Phased-Array Radar Unique Capabilities

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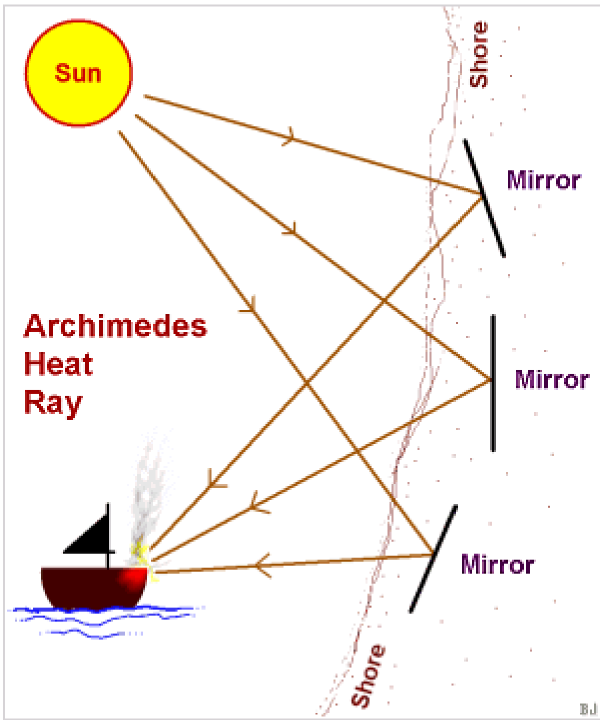
Multifunction Phased-Array Radar Symposium
Phased-Array Radar Workshop

17 November, 2009

Pioneer Use of Array Capabilities

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



Source: Wikipedia

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**

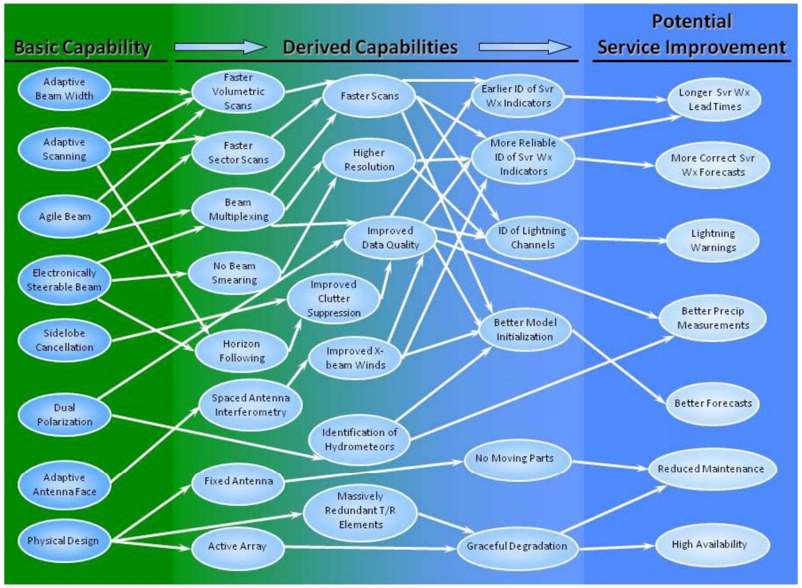


Figure 3: Illustration of potential for PAR capabilities to translate into weather service improvements

What's Unique to PAR?

Parabolic Antenna

- Single radiation element
  - Single transmitter
  - Single receiver
- Non-conformal
- Fixed beam pattern
- Mechanical steering

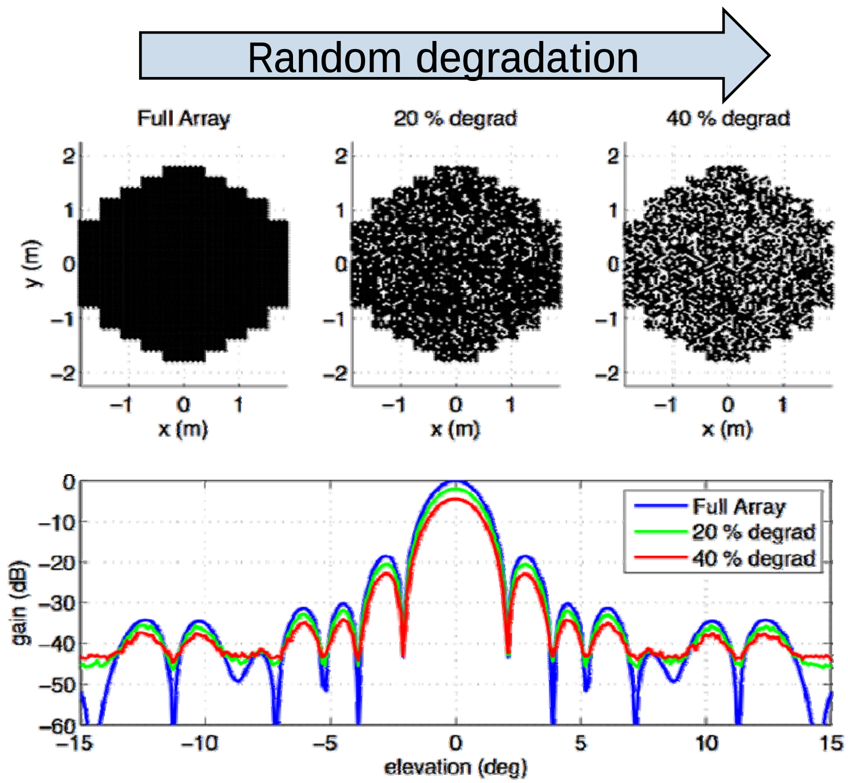
Phased Array Antenna

- Multiple radiation elements
  - Multiple transmitters
  - Multiple receivers
- Conformal
- Variable beam pattern
- Electronic steering

1 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)

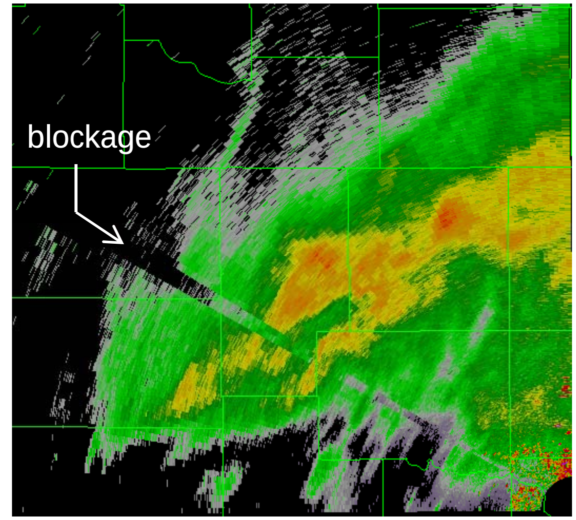


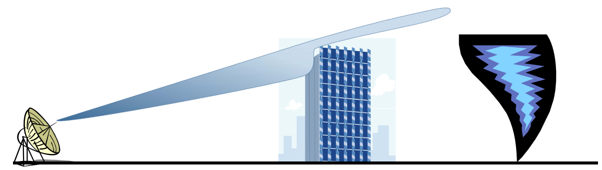
Source: Evaluation of the MPAR Planning Process (NRC 2008)

2

Beam Blockage Mitigation

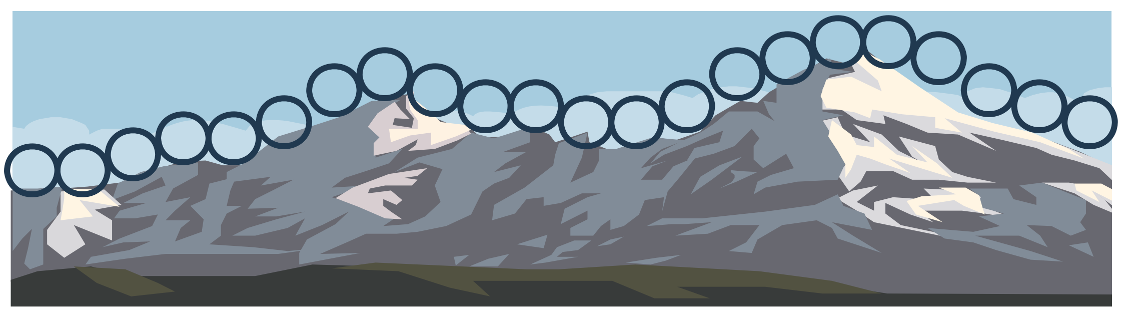
- Beam blockage occurs when the radar beam is blocked by terrain
  - Blockage may be total or partial
  - Blockage introduces biases in meteorological products





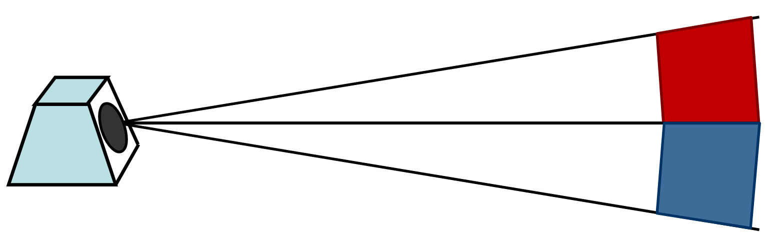
- Electronic steering can be exploited to “graze” the horizon

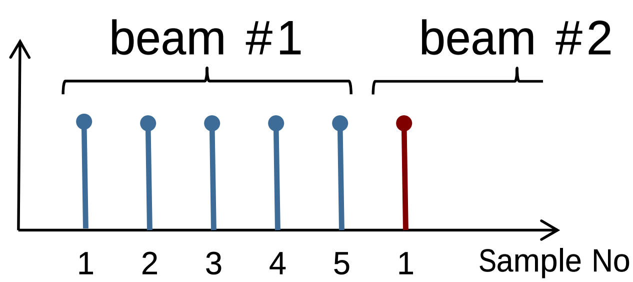
Electronically Steered Elevation



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!

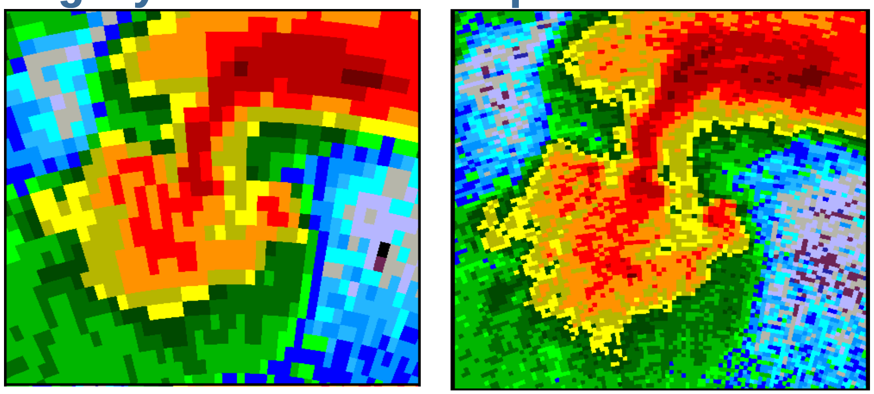




Spatial Resolution

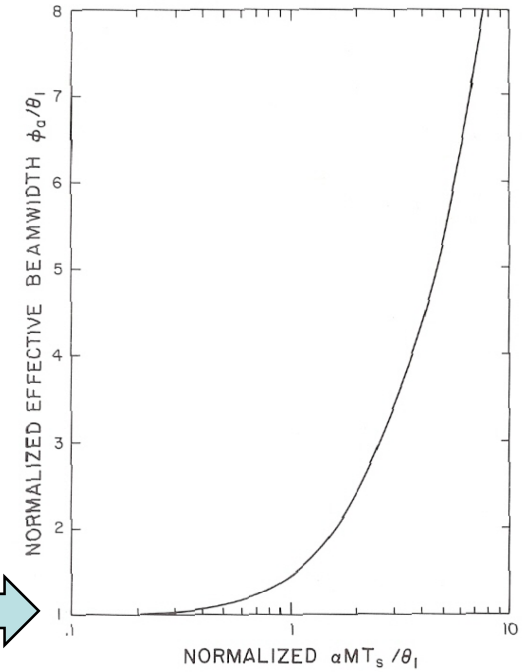
- Antenna motion creates effective broadened beamwidth
  - Mitigated via signal processing at the price of larger errors of estimates

Legacy Resolution **Super-Resolution**



Tornado outbreak in Oklahoma City, 9 May 2003
(Source: Curtis et al. 2003)

Effective beamwidth for a scanning antenna as a function of rotation rate

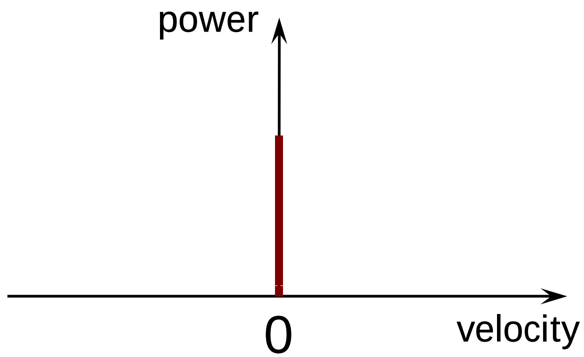


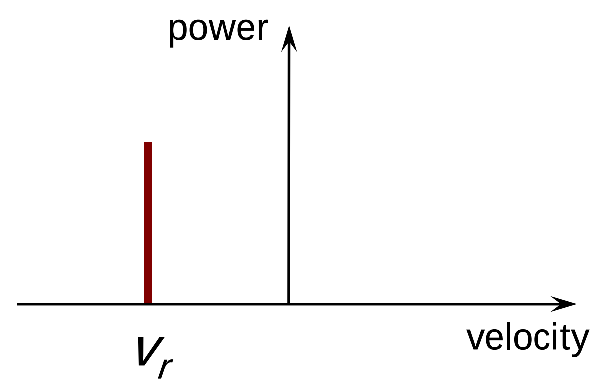
Source: Doppler Radar and Weather Observations (Doviak and Zrnic 1993)

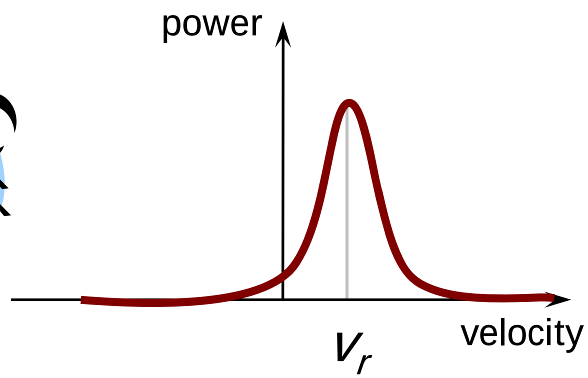
  - A PAR uses intrinsic beam resolution without degradation in data quality

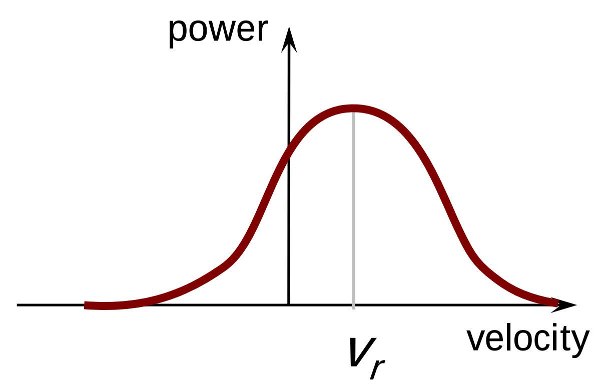
The Doppler Spectrum

- Power-weighted distribution of Doppler velocities in the radar volume



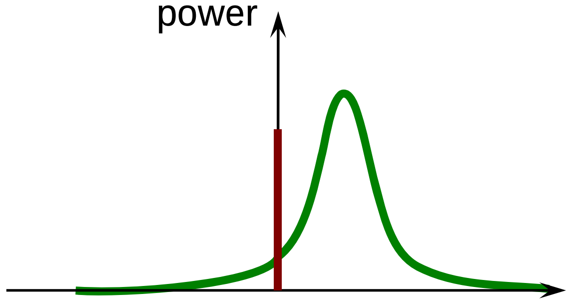




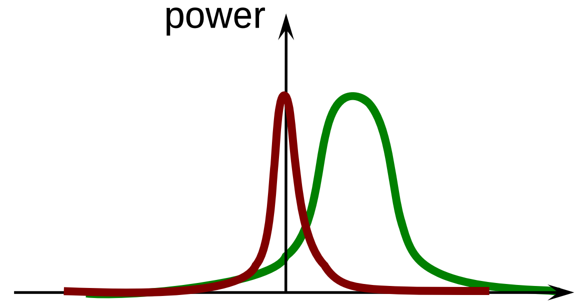


4 Ground Clutter Filtering

- 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



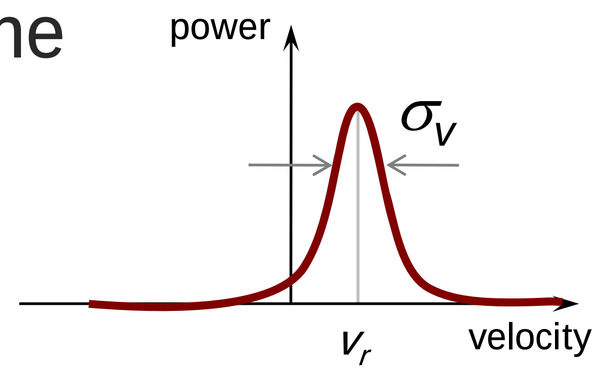
Ideal Spectrum



Smeared Spectrum

Spectrum Width Measurements

- The spectrum width measures the relative motion of scatterers in the radar volume
  - Turbulence and shear



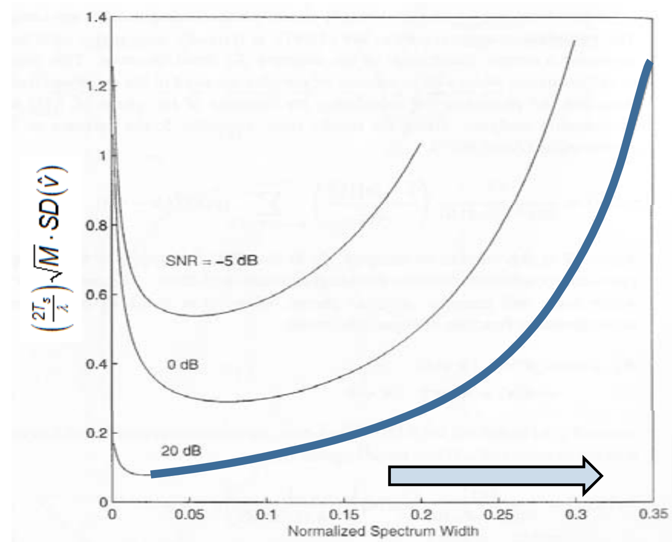
- The spectrum width depends on beam smearing

$$\sigma_v^2 = \underbrace{\sigma_s^2 + \sigma_d^2 + \sigma_o^2 + \sigma_t^2}_{\text{Meteorological}} + \underbrace{\sigma_\alpha^2}_{\text{Beam smearing}}$$

  - 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

6 Spectrum Width and Data Quality

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



Source: Polarimetric Doppler Weather Radar (Bringi and Chandrasekar 2001)

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

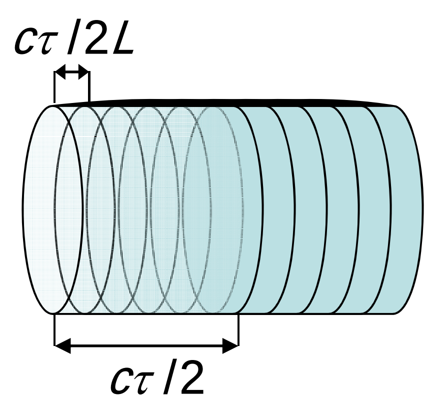
Meteorological ($\sigma_s^2 + \sigma_d^2 + \sigma_o^2 + \sigma_t^2$)

Beam smearing (σ_α^2)

- No beam smearing leads to
  - More accurate velocity estimates

Data Quality vs. Update Time (I)

- 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

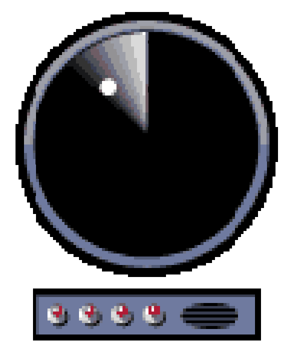


Range Oversampling

7

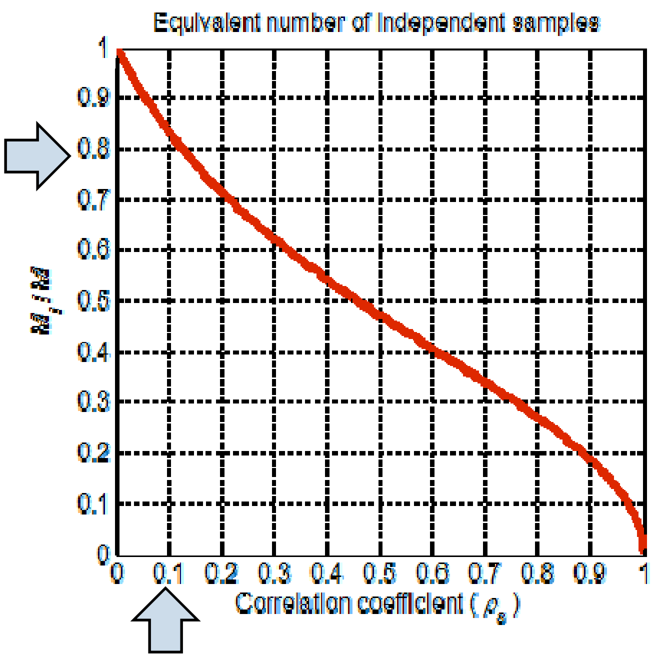
How Fast Can We Go?

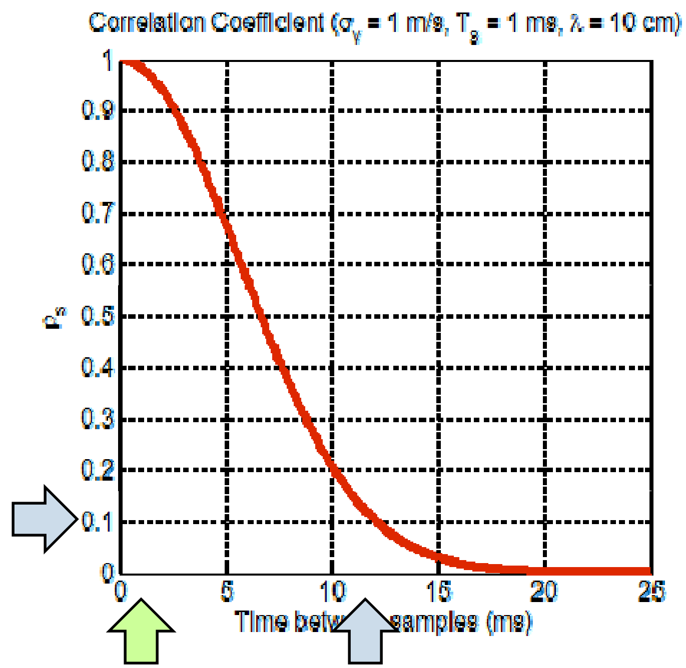
- Faster updates
  - Mechanically steered antenna
    - Higher antenna rotation rates
      - Increased wear and tear
      - Limited by pedestal characteristics
      - Possible loss of gain
  - Electronically steered antenna
    - Can dwell as short as needed on each position



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!

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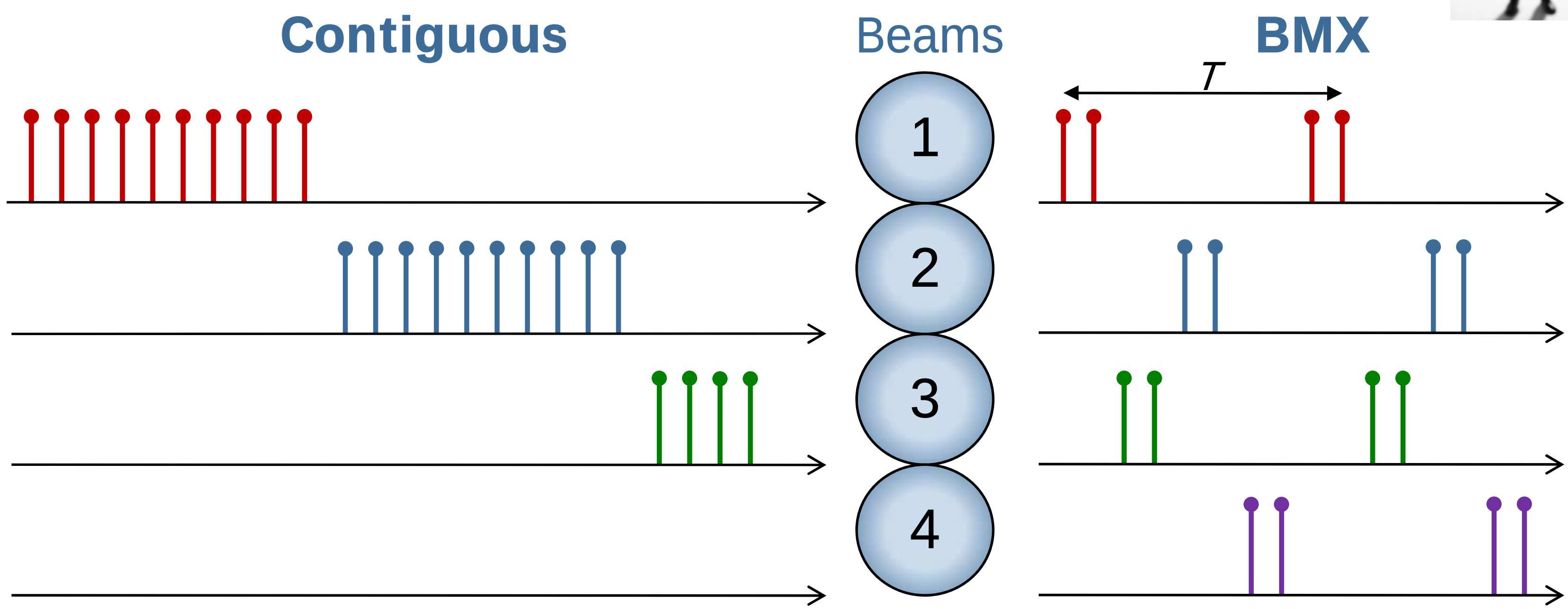
Beam Multiplexing

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

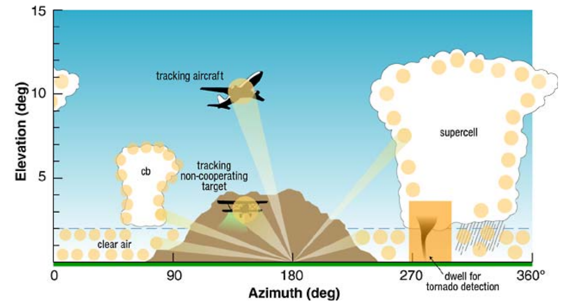


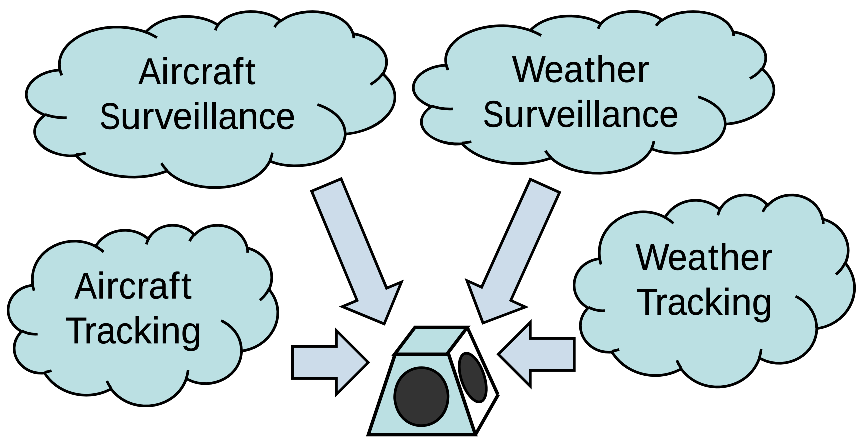
☺ **Faster updates and/or lower errors**

☹ **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 **overload**!





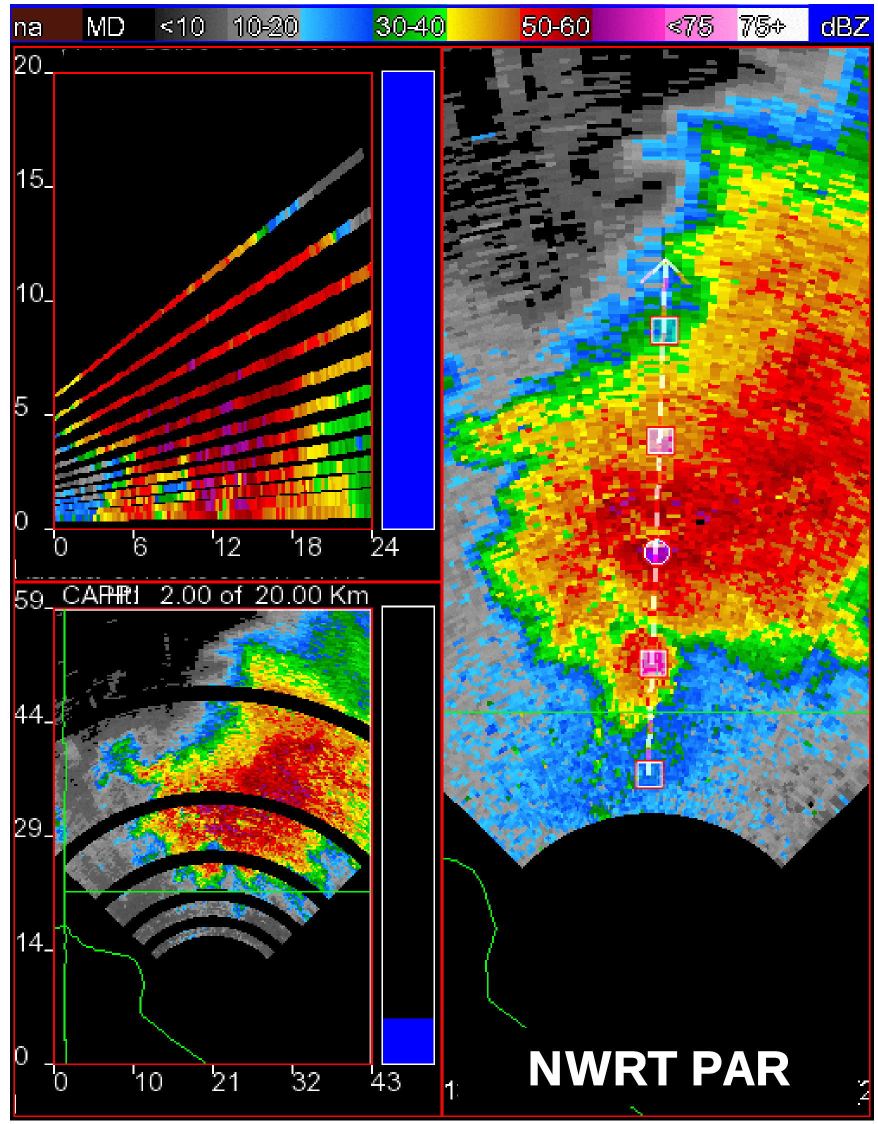
☺ **Resource sharing**

☹ **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



13 May 2009

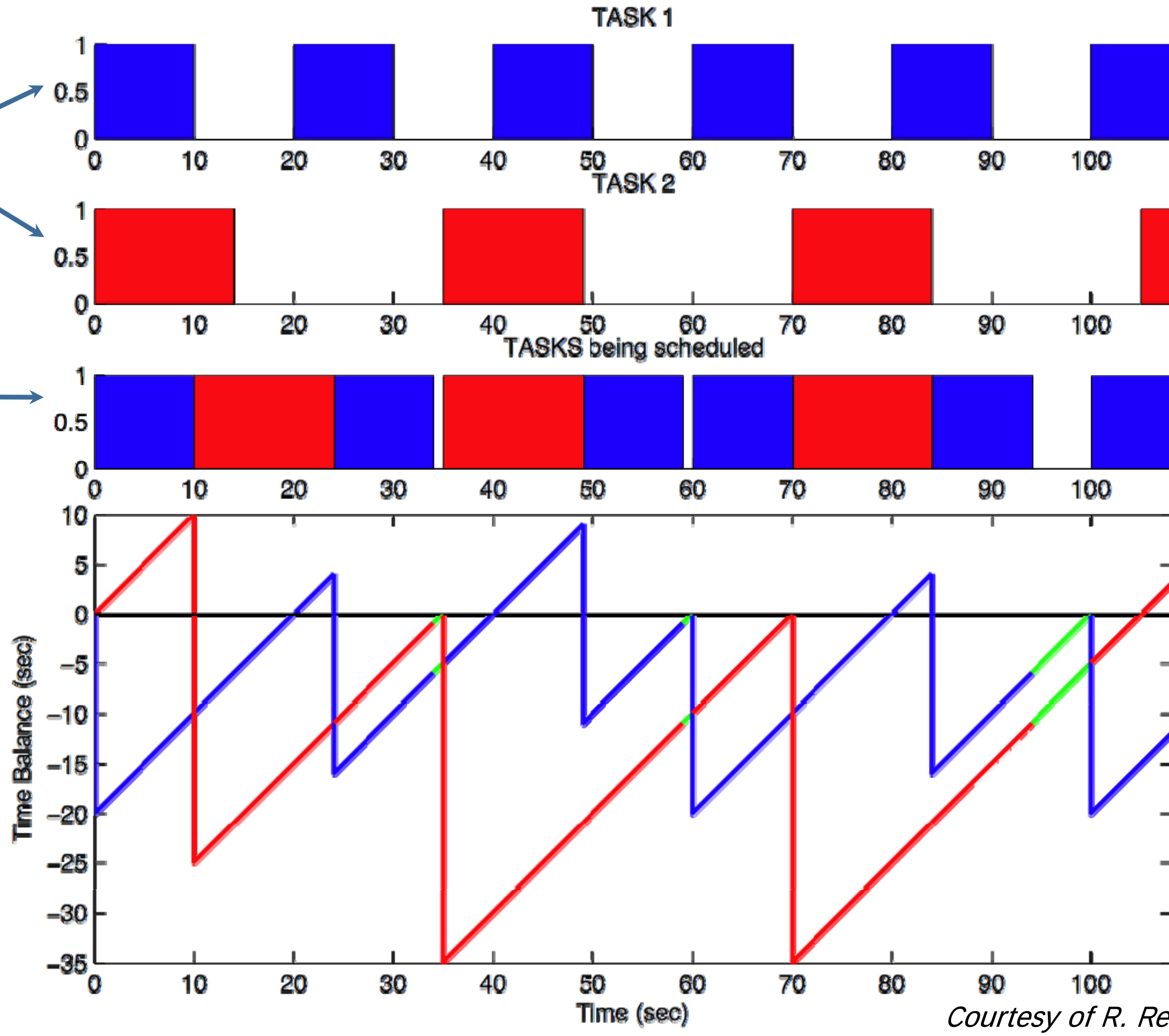
Courtesy of P. Heinselman (NSSL)

Scheduling Multiple Tasks

Tracking two cells and surveillance

Tasks **requested**

Tasks **scheduled**

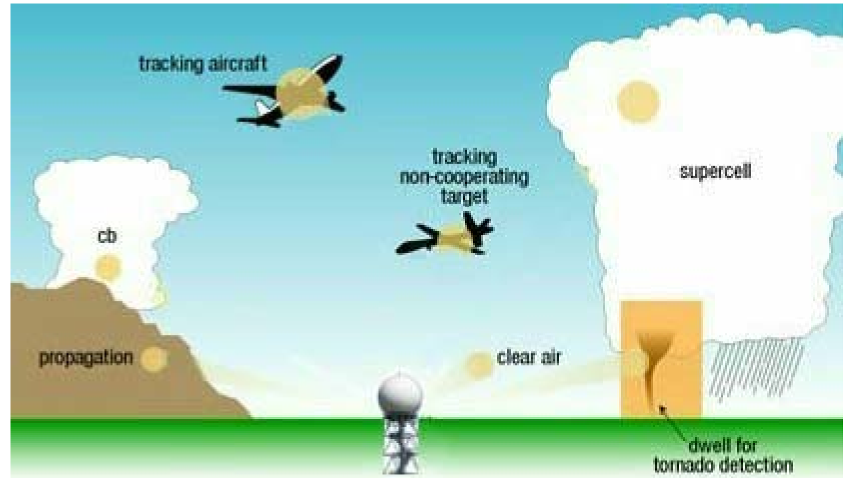


Courtesy of R. Reinoso (OU)

Adaptive Scanning (I)

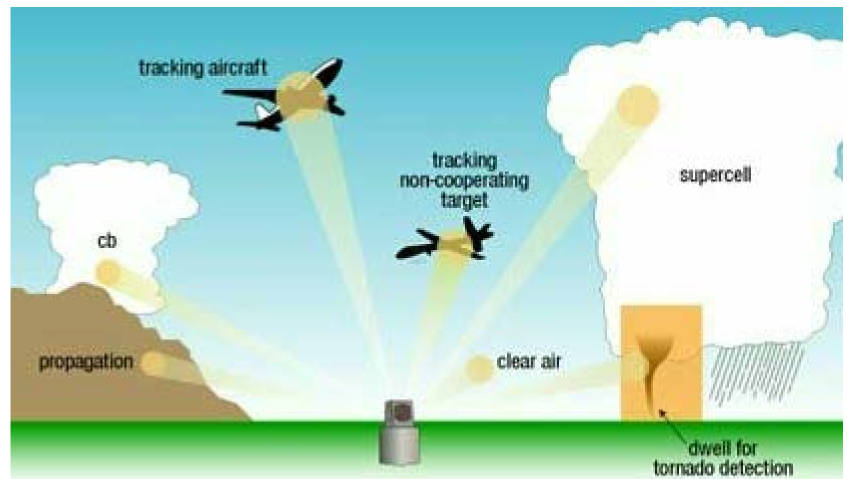
Conventional scanning

Everywhere
Sequential



Adaptive scanning

Areas of interest only
Arbitrary



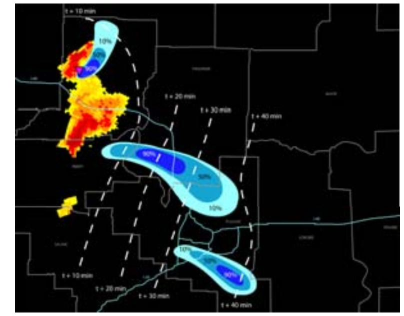
Courtesy of C. Curtis (NSSL)

☺ **Faster updates**

☹ **May miss new developments**

10 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



Warn on forecast vision

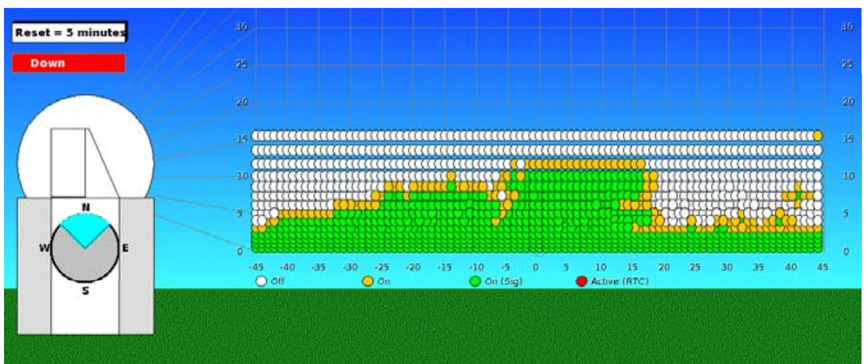
☺ Faster updates

☺ Improved data quality

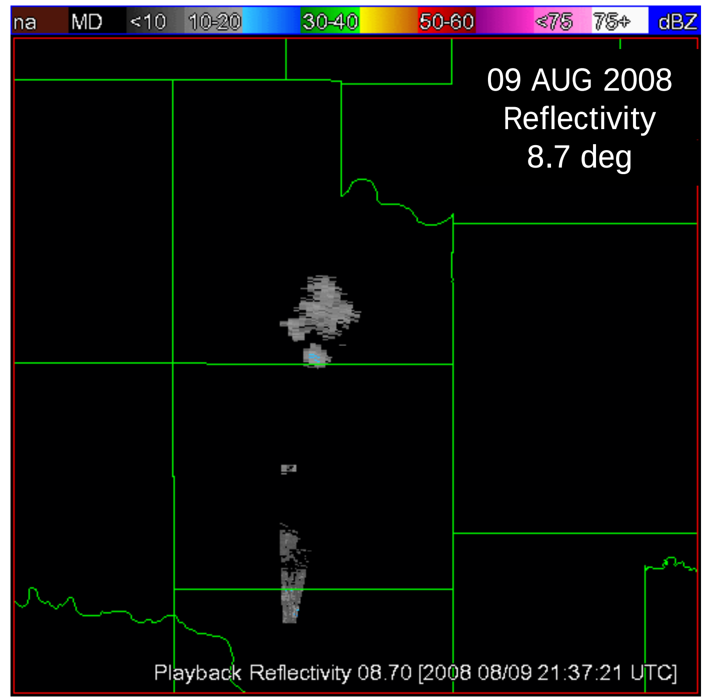
☹ Complex decisions

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

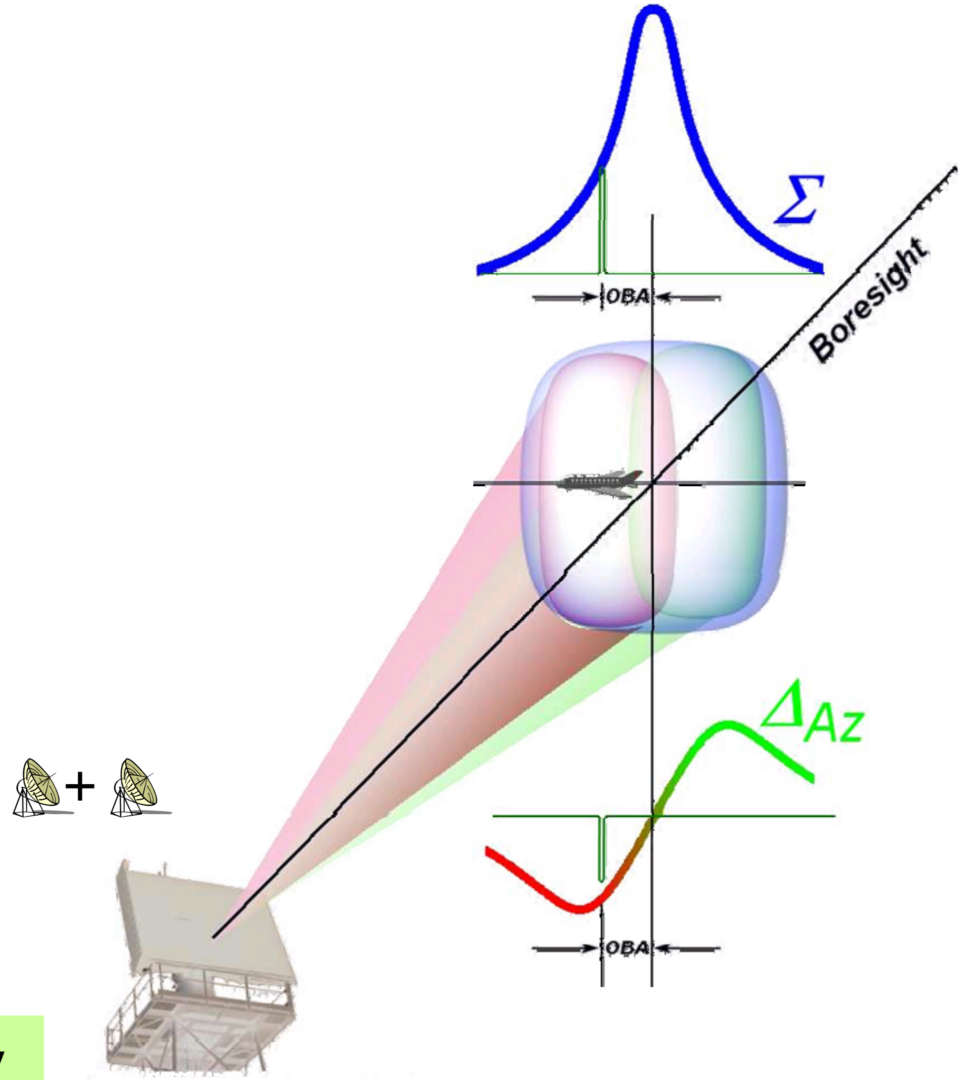


11 Monopulse Tracking

- 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 (Σ) and difference (Δ) channels

☺ **Improved tracking accuracy**

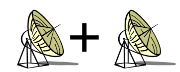
☹ **Computational complexity**



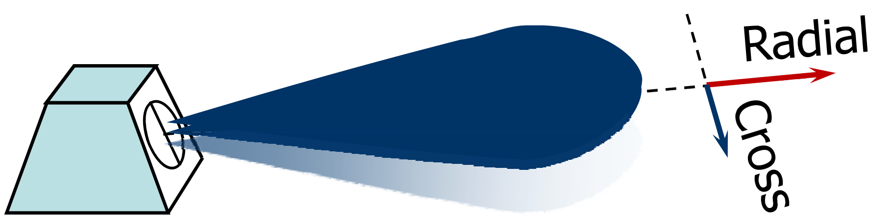
Source: www.radartutorial.eu

12 Interferometry

- Spaced antenna interferometry (SAI)
  - Complementary to the Doppler method
    - Used by wind profilers for 50+ years
  - Uses two or more spaced antennas



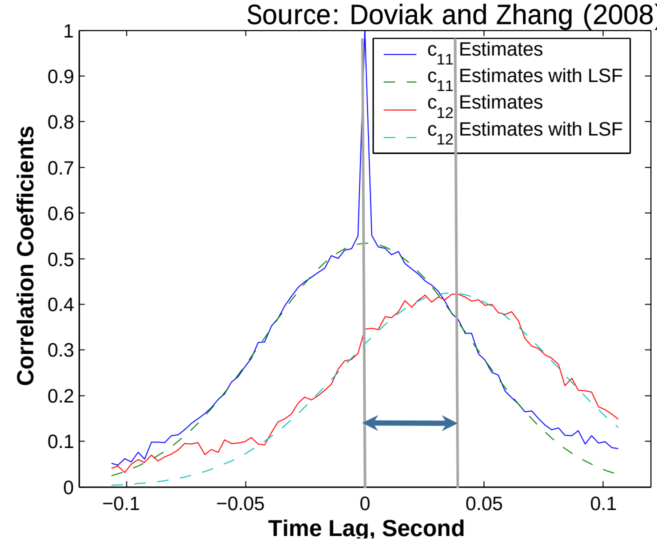
    - Cross-correlation of signals from spaced antennas can be used to measure winds & shear perpendicular to the beam direction



☺ **Better wind measurements**

☹ **Long dwell times**

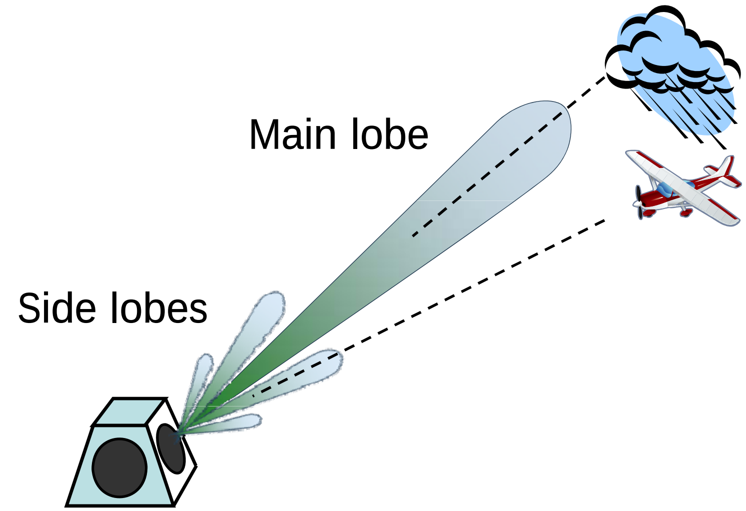
Source: Doviak and Zhang (2008)

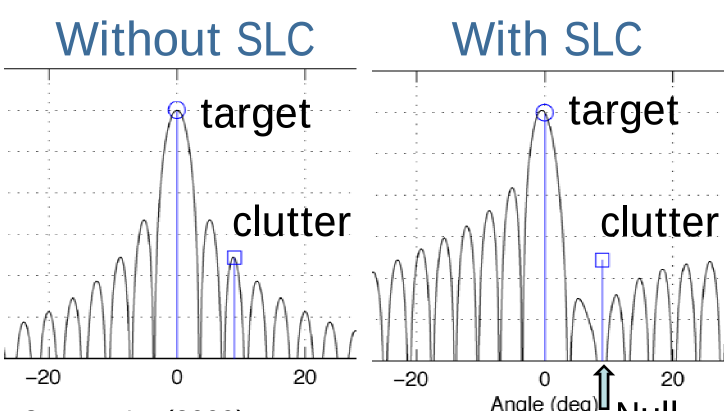


Cross-correlation peak shifts due to signal delay passing over spaced antennas

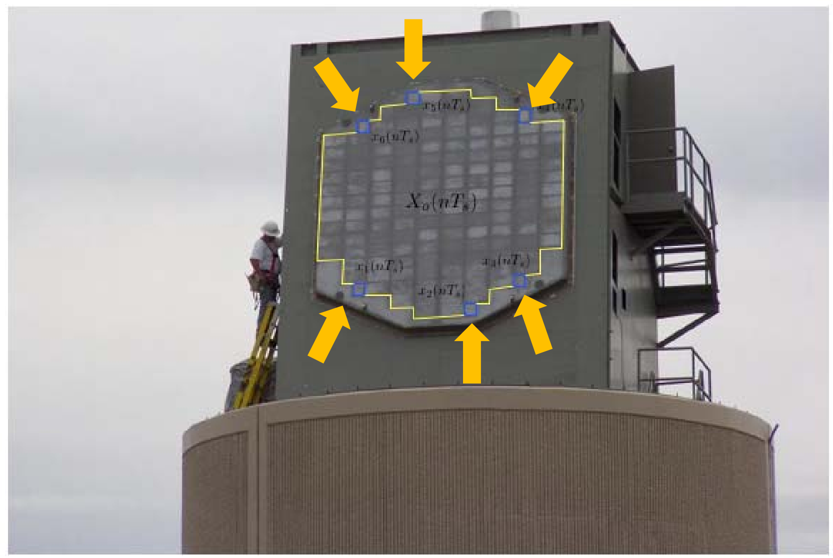
Adaptive Beamforming

- 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**

14

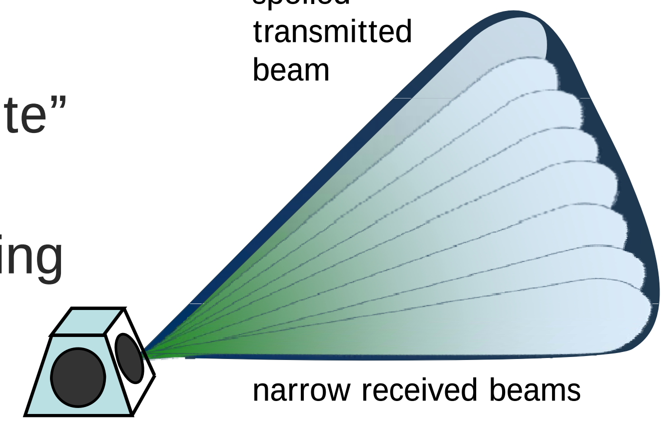
Imaging Radar

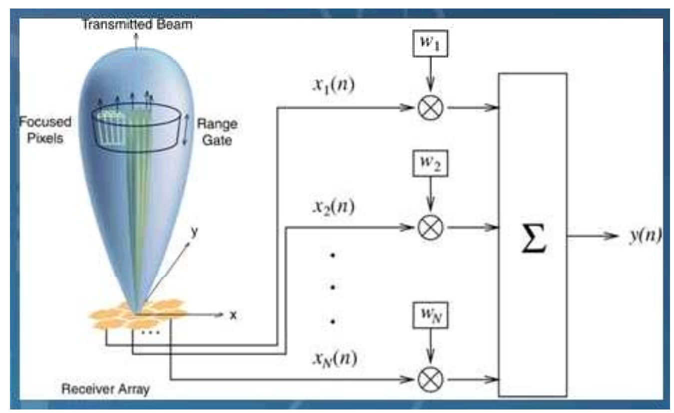
- Wide ("spoiled") transmit beam
  - Rapid volumetric coverage
  - In the extreme: ubiquitous radar
- Narrow receive beams
  - "Atmospheric camera"
  - Digital beamforming can generate "infinite" simultaneous beams via software
  - Can control resolution and spatial sampling
  - Can mitigate clutter contamination
- Simultaneous multifunction
  - No time multiplexing
  - Limited by BW & processing capacity

☺ **Faster updates**

☹ **Sensitivity loss**

☹ **Computational complexity**

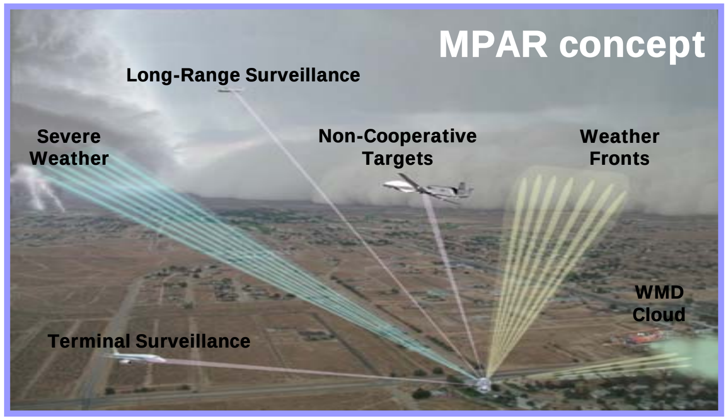




Source: Isom et al. (2009)

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