Phased-Array Radar
Unique Capabilities

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Multifunction Phased-Array Radar Symposium
Phased-Array Radar Workshop

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Pioneer Use of Array Capabilities

• Archimedes heat ray (215-212 BC)
  - Mirrors acting collectively as a parabolic reflector

Outline (and Disclaimer)

• **PAR Unique Capabilities** derived from
  - Antenna physical design
  - Electronically steerable beam
  - Adaptive array

• My approach for this workshop
  - What is possible vs. what makes sense
  - Derived capabilities
  - No calculus!
  - Background material
  - Not comprehensive
  - A little biased towards weather

😊 Advantage

😢 Disadvantage

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Figure 3: Illustration of potential for PAR capabilities to translate into weather service improvements.
# What's Unique to PAR?

<table>
<thead>
<tr>
<th>Parabolic Antenna</th>
<th>Phased Array Antenna</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Single radiation element</td>
<td>- Multiple radiation elements</td>
</tr>
<tr>
<td>- Single transmitter</td>
<td>- Multiple transmitters</td>
</tr>
<tr>
<td>- Single receiver</td>
<td>- Multiple receivers</td>
</tr>
<tr>
<td>- Non-conformal</td>
<td>- Conformal</td>
</tr>
<tr>
<td>- Fixed beam pattern</td>
<td>- Variable beam pattern</td>
</tr>
<tr>
<td>- Mechanical steering</td>
<td>- Electronic steering</td>
</tr>
</tbody>
</table>

[Parabolic Antenna Image](image1.png)
[Phased Array Antenna Image](image2.png)
Graceful Degradation

- Passive array or conventional radar
  - One transmitter/receiver
  - Catastrophic loss of function
- Active array
  - Many T/R elements
  - No single point of failure
  - Maintenance not urgent

"The Navy's experience with the SPY-1 PAR demonstrates that up to 10% of the T/R elements can fail before there is significant degradation in performance."
(Source: JAG/PARP report 2006)

Source: Evaluation of the MPAR Planning Process (NRC 2008)
Beam Blockage Mitigation

- Beam blockage occurs when the radar beam is blocked by terrain
  - Blockage may be total or partial
  - Blockage introduces biases in meteorological products

- Electronic steering can be exploited to “graze” the horizon
Elimination of Beam Smearing

- Radars use many samples of a resolution volume to reduce errors of estimates
  - Mechanically steered antenna
    - Samples come from different volumes
    - Beam is smeared
  - Electronically steered antenna
    - Samples come from the same volume
    - Beam is not smeared
    - No moving parts!
Spatial Resolution

- Antenna motion creates effective broadened beamwidth
  - Mitigated via signal processing at the price of larger errors of estimates

Legacy Resolution  Super-Resolution

- A PAR uses intrinsic beam resolution without degradation in data quality
The Doppler Spectrum

- Power-weighted distribution of Doppler velocities in the radar volume
Ground Clutter Filtering

- Beam smearing leads to decorrelation of signals
  - Each sample comes from a slightly different volume!
- Beam smearing leads to spectral broadening
  - Ground clutter contaminates a larger fraction of the spectrum and overlaps more with signal of interest
Spectrum Width Measurements

- The spectrum width measures the relative motion of scatterers in the radar volume
  - Turbulence and shear
- The spectrum width depends on beam smearing
  \[
  \sigma_v^2 = \sigma_s^2 + \sigma_d^2 + \sigma_o^2 + \sigma_t^2 + \sigma_\alpha^2
  \]
  - Meteorological
  - Beam smearing
  - For typical rotation rates on the WSR-88D
    - \( \sigma_\alpha \approx 10\% \) of typical spectrum width of weather signals
- No beam smearing leads to
  - More meaningful spectrum width estimates
Spectrum Width and Data Quality

• Spectrum width dictates the variance of measurements
  - Larger spectrum widths lead to larger errors of velocity estimates

\[ \sigma_v^2 = \sigma_s^2 + \sigma_d^2 + \sigma_o^2 + \sigma_t^2 + \sigma_\alpha^2 \]

Meteorological \hspace{1.5cm} Beam smearing

• No beam smearing leads to
  - More accurate velocity estimates
Data Quality vs. Update Time (1)

- Faster updates vs. data quality
  - Update time depends on time spent at each position
  - Faster updates can be achieved by spending less time at each position
    - Reducing the number of positions is not an option!
  - Less time at each position results in fewer samples for integration
  - Fewer samples for integration lead to larger variance of measurements
    - Techniques can be used to maintain the variance while reducing the number of samples
      - Range oversampling
      - Pulse compression
How Fast Can We Go?

- Faster updates
  - Mechanically steered antenna
    - Higher antenna rotation rates
      - Increased wear and tear
      - Limited by pedestal characteristics
      - Possible loss of gain
  - Electronically steered antenna
    - Can dwell as short as needed on each position
Data Quality vs. Update Time (II)

- Variance reduction from integration depends on number of samples
  - More independent samples can be obtained by increasing the time between samples

- Increasing the time between samples increases the update time!
Beam Multiplexing

- Allows more time between samples without increasing the update time
  - Multitasking leads to faster updates

Faster updates and/or lower errors

Incompatible w/ standard processing
Multifunction

- Single radar can be shared among more than one radar function
  - Frequency diversity
    - Same as multiple radars sharing one antenna
    - Not unique to PAR
  - Imaging radar
    - Beams formed via signal processing
    - High data throughput
    - Computationally intensive
  - Time multiplexing
    - Tasks are interleaved
    - Needs scheduling
      - Priority, location, severity, …
    - Possibility of overloads!

Resource sharing

Feasibility
Elevation-Prioritized Scanning on the NWRT PAR

• Strategy yields different update times at different elevations by scheduling 14 tilts in a non-sequential manner
  - Low-levels: 42 s updates
  - Midlevels: 84 s updates
  - Upper-levels: 126 s updates

• Currently working on schedule-based scanning
  - Multifunction capabilities
    • Aircraft tracking
    • Weather surveillance
Scheduling Multiple Tasks

Tracking two cells and surveillance

Tasks requested

Tasks scheduled

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Courtesy of R. Reinoso (OU)
Adaptive Scanning (1)

Conventional scanning
- Everywhere
- Sequential

Adaptive scanning
- Areas of interest only
- Arbitrary

- Faster updates
- May miss new developments

Courtesy of C. Curtis (NSSL)
Adaptive Scanning (II)

- Focused Observations
  - Scan areas of interest only
  - Perform periodic surveillance

- Adaptive Acquisition
  - Adjust acquisition parameters on the fly
  - Number of samples
    - Spectral Processing
  - Pulse repetition time
  - Waveform
    - Staggered PRT
    - Phase coding
    - Beam Multiplexing

😊 Faster updates
😊 Improved data quality
😃 Complex decisions
Adaptive Scanning on the NWRT PAR

- **ADAPTS**: Adaptive DSP Algorithm for PAR Timely Scans
  - Beam positions are classified as *active* or *inactive*
    - Only *active* beam positions are scanned
    - Full volume scans are scheduled periodically
  - Active beam positions meet one or more criteria
    - Elevation angle
    - Continuity and coverage
    - Neighborhood

![Real-time display of active beam positions](image)
Monopulse Tracking

- Single beam tracking
  - Cannot resolve position within the beam
- Conical-scan tracking
  - Errors due to noise and target fluctuation
  - Easily jammed
- Monopulse tracking
  - Split antenna aperture
  - Received sum ($\Sigma$) and difference ($\Delta$) channels

😊 Improved tracking accuracy
😊 Computational complexity

Source: www.radartutorial.eu
Interferometry

- Spaced antenna interferometry (SAI)
  - Complementary to the Doppler method
  - Used by wind profilers for 50+ years
  - Uses two or more spaced antennas
  - Cross-correlation of signals from spaced antennas can be used to measure winds & shear perpendicular to the beam direction

Better wind measurements

Long dwell times

Cross-correlation peak shifts due to signal delay passing over spaced antennas

Source: Doviak and Zhang (2008)
Adaptive Beamforming

• Spatial filtering
  - Antenna pattern can be altered using active array or auxiliary channels
  - Nulls can be placed in the direction of clutter

Source: Le (2009)

😊 Improved data quality
😊 Computational complexity
Imaging Radar

- Wide ("spoiled") transmit beam
  - Rapid volumetric coverage
  - In the extreme: ubiquitous radar

- Narrow receive beams
  - "Atmospheric camera"
  - Digital beamforming can generate "infinite" simultaneous beams via software
  - Can control resolution and spatial sampling
  - Can mitigate clutter contamination

- Simultaneous multifunction
  - No time multiplexing
  - Limited by BW & processing capacity

😊 Faster updates
 ربما Sensitivity loss
 ربما Computational complexity
Summary

• Agile beam, active phased array radars like the proposed MPAR have unique capabilities relative to conventional rotating-antenna radars
  - Antenna physical design
  - Electronically steerable beam
  - Adaptive array

• Careful tradeoff analyses should be conducted before implementing one or more of these capabilities
Thank you!

Any questions?

For more information about the demonstration of new capabilities on the NWRT PAR visit:

http://cimms.ou.edu/~torres