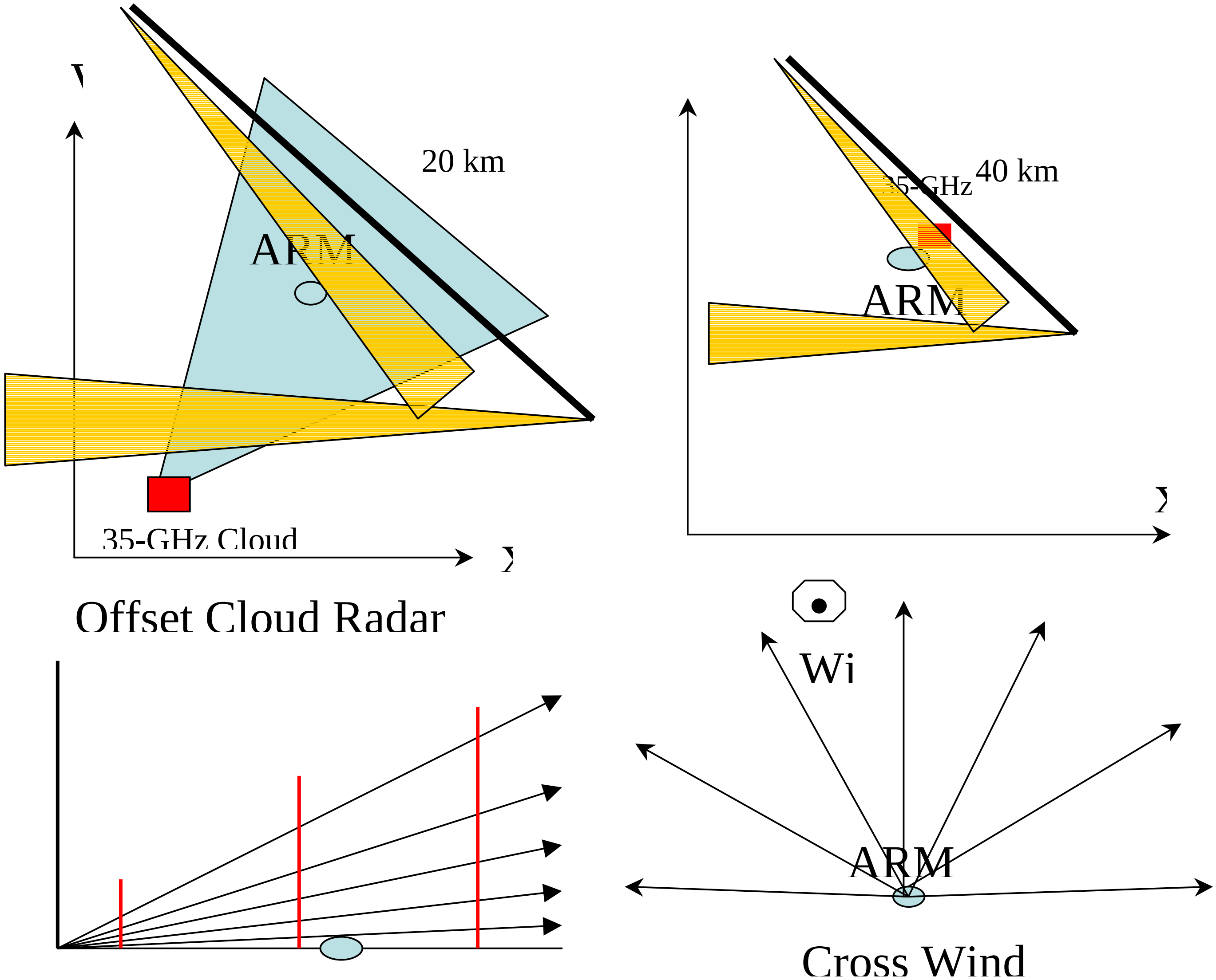


Fig. 2. Two suggested AVA spacing and scanning configurations: (a) offset the 35-GHz radar from the ARM SGP site and scan a 3D sector centered at the vertically pointing radars (left); the two 9.4-GHz radars are spaced 20-30 km apart and provide 3D surveillance coverage and supplementary coverage for areas where the offset 35-GHz radar will have difficulty providing coverage (at very short and very long range from the radar location); (b) place the 35-GHz at the Central Facility, make simple cross-wind 180^{o} scans, and use the wind to map the 3D structure of clouds (right); for this mode, the two 9.4-GHz radars would conduct autonomous volume scans independently from the 35-GHz radar.