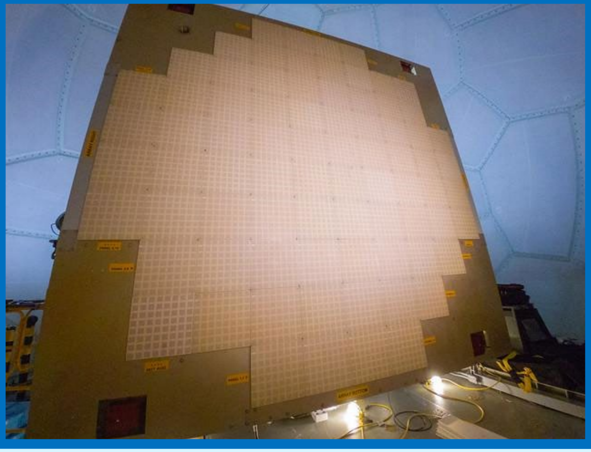
Observations and Understanding

# Phased Array Radar R&D Overview

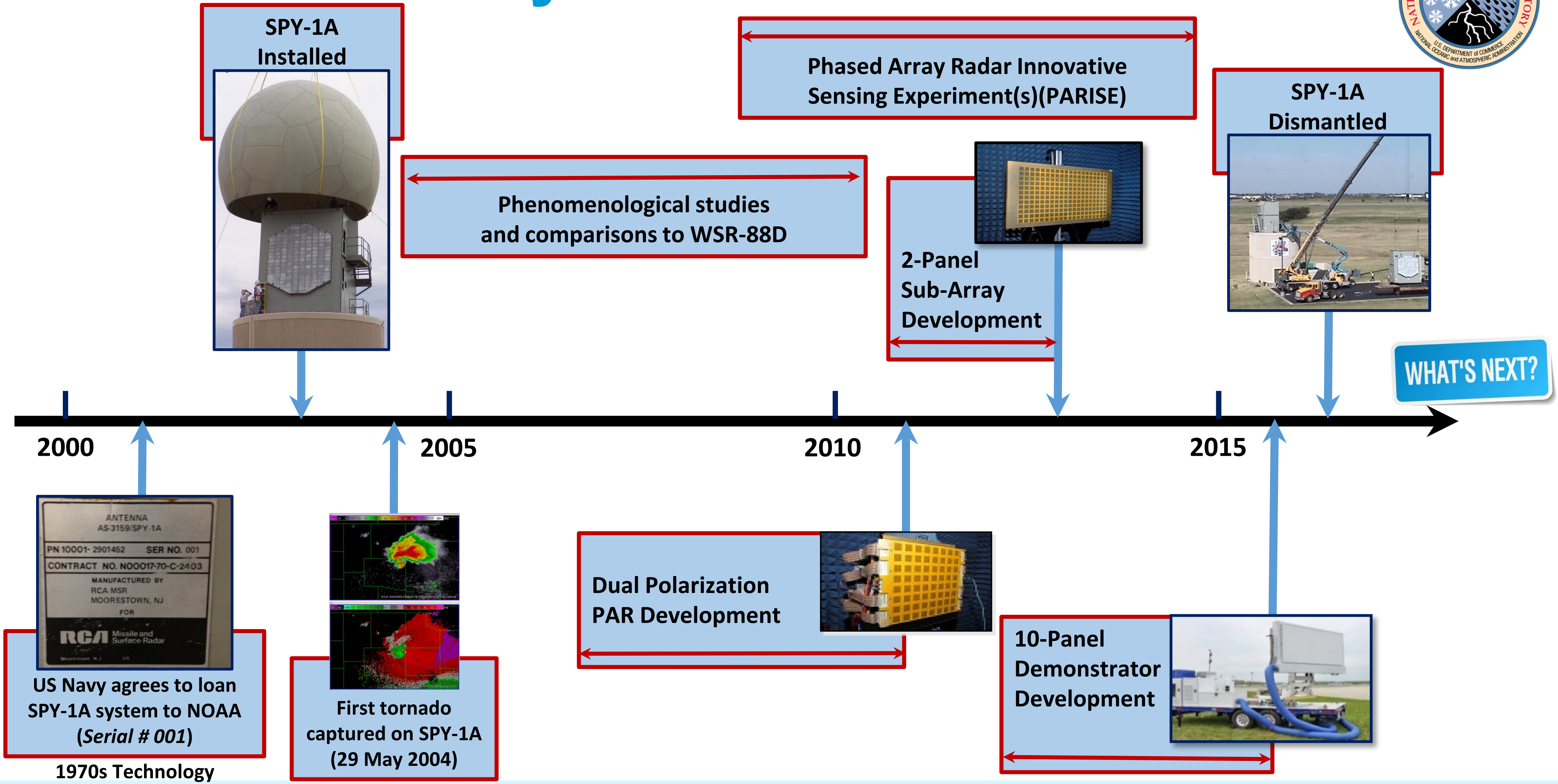
Kurt Hondl, NSSL Deputy Director & PAR R&D Manager

# Radar Observations are Important

- **NSSL is severe weather lab**
  - Radar is primary input for forecasters issuing warnings for severe weather
- **NSSL is NOAA's de facto Radar Laboratory**
  - Developed Doppler weather radar (1970s) which led to the deployment of the WSR-88D network in the early 1990s
  - Developed Dual Polarization technologies (1980s-2000s) which led to WSR-88D system upgrade in 2012-2013
- **NSSL is working on the Future Weather Radar program**
  - Began investigation of Phased Array Radar (PAR) for use as a weather radar in 2003
  - Current WSR-88D network is estimated to be viable through ~2035

# PAR R&D History



# Relevance In Support of NOAA's Mission

- **Congress**
  - Weather Research and Forecasting Innovation Act of 2017, 15 U.S.C. § 8501;
- **DOC Strategy:** Reduce Severe Weather Impacts
- **NOAA R&D Plan:** Reduce societal impacts from hazardous weather
- **OAR R&D Strategy**
  - Make Forecasts (*and Warnings*) Better
    - Design tools and processes to forecast high-impact weather events
    - Transition science that meets users' current and future needs
  - Drive Innovative Science
    - Invest in high-risk, high-reward science
    - Accelerate the delivery of mission-ready, next-generation science
- **OAR Implementation Plan**
  - Demonstrate Warn-on-Forecast can provide guidance for NWS tornado warnings at least one hour in advance
  - Assess the capabilities of phased array technology (compared to the current WSR-88D) for meteorological applications and inform NOAA's future weather radar system investment decisions
- **NWS Weather Ready Nation**

# NSSL's Radar Mission / Objective

- **Ensure that NOAA has the best radar tools to accomplish its mission.**
  - **NSSL Grand Challenge:** Investigate PAR and its capabilities to provide the future weather radar observations needed by NOAA to accomplish its mission
    - Develop, refine, and evaluate the engineering and science technologies of new radar systems and understand their application to weather radar operations.
    - This knowledge provides the foundation that will enable an informed and pivotal decision on the technological and operational design of the next generation weather radar network that must be robust enough to serve us decades into the future as a critical piece of the national infrastructure

# Rapid Update PAR Data

- **Demonstration of rapid update PAR data (1-min) vs WSR-88D update (5-min) from 24 May 2011**

## NSSL used the SPY-1A system for 13 years

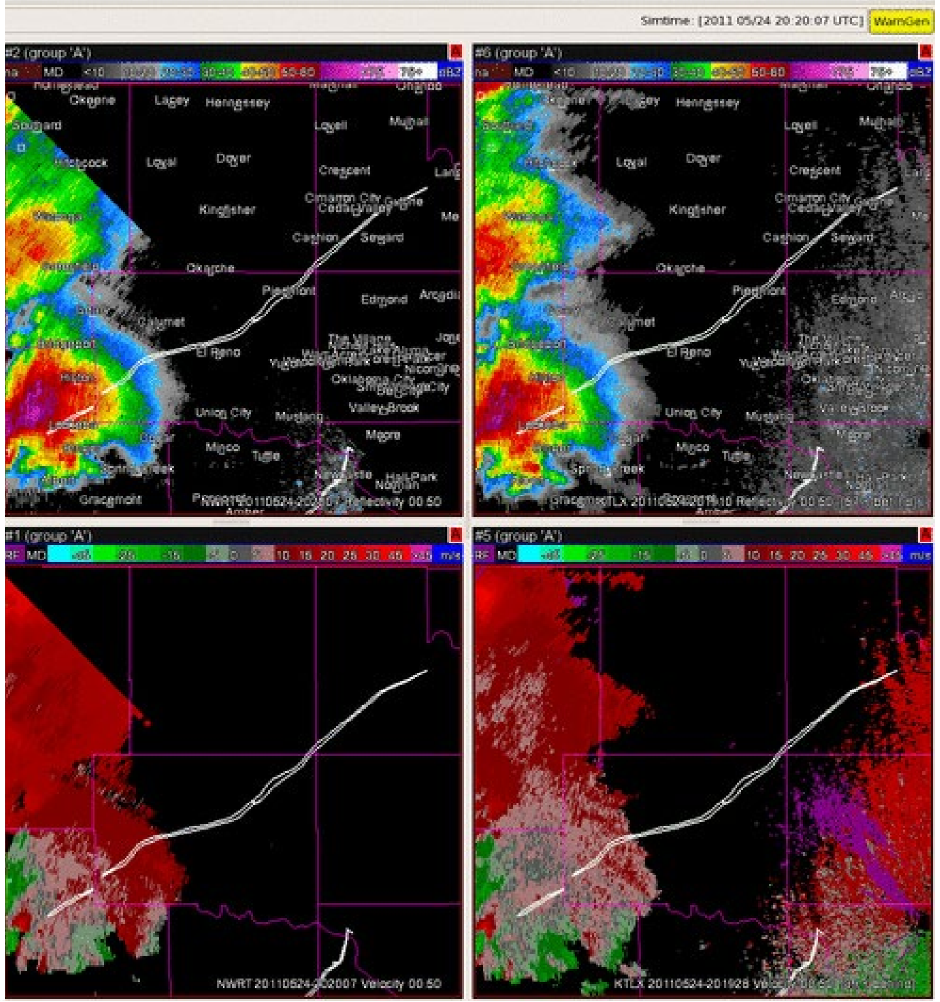
**PAR Meteorological Studies of Rapid-Update Data**

- Examination of circulation and other severe weather signatures and phenomena
- Integration into Warn-on-Forecast models
- Forecaster evaluations in the Hazardous Weather Testbed

**PAR Technology Developments**

- Adaptive scanning concepts
- Interlaced weather and aircraft scanning
- Signal processing and data quality investigations

**(1-min update) PAR SPY-1A** | **(5-min update) WSR-88D KTLX**



https://wdssii.nssl.noaa.gov/web/wdss2/products/radar/rtmp/6xNWRT_24May11.gif

# What We've Learned from PAR R&D

**National Weather Radar Testbed (NWRT) SPY-1A (2003-2016) phased array radar system demonstrated ability to provide rapid volume updates.**

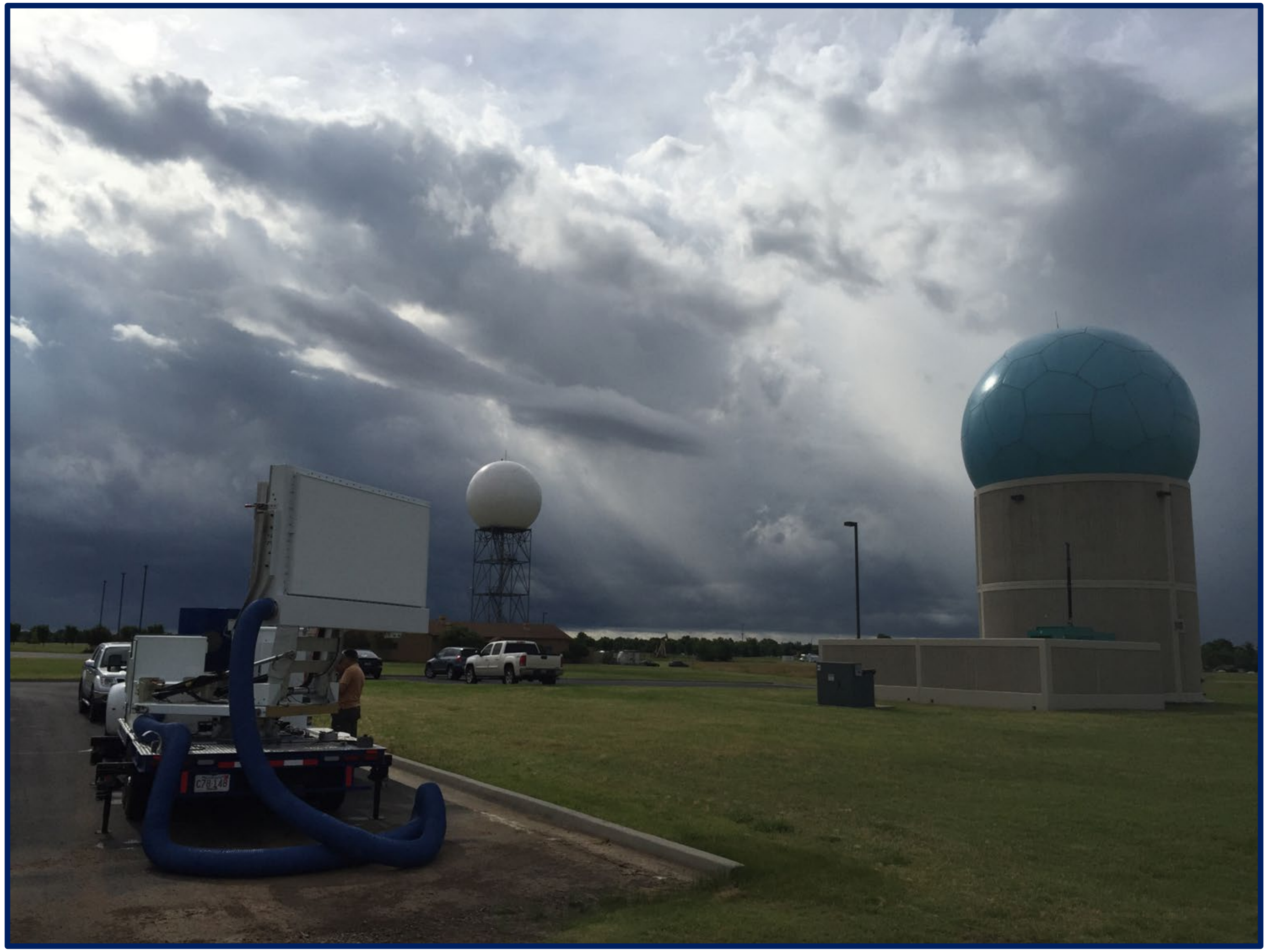
*With electronic scanning and adaptive scan strategies we were able to collect volumetric updates in 45-75 seconds within a 90-deg sector.*


## What we learned with rapid update volume data from the SPY-1A ...

- Improved scientific understanding of the storm evolution processes
- Demonstrated potential to increase tornado and severe weather warning lead times
- Demonstrated improved depiction of probabilistic guidance via data assimilation into storm-scale numerical weather prediction models (i.e., Warn-on-Forecast studies)

# Quality is our Mission

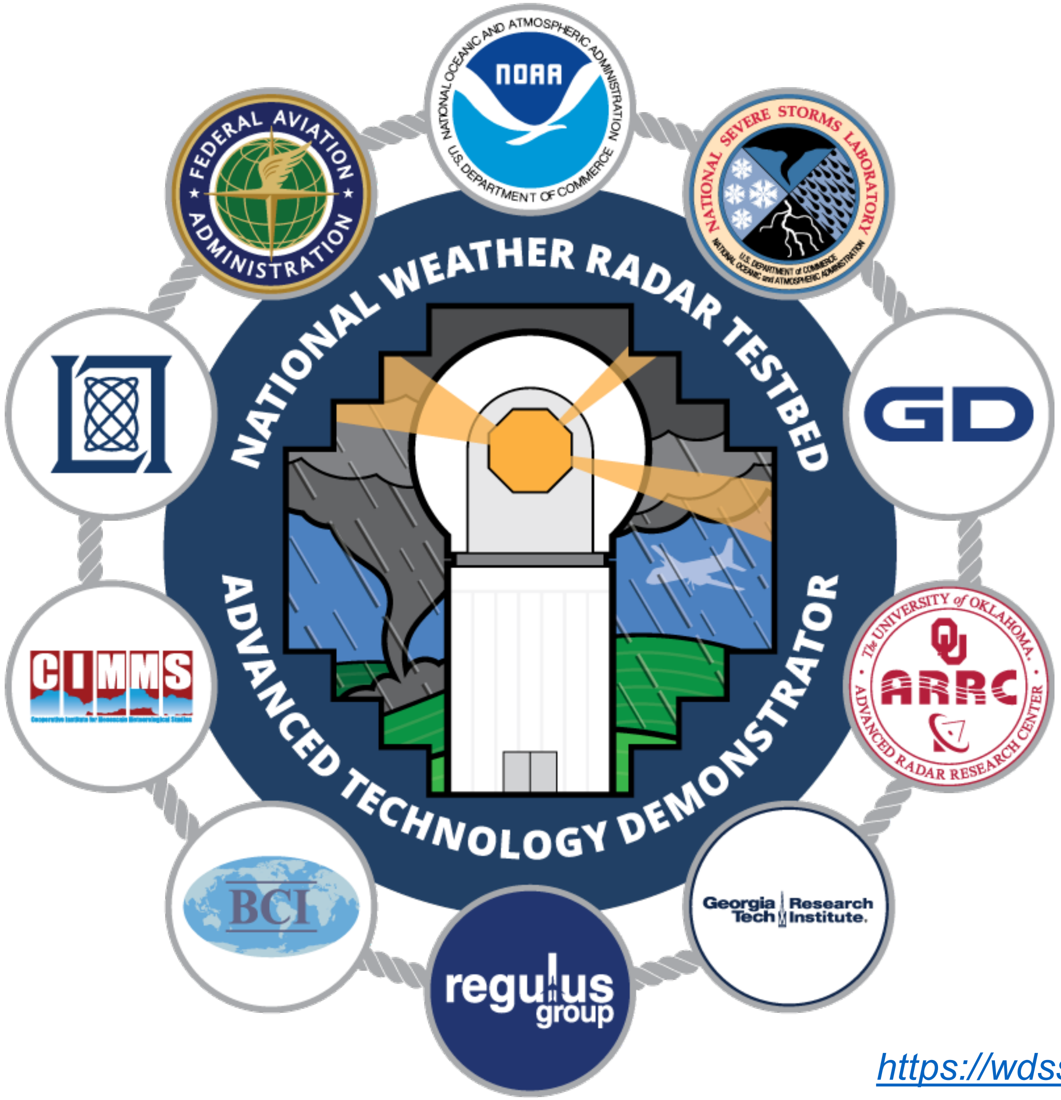
- **34 formal publications concerning "phased array" from 2016-2021**
  - Both meteorological and engineering subjects
- **9 NSSL technical reports**
  - Documenting technical data that may not be appropriate for journal publications, but necessary for external collaborations
- **Problem solving**
  - Building, testing, and calibrating a dual polarization PAR



# Performance - Pushing the Boundaries

- **Developed the most advanced dual polarization PAR Advanced Technology Demonstrator (ATD) for evaluation as a weather radar**
- **3 Written reports and numerous briefings to Congress on PAR R&D activities**
- **All this led to support from Congress and the Administration resulting in increased appropriations for PAR R&D**

# Collaborations on PAR R&D

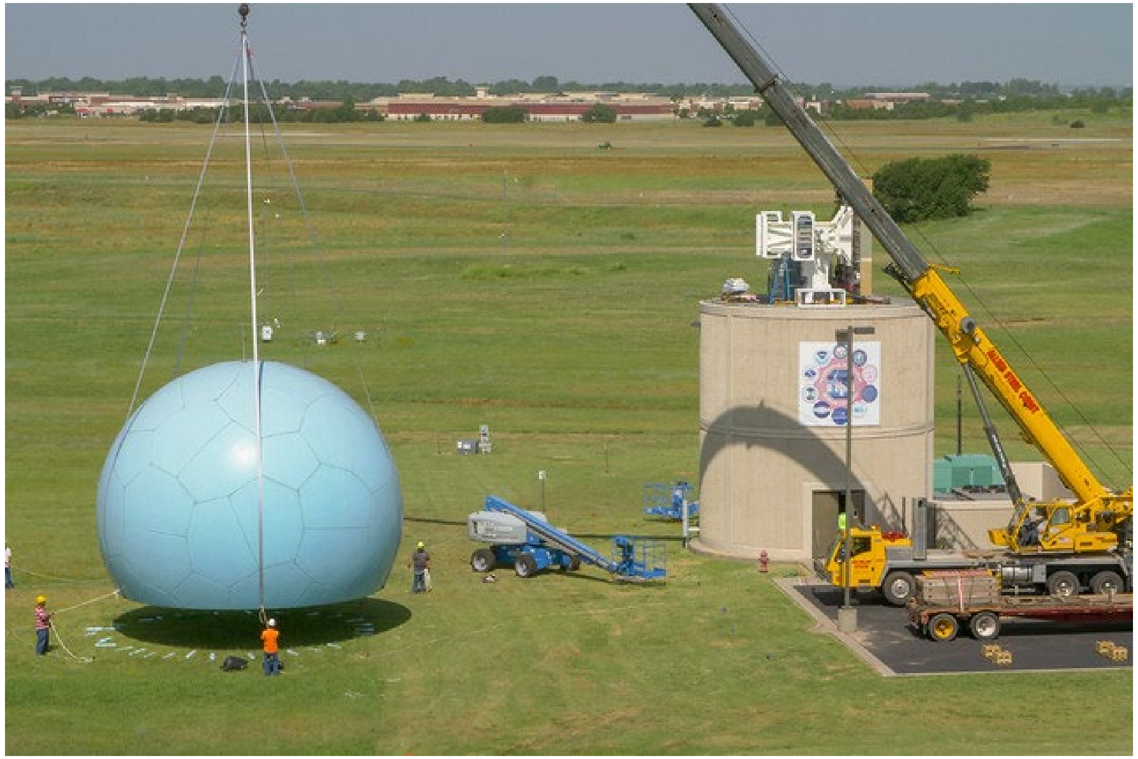



MACOM
Partners from RF to Light

Ball

LOCKHEED MARTIN

COBHAM
ADVANCED ELECTRONIC SOLUTIONS



https://wdssii.nssl.noaa.gov/web/wdss2/products/radar/NWRTatd/AGIF_ATD_install.gif

# Previews of Coming Presentations

## What answers will PAR R&D provide?

- Can we perform the polarimetric calibration of a planar PAR over the field of view and trust its performance?
- Can a PAR provide weather radar data quality commensurate with NWS requirements?
- What are the benefits of adaptive scanning and rapid-update dual polarization data?

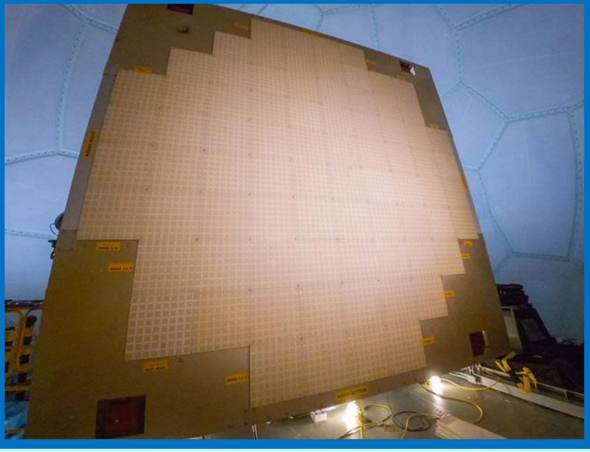
***PAR R&D is necessary to establish NOAA's knowledge of dual polarization PAR technology prior to NOAA's future radar investment decisions.***

# Observations and Understanding

## *Phased Array Radar R&D*
## *Advanced Technology Demonstrator*

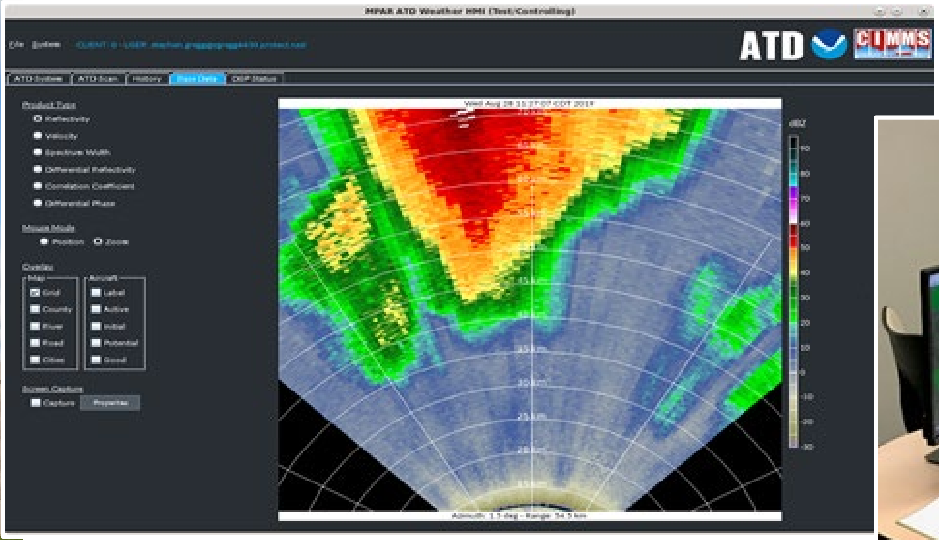
*Daniel Wasielewski, Electronics Engineer, RRDD*

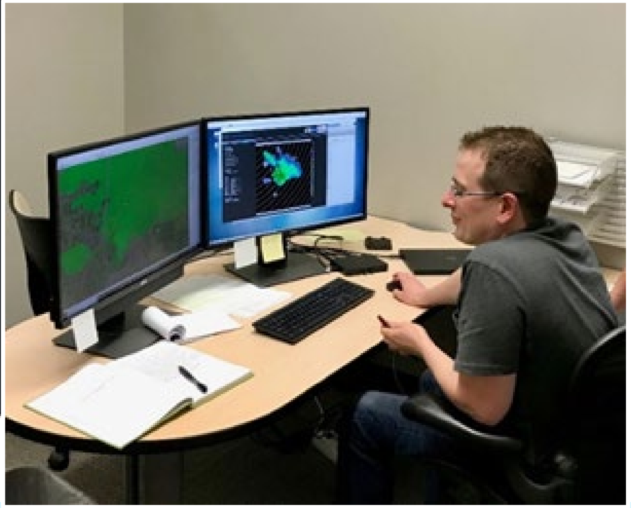




# What is the ATD?

Following up the success of the SPY-1 NSSL initiated the development of the first full-scale S-band, dual-pol, phased array radar for weather observations—the *Advanced Technology Demonstrator* (ATD)



# Why Invest in the ATD?

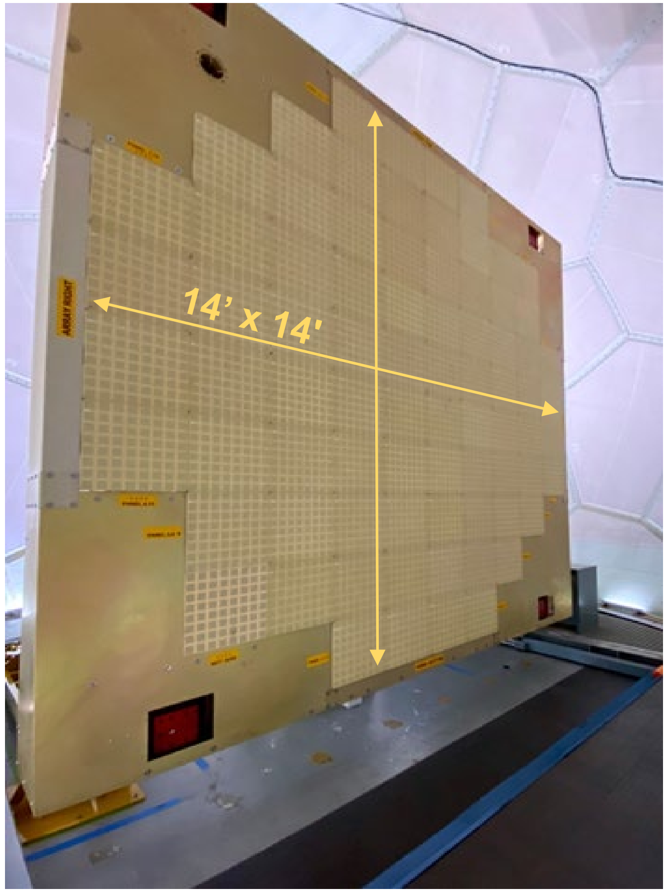
## The ATD explores the combination of dual-polarization and phased array radar technology

- *Dual-polarization:* more information → discriminate between rain, snow, etc.
- *Phased array:* more flexible scanning → faster, adaptable to weather

## ATD purposes

1. One of NSSL's major severe weather **research tools** for the next decade or more
2. A **proof of concept** of dual-pol phased array technology for the National Weather Service
    - Demonstrate benefits
    - Reduce technical risk

# Inside the ATD




**Left:** ATD antenna composed of 76 panels.  Modular panel architecture makes it serviceable and scalable.

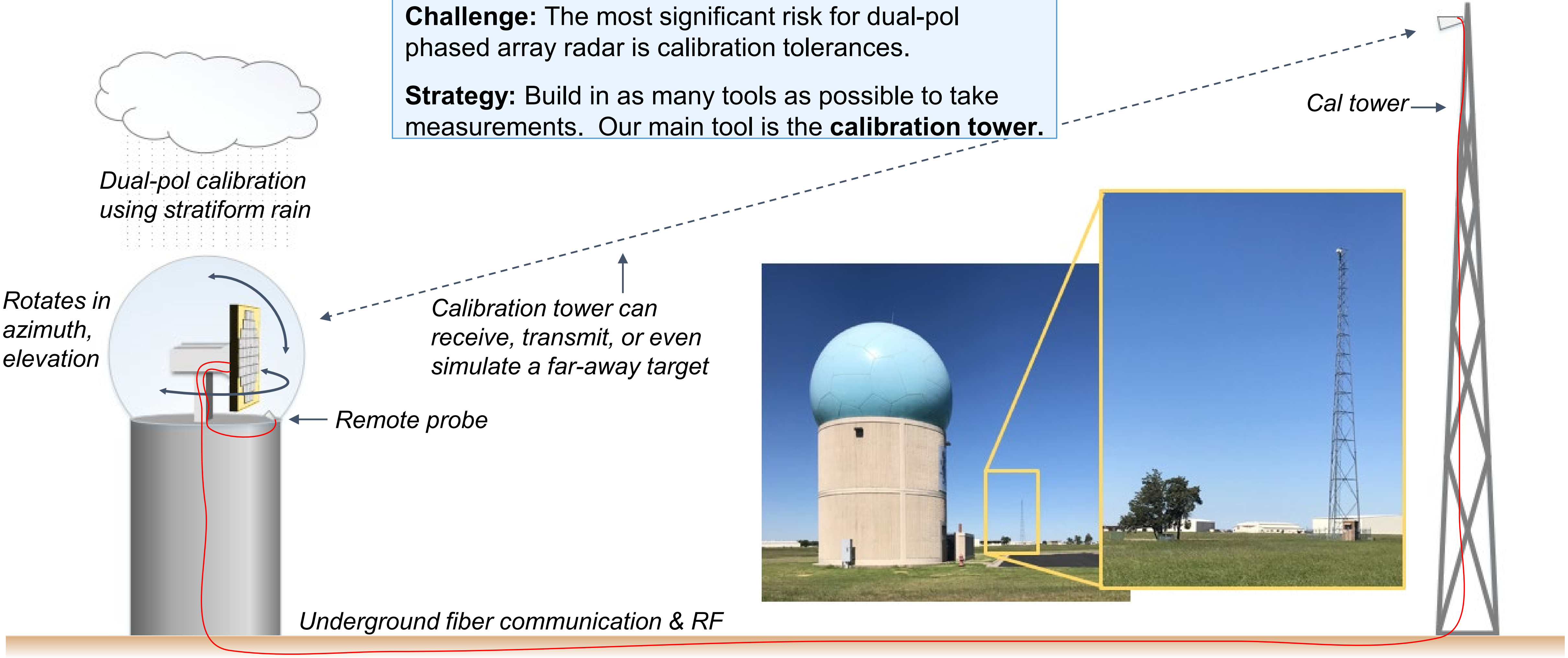
**Below:** Reverse side of the ATD antenna, with person for scale.  More than two thousand connections and a mile of cables connect the equipment on the pedestal.

**Above:** Completed system inside radome. Equipment racks on the elevation pedestal serve as counterweight and minimize the connections through a moving interface.

# Calibration Infrastructure

**Challenge:** The most significant risk for dual-pol phased array radar is calibration tolerances.

**Strategy:** Build in as many tools as possible to take measurements. Our main tool is the **calibration tower.**

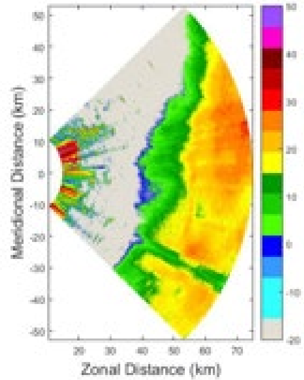


# ATD Timeline

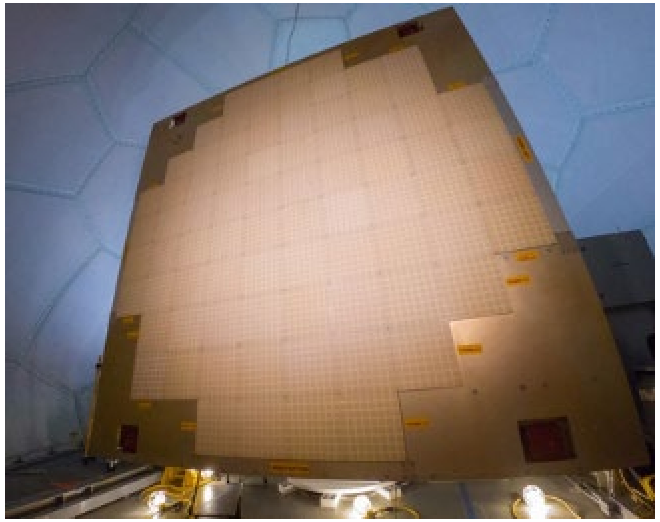
Greenlight for full-scale ATD

Dual-pol phased array prototype completed

ATD Installation in Norman




First weather images



**System testing successful**
**Declared operational!**

Production

Integration and Test

2014 2015 2016 2017 2018 2019 2020 2021

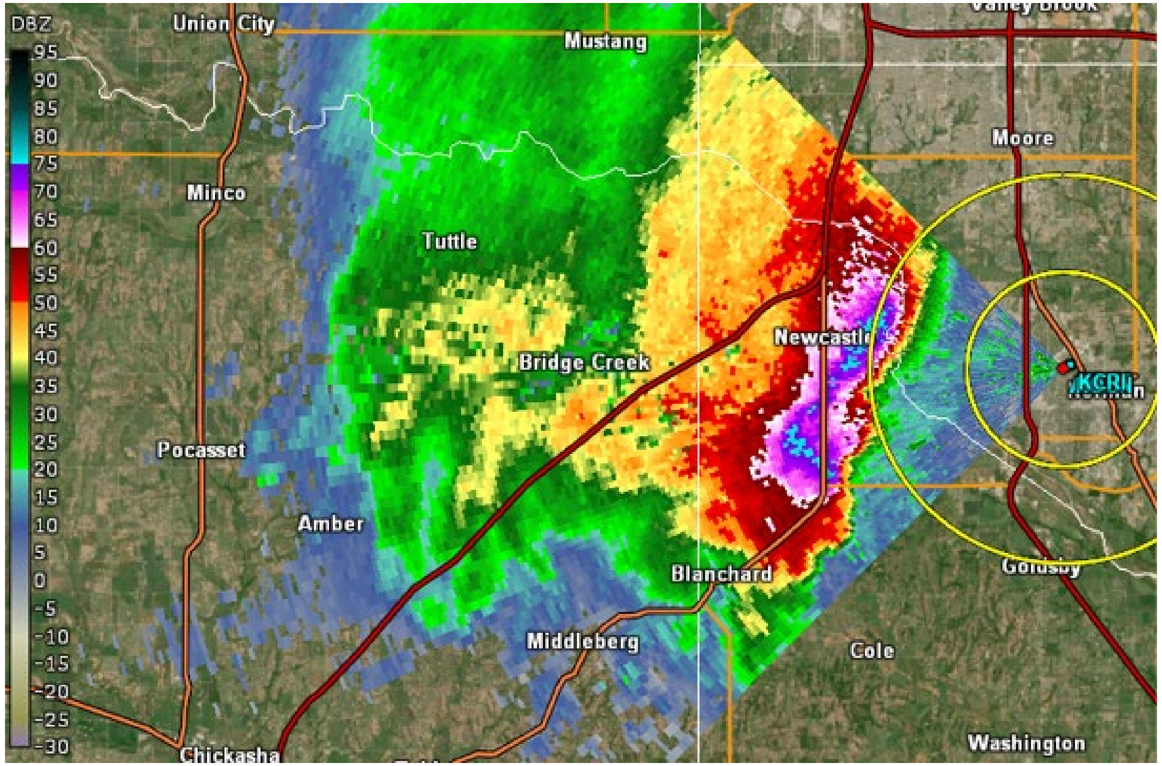
# ATD Engineering Status

## NSSL declared Initial Operating Capability (IOC) April 30, 2021

- IOC implies the ATD is deemed qualified for meteorological research—baseline functionality and trustworthy weather products
- Attention will turn toward proving meteorological benefits, but engineering R&D will continue

## Near future engineering work

- Focus on robust, reliable operation
- Improve the quality and repeatability of calibration measurements
- Inform NOAA and industry of design considerations and lessons learned



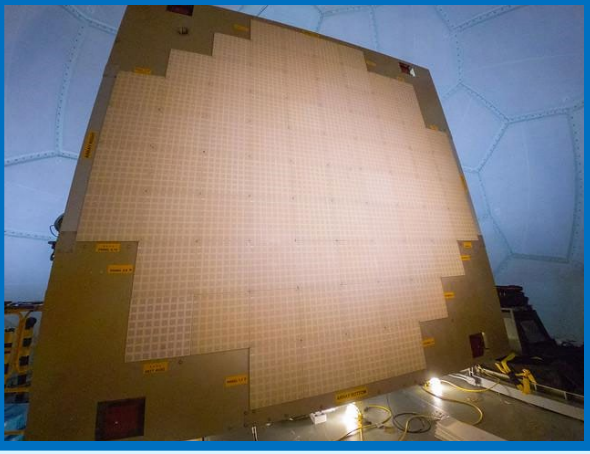
April 28, 2021 Norman hailstorm

# Observations and Understanding

## *Phased Array Radar R&D*

### *Engineering R&D*

*Sebastián Torres PhD, CIWRO Assistant Director for Radar R&D and Sr. Research Scientist, RRDD*

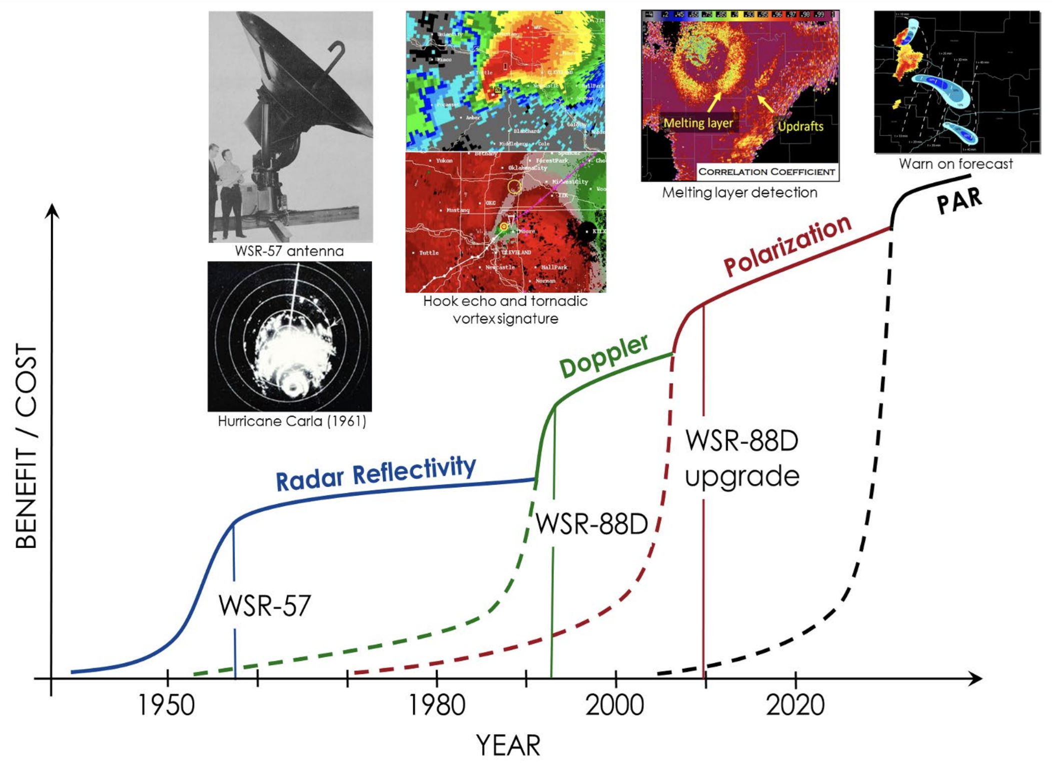
# PAR Engineering R&D

## Technology with a mission

- Is PAR the next radar revolution?

## Challenges and opportunities

- Developing **calibration** processes to produce high-quality radar data
- Designing an affordable **system** that can meet current/future NWS needs
- Exploiting **unique capabilities** to meet evolutionary radar requirements




## Our work will inform NOAA's future weather radar system investment decisions

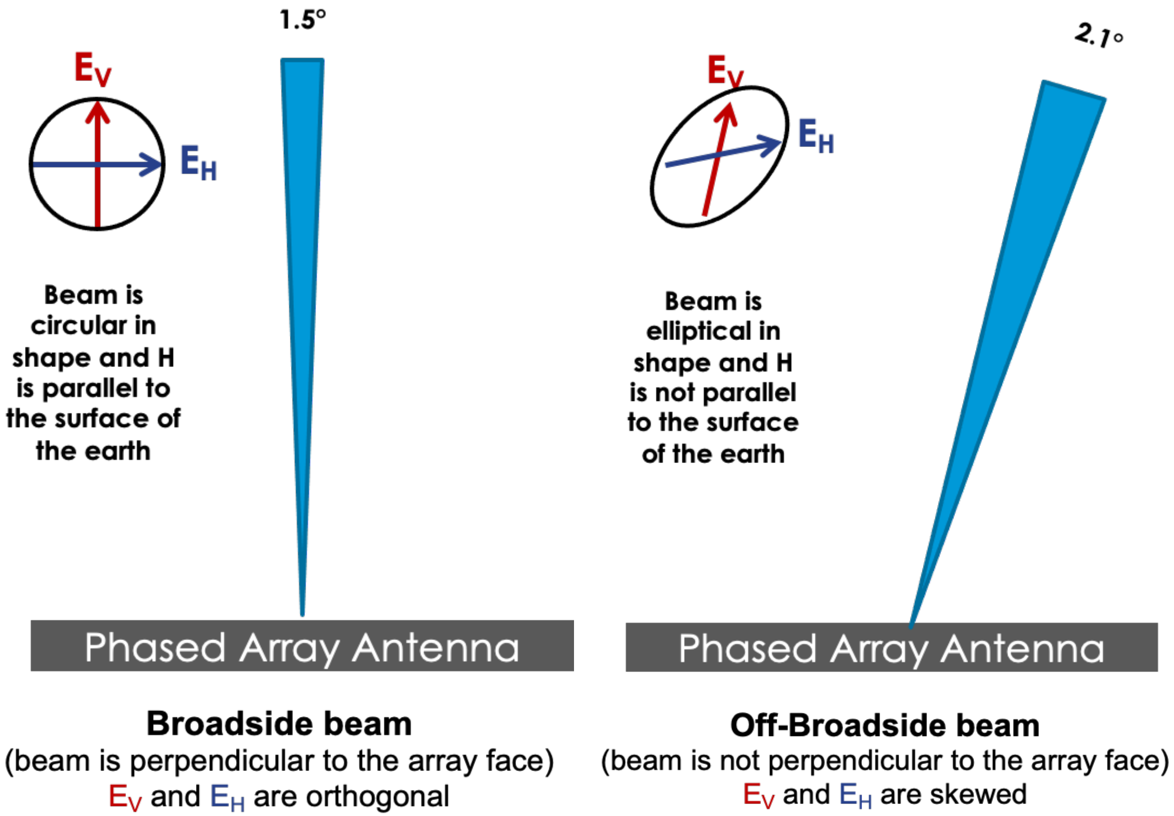
# The Challenge of PAR Calibration

## Polarimetric radars require precise characterization of radar beams

- The quality of weather observations depends on our ability to account for the radar system

## PAR electronic steering changes radar beams

- Pointing direction, beam shape, polarization orientation

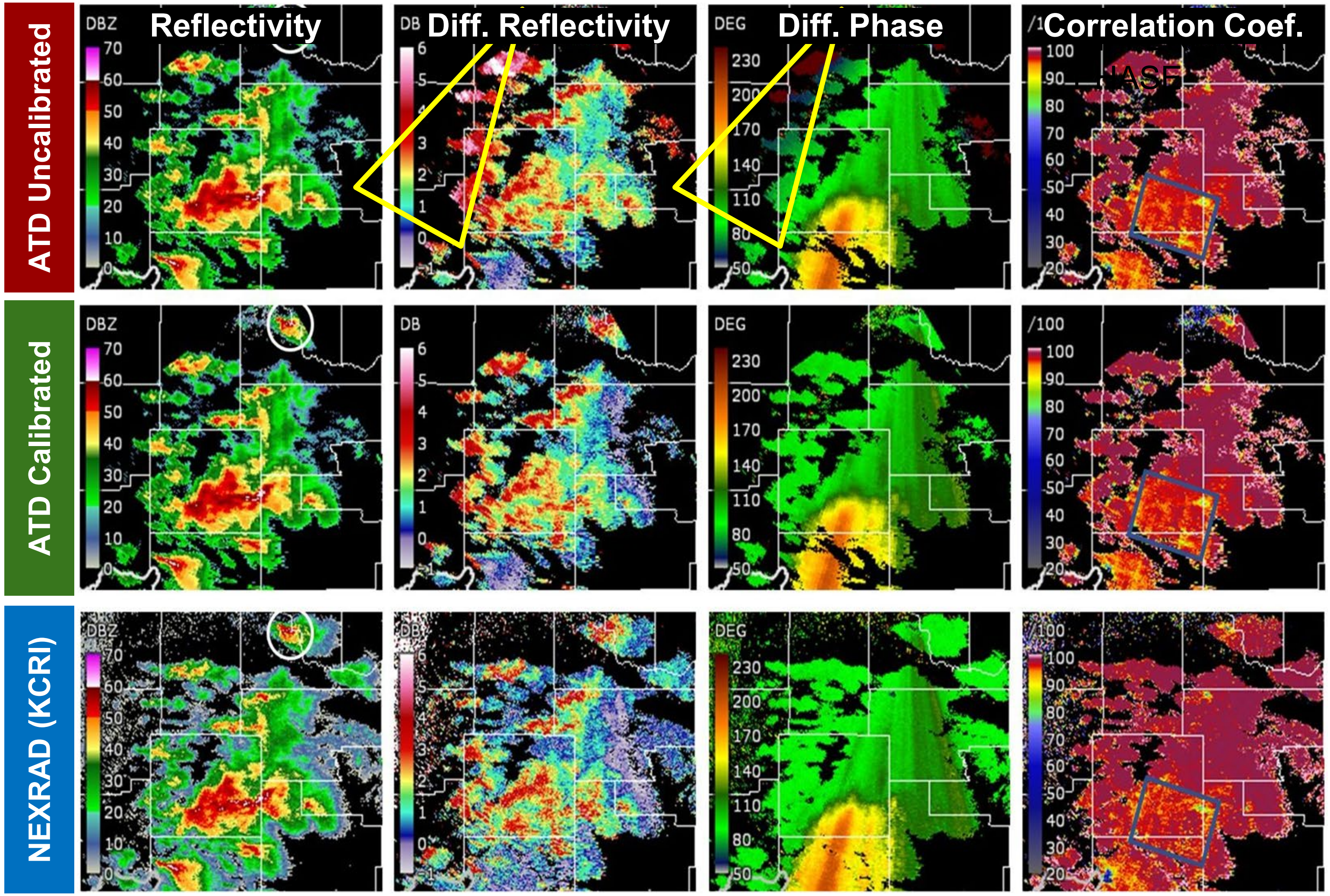



**Calibration of a dish antenna = characterize 1 beam**
**Calibration of a PAR antenna = characterize 1,000s of beams**

# ATD Calibration Demonstration

**ATD uncalibrated data show expected electronic steering artifacts**

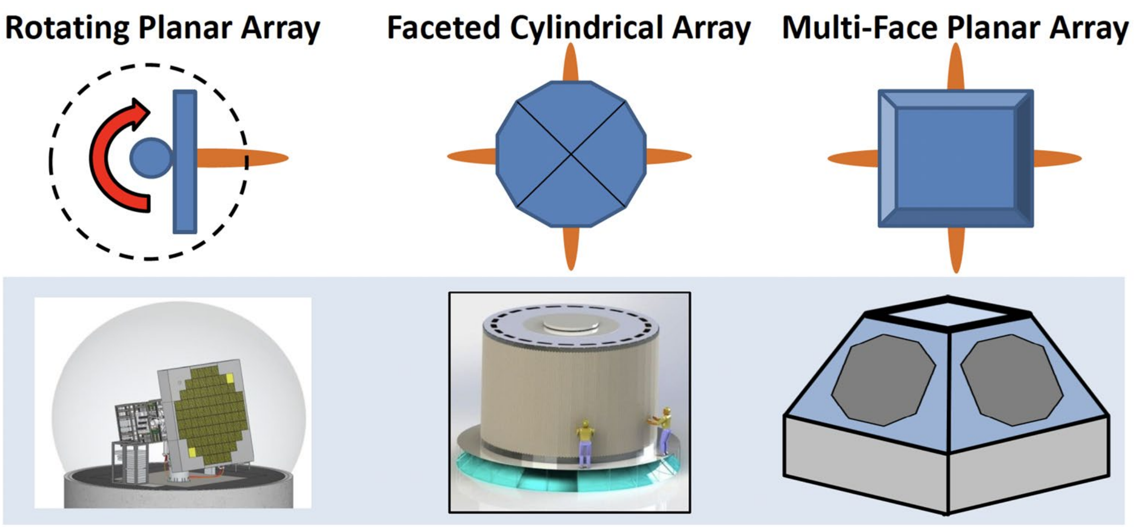
**ATD calibrated data agree well with data from a NEXRAD radar**

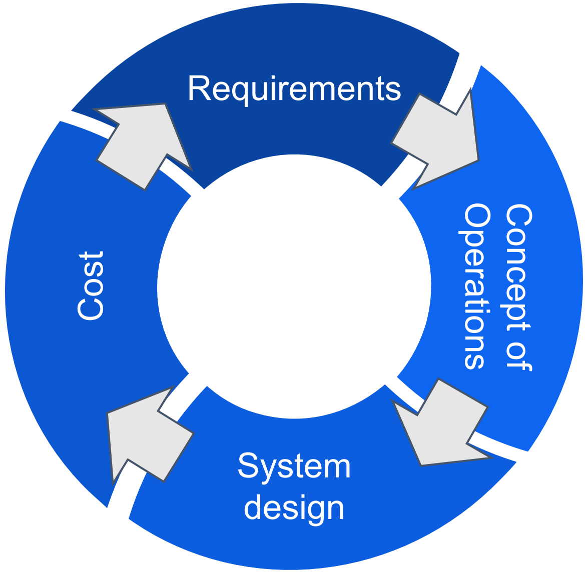


# The Challenge of PAR System Design

## PARs come in many *flavors*

- **Architecture** and **geometry** are key characteristics
- More advanced capabilities require more complex systems



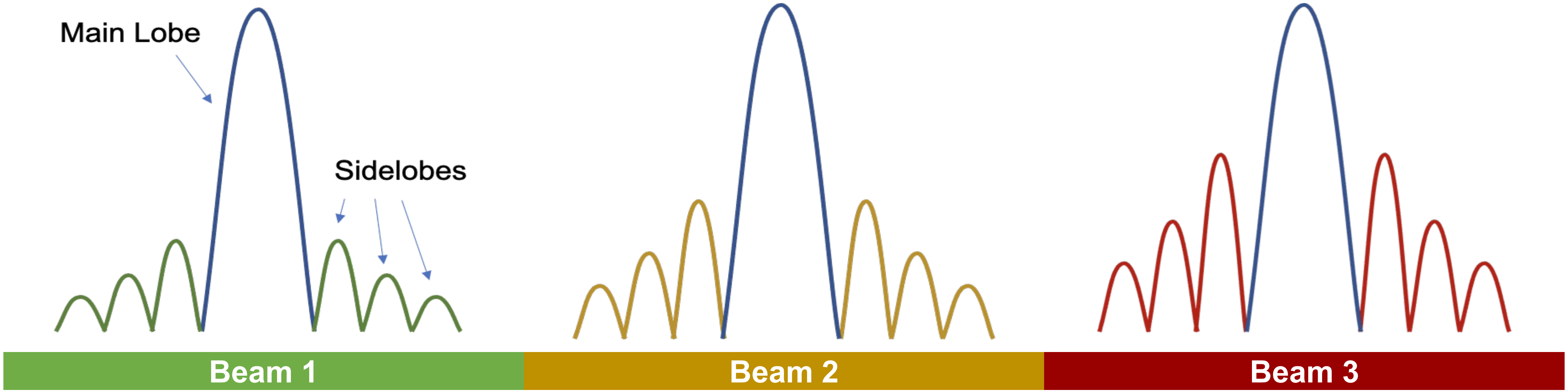

## PAR designs must consider trade-offs between cost and capabilities

- Any *concept of operations* meeting NWS requirements must be compatible with the capabilities/performance of the radar system

# Data Quality Simulations

## Simulator produces radar data as if they were obtained by radars with different characteristics

- Analysis of cost-driving **requirements**
- Evaluation of impacts to **forecaster interpretation**




From left to right, increasingly **degraded beam shapes**

# Data Quality Simulations

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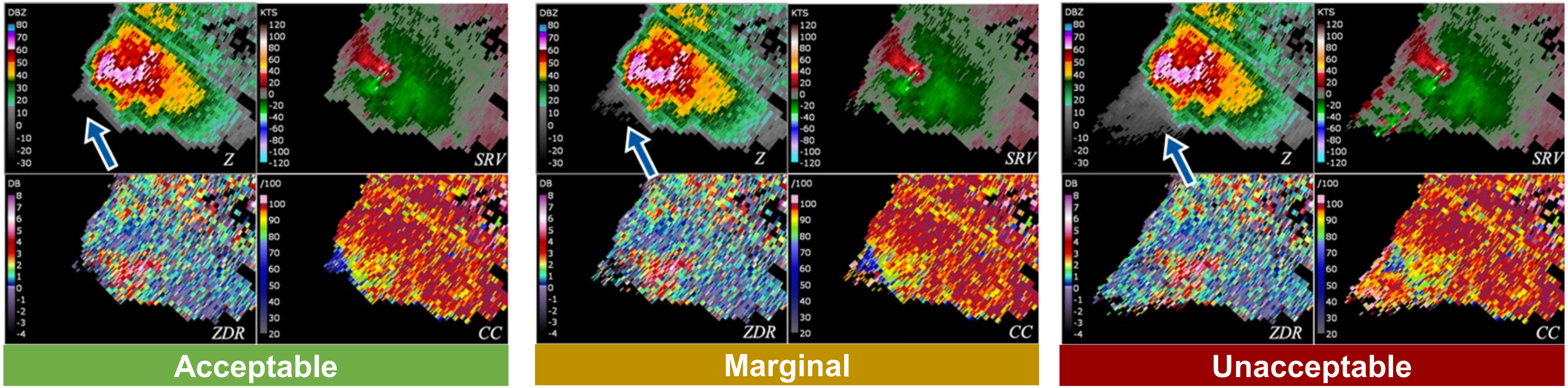



From left to right, simulated radar data obtained by radars with increasingly **degraded beam shapes**.
Impacts to forecaster interpretation are greater as the beam degradation increases.

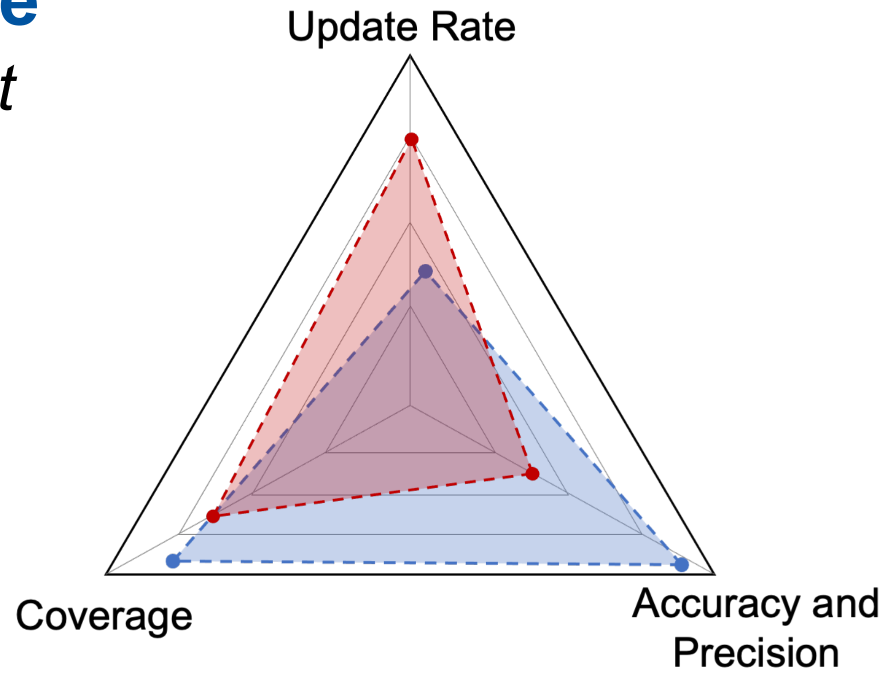
# The Opportunity of PAR Adaptive Scanning

## Adaptive scanning: automatically changing what the radar does in response to changes in the atmosphere

- *The radar you need when and where you need it*

## PAR's beam agility is the key to unlock the full potential of adaptive scanning

- Scans can be **focused** on regions of interest and **tailored** to get the best observations
- Fundamental **trade-offs** can be optimized to produce the radar data that users need, when and where they need it

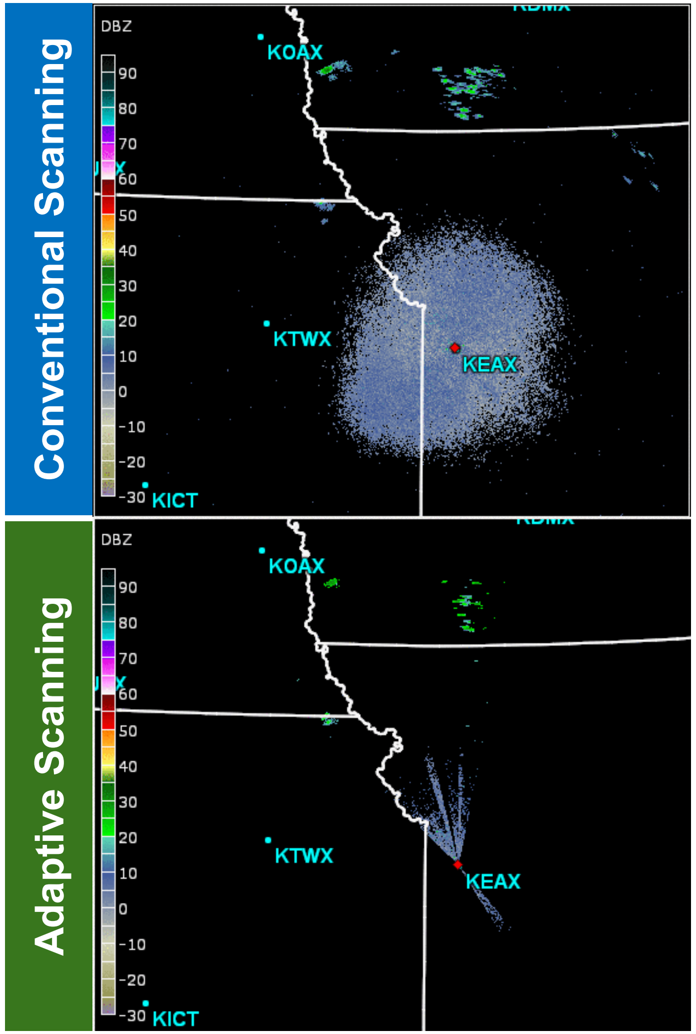



**Triangle of radar scanning trade-offs**
*area* = radar resources (constant)
*vertices* = scan performance (adaptable)

# Adaptive Scanning Simulations

## Simulations allow the development, demonstration, and evaluation of advanced scanning techniques

- compare performance of different techniques
- evaluate performance on different weather events
- compare performance of different radar designs




Simulated reflectivity fields obtained with conventional and adaptive scanning (**focused** and **tailored** scans). For this case, update times with adaptive scanning are **~5x faster** than with conventional scanning

# Future work

## Demonstrate PAR calibration

- Use ATD to assess calibration performance and to develop operational calibration techniques

## Demonstrate PAR capabilities

- Use ATD and simulations to evaluate radar design trade-offs and demonstrate advanced scanning and processing techniques

## Complete analysis of different PAR designs

- Explore single-face rotating geometry
- Demonstrate “all-digital” architecture (ARRC)

## Lead the design of future systems

- Assess NWS Radar Functional Requirements (MIT/LL)
- Use ATD to understand long-term O&M costs
- Document *lessons learned* to inform future developments

# Observations and Understanding

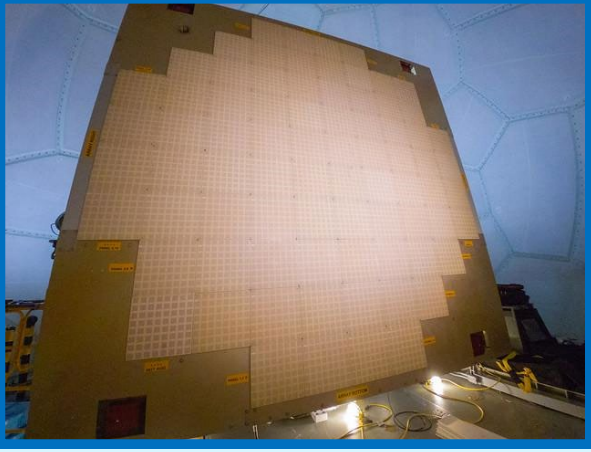
## *Phased Array Radar R&D*

### *Meteorological R&D*


*Charles Kuster*

*CIWRO Research Associate, RRDD*





# Determining Meteorological Benefits of Phased Array Radars

## Multiple pathways for looking at potential benefits

- Replace current radar network with phased array radars?
  - Requires proof of the benefits
- Process began with multi-year operational demonstration experiment
  - Continues with rapid-update dual-polarization studies

Forecasters providing feedback about rapid-update radar data

Collecting rapid-update dual-pol data

# Phased Array Radar Innovative Sensing Experiment (PARISE)

## Goal: Does radar update time matter?

- Build on previous PARISE experiments
- Involved participation of 30 NWS forecasters
- Forecasters saw various update times (1, 2, or 5-min) of single-pol data
- Warnings issued on severe weather hazards
- Focus groups to gather feedback and insights
- Eye-tracking experiment to gather even more quantitative information

Forecaster working a supercell case

Forecaster working through eye-tracking case

# Phased Array Radar Innovative Sensing Experiment (PARISE)

## PARISE Results:

- Use of rapid-update radar data:
  - Improved all tornado warning metrics
    - 1 min better than 2 min
  - Increased confidence in warning decision
  - Changed *when* warning was issued but not *how* it was issued
- Changes in displays, training, and warning paradigm likely needed
- What about dual-pol data?

| Warning Metric | 1-min Updates | 2-min Updates | 5-min Updates |
|---|---|---|---|
| Tornado warning lead Time (min) | 12.7 | 8 | 9 |
| Tornado warning probability of detection | 0.78 | 0.74 | 0.62 |
| Tornado warning false alarm ratio | 0.29 | 0.45 | 0.44 |

Wilson et al. (2017)

# KOUN Used to Provide Dual-Pol PAR Proxy

- Research WSR-88D (KOUN) can collect rapid-update dual-pol data
  - 90° sector scans every 1.5–2 min as a proxy for dual-pol phased array radar

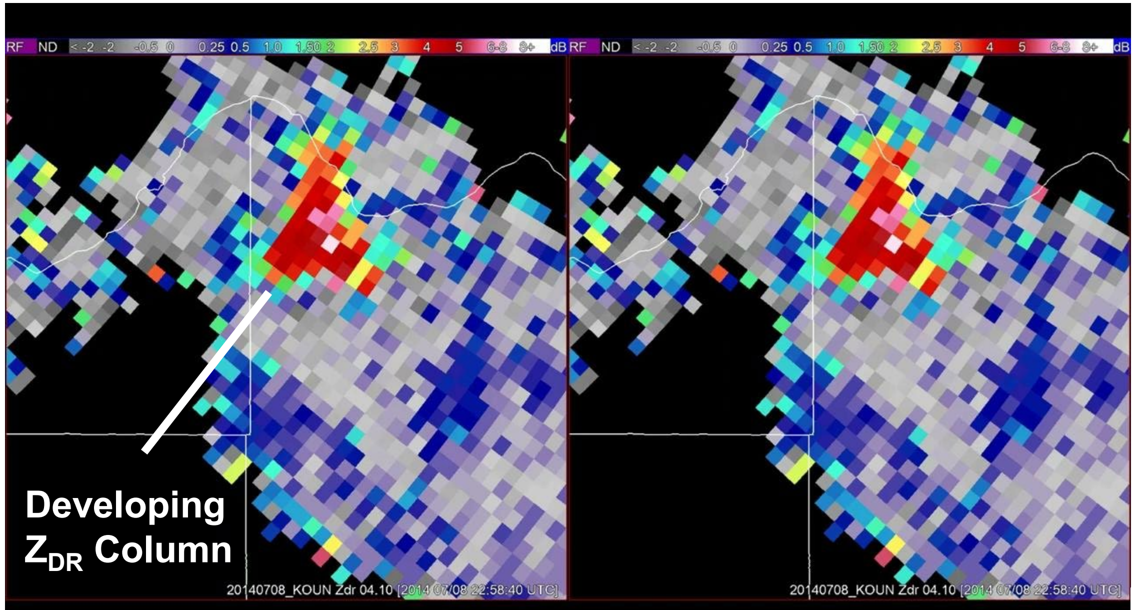
# Advantages of Rapid-Update Data to Forecasters

## Severe Storms

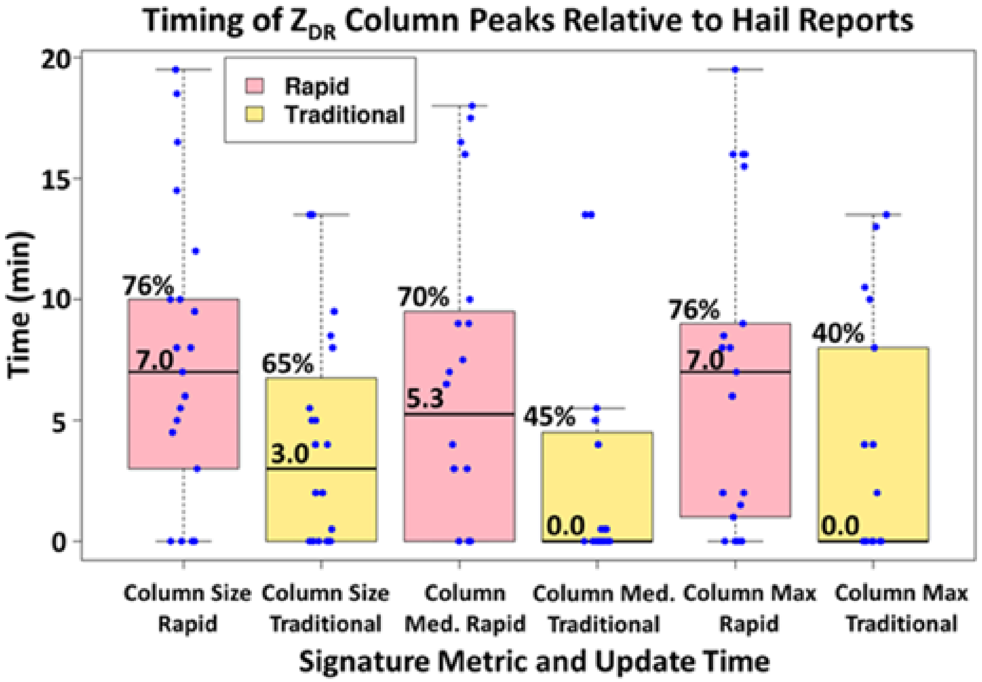
## Research radar (KOUN) collects rapid-update dual-pol data

- Goal: Can rapid-update dual-pol data be used to gauge storm severity?
- Data used to examine relationships between rapid-update dual-pol features and storm severity
- Useful signatures observed with severe hail and downbursts

**2-min data** **6-min data**




Animation:
https://drive.google.com/file/d/1-jLIFUxfhClr_3ltiey436V0iSEu4rZU/view?usp=sharing



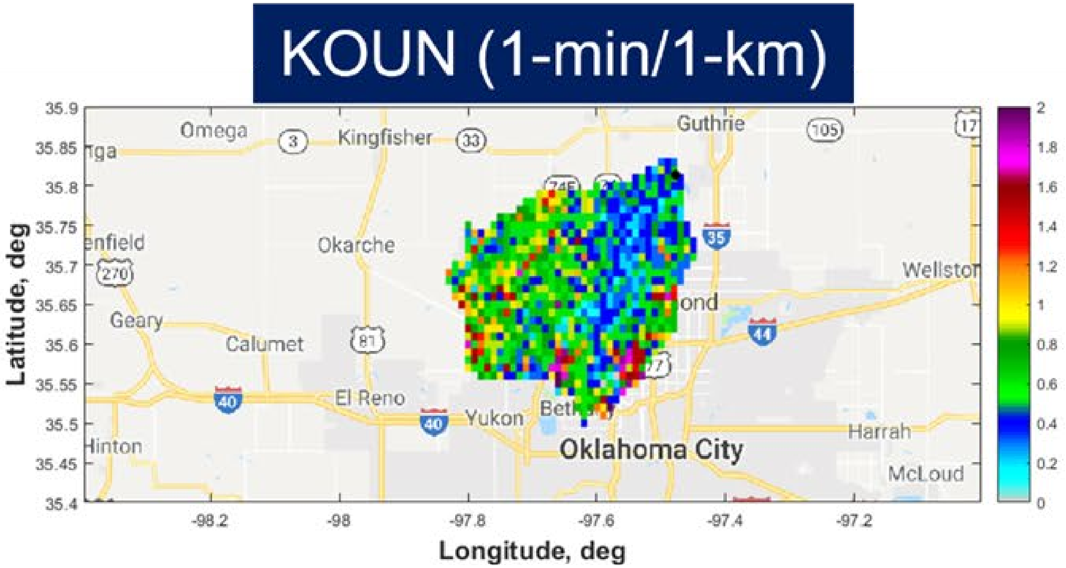

Rapid-update data (~2-min updates) observes $Z_{DR}$ column maximum strength earlier and more often than traditional-update data (~6-min updates). From Kuster et al. (2019).

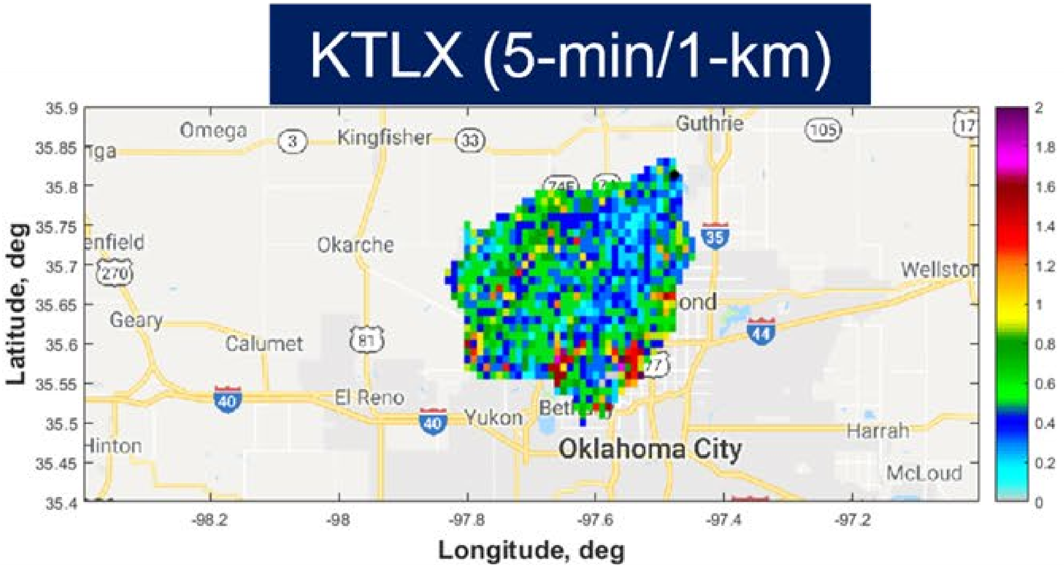
# Advantages of Rapid-Update Data to Forecasters

## Flash Floods

### Research radar (KOUN) collects rapid-update dual-pol data

- Goal: Can rapid-update dual-pol data be used to improve hydrologic models?
- Data used to examine impacts of different update times and datasets
- Compared to KOUN, **KTLX missed 50% of flash flood area**

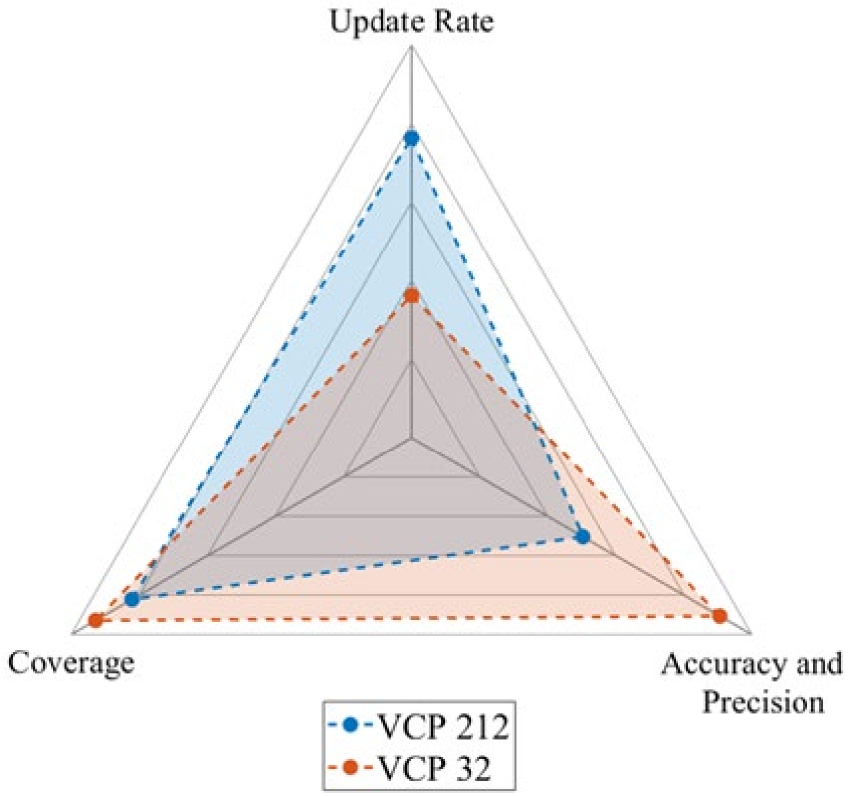



Wen et al. (2021)

# Future Work

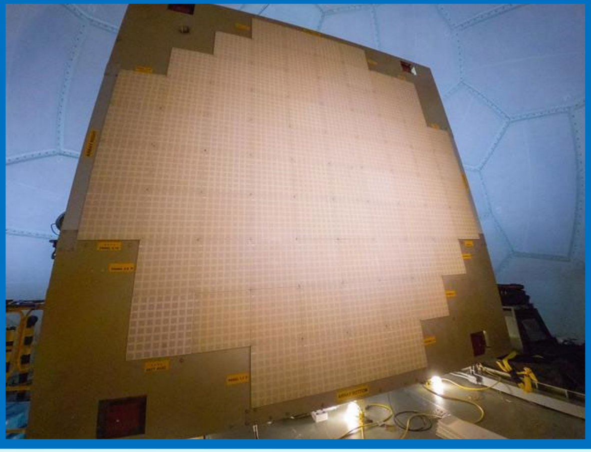
- Continue investigation of dual-pol benefits in predicting downbursts and tornadoes
- Work to understand tradeoffs between update rate, spatial sampling, and data quality for each unique severe weather hazard.
  - Evaluate ability of the ATD to perform WSR-88D function and any impact on forecasters and algorithms.
  - Develop more advanced scanning strategies
- Investigate how existing radar algorithms can best take advantage of the ATD's capabilities.
- Evaluate how rapidly- and adaptively- scanned radar observations can be integrated into future forecast and warning paradigms that are likely to include 1) advanced numerical models, 2) probabilistic warnings for severe weather hazards, and 3) MRMS.



# Observations and Understanding

# **Phased Array Radar R&D Future Plans**

Kurt Hondl, NSSL Deputy Director & PAR R&D Manager

# Current State of PAR R&D

- **Phased Array Radar capabilities**
  - Benefits of rapid updates
  - Adaptive scanning
  - All-digital technologies
- **Phased Array Radar challenges**
  - Dual polarization calibration
  - Rapid scanning technologies
  - Data quality
- **Warning and Forecast benefits**
  - Improved warning lead times
  - Improved guidance via Warn-on-Forecast
- **Additional R&D**
  - Rotating PAR concept
  - PAR technical configurations

**July 2021**

BAMS Article

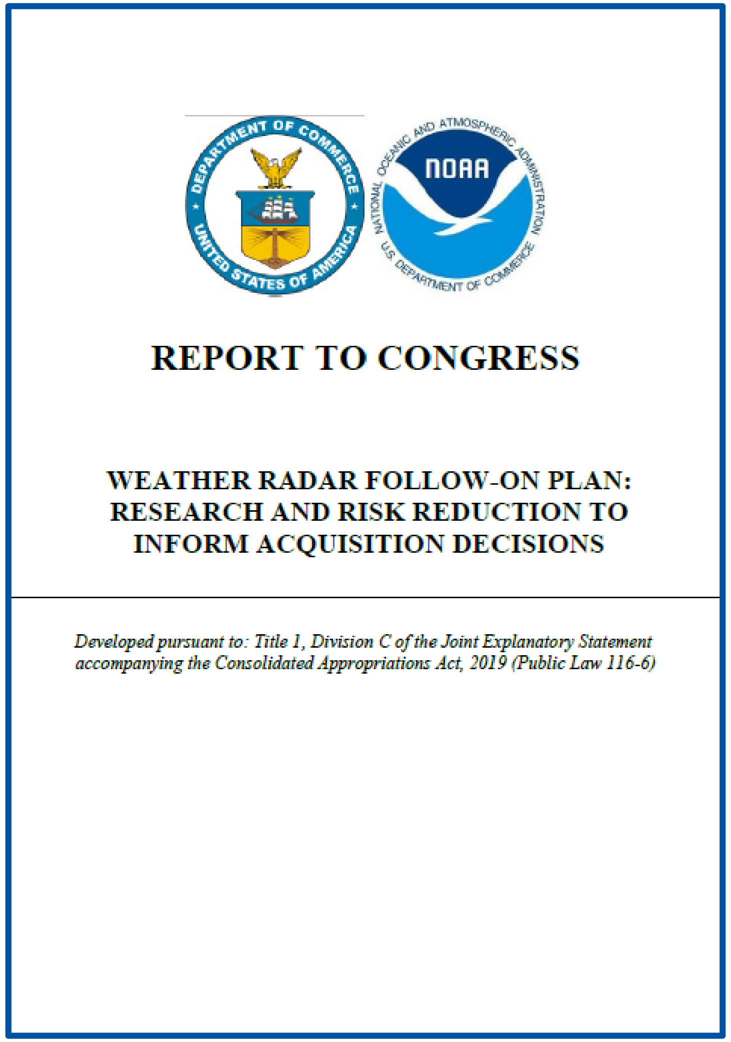
### Towards the Next Generation Operational Meteorological Radar

**Mark Weber**, **Kurt Hondl, Nusrat Yussouf**, Youngsun Jung, **Derek Stratman**, Bryan Putnam, Xuguang Wang, **Terry Schuur**, **Charles Kuster**, **Yixin Wen**, Juanzhen Sun, Jeff Keeler, Zhuming Ying, John Cho, James Kurdzo, **Sebastian Torres**, **Chris Curtis**, **David Schvartzman**, **Jami Boettcher**, **Feng Nai**, Henry Thomas, **Dusan Zrnić**, **Igor Ivić**, **Djordje Mirković**, Caleb Fulton, Jorge Salazar, Guifu Zhang, Robert Palmer, Mark Yeary, Kevin Cooley, Michael Istok, and Mark Vincent

This article summarizes research and risk reduction that will inform acquisition decisions regarding NOAA's future national operational weather radar network. A key alternative being evaluated is polarimetric phased-array radar (PAR). Research indicates PAR can plausibly achieve fast, adaptive volumetric scanning, with associated benefits for severe-weather warning performance. We assess these benefits using storm observations and analyses, observing system simulation experiments, and real radar-data assimilation studies. Changes in the number and/or locations of radars in the future network could improve coverage at low altitude. Analysis of benefits that might be so realized indicates the possibility for additional improvement in severe-weather and flash-flood warning performance, with associated reduction in casualties. Simulations are used to evaluate techniques for rapid volumetric scanning and assess data quality characteristics of PAR. Finally, we describe progress in developing methods to compensate for polarimetric variable estimate biases introduced by electronic beam-steering. A research-to-operations (R2O) strategy for the PAR alternative for the WSR-88D replacement network is presented.

# Weather Radar Follow-On Plan

- **Consolidated Appropriations Act of 2019 requested NOAA's weather radar follow-on transition-to-operations plan**
- **Key Elements ...**
  - Sustain and enhance NEXRAD through current expected service life (2035)
  - Conduct PAR R&D to reduce technical risk and inform future acquisition
  - Protect NEXRAD spectrum
  - Organize for success



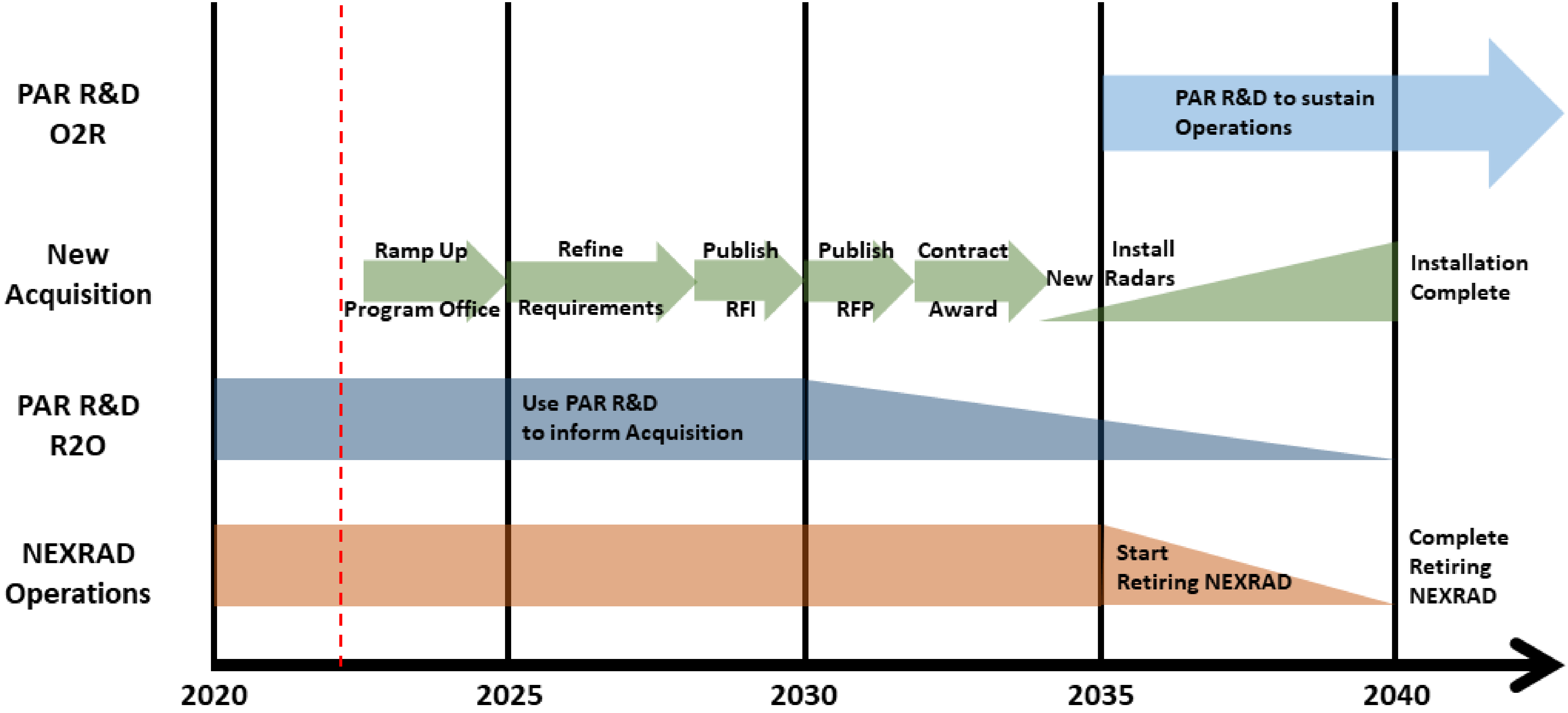
REPORT TO CONGRESS

WEATHER RADAR FOLLOW-ON PLAN: RESEARCH AND RISK REDUCTION TO INFORM ACQUISITION DECISIONS

*Developed pursuant to: Title 1, Division C of the Joint Explanatory Statement accompanying the Consolidated Appropriations Act, 2019 (Public Law 116-6)*

# SCHEDULE – PAR R&D Program
## (FY20 and beyond)

Adapted From the ***Weather Radar Follow-On Plan*** Report to Congress delivered 15 June 2020



# Weather Radar Follow-On Plan

- **Future Acquisition Key Decision in ~2030**
  - **Analysis of Alternatives** including cost/benefit analysis
    - Another Service Life Extension Program for the WSR-88D
    - Replace WSR-88D with modern reflector dish technology
    - Replace WSR-88D with PAR technology
      - Multiple PAR configurations possible
  - Key decision timeline gives us 8 years of PAR R&D to ensure PAR is a viable alternative as a WSR-88D replacement
    - Will necessarily include industry engagement
  - What will PAR technology alternative look like?

# PAR R&D Next Steps

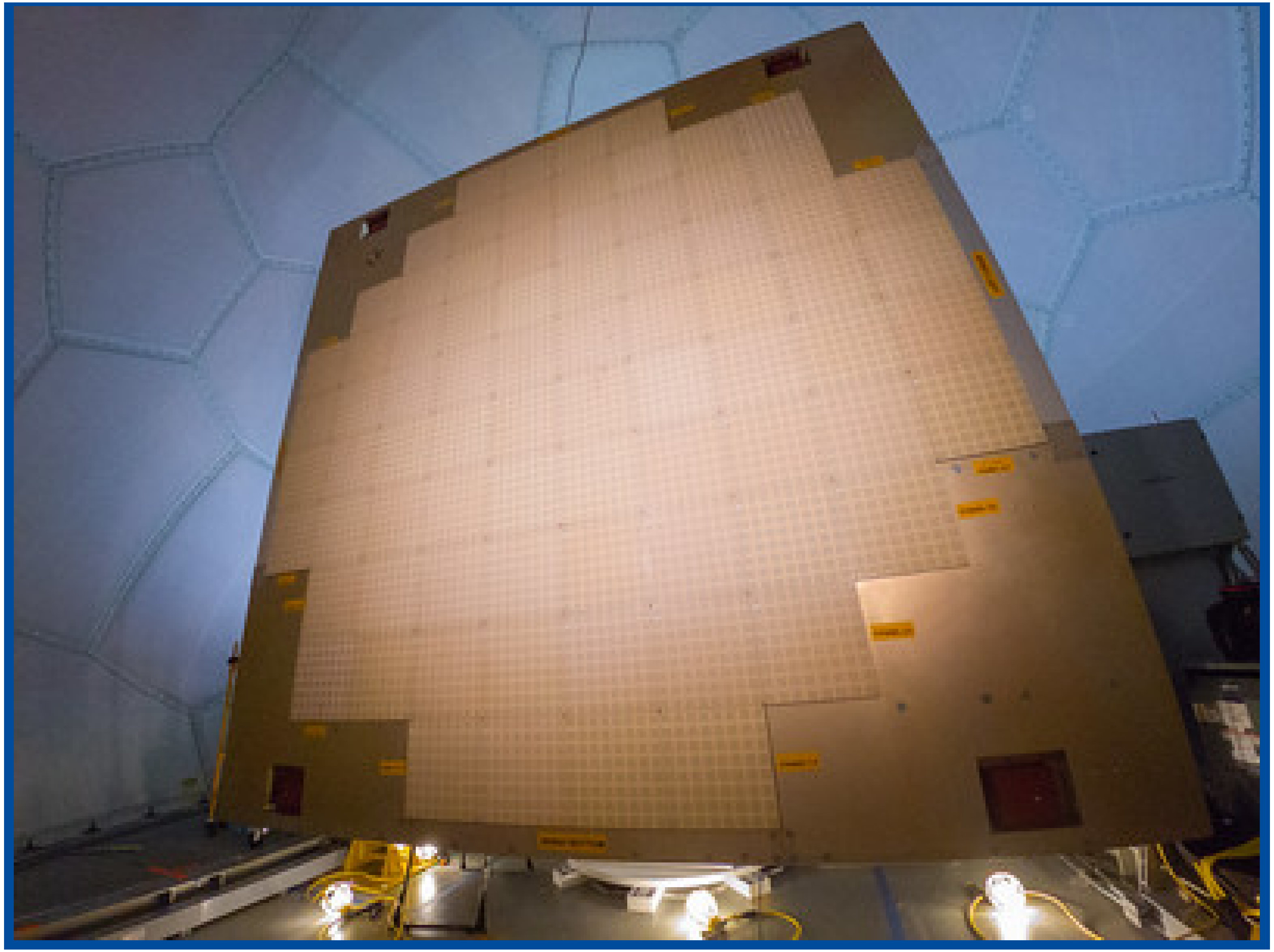
- **Gain useful information from ATD**
  - Development of calibration tools suitable for an operational platform
  - Meteorological studies of rapid update dual polarization observations
- **Gain useful information from other technology demonstrators**
  - Funded all-digital PAR development at OU Advanced Radar Research Center (ARRC) and Massachusetts Institute of Technology Lincoln Laboratory (MIT/LL)
- **Continue research as outlined in *Weather Radar Follow-On Plan* …**
  - Develop additional technology demonstrators to further reduce risk
  - Work with NWS to establish collaborative R&D and acquisition planning

# PAR R&D - Key Questions for Next Review

- Will PAR be a viable alternative as a WSR-88D replacement?
- How can we ensure that future WSR-88D replacement meets the needs of future NWS operational requirements?
- What will the PAR alternative look like?

# Thank You

on behalf of the NSSL PAR R&D team.



More photos and videos of the ATD can be found here … https://www.flickr.com/photos/noaanssl/albums/72157699464311325/with/43118021910/