Virtual Workshop on Atmospheric Science Applications of Ground Based Phased Array Radars

25 May 2021

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1. Introduction

Ground-based phased array radars (PARs) have become increasingly utilized for research within the atmospheric sciences over the past 20 years. The first PARs developed or adapted for the atmospheric scientific community provided important insight into their potential for science research (primarily focused on severe weather). However, these prototype PARs lacked polarimetric capability and possessed other limitations (e.g., coarse spatial resolution, limited scanning flexibility). Recently, PAR technology innovations introduce new capabilities for science research that address many of these limitations, including dual-polarization capabilities and greater maturity of electronic scanning options. As a result, these new PAR systems create a fertile ground for transformative research in many subdisciplines of atmospheric science over the next few decades.

The need for PAR technology is well-documented in past National Research Council reports (e.g., Beyond NEXRAD), the AMS Radar Workshop in 2012, and the In Situ and Remote Sensing Capabilities in Convective and Turbulent Environments (C-RITE) Community Workshop in 2017. At a broad level, these workshops and reports identified that higher temporal resolution observations can benefit studies of convective processes and severe hazards as well as capturing the 4D depiction of microphysical and dynamic processes. Moreover, they emphasize a need for a community-accessible phased array radar for research and education.

While these past reports and workshops identify that PAR technology is important to the atmospheric science community, the broad nature of these reports and workshops provided limited discussions on specific science topics and new technologies specific to different types of phased array radars. The AMS Radar Workshop in 2012, in particular, is the most relevant to this workshop and occurred almost a decade ago. Since then, PAR technology has rapidly evolved and considerable experience has been gained by the community with first-generation PAR prototypes for science research. Thus, a focused community discussion is critically needed to explore how emerging PAR technology (e.g., with dual-polarization capability) can advance an array of different atmospheric science research areas.

The goal of this virtual workshop is to engage an interdisciplinary group of atmospheric scientists, engineers, and students to:

1) Identify the primary drivers of atmospheric science research that benefit from PAR technology
2) Discuss novel uses for PAR technology that leverage its capabilities beyond just rapid-scan observations
3) Explore what capabilities existing PAR technology offers to address science frontiers and identify what new technology is needed to enable new discoveries

In the interest of time, the half-day workshop's scope was necessarily limited. The workshop focused on basic science research applications of phased array radars rather than operational applications. For example, discussions centered on how PARs can enable new research about microphysical and dynamics processes related to microbursts rather than how a future operational PAR can improve microburst detection. In addition, technology discussions centered on future PAR technology for research applications rather than the design of a replacement network for the NEXRAD network. Science and technology discussions were also limited to ground-based PAR systems to further focus discussions. Future, in-person workshops would be better positioned to more broadly discuss different types of PAR technology (e.g., airborne, spaceborne), operational applications of PARs, and the design of the future operational radar network.

2. Workshop Structure and Participation

The workshop was held virtually using the Zoom teleconferencing platform since COVID-19 prevented an in-person workshop. A 4.5-hour agenda was created for the workshop, combining 10-min lightning round talks, two breakout sessions, and full group discussions (the full agenda is provided in Appendix A).

The workshop commenced with a keynote talk by Robert Palmer on the evolution of ground-based PAR technology. Then, seven lightning round talks were presented on different PAR science topics to stimulate discussions. The lightning round talks were followed by the first set of breakout sessions on specific PAR science applications. Topics included: severe storms (tornadoes, severe winds, hail, lightning), physical and dynamic meteorology (deep convective processes, boundary layer, precipitation processes), and numerical weather prediction. In addition, a student-and-postdoc-only breakout session was held to gather input on how PAR technology can impact their careers and what they envision as the most impactful science topics. The second set of breakout sessions focused on technology needs for ground-based PARs, motivated by previous science application discussions. Following each breakout session, a group discussion and report out was conducted where breakout session leaders reported the main points discussed in the workshop and full group discussions ensued.

Aside from safety during the pandemic, the primary benefit of the virtual workshop is the removal of any significant barriers to attending (e.g., travel costs and extended time commitments). While we focused on recruiting researchers, students, and other meteorology professionals interested in PARs, the workshop was fully open to anyone interested and advertised via social media. **A total of 166 people participated in the workshop from 30 different universities and eight different countries (26 international participants).** Participants included 49 students and postdoctoral fellows. A full list of participants can be found in Appendix B.

3. Summary of Large Group Discussions

a. Science Large Group Discussion and Report Out

After the report outs, the ensuing discussion focused largely on broadening access to PAR systems, PAR data, and expanding the breadth of PAR science cases available. Most institutions do not yet have access to PAR systems (and many do not have access to parabolic reflector systems either). As a community, we need to make sure education is as equitable as possible and that these resources can be provided broadly to educational institutions in the atmospheric sciences to maintain our nation's edge in research capabilities. In addition, equitable access is also critical for ensuring that underrepresented groups obtain hands-on experience with PAR technology and data. Short experiences with research-grade instrumentation and field work can provide important benefits to students' careers. PAR technology demonstrations with K-12 schools can also help inspire students to see new career paths with emerging technology.

Openly available PAR data sets are presently limited in number and diversity of cases available. Expanding the number and type of PAR data sets available to the scientific community can more rapidly impact education than bringing PAR systems to every institution (may take time to reach all institutions). To facilitate this, there needs to be software and tutorials to help students at all levels, including those with potentially limited access to resources, plot and analyze PAR data. Emphasizing the benefits of PAR beyond severe weather and collecting data sets in different regions can also stimulate more interest from students.

b. Technology Large Group Discussion and Report Out

The technology breakout sessions noted areas where new PAR technology could be developed to address outstanding science questions. Presently, PAR technology in the atmospheric sciences is limited to S to X bands. Higher frequencies offer intriguing potential for cloud research where rapidly evolving 3D structures cannot be captured by existing mm-wavelength radar technology. In addition, the narrow beamwidths of such systems provide much better spatial resolution than lower frequency systems, which could aid in better resolving fine-scale characteristics of winds in clouds and tornadoes. Participants also discussed what temporal resolution is needed and noted that we don't truly know how quickly we need to scan different phenomena without having collected the data (e.g., can speculate based on models). Faster scans often come with a data quality tradeoff, and thus understanding the temporal resolution requirements is important.

The agility of the scanning capabilities of a phased array radar boast significant promise, but the effort to take advantage of these capabilities for science research is significant. A key open question is how to adapt scanning strategies to different meteorological scenarios and for different goals. For example, adaptive scanning strategies and associated data quality requirements for quantitative precipitation estimation (QPE) are different from more qualitative data uses (e.g., trends in ZDR columns). Given the complexity of data quality from different scanning strategies, data quality metrics need to become standard in data formats. Finally, Artificial Intelligence (AI) applications of PARs will require large benchmark datasets and accessible formats to facilitate this research.

Open access to data, software, and PAR systems reemerged in the group discussions. Open-source software will need to evolve with PAR systems and their data. Dated software (e.g., SOLO) may not be able to handle large volumes of data and have a large IT barrier to use. Since not all universities have the same IT resources, software for analysis and visualization must be easy to install and use. Significant progress in developing PAR capabilities could result from developing open-source APIs for radar control, around which different scanning patterns can be built. There is a desire for additional funding support for curating data sets and developing software to support PAR research.

4. Detailed Summary of Science Breakout Sessions

a) BOS #1: Big Picture of PAR Science (Breakout Session Moderators: Robin Tanamachi and Pavlos Kollias; Rapporteur: Charles Kuster)

While the other breakout sessions focused on specific science research areas for phased array radars, this breakout session explored the opportunities for phased array radar science at a broad level. Specific questions included:

1) Q1: What are the key areas where PARs can contribute to atmospheric science research and what areas are underexplored?

2) Q2: How can PAR technology enhance future field experiments working synergistically with other instrumentation (e.g., aircraft/UAS, satellite, profiling systems)?

Key research areas and underexplored topics

Participants identified a wide range of potential research areas for phased array radars and noted a need to diversify the meteorological data sets collected with phased array radars. While rapidly evolving phenomena are commonly associated with tornadoes and other severe hazards, science research with PARs can benefit studies of the dynamics and microphysics of deep convection, boundary layer processes, and precipitation processes in ice clouds and over complex terrain.

Capturing dynamic and microphysical processes of deep convection across the lifecycle and spectrum of convective modes emerged as a common theme for underexplored research. With polarimetric PARs and different techniques to retrieve 3D winds (e.g., multi-Doppler or bistatic approaches), coupled studies of updraft/downdraft characteristics and microphysical processes are important to understanding the convective lifecycle (e.g., cold pool development, upscale growth). Such studies need to include the upper-levels of deep convection often neglected in radar scanning patterns to improve knowledge about upper-level updraft properties. Details of the structural evolution of updrafts (e.g., embedded thermal plumes) are poorly captured by existing radar technology, and PAR technology would provide the volumetric update rate needed to capture changes in updraft characteristics (e.g., widths, intensities) and convective processes impacting updrafts (e.g., entrainment).

Microphysical processes and studies of shallow convection could benefit from multiple frequency PAR observations and the development of millimeter-wavelength PAR technologies. Millimeter-wavelength observations would help identify relevant microphysical processes and verify microphysical parameterizations. Dual-wavelength PAR studies (particularly including Ka band) would be transformative for winter storm research, particularly when leveraging polarimetric and spectral capabilities. Processes related to shallow cumulus are poorly observed by existing scanning radars and require rapid-scan, mm-wavelength observations to capture their 3D structure and evolution.

While tornadoes have been studied most extensively using phased array radars, other severe weather hazards have not been deeply explored such as hail and downbursts. The group suggested that using PARs to obtain deeper volume scans and polarimetric capabilities can benefit research on hail and downbursts (given the important role of microphysical processes and vertical motions). To achieve such scans, PARs must provide custom scanning capabilities and offer flexibility to cover deep volumes. Wake lows and heat bursts may also benefit from PAR observations, including clear-air scanning capabilities. For tornado research, tornadoes produced by quasi-linear convective systems form rapidly and without few precursor signatures, and thus rapid-scan, polarimetric observations are needed to understand tornadogenesis in this convective mode and identify what (if any) precursor signatures exist. Through improved scientific understanding of these severe weather hazards and identification of new signatures, phased array radar observations can help update forecaster conceptual models.

With existing and new PAR technology, the existing paradigms of scanning should be evaluated to take advantage of scanning agility. PARs offer unique flexibility to tailor observations in time and space to the users' needs for the particular phenomena observed. In addition, participants questioned whether or not PPI and RHI scans are the optimal approach or scanning modes should be re-envisioned to more optimally track rapidly evolving features in time. In addition, the aperture can also be split to scan different targets or retrieve cross-beam winds.

Analysis techniques and modeling applications of PARs are currently underexplored. Machine learning and artificial intelligence techniques offer promising potential for PAR research and are currently underutilized. Data assimilation of PAR observations is also noted as an underexplored area of research. This includes assimilation into large-eddy simulation models to improve the model's dynamical prediction of key features in convection.

Using PAR technology synergistically in future field experiments

A notable advantage of a PAR is that scanning flexibility and faster volume scans create less competition among different field campaign objectives while guiding field experiment activities. Coordination of multiple PARs for multi-Doppler wind retrieval would alleviate most uncertainty about asynchronous scans and evolution during long volume times. Adaptive PAR scanning with beam positions following UAS or aircraft can provide valuable context for interpreting in-situ measurements. These observations would also help improve microphysical, dynamic, and thermodynamic retrievals from in-situ sensors. The ability to optimize scanning strategies for clear-air observations might increase potential for boundary layer studies, such as Bragg scatter detection at longer wavelengths (C, S bands).

With the new GOES series, geostationary satellite observations are available at much higher temporal resolution. In mesoscale sectors, satellite data are available as quickly as every 30 s. Combining rapid-scan radar observations with satellite observations of cloud-top processes (e.g., overshooting tops) and lightning can enable new understanding and improved severe weather hazard detection. In addition, combining PAR data with low-earth orbiting satellites and observations from radiometers and spaceborne radars could be impactful.

An important point raised is that taking advantage of all of these PAR adaptive scanning techniques will require significant software development and testing of new algorithms to guide scanning decisions. PAR scans could be optimized by ranking science questions for target phenomena and applying cost functions. Robust automatic feature tracking is an important input into the radar control system necessary to leverage these adaptive scanning techniques.

b) BOS #2: Building the Atmospheric Column of Coupled Microphysics and Dynamics (Moderator: Pierre Kirstetter; Rapporteur: Yagmur Derin)

Understanding coupling between microphysical and dynamic processes is critical to advancing scientific understanding of shallow and deep convection and precipitation processes worldwide. The key questions for this breakout session include:

1. How can PAR observations with polarimetric and 3D wind observations (e.g., from multi-Doppler retrievals, possibly passive radar) further our understanding of coupled microphysical and dynamic processes?
2. What knowledge gaps can be addressed with PARs providing continuous vertical coverage from top to bottom in deep convection?

Participants noted that processes in convective clouds and precipitation are poorly captured by existing radars because microphysical and dynamic processes occur on faster time scales. In addition, vertical sampling of microphysical processes by radars is insufficient. PARs can address both the temporal resolution issue and provide finer vertical resolution. The specific use cases noted by participants include:

- Documenting the evolution of individual thermals and the evolution of microphysical and dynamic processes. Presently, no observational method captures the evolution of microphysical processes in thermals and such data would be invaluable to evaluate how models handle these processes.
- Understanding of warm rain formation using rapid-scan, dual-polarization PAR data
- Simultaneously capturing rapidly evolving warm and cold cloud processes with optimized adaptive scanning parameters (e.g., collision/coalescence and ice multiplication)
- Focusing on vertical scanning and RHIs to better capture microphysical processes to capture fluxes through the melting layer
- Vertical scanning and RHIs to capture the evolution of polarimetric signatures associated with microbursts
- Reducing uncertainties in understanding of the coupling of microphysical and dynamic processes through collocated high-temporal resolution polarimetric and 3D wind observations
- Understanding the coupling of convective updrafts and microphysical processes, and their relationship to fluxes in convective anvils.

To make significant scientific advancements, participants noted that the synergy of PARs with other field campaign instruments is critical as well as accessibility of PAR systems and data to all users. In particular, they noted that:

- Advancing understanding of the convective lifecycle in different environments is critical. Thus, PAR observations must be collected concurrently with other instrumentation providing environmental data (e.g., soundings, UAS)
- PAR observations can provide much needed spatial and temporal information about microphysical and dynamic processes needed to contextualize in-situ aircraft or UAS measurements.

c) BOS #3: Storm Electrification and Hail (Moderators: Matthew Kumjian and Larry Carey; Rapporteur: Laura Shedd)

The hail and storm electrification breakout session focused on two key questions:

1) What new hail and storm electrification research is enabled by deep, vertically continuous scans possible with polarimetric PARs?
2) How can flexible polarimetric or frequency-agile capabilities (e.g., dwell-to-dwell polarization changes or multi-frequency measurements) be used to capture more information?

Participants noted that current understanding of physical and dynamic processes in both hailstorms is limited by inadequate temporal resolution and poor coverage of mixed-phase regions of deep convection. In addition, fully controllable PARs with adaptive scanning and highly flexible polarimetric capabilities can instigate new scientific understanding. Specific examples of PAR use cases for hail and lightning include:

- Capturing the spatiotemporal variability of hail fall using RHIs and rapid updates
- Examining kinematics associated with eddy-scale processes in updrafts and their role in charging
- Obtaining detailed observations of mixed phase regions (0 to -40ºC) while still capturing the rest of convective storms would be valuable for hail and lightning research
- Exploring the change in polarimetric variables in melting hail by tracking its evolution vertically
- Cleverly designing PAR scans with different polarization (and spectra) and frequency could provide more information about hail orientation and shape (could scan one area slowly or stare while still scanning elsewhere)
- Improving hail trajectory studies with rapid-scan, multi-Doppler observations (e.g., residence time in updrafts) in different environments to help explain differences in resultant hail size
- Using closely-spaced frequencies (in-band) and leveraging PAR's flexibility to quantify the size of hail
- Using high-temporal resolution data to improve understanding of how different ice hydrometeors contributes to charging (e.g., LMA and polarimetric data overlays)
- Exploring transitions between charge structures that occur on time scales of tens of seconds. Sub-minute sampling is critical to understanding these changes in charge structure
- Documenting the 3D structure of hydrometeors, kinematic structure, and lightning in supercells. PAR data can match LMA temporal resolution and 3D observations to help clarify the role of microphysics and dynamical processes in charging and producing lightning holes.
- Examining depolarization streaks in a 3D sense for the first time to explore the spatial variations in vertical charge structure. Switching polarizations would also be highly beneficial (e.g., circular vs. slant-45).

- Capturing scattering from plasma with very high temporal resolution scans. It may be possible to determine the plasma temperature and understand how charge is transported (light vs. RF emissions).

Specific scanning strategy considerations:

- High data quality combined with rapid-scan data would be important for exploring microphysical and dynamic processes important to hail and lightning
- Consider changing the beam structure to adaptively scan to provide optimal vertical coverage (fewer elevations needed at long range)
- Determining the best place to perform an RHI scan in real-time is difficult, so collecting vertically continuous data through storms with a PAR obviates this limitation
- LMA or GLM data are essential for context for lightning research, so PAR data must be collected with these instruments for significant progress

d) BOS #4: Tornadoes and Severe Winds (Moderators: Michael French and Jana Houser; Rapporteur: Casey Griffin)

The key questions for the breakout session on tornadoes and severe winds include:

1) With rapidly collected polarimetric and single-/dual-Doppler wind measurements, how can phased array radars advance our understanding of physical processes leading to tornadogenesis/failure and a wide spectrum of ensuing tornado behavior (e.g., intensities, durations)?
2) How can rapid-scan polarimetric and 3D wind observations close gaps in understanding the formation of severe winds (MCSs, microbursts)?

Participants first discussed several needs to improve understanding of processes related to tornado formation and ensuing tornado behavior. Specifically, they noted that PARs could:

- Help capture tornadogenesis precursor polarimetric signatures in different convective modes, such as supercells and quasi-linear convective systems
- Conduct rapid-scan, dual-Doppler experiments to retrieve 3D winds and obtain both microphysical and dynamical processes during all tornado lifecycle stages
- Use rapid-scan, dual-Doppler to attempt thermodynamic retrievals
- Use dense vertical sampling to capture shallow tornado inflow and track features vertically (e.g., descending reflectivity cores)
- Capture the time evolution of vertical vortex evolution (e.g., velocity, diameter changes, tilt)
- Calculate d/dt terms in severe storms to better understand dynamics

In addition to science questions, participants advocated for several different types of technology for tornado observations:

- Tradeoff: Is it better to have more simple, smaller PARs or a single, more complex and capable PAR?
- Bistatic passive radars were suggested to obtain 3D winds without a second PAR being needed. These inexpensive systems reduce costs and increase the number of dual-Doppler “nodes”
- Digital beamforming may provide faster volumetric scanning than other techniques

Following the discussion on tornadoes, participants focused on applications of PARs for understanding severe wind events. The following specific cases were noted:

- The primary benefit for downburst studies is to trace downbursts in time and evaluate our conceptual models with observations.
- Exploring vertically-oriented K_{dp} precursors to microbursts
- Need to obtain detailed observations of how downbursts spread out at the surface and what the 3D wind structure looks like in general
- Understand the respective roles of dynamics vs. thermodynamics in generation of downbursts

e) BOS#5: Boundary Layer Meteorology and Turbulence (Moderators: Robert Palmer and Dusan Zrnic; Rapporteur: Tyler Bell)

In this breakout session, participants examined boundary layer and turbulence applications for PARs. These included two types of measurements, large-scale velocity measurements (e.g., structures of large-scale eddies like convective rolls) and small-scale measurements (e.g., sub-resolution volume). Wavelength dependence of turbulence measurements and scatterer type are important considerations for these applications. Shorter wavelengths are more sensitive to insects which have motions that deviate from the wind (particularly when considering variance quantities for turbulence). Longer wavelengths (e.g., S band) are more sensitive to Bragg scatter and can provide direct measurements of turbulence.

The participants noted the following specific applications and challenges for boundary layer and turbulence research:

- Turbulence pathways, such as Kelvin-Helmholtz billows, evolve quickly and could be documented with PARs. Documenting their temporal evolution could help validate and verify theories
- Gust fronts and outflow create shear-generated turbulence. Documenting fine-scales requires fast scans and high spatial resolution (e.g., vertically dense observations).
- Rapid-scan 3D winds in the boundary layer are highly desirable. However, dual-Doppler measurements are challenging due to sensitivity requirements in clear air. This requires two PARs to be developed.
- If multiple Doppler retrievals are possible, thermodynamic retrievals would be of high interest.
- Need to consider synergy of PARs with other boundary layer instrumentation

- Explore how spectral data can be used in clear air (e.g., distinguishing insects and Bragg scatter)

f) BOS#6: Leveraging PAR Data in Next-Generation NWP Models (Moderators: Xuguang Wang and Tian-You Yu; Rapporteur Sam Degalia and Xongjie Huang)

Phased array radars offer intriguing potential for NWP studies by improving numerical weather prediction forecasts through data assimilation, creating new scientific discoveries using NWP model output with PAR data assimilation during field experiments, and providing high-temporal resolution data to evaluate physical processes and their parameterization in numerical models. To examine these applications, the NWP breakout session examined the following key questions:

1) What are the science opportunities and challenges for assimilating high-temporal-frequency and potential non-uniform PAR observations for scientific analysis and improving numerical weather forecasts?

2) What role can rapid-scan observations play in NWP model simulation and forecast validation, and parameterization scheme improvements by capturing the "d/dt" of physical and dynamic processes?

Regarding the science opportunities and challenges for assimilating high-temporal-frequency PAR observations, participants noted the following (O: Opportunities, C: Challenges):

- O: Flexible PAR scanning can allow the forecast to drive the sampling strategy
- O: Use adaptive sampling to provide targeted observations for DA that blend tradeoffs of temporal resolution and data quality
- O: Continuous high-resolution analysis can be obtained for the entire storm
- O: Clear-air observations can be improved with flexible scanning of the near-storm environment
- O: Observations can fill a data gap in the planetary boundary layer and improve depiction of the vertical profile
- O: NWP analyses for science research can improve understanding of tornadogenesis, downbursts, lightning, and hail
- C: Dual-polarization data assimilation remains challenging and operator development is needed (even for dish systems)
- C: Assimilation of data at PAR temporal resolution can create model imbalance and may need smoothing
- C: Need to develop technology to drive adaptive sampling based on NWP needs (e.g., cost functions for determining sectors)
- C: Adaptive observation errors are likely needed to treat different errors in each sector (and possibly different scan modes)

The participants identified the following roles for PAR observations for NWP model simulation, forecast validation, and parameterization scheme improvements:

- **Improving microphysical parameterization schemes** by capturing hydrometeor information (concentration, diversity) and the vertical gradients of dual-polarization variables
- Analyzing PAR data beyond base products and looking at tendencies (d/dt)
- Determining the type of microphysics scheme needed (two, three moment)
- **Improving planetary boundary layer parameterization schemes** through high temporal resolution observations of 3D winds
- **Validation of microphysical and dynamic processes and their interaction across multiple spatial and temporal scales**
- Collocated aircraft in-situ observations with PAR data would help explain physical processes related to enhancements of ZDR and KDP and validate polarimetric ice retrievals

g) BOS#7: Student and Postdoc Discussion (Moderators: Addison Alford and Alison LaFleur; Rapporteur: Rachael Cross)

The breakout session for students and postdocs allowed students to explore how PARs could impact their education and careers and examine research applications. The moderators identified three key questions to pose in the breakout session. The responses to each key question are provided below.

1) How does PAR change your goals in your early career in terms of your approach to science questions you want to address and the methods by which you want to answer them?

- *Participants noted that PARs provide an opportunity to do more with their research, apply creative techniques to get more information out of observations, and maintain their interest in atmospheric sciences.*
- PARs can help capture changes in microphysics that wouldn't be observed with slower scanning radars.
- PARs offer exciting opportunities for students to work with state-of-the-art observations and stimulate interest in different atmospheric science disciplines.
- Since not all students start in meteorology, exciting new radar systems may encourage students to change majors to meteorology. Making these radars accessible is important! Teaching tools for PARs will also be needed.
- *A key charge from the student BOS to faculty and educators was to develop new ways to use PAR more broadly in the classroom to maintain this strong student interest.*

2) Are there questions that you see as being very difficult if not impossible to address without PAR?

- High-temporal resolution over a large area (ZDR arcs and columns) are almost impossible to do with dish radars.
- QLCS tornadoes: These tornadoes often last only one volume scan in most operational radars. PARs could help us determine how these tornadoes form.
- FFD and streamwise vorticity currents: took PPIs and RHIs through FFD. Updates were minutes apart – getting the continuous sampling across boundaries would be great.
- Global Lightning Mapping (GLM) array data: using a dish radar makes it hard to point dish exactly where lightning is occurring
- In many different fields, PARs may lead to unique discoveries from higher temporal resolution even where rapid-scan is not traditionally thought to be important.

3) The trajectory of a career is often a function of the available tools at your disposal. How does PAR integrate within your current research practices and available toolsets now and in the future?

- Advection correction: difficult to do in landfalling hurricanes. Low temporal sampling with mechanical sampling radars only goes so far because things evolve at temporal scales faster than what we can achieve. So, having PARs observe landfalling hurricanes would be great!
- Being able to use rapidly updating dual-pol data to observe hook echoes
    - High temporal/spatial resolution of the hook echo
- Bistatic radars are currently used with dish radars, but these studies would be greatly augmented with PAR data for rapid-scan observations.

A key point noted was that phased array radars help students and early career researchers do better quality research. Finally, the students presented a charge to faculty and researchers to develop creative ways to integrate phased array radars into educational activities.

5. Detailed Summary of Technology Breakout Sessions

a) BOS#1: Identifying PAR technology needs for boundary layer and cloud research (Moderators: Stephen Frasier and Jorge Salazar; Rapporteur: Morgan Schneider)

Previous science discussions note a need for phased array radar technologies to examine fine-scale processes in clouds and the planetary boundary layer. The purpose of this breakout session is to explore the PAR technology needs for these applications and determine what existing or future technologies could address these observing gaps. Discussions focused on the following two key questions:

1) What are the strengths and limitations of existing PAR technology and/or wavelengths for observing the convective boundary layer and clouds?

2) What new PAR technology is needed to address shortcomings?

Participants responses are summarized below:

- PAR technology at mm-wavelengths would be important for obtaining fine-temporal resolution observations of clouds that aren't possible with dish radars (e.g., 3D imagery)
- Technology at mm-wavelengths remains challenging because the required spacing of electronics is smaller and less space is available for integration of components
- Recommended techniques for a mm-wavelength PAR are to use fewer active array components and simplify the architecture to make PARs feasible (e.g., exclusively use digital beamforming, multi-beam techniques)
- Boundary layer observations remain challenging because insects are the primary scatterers
- Insects provide pretty good estimates of mean wind motion, but different sizes of insects introduce different biases
- Turbulent statistics are challenging from boundary layer observations of insects (e.g., velocity variances)
- More broadly, the conversation steered toward preserving momentum of ideas with PARs, determining the evolution of PAR technology, assessing the size of the user bases, and expanding accessibility to PAR systems and data
- PARs will probably not be widespread in the near-term, but research-oriented systems can still play an important role
- Research-focused testbeds (e.g., for data assimilation studies) and openly accessible websites with PAR data (Stony Brook website contains downloadable PAR data) are possibilities for expanding research use

b) BOS#2: Identifying PAR technology needs for research on coupled physical and dynamic processes (Moderators: Pierre Kirstetter; Rapporteur: Yagmur Derin)

Previous science discussions focused on different applications of PARs for understanding physical and dynamic processes in clouds and precipitation. This breakout session focused on determining the technology needs to capture these processes, including scanning strategy needs and methods to retrieve highly desired 3D winds. Discussions centered around the following two key questions:

1) What ground-based PAR technology provides the best capability to holistically capture processes from near the surface to cloud top?
2) What are the strengths and weaknesses of different methods for retrieving 3D winds with phased arrays?

Participant responses are summarized below:

- Warm rain initiation was discussed as an example science application for PARs to identify technology needs.
- PAR technology can address the need to observe different scales of turbulence that impact warm rain formation
- Collocating two apertures is important for understanding most events. For example, combinations of S and X band phased arrays were desired to scan the same volumes to obtain more microphysical information.
- It is possible that past limitations of non-synchronous dual-wavelength measurements can be alleviated by rapid-scanning phased array ensuring that volumes are collocated.
- Doppler capability and 3D winds are very important
- Need to get PARs with modular designs and platforms, eventually placed on balloons, UAS, and planes.

c) BOS#3: Identifying PAR technology requirements for severe weather research (Moderators: Casey Griffin and Matt McCord; Rapporteur: Charles Kuster)

PAR technology has been most used for severe weather research to date. Thus, this breakout session sought to build upon past perspectives from past field campaigns to identify the strengths and limitations of PARs and identify what new technology is needed for severe weather research. The following key questions guided the discussions:

1) What are the strengths and limitations of existing PAR technology or observing severe thunderstorms?
2) What new PAR technology is needed to address these shortcomings?

Participants noted the following opportunities and challenges with PARs for severe weather research:

- We need to consider technologies that can provide higher spatial resolution observations of tornadoes, not only higher temporal resolution. X-band radars only finely resolve larger tornadoes.

- Ka-band tornado-scale radar observations document these benefits of excellent spatial sampling well, capturing the tornado's core flow and vertical structure of winds (e.g., in tornadic inflow)
- How do we balance the reward vs. risk of shorter wavelength observations for severe weather (e.g., attenuation vs. unprecedented spatiotemporal resolution observations)?
- A notable challenge with PARs is the ability to save time series data and handle the data processing of increasing complex PARs with multiple channels. AIR data were 1 TB/hour for moment data, and HORUS is 2 GB/s.
- Operators will have to be judicious when deciding what I/Q data to save due to very high data storage requirements. The drawback is that this limits reprocessing opportunities and I/Q-based algorithms must be applied in real-time.
- When adopting technology from military or other sectors, a lot of groundwork was necessary. Meteorology-specific requirements may not be obvious to other sectors (e.g., need to level the radar truck).

Once the discussion shifted to 3D wind observations, participants noted the following opportunities for research as well as different techniques and technologies for 3D wind retrievals:

- Future technologies providing high-quality information about microphysics and 3D wind retrievals are highly sought.
- Dual-Doppler retrievals at the tornado-scale would require high temporal resolution and enable unique trajectory analysis.
- Very fast volume scans (e.g., with imaging) can largely eliminate the need to synchronize scans in time.
- Similar needs for rapid-scan, dual-Doppler exist within the tropical cyclone community.
- From single-Doppler observations, feature tracking or single-Doppler variational wind retrievals are intriguing (but require validation with dual-Doppler).
- Bistatic passive radars can be made mobile and eliminate need for time syncing of two scanning radars.
- PAR technology, especially with 3D winds, can provide important data to understand how well very-high-resolution simulations of tornadoes capture physical processes in nature.

d) BOS#4: PAR adaptive scanning strategies (Moderators: Angela Rowe and Sebastian Torres; Rapporteur: David Schvartzman)

The preceding science discussions illuminated a wide range of use cases requiring different PAR scanning strategies. With new PAR technologies providing diverse scanning techniques and beam types that can different science objectives (even simultaneously), this breakout session discussed the opportunities for adaptive scanning with PARs, the practical questions about the tradeoffs of these techniques, and the challenges for implementing and applying these scanning techniques in field experiments.

The key questions for this breakout session included:

1) Adaptive scanning involves the dynamic change of a radar's scanning strategy in response to changing observing needs, resulting in tradeoffs between data quality, temporal resolution, and spatial coverage. How do we improve radar observations with these tradeoffs in mind and what would be the expected scientific outcomes?

2) What balance of human vs. automated decision making is needed and what new software is required to implement these strategies?

For the first question about adaptive sampling's benefits and tradeoffs, participants noted the following:

- PARs offer much more flexibility. Nothing is free, but compared to a parabolic-reflector, these tradeoffs can be nearly free (in a data quality sense).
- PARs offer the opportunity to address multiple user goals simultaneously, but there is still a time scheduling limitation. For a shared resource (e.g., one PAR), we need to explore how different users can achieve their goals in harmony.
- Even without adaptive scanning, PARs can provide significant improvements. However, adaptive scanning can provide benefits in almost any scenario.
- A broad challenge is making data quality tradeoffs more understandable to the scientific community and communicate real-time quantification of tradeoffs (e.g., errors) to the user.
- For determining the atmospheric state (e.g., providing more targeted observations), fusion of radar and non-radar data might provide opportunities for PARs. This could lead to a data-driven, dynamic observing system.
- Multi-radar cooperation could also be fostered by PARs, including other PARs or dish systems.
- Arrays provide more options, such as digital beamforming to increase the volume scan rate or per pulse adaptive beamforming by dithering the beam in volume space for pulse

processing gain.

- All radars could park to save power if there isn't anything interesting occurring.
- All-digital systems should provide more dynamic range and achieve the same or better results with fewer pulses.

For the second question involving human vs. automated scanning strategies, participants noted the following:

- Most of the time the decision making can be automated. However, there should be a manual override for an expert meteorologist to make decisions (similar to self-driving cars).
- Sensor can decide fidelity/activity and operate can override it to obtain more traditional observations.
- PAR scanning systems could be trained using AI from expert input.
- Human intervention should be used to transition the radar from fully manually to fully automated (over a long period of time) as algorithms and adaptive concepts are refined and improved.
- Real-time computations needed to run adaptive scanning autonomously are likely computationally expensive.
- Research techniques can proceed in scanning strategy automation more quickly whereas operational applications will require more careful transitions.

Additional discussion focused on specific science applications and NWP:

- For NWP applications, the goals need to be clear. Is the goal a better forecast, better QPE, better temporal resolution?
- Data assimilation and real-time model output could help guide real-time scanning decisions by where to sample (e.g., where PAR observations will benefit forecasts the most). The challenge is that models are not perfect and introduce errors as well.
- PARs could be used to do unique scanning on the fly, such as scanning at 90º or high elevations to capture vertical velocities or dwell for velocity distributions.
- Adaptive techniques to examine ZDR columns or KDP pools could help understand physical processes underlying their observed behavior.

e) BOS#5: AI/ML and Open-Source Software (Moderators: Scott Collis and Jim Kurdzo; Rapporteur: Brandon Cohen)

This breakout session focused on several key tools that the scientific community will use for PAR research. Emerging artificial intelligence (AI) and machine learning (ML) techniques applied to weather radar are well-positioned to take advantage of PAR data that are more difficult to analyze manually in an exhaustive manner. The scientific community can also benefit from adaption of existing open-source radar software suites for PARs. To explore these opportunities and challenges, participants were asked the following key questions:

1) What opportunities exist to use machine learning and artificial intelligence to explore large data volumes that are difficult to analyze manually?
2) What opportunities and barriers exist to expanding and creating new open-source software to assist scientists with PAR data analysis and quality control?

For ML/AI opportunities, participants provided the following inputs:

- AI can help guide scanning strategies to optimize use of RHIs and adaptive scanning to extract as much information as possible
- AI requires significant upfront management of data sets
- Need high-quality labeled datasets with specific features of interest
- Benchmarks are lagging for radar AI. Need a benchmark like Imagenet for radar
- Data standardization will be important for ingesting data into AI. Quality control algorithms, data ingest pipelines, and other preprocessing steps should be standardized

For open-source software and data needs, participants noted the following opportunities and barriers:

- Need to develop new standards for PAR data, particularly where radar data may not be collected in continuous rays (do CF/Radial and other standards require updating?)
- Scientific community needs to adhere to radar format standards
- Greater access to I/Q data would promote innovations in signal and array processing and enable open-source contributions
- Example workflows with PAR data would be beneficial to allowing contributors to become productive more quickly
- Intellectual property and licensing can be obstacles to making radar software open source. This depends on institutional policies.
- Open data is critical to enabling research advances and improving open-source software for different PAR applications
- Need better ways to read radar data, more seamlessly visualize it, and edit it. SOLO-II is still “the standard”, but it needs to be updated.
- Data quality needs to be communicated in data formats
- Software development needs solid funding from agencies

f) BOS#6: PAR education and training needs (Moderators: Jana Houser and Daphne LaDue; Rapporteur: Rachael Cross)

The final BOS explored the education and training needs for PARs to understand how students can benefit from access to PAR systems and data and the broader training needs for the meteorology community. Participants were asked the following key questions to guide discussions:

1) What education and training opportunities would help prepare students for future careers using PAR technology and data (e.g., classroom activities, summer internships, short courses)?

2) What training is needed to help the meteorological community understand PAR technology and facilitate broader usage of PAR data in research, operational forecasting, and the private sector?

For educational activities, participants noted the following specific points:

- A brief interaction with radar technology can have profound impacts on students' careers and comfortable level with radar data (e.g., DOW educational deployments), and should be extended to PAR technology
- Hands-on activities and courses are important for PARs
- Since students may have never seen a PAR before, they might exploit it in an original manner
- Could show students differences between the scanning strategies for parabolic dish radars and PARs
- Could have a traditional parabolic dish radar and PAR deployed together to explore benefits and limitations of each
- A nationally available weather camp, similar to NASA's space camp, could be developed to involve younger students
- Students noted that they didn't use radar data until graduate school. So, knowing how to use the data and getting practice is important.
- There are barriers for institutions with less IT resources since they cannot plot/use data. Should consider free software platforms (e.g., Python) and online learning modules.
- Need to consider that not all institutions (and their students) have large amounts of storage space
- Data sets need to be easily available, in unified formats, and more diverse data sets are needed.

For training applications, participants noted the following:

- Lessons can be learned from past paradigm shifts in technology, such as the WSR-57 to

WSR-88D.

- Need easy to follow, web-based training for meteorologists and non-meteorologists. The WDTD dual-polarization training modules for forecasters and non-meteorologists are great examples.
- A training session/meeting for PARs at a place where many meteorologists and students are gathered could be beneficial (e.g., AMS).
- Need to emphasize the wide range of applications for observing different types of atmospheric processes and non-meteorological applications
- Data sets need to be easy to work with and example workflows should be provided
- Barriers to PAR data access must be addressed: How do we incentivize rapid turnaround of data between PIs and users?

g) Concluding Remarks and Recommendations

The virtual PAR workshop brought 166 people together to discuss the future of PAR science and technology. Participants came from 30 different universities and eight different countries (26 international participants) and included 49 graduate students and postdoctoral fellows. Participants highlighted a wide array of science applications of PARs that can significantly advance basic atmospheric science research. These topics included, but were not limited to, formation and evolution of severe thunderstorms, the lifecycle of deep convection and microphysical and dynamic processes, shallow clouds and boundary layer processes, and numerical weather prediction and model parameterization improvement. A common thread among these applications is a desire to obtain microphysical and dynamic information (e.g., from dual-polarization and 3D wind observations) at high temporal resolution and with dense vertical sampling. With such data, scientists can explore the full cycle of shallow and deep convection and obtain more information about microphysical and dynamic processes in a broad spectrum of convective modes and environments. Dense vertical sampling and time rate of change of radar quantities can elucidate warm rain formation mechanism or melting processes for snow and hail. Understanding of convective dynamics can be improved by capturing *all* levels of shallow and deep convection, including substructure of convective updrafts (e.g., thermals) and upper-level updrafts.

The scientific applications helped identify several common requirements for future PAR technology:

- High-temporal resolution, dual-polarization and 3D wind measurements are strongly desired to understand microphysical and dynamic processes.
- Adaptive scanning techniques are key tools for obtaining deep vertical scans and improving the vertical resolution of radar observations (e.g., moving toward vertically continuous scans in convection).
- To achieve both high-temporal resolution and vertically continuous scans, PARs must have significant flexibility to implement a wide range of adaptive scanning techniques. Applications requiring very high temporal resolution (e.g., lightning, tornadoes,

turbulence research) can also benefit from this flexibility since much faster volumetric update rates can be obtained.

- The control software for PARs must be capable of leveraging different PAR scanning strategies, adapted to evolving phenomena and the scientific goals of the project.
- A greater breadth of radar wavelengths is needed for PAR technology, currently limited to S and X bands. Higher frequencies would be particularly beneficial since they provide finer spatial resolution and sensitivity to cloud particles. Multiple-wavelength PAR architectures should be considered. OU's C-band Polarimetric Atmospheric Imaging Radar (PAIR) will be complete in 2022, so PARs at S, C, and X bands will be available soon.

In the broader group discussion and report out, participants noted a strong need for community-accessible PAR systems and data for research, education, and outreach activities. Openly accessible PAR data sets remain difficult to find and access, and the breadth of PAR data sets remain limited (e.g., most past PAR studies have focused on tornadoes). In addition, the scientific community cannot request PAR technology through NSF or other science agencies. Community software platforms have also not yet been adapted to PAR technology.

Several short-to-medium range steps can be taken to address these issues. In the short term, PIs of past PAR field campaigns are strongly encouraged to share and advertise the availability of existing PAR data. In many cases, such data may be available upon request, but this offers few opportunities for data discovery. A recent NSF Geoscience Directorate "Dear Colleague Letter" encourages proposals that make existing data accessible and develop new educational curricula. In addition, field campaigns should make a concerted effort to involve PAR systems to collect observations spanning a greater breadth of atmospheric phenomena to explore different science applications of PARs and stimulate broader interest. Community-accessible PAR systems remains strongly desired, but a traditional request mechanism (e.g., the LAOF deployment pool) for PARs does not yet exist for research or education.

Appendix

a) Agenda

Virtual Workshop on Atmospheric Science Applications of Ground-Based Phased Array Radars
May 25, 12:00 – 4:30 PM CDT

Open to all interested, but pre-registration is required

The scientific community has expressed a strong desire to observe atmospheric sciences at finer temporal and spatial scales and obtain more information about physical and dynamic processes. Field campaigns currently operate mechanically scanning radars due to their relatively low cost and complexity. However, such radars require several minutes to complete volume scans and leave undesirable observing gaps at the middle and upper levels of precipitating systems between sparse elevation angle scans. Likewise, such systems have limited capability to scan adaptively, requiring significant additional time to include range-height indicator scans to a traditional volume scan. With the advent of phased array radars, scientists can move past these inherent limitations of current radar systems to gain much faster volumetric scanning speeds and operate radars that provide a blank canvas for creativity with adaptive scanning techniques like digital beamforming and beam multiplexing. Modern phased array radar (PAR) technology can also enable unique polarization studies (e.g., rapid switching of polarization and polarization modes) as well as three-dimensional wind retrieval capabilities. ***The goal of this workshop is to identify and discuss science applications of ground-based PARs for atmospheric science research, explore how existing PAR technology can be leveraged to achieve these science goals, and determine where critical gaps exist in PAR technology.***

While PAR science research to date has largely focused on severe weather, many important opportunities remain to leverage emerging polarimetric capabilities and 3D wind retrievals and study a wide range of severe storms across the world. More critically, the potential of PARs to advance understanding of the dynamics and microphysics of clouds and precipitation remains untapped. With adaptive scanning techniques and vertically continuous views, the forthcoming generations of dual-polarization PARs can enable unique studies of tropical convection, orographic precipitation, or polar precipitation processes. PARs have the potential to fundamentally advance boundary layer meteorology and turbulence studies by providing rapid-scan clear air measurements. The data deluge from PAR technology also fosters unique opportunities and challenges for data assimilation and Artificial Intelligence research to handle and extract as much information as possible from PAR data.

Workshop Agenda

Zoom Info (please do not share this link):
https://oklahoma.zoom.us/j/98242264594?pwd=bW1SVlJNVjI2dnpIV0U1OFhnektWUT09

Meeting ID: 982 4226 4594
Passcode: 83165557

12:00 – 12:30: Opening Remarks

- Workshop Scope, Goals, Key Questions (David Bodine – Univ. of Oklahoma)
- Keynote Talk: Evolution of PAR technology for Science (Bob Palmer – Univ. of Oklahoma)

12:30 – 1:40: 10-min Lightning Round Talks on PAR Science and Technology

- Applications of PARs in Physical and Dynamic Meteorology – (Pavlos Kollias – SUNY Stonybrook)
- Fine-scale Observation of TC Tornado Using Phased Array Weather Radar in Japan (Toru Adachi –MRI)
- Review of Findings from Past PAR Severe Weather Studies – (Casey Griffin – SUNY Brockport)
- Studies of Deep Convection and Field Experiment Perspectives (Steve Nesbitt – Univ. of Illinois)
- Benefits of PAR Technology in a Future Operational Radar Network (Pam Heinselman – NOAA/NSSL)
- PAR Adaptive Scanning Strategies (Mark Weber – MIT LL)
- 3D Wind Applications and Retrievals (Alan Shapiro – Univ. of Oklahoma)

1:40 – 1:50: Break

Note: No separate Zoom login is needed for the breakout sessions.

1:50 – 2:30: Breakout Sessions on Science Applications

- BOS 1: Big Picture View of Science Applications (Moderators: Pavlos Kollias and Robin Tanamachi)
- BOS 2: Building the Atmospheric Column of Coupled Microphysics and Dynamics (Moderator: Pierre Kirstetter)
- BOS 3: Storm Electrification and Hail (Moderators: Larry Carey and Matt Kumjian)
- BOS 4: Tornadoes and Severe Winds (Moderators: Jana Houser and Mike French)
- BOS 5: Capturing Turbulent Atmospheric Flows: Boundary Layer Meteorology and Environmental Applications (Moderators: Robert Palmer and Dusan Zrnic)
- BOS 6: Leveraging PAR data in Next-Generation NWP Models (Moderator: Xuguang Wang and Tian-You Yu)
- BOS 7: Student and Postdoc Discussion on PAR Science and Opportunities (Moderators: Addison Alford and Allison LaFleur)

2:30 – 3:20: Open Discussion on Science Drivers and Brief Report Outs

3:20 – 3:35: Break

3:35 – 4:05: Breakout Session on Future Technology Needs

- BOS 1: Identifying PAR Technology for Boundary Layer and Cloud Research (Moderators: Stephen Frasier and Jorge Salazar)
- BOS 2: Identifying PAR Technology for Research on Coupled Physical and Dynamic Processes (Moderators: Pierre Kirstetter and Caleb Fulton)
- BOS 3: Identifying PAR Technology Requirements for Severe Weather Research (Moderator: Casey Griffin and Matt McCord)
- BOS 4: Adaptive Scanning Strategies (Moderators: Angela Rowe and Sebastian Torres)
- BOS 5: AI/ML and Open-Source Software Applications of PARs (Moderators: Scott Collis and Jim Kurdzo)
- BOS 6: Education Opportunities and Training Needs (Moderators: Jana Houser and Daphne LaDue)

4:05 – 4:30: Open Discussion on Technology Needs, Report Outs, and Wrap Up

b) Full Participant List

Aaron Pyzik
Addison Alford
Ahoro Adachi
Alan Shapiro
Alec Prosser
Alethia Kielbasa
Alex Marmo
Alex Schueth
Alexander Ingalls
Alexander Martínez
Aline Esperanza Maza Vázquez
Allison LaFleur
Angela Rowe
Anthony Reinhart
Bob Palmer
Brad Isom
Brandon Cohen
Brenda Javornik
Brian Hirth
Bruno Stephane Rojas

Caleb Fulton
Casey Griffin
Charles Kuster
Chris Schwarz
Christopher Cook
Christopher Sohl
Christopher Weiss
Chuck Kuzy
Claire Milligan
Colin Willingham
Dana Storm
Daniel Chacon Fernandez
Danny Wasielewski
Daphne LaDue
David Bodine
David Schvartzman
David Warde
Dean Paschen
Derek Stratman
Dusan Zrnic
Dylan Reif
Dylana Vargas
Edward Luke
Elizabeth Ramos
Ellie Langley
Eric Bruning
Erica Griffin
Fabian Vazquez
Gabriela Chinchilla
Geun-Hyeok Ryu
Greg McFarquhar
Greg Schoor
Heather Grams
Howard Bluestein
Hyeri Kim
Igor Ivic
Isaac Medina
Ivan Arias
Ivan Sloan
Jack Kain

Jacob Carlin
Jacob Hinson
Jake Segall
Jami Boettcher
Jana Houser
Jeff Snyder
Jessica Souza
Ji-Young Gu
Jim Kurdzo
Joe Friday
John Cho
Jordan Robinson
Jorge Salazar Cerreno
Jose Alberto Navarro Perez
Joshua Pan
Joshua Wurman
Josue Chamberlain
Juan Pablo Mangual
Julio Ordonez
Kaelia Okamura
Karen Kosiba
Kerstin L Gillespie
Kristen Rasmussen
Kristofer Tuftedal
Kurt Hondl
Kyle Pittman
Laura Shedd
Lawrence Burkett
Lawrence Carey
Leigh Orf
Lexy Elizalde
Loren White
Lucía de Santos
Luis Andres Cespedes
Rodriguez
Lydia Spychalla
M Cuellar
Marcus Van Lier-Walqui
Mark Fosberry
Mark Weber

Mark Yeary
Matthew Anderson
Matthew McCord
Matthew Robert Kumjian
Mauricio Noriega
Mia Thedens
Michael Dubois
Michael French
Michihiro Teshiba
Milind Sharma
Mohan Bhowmik
Morgan Schneider
Naoko Sakaeda
Nathan Erickson
Nicholas Price
Nusrat Yussouf
Octavio Farias
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Pam Heinselman
Patrick Servello
Paul Markowski
Pavlos Kollias
Pedro Segura
Pierre Kirstetter
Qing Cao
Rachael Cross
Rafael Mendoza
Randy Silver
Reece Reinke
Renato Barresi
Ricardo Reinoso Rondinel
Robin Tanamachi
Roelof Bruintjes
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Scott Collis
Sebastian Torres

Shannon McCloskey
Stephanie Weiss
Stephen Frasier
Steve Nesbitt
Sun Jin Mo
Syo Yoshida
T. Oohira
Taku Suezawa
Terry Schuur
Theresa Dixon
Tian You Yu
Tom McNellis
Toshinori Kudo
Tyler Bell
Vincent Pellegrino
Vincent Wood
Vitor Goede
Vivek Mahale
Wen-chau Lee
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Ya-Chien Feng
Yagmur Derin
Yixin Wen
Yongjie Huang
Zhi Li