Leading Edge Radar

The Upgraded ARM Network

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With significant upgrades over the last decade, the Department of Energy's Atmospheric Radiation Measurement (ARM) radar network now features multiple scanning dual-polarization Doppler radars to exploit polarimetric, multifrequency, and multi-Doppler capabilities. The network provides a wealth of information on cloud and precipitation microphysics and dynamics under a wide range of conditions thanks to radars that operate at four frequency bands covering a wide range of scattering regimes.

ARM first deployed vertically profiling millimeter-wave-length radars in the 1990s. In improving upon this configuration, the network maintains its focus on column (profiling) measurements of radiation, aerosols, and clouds, but now provides more comprehensive, calibrated, and multiparametric measurements of clouds and precipitation. The overarching goal is to provide a comprehensive characterization of the three-dimensional cloudy atmosphere as a laboratory for the study of cloud processes.

To detect both small and large hydrometeors and precipitation systems over a large domain, ARM had to pioneer the first systematic, large-scale symbiosis of centimeter-

and millimeter-wavelength radars. The former penetrate precipitation with little attenuation, while the latter suffer attenuation but are sensitive to small droplets. The relationship between radar reflectivity factor and particle size gets much more complex for frozen particles, yielding large uncertainties in estimating hydrometeor properties. For this purpose, ARM deployments included dual- and triple-frequency radars.

The first generation millimeter-wavelength cloud radars (MMCRs) were replaced by the Ka-band ARM zenith radars (KAZRs) in 2011. The KAZR could transmit a short pulse and a longer pulse simultaneously with faster cycling between modes, thus offering higher temporal resolution data. In parallel, a motion-stabilized W-band ARM cloud radar (WACR) was developed for ship-based deployments. Also developed were scanning ARM cloud radars (SACR); each of these systems had dual-frequency capabilities enabling improved quantitative microphysical retrievals. The two recently fielded second-generation Ka-/W-band SACRs offer full dual-polarization capability to expand information content on nonspherical hydrometeors.

To expand research into precipitating clouds and deeper convection, X-band scanning ARM precipitation radars (XSAPRs) were deployed at ARM North Slope of Alaska (NSA) observatory and at the ARM Southern Great Plains (SGP). A C-band scanning ARM precipitation radar (CSAPR) was also deployed to the ARM SGP observatory. By 2017, ARM had fielded two unique, second-generation SAPRs, at the Eastern North Atlantic (ENA) observatory and with ARM Mobile Facility (AMF) deployments.

ARM's strategy is to collect long-term continuous observations augmented by shorter, intensive field campaigns. Radars are highly configurable, so they fall somewhere these time scales. For instance, the SGP site hosts a KAZR, a Ka-/W-band SACR, three XSAPRs, a dual-polarization XSAPR, and a CSAPR group of five different radars, constituting the

The heterogeneous, distributed ARM radar network at the SGP. The SGP observatory has installed profiling modules (red stars) at four Extended Facilities to provide additional measurements.

first continuously operating heterogeneous, distributed radar network intended to sample from shallow cumulus to severe convective cells. One motivation for ARM's recent upgrade to its SGP facility was to develop a multi-Doppler radar network that could improve vertical wind retrievals at heights above 6 km.

In contrast, the NSA site radars have pioneered application of multifrequency, dual-polarization, and spectral radar observations to mixed-phase cloud studies, while recent Eastern North Atlantic site radars facilitate marine boundary layer cloud and drizzle research.

The operation and characterization of the ARM radars is a strenuous challenge. The radar network has more than 20 radars around the world, often in remote areas with poor power and limited connectivity. The small engineering and operations team deals with radars developed by different manufacturers and operating at different frequencies, with varied scheduling demands limiting maintenance periods.

ARM designed the Watchdog for ARM Radar Network Operations (WARNO) software to monitor hundreds of diverse streams of data on each radar and homogenize them. WARNO's plugin architecture allows for quick assessment of radar health. Because the network includes both profiling and scanning millimeter- and centimeter-wavelength radars,

ARM developed a portable millimeter-wave calibration kit and uses corner reflectors when feasible for absolute calibration.

Spaceborne radar, such as NASA's *CloudSat* Cloud Profiling Radar (CPR) can be used to characterize the calibration of profiling millimeter-wavelength radars. In total, ARM cloud profiling radar observations from 18 different fixed and mobile sites, totaling more than 43 years of observations, have been calibrated. The Earth Clouds Aerosols and Radiation Explorer (EarthCARE), scheduled to launch in 2022, will continue spaceborne evaluation of ARM radar calibration.

Examples of ARM radar network radars:
 (a) the KAZR at the Southern Great Plains, Oklahoma, site; (b) the KAZR and the M-WACR during the Marine ARM GPCI Investigation of Clouds deployment on board the container ship *Horizon Spirit* out of Long Beach, California; (c) an SACR during the ARM West Antarctic Radiation Experiment deployment in McMurdo Station, Antarctica; (d) one of the three XSAPR's at the Southern Great Plains, Oklahoma, site; (e) the XSAPR2 and the SACR2 at the Eastern North Atlantic fixed observatory; and (f) C-SAPR2 during the Cloud, Aerosol, and Complex Terrain Interactions deployment in Argentina.

ARM data collected from over 400 instruments in more than 25 years represent a wealth of information. ARM is now working with users to identify and characterize data epochs—specific data streams and time periods with known calibration, quality, and quantified uncertainties. This requires a new way of thinking about packaging, such as merging datasets to common temporal resolution.

Science applications

The new radars opened new opportunities to study clouds and precipitation. New capabilities include retrieval of hydrometeor spatial distributions, rainfall rates, and rainfall accumulations over a large domain. For example, the 2006 upgrade of the ARM profiling radars enabled removal of radar artifacts, identifying and filtering out returns contaminated by insects, detecting supercooled liquid in mixed-phase clouds, and exploiting “Mie notches” (i.e., reductions in the backscattered power

with increasing particle size) to retrieve both raindrop size distributions and air motions simultaneously.

Vertically pointing sensors can provide information about the horizontal structure of clouds that would otherwise be difficult to obtain. On average, the SACR's spend 25%–50% of the time pointing vertically, reducing the uncertainty in the microphysical parameters extracted from the radar observables. The difference in radar reflectivity (in dB) measured at two wavelengths can indicate hydrometeor mass content and size and allow retrieval of liquid water content in clouds. Overall, the column measurement capabilities of the ARM radar network have improved substantially with the upgrades.

At the ENA observatory, XSAPR2 can map the mesoscale cloud and precipitation organization over an effective range of 40–60 km. A combination of scanning and vertically pointing radar remains the best

The Search for W: Vertical Air Motion in Deep Convection

The need for detailed and long-term observations of deep convection vertical velocities motivated upgrades to ARM's SGP facility. Multi-Doppler radar wind retrieval techniques have been widely used to estimate the vertical air motion in convective clouds. The SGP facility combines 4 scanning weather Doppler radars. The Oklahoma tornadic supercell event of 23 May 2011 was an example of the SGP facility combining 4 scanning weather Doppler radars for wind retrievals.

Shown here is (a) the vertical cross section of radar reflectivity with multi-Doppler wind field retrievals (arrows) through the supercell core. The vertical cross section corresponds to the A-A' line as drawn on (b) the constant altitude (3-km agl) PPI of the radar reflectivity and horizontal wind field retrievals. White circles correspond to the locations of the ARM radars used to perform these wind field retrievals.

Vertical air motion retrievals in the upper part of convective clouds (above 6 km) remain challenging using the SGP radar network. Significant improvements are required, perhaps rapid scan radars and adaptive scan strategies to reduce the sampling time. Nevertheless, statistical composites of deep convective dynamics based on routine ARM operations may elucidate climate model scale connections between convective updrafts, precipitation, and storm life cycle.

option for characterizing weak meteorological events. Similarly, when cloud and precipitation particles are mostly spherical, millimeter-wavelength radar and near-infrared lidar have been combined to retrieve properties such as rain rate.

ARM's new dual-polarimetric CSAPR can monitor the evolution of storms at a distance and document vertical structure overhead. Additionally, CSAPR is designed to investigate the melting layer, differentiate hydrometeor types, estimate drop-size distribution parameters, and estimate rain rates.

To realize the full potential of these advancements, we will need to work toward synergy with other observations, improved modeling, and well-designed data-model integration. Radar observations help evaluate models of various scales and complexity. Forward simulators, which convert modeled hydrometeor properties to sensor observables, allow us to investigate the relationships between observational and model data and facilitate a more complete evaluation of modeled processes.

Uncharted territory

Coupling the radars with other ARM technology provides a unique, continually advancing community resource. The increased reliability, improved functionality, and reduced cost of these radars facilitate cloud research in tens of locations around the world.

Now ARM is in uncharted territory as it bridges multiple wavelength radar from different vendors in holistic operations. Despite the steep learning curve for engineers, ARM can pioneer systematic, multiwavelength, polarimetric, and spectral-based radar studies of clouds. In the process, ARM has brought together engineers and scientists from the weather, climate, and radar communities—a merger fostering new perspectives and innovative ideas. By tearing down traditional, artificial barriers between the cloud and precipitation communities both in observations and modeling, ARM is closer to developing holistic, surface-based observatories. ●●

METADATA

BAMS: What would you like readers to learn from this article?

Pavel Kollias (SUNY-Stony Brook, Brookhaven National Laboratory, and University of Cologne): *This was a 10-year effort to transform ARM observatories from profiling cloud measurements to 3-dimensional cloud and precipitation observatories. There is a historical progression in the development of these surface-based observatories and valuable lessons regarding operating such diverse radar facilities in remote areas around the world. However, the most important lesson is what triggered this transformation: the need to observe both clouds and associated precipitation over a large domain so we can capture their organization and evolution as one integrated system.*

BAMS: What surprised you the most about this project?

PK: *Implementing and operating these fields of beams at the ARM observatories was at times a humbling experience. Even though radars have been used for meteorological applications since the 1960s, they are far from plug-and-play instruments. Thus, one of the surprises we collectively experienced over the last 10 years is that operating research-quality radars in remote environments with poor power and limited connectivity can be very challenging.*

BAMS: What was the biggest challenge you encountered in this work?

PK: *There is reasonable expectation that the ARM fixed and mobile observatories will deliver the required, high-quality, science-relevant observations. It is far more challenging to successfully untangle the contribution of the different factors that affect the properties and evolution of cloud and precipitation systems.*

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