RADAR IN ATMOSPHERIC SCIENCES AND RELATED RESEARCH Current Systems, Emerging Technology, and Future Needs

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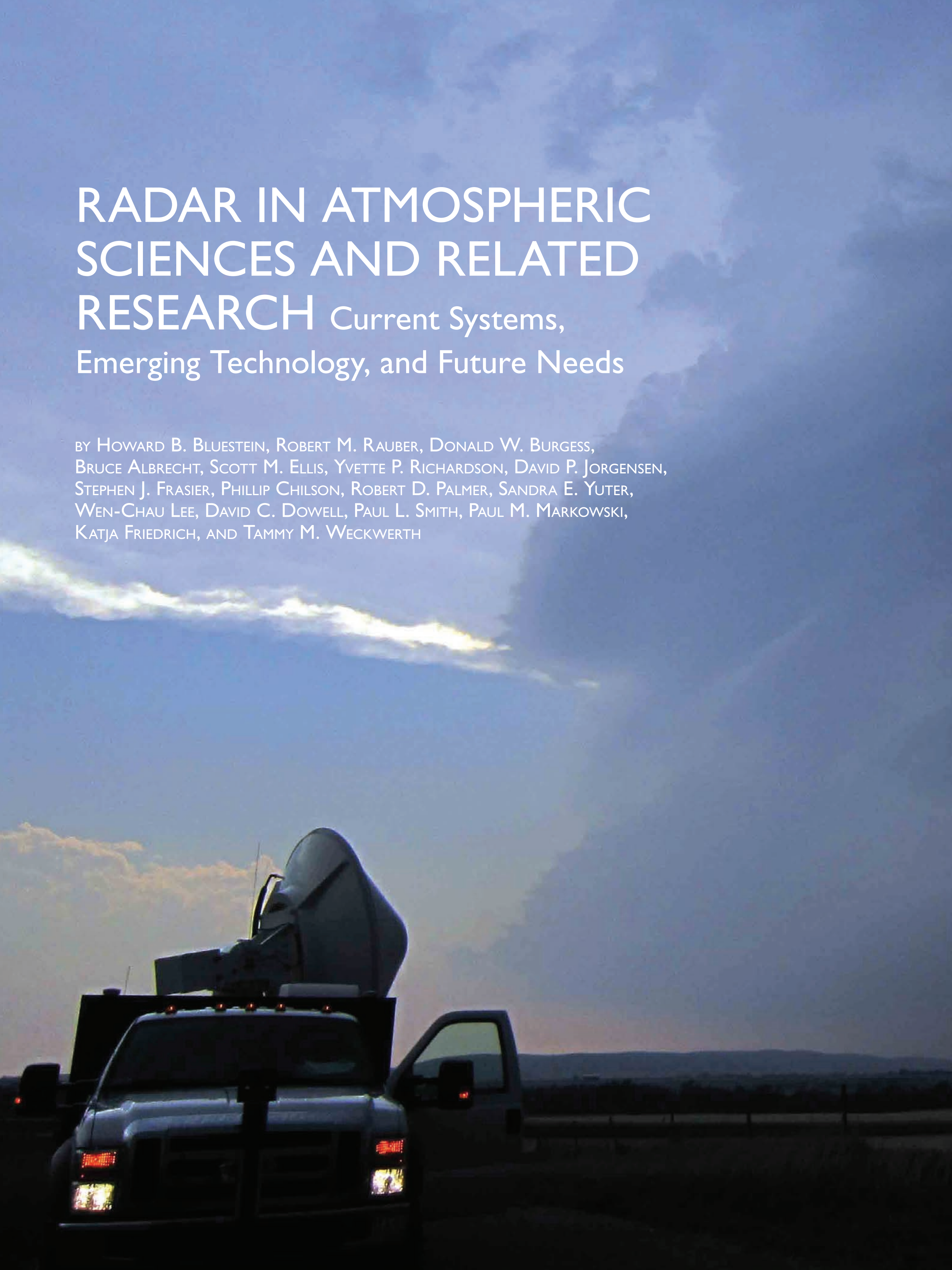

Emerging radar technologies best suited to addressing key scientific questions and future problems are identified and discussed.

To help its Lower Atmosphere Observing Facilities (LAOF) program provide researchers with instrumentation and platforms, the National Science Foundation (NSF) convened a community workshop[1] with the purpose of defining the problems of the next generation that will require radar technologies and to determine the suite of radars best suited to solving these problems. The workshop addressed a subset of the instruments[2] mentioned by the National Research Council (2009) as being or eventually becoming essential operational facilities. Climate scientists have also recommended similar reviews of instrumentation, in part because "we may . . . need easily deployable short-term observational technologies to monitor potential abrupt changes or important regional trends" (National Research Council 2010).

Based on presentations and discussions at the NSF workshop (Figs. 1 and 2), we considered the following questions: ▶

[1] The workshop was held at the NCAR in Boulder, Colorado, from 27 to 29 November 2012. There were over 120 participants who represented six countries (United States including Hawaii, Canada, France, Germany, Japan, and Taiwan) and three continents. Additional participants attended by web conferencing. More information about the workshop including presentations and posters may be found online (at www.joss.ucar.edu/nsf_radar_wksp_nov12/).

[2] Spaceborne radars, which would require collaboration among NASA, NOAA, and NSF, were not considered during the workshop.

A rapid-scan, X-band, polarimetric, Doppler radar (RaXPol) probing a supercell in southwestern Oklahoma on 23 May 2011. (Courtesy of H. Bluestein.)

Fig. 1. Small discussion group (from left to right: John Williams, Bob Palmer, Jim Wilson, and Phil Chilson) during the radar analysis and software session. (Courtesy of H. Bluestein.)

1) What current radar technologies are considered critical to answering the key current and emerging scientific questions? What are the strengths and weaknesses of those technologies as they are currently implemented?
2) What emerging radar technologies would be most helpful in answering the key scientific questions?
3) What gaps, if any, exist in radar observing technologies? (A "gap" can mean the absence of a critical technology or a lack of access by the general research community to an existing technology.)

While we address these questions here, an online supplement (available online at http://dx.doi.org/10.1175/BAMS-D-13-00079.2) reviews in more depth the radar technology currently in use (see Tables 1–3 for surveys of current ground-based mobile, airborne, and deployable radars, respectively) and provides more information about the workshop itself.

EMERGING RESEARCH FRONTIERS. Future research[3] with radar will involve multiplatform, multimodel investigations. There will be four major research themes involving radar.

Extreme weather. Studies of tropical-cyclone genesis including spatial structure, rapid intensification, and evolution during landfall, convective weather systems, and winter weather systems will all require radar. It was proposed that this should include a rapid-response capability to facilitate study of extreme weather events that are predictable days in advance.

Hydrology and water resources. Studies of tropical–extratropical transition, flooding from landfalling tropical systems, midlatitude convective systems, atmospheric rivers, the interaction of weather systems with orography and topography, weather modification for precipitation enhancement, and mapping the water vapor field for numerical weather prediction

[3] This section is based on a presentation by Robert Rauber at the workshop.

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and estimating precipitation rates will also all require radar.

Global and regional climate and climate change. Radar will be needed to study, for example, tropical cloud systems, oceanic tropical convection and its impact on climate, the effects of aerosols on cloud microphysics, and global and regional orographic precipitation as a source of water supply. Dr. Rauber suggests that during the next two decades global climate change impacts are likely to drive research more and more.

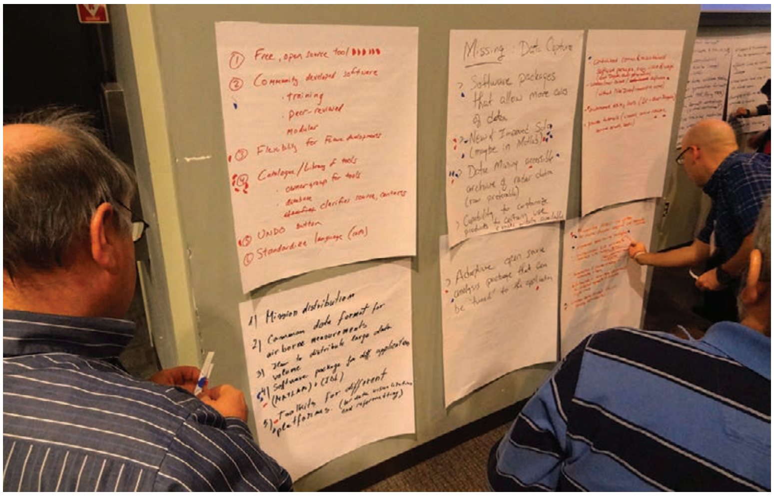


Fig. 2. Participants (Dave Jorgensen on the left; unidentified on the right) checking lists of priorities posted on the walls (gallery walk) during radar analysis and software session. (Courtesy of H. Bluestein.)

Integration of radar data with numerical models. This particularly applies to developing high-resolution regional and global models that make use of assimilated radar data.

To address these scientific problems, radars will be needed on diverse platforms including ships, aircraft, and stationary and mobile ground-based platforms. Some of the latter platforms may be quasi mobile: able to move the radar to a fixed location for an extended period. Other radars will be permanently installed at fixed locations and may be part of a network of either high-powered, widely spaced radars or low-powered, closely

Table 1. Ground-based mobile radars survey.

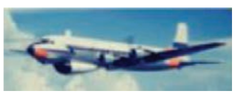
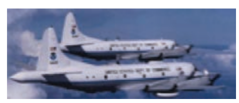
Name	Band	Beamwidth	Polarization	Scan rate	Owner
Shared Mobile Atmospheric Research and Teaching Radar (SMART-R)	C	1.5°	1 dual, 1 single	$33°\ s^{-1}$	University of Oklahoma (OU)/ Texas Tech
Seminole Hurricane Hunter	C	—	single	$10°\ s^{-1}$	Florida State University (FSU)
Doppler on Wheels (DOW)	X	0.9°	2 dual	$50°\ s^{-1}$	Center for Severe Weather Research (CSWR)
NOAA X-band, dual-Polarized radar (NOXP)	X	1°	dual	$30°\ s^{-1}$	NOAA
UMass dual-polarized X-band mobile Doppler radar (X-Pol)	X	1.25°	dual	$20°\ s^{-1}$	UMass
Mobile Alabama X-Band (MAX)	X	1°	dual	$18°\ s^{-1}$	University of Alabama in Huntsville (UAH)
Texas Tech Ka-band (TTUKa)	Ka	0.33°	2 single	$20°\ s^{-1}$	Texas Tech
UMass W-band	W	0.18°	dual	$5°\ s^{-1}$	UMass
Rapid DOW	X	1°	single	$50°\ s^{-1} \times 6$ beams	CSWR
Rapid-scanning, X-band, polarimetric mobile radar (RaXPol)	X	1°	dual	$180°\ s^{-1}$	OU
Mobile Weather Radar, 2005 X-band, Phased Array (MWR-05XP)	X	1.8° × 2°	single	$180°\ s^{-1}$ up to 55°	Naval Postgraduate School (NPS) Center for Interdisciplinary Remotely-Piloted Aircraft Studies (CIRPAS)
UMass X-band phase-tilt array	X	2° × 3.5°	dual	$90°\ s^{-1}$	UMass
AIR	X	1° × 25°	single	$40°\ s^{-1}$	OU
PX-1000	X	1.9°	dual	$50°\ s^{-1}$	OU

spaced radars. There will also be a diversity of scanning strategies, ranging from traditional scanning radars [for surveillance, range–height indicator (RHI), and sector scans] to rapid-scan radars and vertically pointing profilers, as well as airborne scan strategies and airborne profilers. There will also be a need for diversity of wavelengths and polarization configurations. Typical bands (wavelengths) used range over the S (~10 cm), C (~5 cm), X (~3 cm), K_a/K_u (~1 cm), and W (~3 mm) bands and will vary according to the platform used. Radars will usually constitute just one component of multisensor, multiplatform, and multimodel investigations of meteorological phenomena.

EMERGING TECHNOLOGIES. Emerging technologies in meteorological radar[4] include solid-state transmitters with pulse compression, polarimetric phased-array radar, imaging radar (or "ubiquitous radar"), and "adaptive collaborative" radar networks such as the Collaborative Adaptive Sensing of the Atmosphere (CASA; McLaughlin et al. 2009).

[4] Reviewed by R. Palmer at the workshop.

Table 2. Airborne radars survey.

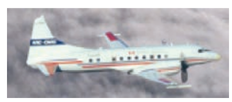
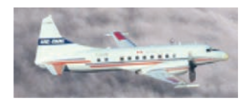
				
Radar name	**Hurricane surveillance**	**NOAA P-3**	**ELDORA**	**Wyoming Cloud Radar (WCR)**
Owner	NOAA [Environmental Science Services Administration (ESSA)]	NOAA	NSF/NCAR	University of Wyoming
Platform	DC-6	P-3 Orion 4-engine turboprop	Electra, NRL P-3	King-Air, C-130
Scanning	RHI scan tied to drift angle	RHI–fore–aft ±20° normal to heading	RHI–fore–aft ±20° normal to heading	Vertical or horizontal dual beam
Radar type	Noncoherent	Doppler	Doppler	Doppler, dual pol
Frequency	X band	X band	X band	W band
Years	~1964–75	1977–present	1992–2012	1995–present

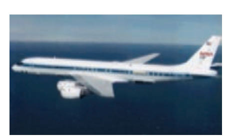
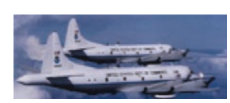
				
Radar name	**ER-2 Doppler Radar (EDOP)**	**Cloud Radar System (CRS)**	**High-Altitude Imaging Rain and Wind Profiler (HIWRAP)**	**ER-2 X-band Radar (EXRad)**
Owner	National Aeronautics and Space Administration (NASA)	NASA	NASA	NASA
Platform	ER-2	ER-2	WB-57, Global Hawk	ER-2
Scanning	Dual beam (fixed, nadir and +35°)	Nadir	Nadir conical, dual beam	Dual beam: conical or cross-track scan about nadir; fixed nadir
Radar type	Doppler, dual pol (LDR)	Doppler, dual pol (LDR)	Doppler	Doppler
Frequency (band)	X	W	K_u, K_a	X
Years	1993–present	2002–present	2010–present	2010–present

Future technologies include "digital at every element" phased-array radar, passive radar, multimission networks, ultra low-cost dense networks, and spectrum sharing.

Solid-state pulse-compression transmitters, which are commercially available, make use of gallium arsenic or gallium nitride technologies. They are low cost, low weight, and low power (so they need longer pulses to achieve high sensitivity) but enable active phased-array and ultra low-cost radars, such as those to be placed on airborne platforms or in large, densely spaced networks. Challenges to their full implementation include suppressing range sidelobe effects and correcting for blind range (Cheong et al. 2013). For conventional pulsed radars, the range resolution degrades as the pulse duration increases. However, using frequency modulated waveforms the range resolution is decoupled from pulse duration and instead is inversely proportional to bandwidth. Unfortunately, range sidelobe contamination and blind range challenges (at close range) are introduced; the nature of the nonlinear modulation must be optimized to reduce the former. Short-pulse blind range-filling techniques are available, but they create

Table 2. Continued.

				
Radar name	**Super Polarimetric Ice-crystal Detection and Explication Radar (SPIDER)**	**Environmental Canada Cloud Profiling Radar (EC CPR)**	**Radar System Airborne (RASTA)**	**National Research Council (NRC) Airborne W and X-band Polarimetric Doppler Radar (NAWX)**
Owner	Japan	Canada	France	Canada
Platform	Gulfstream-II	Convair-580	Falcon 20, ATR-42	Convair 580
Scanning	−40° to +95° scan across flight direction	Fixed zenith and nadir looking	3 down beams, 2 up beams; ±15° sector	Vertical and side looking
Radar type	Doppler, dual pol	Noncoherent	Doppler	Doppler, dual pol
Frequency (band)	W	K_a	W	X, W
Years	1998–present	1999–present	2000–present	2006–present

				
Radar name	**G-IV Tail Doppler Radar**	**High-Performance Instrumented Airborne Platform for Environmental Research (HIAPER) Cloud Radar (HCR)**	**Airborne Cloud Radar (ACR)**	**Imaging Wind and Rain Profiler (IWRAP)**
Owner	NOAA	NSF NCAR	NASA	UMass
Platform	NOAA G-IV	NSF G-V	NASA P-3, DC-8	NOAA P-3
Scanning	RHI-Fore-Aft ±20° normal to heading	RHI	Nadir	Conical scan about nadir, quad beam (30°, 35°, 40°, and 50°)
Radar type	Doppler	Doppler, dual pol	Doppler dual pol	Doppler dual pol
Frequency (band)	X	W	W	C, K_u
Years	2010	2013–present	1995–present	2002–present

an abrupt change in sensitivity at the transition from short to long pulse. Aside from the commercially available pulse compression systems, others are mobile systems at K_a and X bands (Table 2).

The main challenges to including dual-polarimetric capabilities on phased-array antennas are that horizontal–vertical orthogonality is not preserved as the phased-array antenna is steered off the principal planes and that the antenna gain and beamwidth change for off-broadside pointing directions. Engineering development efforts are ongoing at several places, including Massachusetts Institute of Technology Lincoln Laboratories (MIT-LL) for an S-band overlapped subarray, BCI/Lockheed Martin for an S-band 12 × 12 element prototype, and the National Center for Atmospheric Research (NCAR) for a C-band airborne system. Meanwhile, actual weather measurements have been made successfully with an X-band phase tilt antenna from collaboration between the University of Massachusetts (UMass) and Raytheon ("phase-tilt radar"; Orzel et al. 2011) and are planned at the University of Oklahoma (OU) for an S-band cylindrical antenna [Cylindrical Polarimetric Phased Array Radar (CPPAR); Zhang et al. 2011] for the National Severe Storms Laboratory (NSSL) Multi-Function Phased Array Radar (MPAR) program (Zrnić et al. 2007; Weber et al. 2007). The solution to the polarization orthogonality problem for both of these designs is to stay on the principal planes while scanning. The former operates at X band, steers electronically in azimuth and mechanically in elevation, has a 2.5°–3.5° half-power beamwidth, is low powered, and makes use of nonlinear frequency modulated pulse compression; the latter operates at S band, is fully electronically steered using commutating beams around the cylinder (but is frequency steered in elevation for cost reduction), is high powered, and has 4.5° half-power beamwidth.

An alternative to (analog) phased-array technology for rapid scanning is the imaging-radar technique, in which a relatively broad region is illuminated by the transmitted beam. Digital beamforming (by which the phase and amplitude of the signal received at each antenna element are altered digitally at each separate receiver for each antenna element, rather than through separate phase delays for each element, but with just one receiver for all antenna elements) allows for simultaneous measurements with an infinite number (not all independent) of receiving beams each of a given half-power beamwidth: for example, of 1°. The first radar to make use of this technique is the Atmospheric Imaging Radar (AIR) at OU (Isom et al. 2013), in which an elliptical transmitted beam, narrow in azimuth but wide in elevation, illuminates the volume. This radar operates at X band and produces instantaneous RHIs but is scanned mechanically in azimuth. In the future, it will be possible to scan both in elevation and in azimuth through the imaging-radar technique using digital beamforming in two dimensions, not just one. A major advantage is that ground clutter is rejected via adaptive array processing (e.g., spatial filtering). This type of clutter filtering can also reject moving targets, such as aircraft and wind turbines. To date, data from the AIR have been processed by the Fourier method and the robust Capon method, each of which has strengths and weaknesses. So far the AIR has been used to probe tornadoes.

The Toshiba Corporation has designed an X-band phased-array radar system that makes use of both an active phased-array antenna and digital beamforming. The 1° half-power beamwidth antenna

Table 3. Deployable-radars survey.

Large systems	Medium sized	Small	Zenith pointing
NCAR S-Pol	ARM X/Ka	University of Iowa X-Pol	ARM Ka-band zenith radar (KaZR) [Millimeter Wave Cloud Radar (MMCR)]
CSU–CHILL	ARM Ka/W	OU PX-1000	W-band ARM Cloud Radar (WACR)
NASA N-Pol	NASA D3R (Ku/Ka)	CASA Integrated Project 1 (IP-1)	Earth System Research Laboratory (ESRL) W band
	UMass Advanced Multi-Frequency Radar (AMFR) (Ku/Ka/W)		ESRL S band
	ARM C band		
	MIT-LL C band		
Long range: precipitation, clear air	Short–long range: clouds, precipitation	Short range: precipitation, networks	Profiling: clouds, precipitation, microphysics

scans mechanically in azimuth and electronically in elevation. Low powered and making use of pulse compression, it is installed at Osaka University in Japan.

While CASA is a concept in a networked radar system that has been tested in the United States (McLaughlin et al. 2009), in Japan there is another closely spaced network of X-band, solid-state, low-powered, lightweight radars called WITH, built by Weathernews, Inc. These are retrofitted radars having a half-power beamwidth of 6° and are highly mobile (can be easily towed by a car, put on top of buildings, etc.).

In the future, digital-at-every-element phased-array antennas will become available. The real-time computational load will be tremendous, but the degrees of freedom for adaptive beamforming, etc., will be huge. An additional major challenge with such radars will be calibration.

Also in the future, it may be possible for passive radar networks to be set up using "transmitters of opportunity" such as those from television stations, FM radio stations, and cellular phone networks. Examples of such networks include Bistatic Network (BiNet) (Wurman et al. 1993; Friedrich and Hagen 2004), using Weather Surveillance Radar-1988 Doppler (WSR-88D) radars, and the U.S. Department of Defense Integrated Sensor Is the Structure (ISIS), using FM radio transmitters.

Multimission radar networks that can be used for aircraft surveillance, weather observations, and communications may be built with the aim of savings resulting from decreasing the overall number of radars used. Ultra low-cost dense networks making use of solid-state transmitters with pulse compression may be implemented. However, the weather-radar community will face competition from the wireless communication industry, which wants to use some of the weather-radar frequency bands. Some cooperation and coordination of functions will be required. Possible solutions include passive radar networks, adaptive phased-array radar systems (which have tremendous advantages for beam agility and coordination, and interference suppression), and other forms of multimission networks.

RECOMMENDATIONS. To address high-priority research topics, specific radars on specific platforms will be required. We summarize the community's opinion (as it emerged from workshop discussions) of both the specific types of radars and the platforms needed and also the opportunities for radar support of high-priority research. The following findings and recommendations are not ordered according to priority.

Polarimetric radars are needed to study precipitation processes, including those associated with flooding in general and flash flooding specifically; to study cloud processes, especially those associated with mixed-phase clouds; and to study insect and bird behavior and migration. Measurements are especially needed to characterize ice microphysics better, perhaps also using polarization modes other than orthogonal linear. Errors related to dual-polarization technology need to be quantified better, particularly in the simultaneous transmit/receive mode. There should be movement toward quantifying microphysical processes and hydrometeor distributions in four dimensions. Hydrometeor classification could be taken to a new level with new instrumentation such as the A-10 aircraft (www.cirpas.org/a10spa.html) and techniques such as dual-polarization and multifrequency radar techniques, which are currently underutilized. Polarimetric radar observations could also be used for electrification research. Researchers need to be made aware of the different uses of WSR-88D data and, in particular, for the study of ice microphysics, despite the difficulties in using data when both the horizontal and vertical beams are transmitted simultaneously. Real verification of dual-polarization measurements on large scales is needed.

S-band, Bragg scattering radars are needed to study chemical transport and also to study features in clear air, such as upper-level fronts and jets, low-level jets, and surface boundaries along which convective initiation may occur. Currently CASA radars (and in general low-cost radar networks) lack clear-air data collection capabilities, since monostatic X-band radars cannot detect Bragg scattering in clear air. Operational refractivity measurements from the WSR-88D radars need to be developed and exploited so that mesoscale detail in the temperature and moisture fields can be better resolved. The community would like to have access to mobile, S-band radar systems with a 1° half-power beamwidth or less. Soon a transportable (trailer towed) radar will become available from the Naval Postgraduate School (NPS) Center for Interdisciplinary Remotely-Piloted Aircraft Studies (CIRPAS), but with lower spatial resolution.

Airborne Electra Doppler Radar (ELDORA)-like radars are needed to study convection and tropical cyclogenesis over the ocean and convection over land, especially in mountainous or remote areas where ground-based radars cannot be easily deployed (Hildebrand et al. 1994). The existing ELDORA has not been requested much lately because it is difficult to process its data and Naval Research Laboratory

(NRL) support is also needed to fly the P-3. It was suggested that perhaps NSF-sponsored users could piggyback on National Oceanic and Atmospheric Administration (NOAA) experiments. As alternatives to ELDORA, however, the NOAA P-3 radars are difficult to use and expensive and involve a complicated process to obtain; use of them needs to be coordinated with other NOAA experiments. Operations of a NOAA P-3 and ELDORA would be less expensive if they could be deployed for short periods of time (e.g., just a few days) rather than for long field campaigns with long waiting periods. NSF needs to establish a mechanism to funnel funds through NOAA so the cost of using a NOAA P-3 falls. There was brief discussion on how to speed up the replacement of ELDORA, since the NOAA P-3 is not available for 6 months out of the year and is very expensive. There is also a need for replacing ELDORA with multiple-wavelength, dual-polarization capability. W.-C. Lee noted that EOL at NCAR has been evaluating whether the Airborne Phased-Array Radar (APAR) development (replacement for ELDORA) time can be accelerated with more funding by making it possible to perform some tasks simultaneously rather than sequentially.

There should be support for a diversity of radar platforms at several wavelengths. Estimates of snow, ice, and cloud properties and the retrieval of cloud water and water vapor fields will make use of more multiple-wavelength radars, benefiting a wide range of atmospheric studies. It is difficult to study cloud and precipitation processes owing to their high spatial and temporal variability, so improved resolution is required. The range resolution might be sufficient, but angular resolution depends on the antenna size and the range from the radar; shorter-wavelength radars might yield useful cross-range resolution while maintaining antenna dish size. The use of multiple-wavelength radars might solve help mitigate attenuation problems at short wavelengths.

There already is a good mix of truck-mounted mobile radars (including rapid-scan radars) at various wavelengths (C, X, K_a/K_u, and W bands), which need to be maintained. Multiple radars mounted on the same platform are needed to study the microphysics and dynamics of precipitation systems and convective storms. Improvements are needed in instrument integration, so that combined measurements of kinematics, thermodynamics, and microphysics at fine spatial and temporal resolution can be made. Multiple-wavelength airborne radars are also needed.

A very high-frequency (VHF) profiling system with Bragg scattering capabilities for boundary layer applications might be developed and included in the deployment pool for making temperature and moisture observations; this capability could include three dimensions if a network is developed. Since moving many profilers is very expensive, perhaps a network of deployable profilers could be developed. Wind and thermodynamic observations above the planetary boundary layer are also needed; such profilers should be developed. Thermodynamic profiling radars are required also for studying mesoscale features in phenomena such as winter storms and for studying convective initiation. Cloud (high frequency) radars are needed to study cloud and precipitation microphysics associated with convective storms, tropical convection, winter storms, and orographic precipitation.

There is a need to have the capability to make radar observations in data-sparse regions, such as near the poles, over the oceans, and in mountainous areas; to do so, we need, in addition to airborne radars such as ELDORA, ship-based radars and perhaps buoy-borne radars as well. Such radar observations are important for climate research related to tropical convection and polar clouds (e.g., for ice microphysics studies). The concepts of how to move facilities to remote areas should be improved. We need to consider if existing radars can operate in the harsh conditions of remote regions. If not, we need to upgrade the technology. These radars should be inexpensive and be capable of operating unattended for long periods of time and of calibrating themselves. Standards for calibration and providing information on the calibration process for each radar platform will be needed.

Some deployable networks of radars and other instruments are needed for rapid-deployment situations. Such mobile networks of radars are valuable facilities that need to be maintained rather than developed. We need gap-filling radars with easier deployment capabilities to complement larger radar systems in, for example, mountainous regions. Networks in urban areas are also needed to study and monitor air pollution processes, particularly, as noted earlier, in clear air. These networks need improvements in their adaptive scanning strategies to improve trade-offs between operational surveillance and scientific-research functions.

Emerging phased-array technology, which can improve temporal resolution without reducing data quality, would help answer the key scientific questions related to cumulus convection, convective storms, and boundary layer processes. CASA-type radar networks should be upgraded to make use of phased-array technology.

We need better software tools for radar display and analysis. In particular there should be unified radar data archiving (which already exists for large field experiments), open-access data, better coordination of radar data from the various platforms, and improvements in radar data formats, software, and analysis tools (Table 4). We also need the standardization of software packages and toolkits (e.g., open-source algorithms were recommended so that results can be reproduced by other groups), unification of data sharing policies with good documentation, the ability to retrieve information quickly and easily and accessible to everyone, and the integration of diverse datasets. More observational datasets are necessary to verify algorithms and techniques. The Atmospheric Radiation Measurement Program (ARM) and NCAR currently are collaborating to improve radar software capabilities and "CfRadial" will soon replace the Doppler Radar Data Exchange (DORADE) and Universal Formats. The community strongly supports the NCAR-led software development efforts. We also need to provide better products (e.g., precipitation and cloud characteristics) for the modeling community. It was recommended that we need verification of research radar data from WSR-88D radars.

There are a number of ways to enhance availability of radar instrumentation for the community. We need the capability for fast-response, multiagency, multiplatform experiments. In particular, we need the ability to mobilize ground-based and airborne radars (and other instruments) for potentially historic targets of opportunity. It should be easier to access nondeployment pool instruments and coordinate multi-institutional access to facilities. There is a website (http://faesr.ucar.edu) to help investigators locate radar instruments that are not necessarily part of the deployment pool. It is up to the community to keep this online resource updated with new instrumentation and facilities. We need easier and faster facility access for proof-of-concept experiments, including opportunities for more 20-h-type projects [e.g., those available through Colorado State University–University of Chicago–Illinois State Water Survey (CSU–CHILL)] requesting NSF radar facilities. Some feel there is insufficient understanding of different frequency capabilities (e.g., S band versus other bands: e.g., W band, X band, etc.) versus mobile (primarily X- and C-band radars) and deployable (i.e., movable radars primarily operate at S band) systems. Also, there

Table 4. Radar software needs based on combined responses from workshop participants and an online survey of members of the radar community who were unable to attend the workshop. Similar topics among workshop group responses were consolidated. Scores are the number of votes for each topic.

Topic	Personal research needs	Community needs	Total score
NCAR maintained centralized repository for radar software (esp. including wind synthesis) with datasets for sw testing	55	41	96
Standardized software packages and toolkits (multiplatform, modular, menu driven, easy for community to add to, ease of conversion among new and old radar data formats)	30	53	83
Training (workshops/online tutorials)	48	15	63
Ability to integrate radar and nonradar datasets	25	32	57
Open-source tools and software	30	16	46
3D/4D visualization software (with publication quality output)	24	21	45
Next generation wind synthesis software (REORDER/CEDRIC) maintaining current functionality and including new techniques	15	27	42
Common radar data format standard and a common metadata standard	19	15	34
64-bit compatible real-time display software tool	19	11	30
Improved radar data editing (Solo) and documentation	12	20	32
Automated quality control software	14	13	27
Detailed documentation for data products, tools, and code	18	7	25
Improved dual-polarization processing	10	12	22
Accessible variational Doppler radar assimilation and thermodynamic retrieval	7	4	11
	326	287	613

should be more opportunities for access of phased-array radars for the NSF community.

Educational support for larger communities such as undergraduate students could be improved, with more educational outreach and student participation in field campaigns and the inclusion of students in the data analysis process. Complicated microphysical concepts should be taught using NSF radar facilities.

There are several other issues concerning future radar development. Things that we cannot do now but will be able to do with a projected increase in the availability of computer resources include the following: adaptive signal processing and beam forming algorithms, which will improve angular resolution and data quality; integrating data from all radars into a network; recording the full Doppler spectrum routinely for all radars and reducing the cost for archiving data; allowing for full data streaming in real time and improvements in data visualization; and real-time data processing including quality control, vector analysis, merging of datasets, and communicating large amounts of data.

Both universities and NCAR should develop instrumentation, perhaps with universities educating students on instrument development while NCAR develops instruments that can be used directly more quickly; in addition, universities should focus more on unique or more novel instruments. The process of instrument development should be collaborative. NCAR already has visiting programs for undergraduate engineering students [Summer Undergraduate Program for Engineering Research (SUPER) and Technical Internship Program (TIP)], and they should be utilized more. The public could get more involved in some of our activities and more students could be involved by making data and research products available to a larger community, as is done now, for example, with the CHILL radar.

The radar community is relatively small and the number of users of radars needs to grow by including people from other disciplines such as chemistry, modeling, and biology and by advocating cross-cutting research projects to a larger community (e.g., hydrology, climate studies, and engineering). There should be a focus of broad instrument applications,

NOTES ON TERMINOLOGY: SOME SPECIALIZED TERMS USED IN THIS ESSAY.

Pulse compression: The use of special forms of pulse modulation (amplitude or frequency or phase) to permit a radar system to achieve higher range resolution than normally permitted by a given pulse duration. The advantage of pulse compression over simply transmitting shorter pulses is that high range resolution is achieved while maintaining the benefits of high average power. (This is a shortened and slightly edited version of the entry in the AMS *Glossary of Meteorology,* available online at http://glossary.ametsoc.org/wiki/Main_Page.)

Imaging radar: A radar that uses a relatively wide-beamwidth antenna for transmitting and numerous independent antennas for receiving. The signals from the antennas for receiving are used together to implement digital beamforming to achieve narrow beams in selected directions, which provide simultaneous angular sampling within the volume of the transmitted beam. The imaging radar therefore essentially takes an instantaneous snapshot of the atmosphere within the transmitted beam, thereby providing excellent temporal resolution.

Range sidelobe compression: Pulse compression receivers employ a correlation operation on the transmitted waveform. All practical waveforms have correlation functions that spread some energy away from the desired range into "range sidelobes." In many respects, range sidelobes can be thought of as antenna sidelobes but for the range direction rather than the azimuthal or elevation angle directions.

Nonlinear modulation: Conventional pulse compression waveforms use a linear change in frequency with time over the duration of the pulse, which is called linear frequency modulation. Nonlinear frequency modulation uses a nonlinear variation in frequency over the pulse duration. If designed properly, nonlinear frequency modulation can have several advantages, such as a significant reduction in range sidelobes.

Blind range: Pulse compression makes use of a longer pulse in order to increase the sensitivity of the radar. The radar, however, cannot receive signals while this long pulse is being transmitted. The range corresponding to the length of the long pulse and shorter ranges are therefore not observed and called the blind range. This blind range is mitigated by transmitting a short "fill pulse" along with the long pulse.

Frequency steering: By changing the frequency of the transmitted signal, the wavelength is changed. For fixed element spacing, a change in wavelength corresponds to a change in phase, which is how beam steering can be accomplished. Frequency steering is a simple way of steering electronically, but it requires more bandwidth and is therefore not a viable operational solution.

such as for forecasting, climate modeling, and climate studies.

Finally, radar developers need to have the vision to think far ahead (~50 years). What might be useful now might quickly become old technology.

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