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Using a Four–Face Phased Array Radar to Detect Tornadoes and Mesocyclones: A Simulation Study

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Background

- Phased array radar (PAR) antennas that consist of thousands of transmit/receive elements on the flat antenna face are now starting to be used on research weather radars
- By phasing the sequence in which the elements radiate, the beam is scanned electronically in azimuth and elevation without moving the antenna
- The National Weather Radar Testbed has been established in Norman, OK to evaluate the applicability of replacing scanning parabolic antennas with phased array antennas on operational radars

Approach

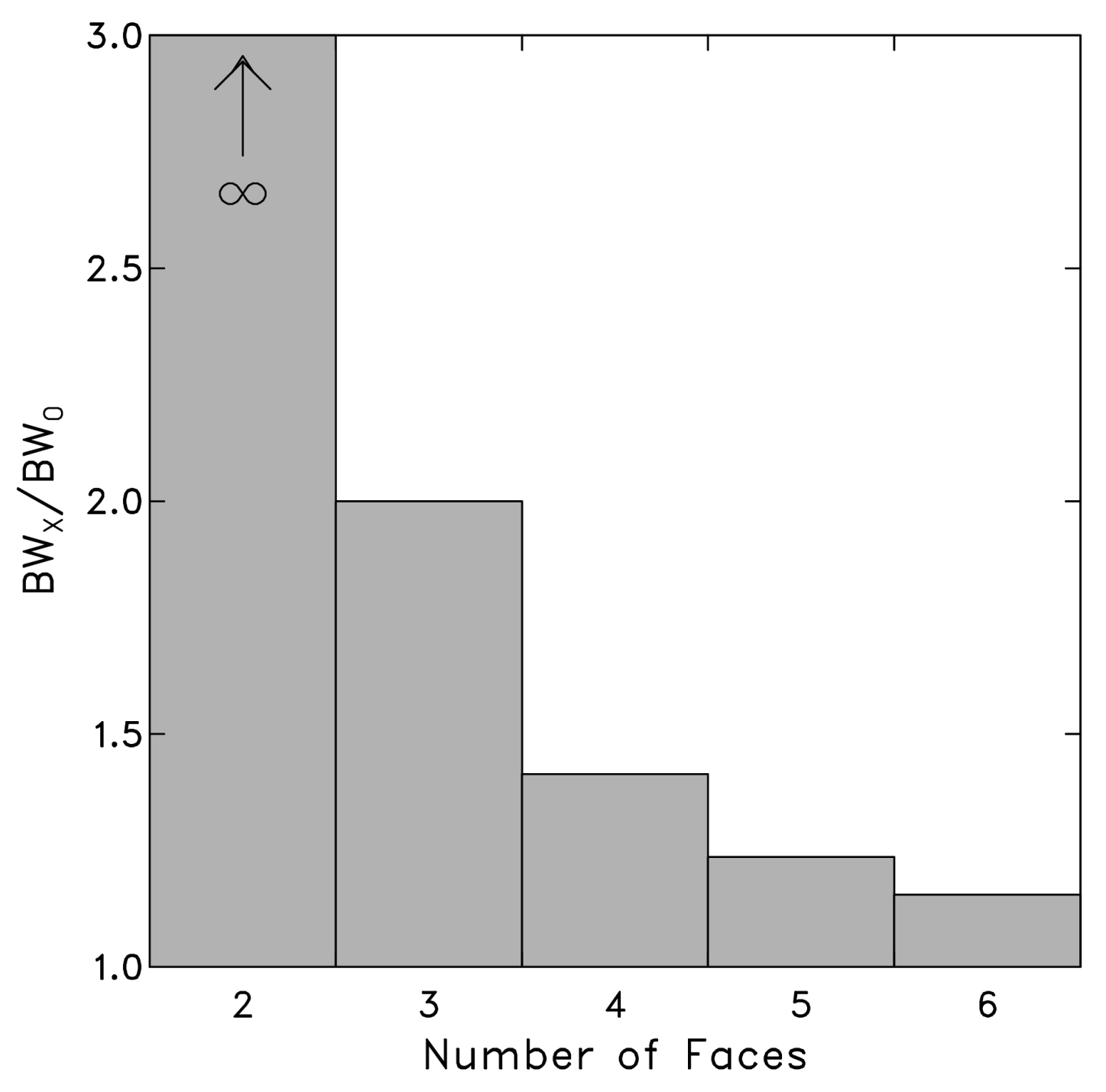
- In anticipation of possible future implementation of PAR antennas on operational radars, we used a simulated PAR to investigate how well tornadoes and mesocyclones could be resolved
- Reflectivity and mean Doppler velocity values were computed from a uniform distribution of data points within a beam having Gaussian–distributed weights
- We scanned one range gate (250 m depth) through the center of Burgers–Rott vortices having the following maximum tangential velocities (V_{max}) and core diameters (CD)

Vortex	V_{max} (m s^{-1})	CD (km)
Tornado 1	100	0.25
Tornado 2	75	0.50
Mesocyclone 1	50	2.5
Mesocyclone 2	25	5.0

- Each vortex was placed at 1° increments across a 90°–wide azimuthal sector and at 1–km increments from 1 to 240 km range (including earth curvature)
- Each tornado (mesocyclone) at each range and azimuth location then was scanned by the radar beam at 0.01° (0.02°) azimuthal increments, producing an azimuthal profile of mean Doppler velocity across the vortex
- For mesocyclones, the average peak tangential velocity was computed from peak positive and negative Doppler velocities across the azimuthal profile
- For tornadoes, the difference between the peak positive and negative velocities was computed (National Weather Service convention)
- **The goal** was to determine the number of PAR faces and the appropriate half–power beamwidth (called "beamwidth") that will be required to maintain the current severe storm detection resolution obtained with WSR–88D radars

Number of Faces

Figure: Ratio of beamwidth at the transitional azimuth between faces (BW_x) to the broadside beamwidth (BW_o) perpendicular to each face as a function of the number of faces used to encompass 360° of azimuth. The azimuthal coverage for each of 2, 3, 4, 5, and 6 faces is ±90°, ±60°, ±45°, ±36°, and ±30°, respectively.



- As the radar beam scans away from the "broadside" azimuth perpendicular to an antenna face, the width of the beam (BW) increases from the broadside beamwidth (BW_o) as BW = BW_o / cos θ, where θ is the angle from the broadside direction
- Based on the drop off of the BW_x / BW_o ratio in the **left figure**, there is no significant decrease in the beamwidth at the transitional azimuth between faces (BW_x) when more than four faces are used
- Given four faces as the optimum choice, curves on the **right** show how the beamwidth for four different broadside beamwidths (BW_o) vary between the broadside azimuth perpendicular to each face and the transitional azimuth between faces

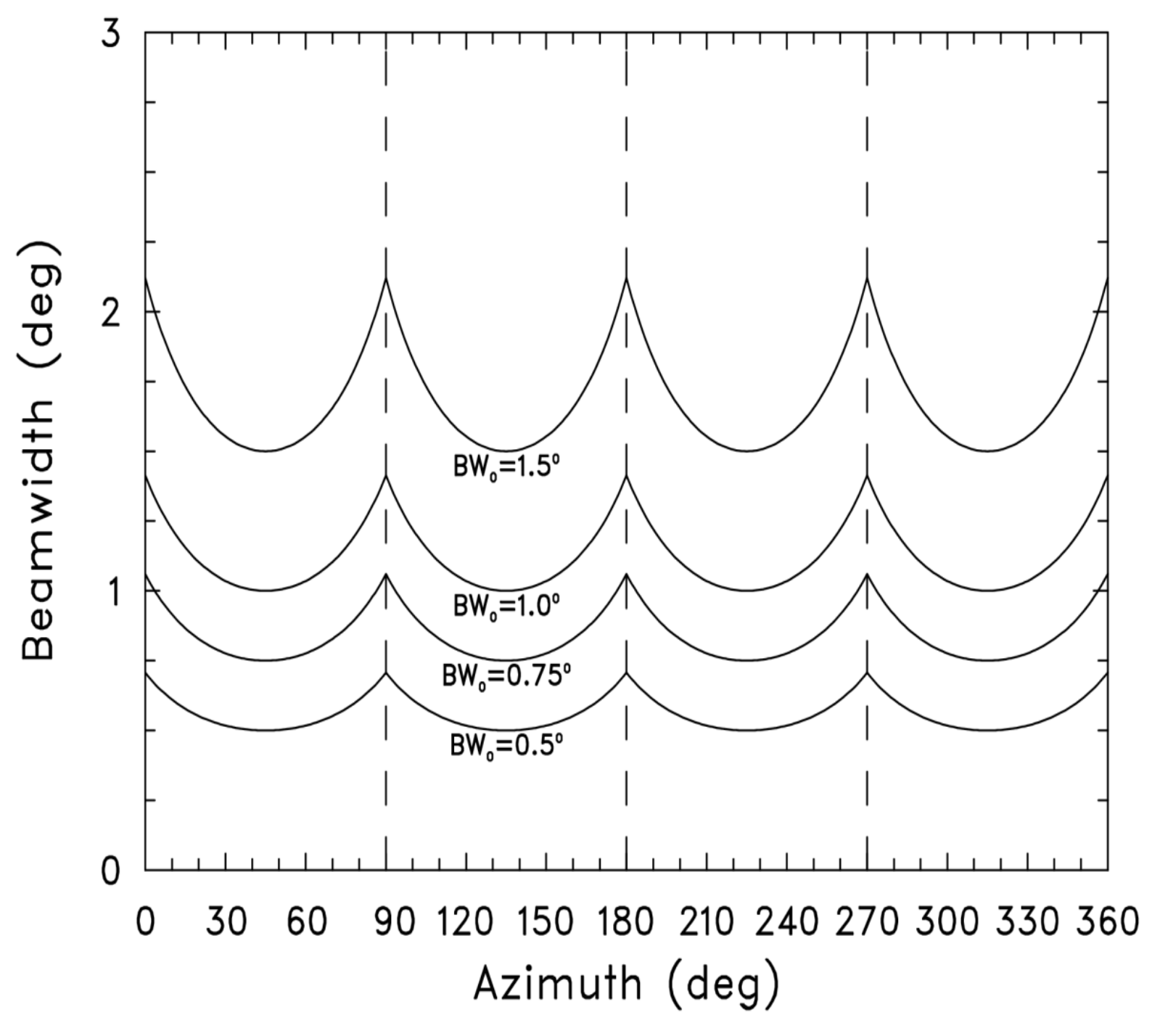
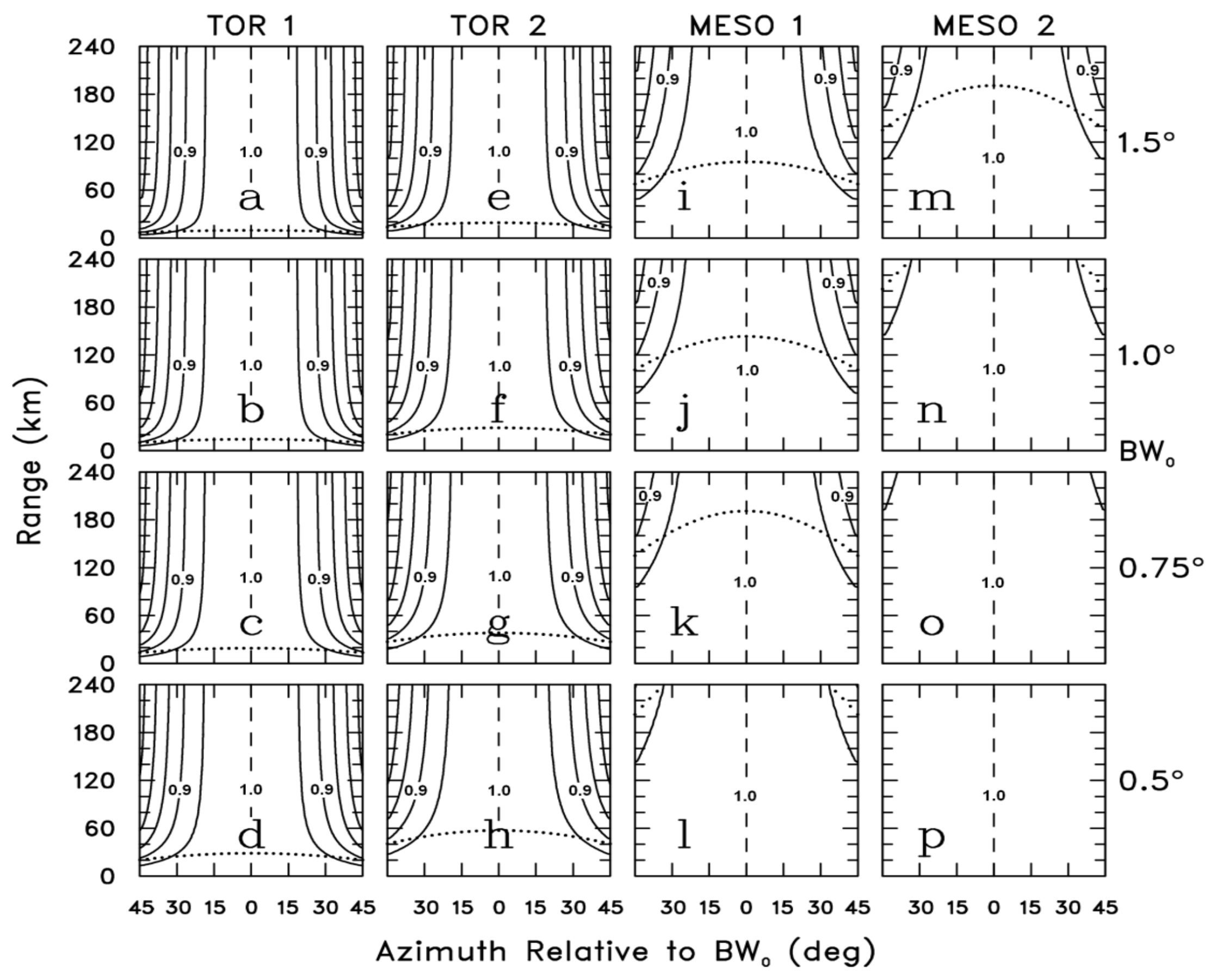


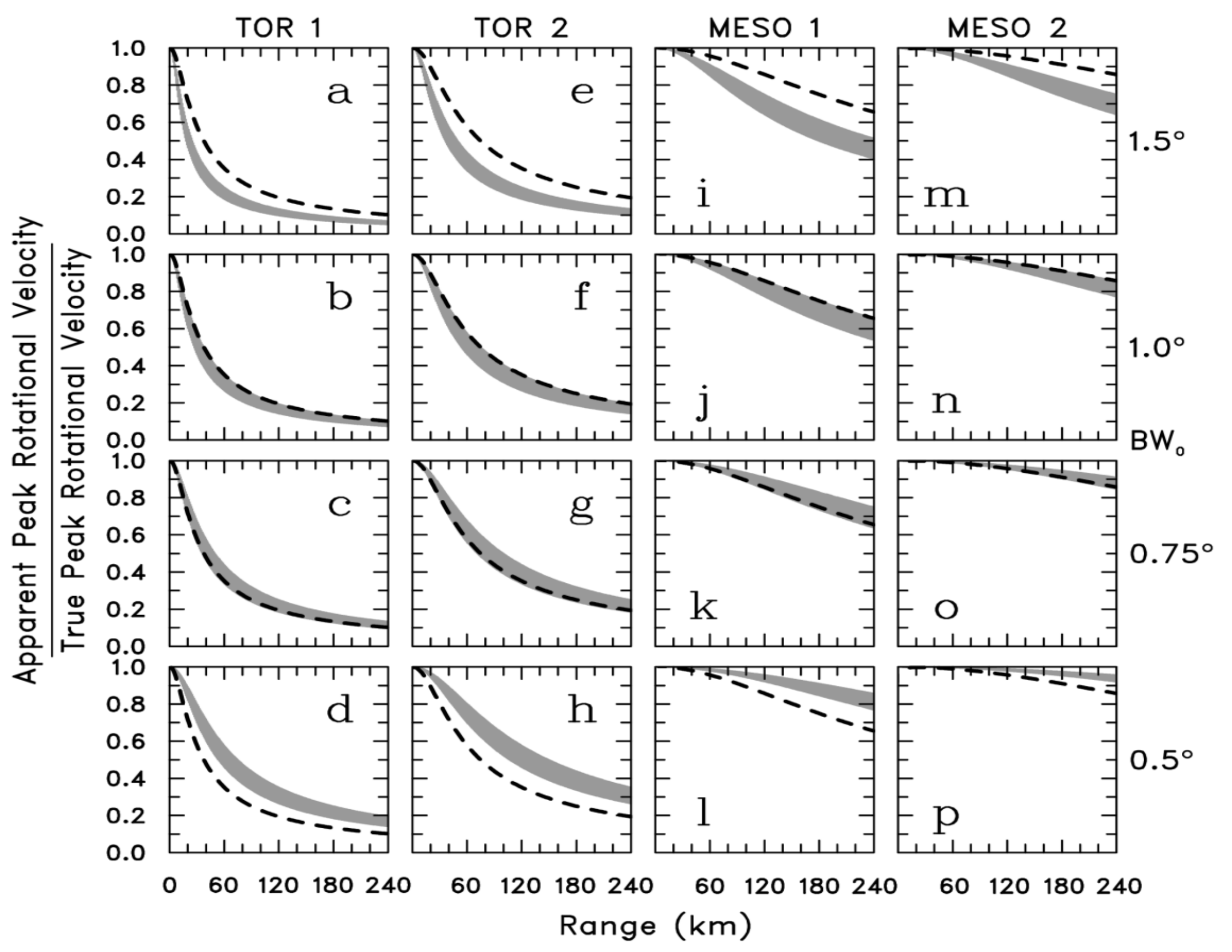
***Figure**. Azimuthal variation of beamwidth for four broadside beamwidths BW_o when using four phased array antennas arranged as a square (facing NE, SE, SW, and NW) for full azimuthal coverage of 360°. Vertical dashed lines mark transitional azimuths between faces where BW_x = 1.414 BW_o.*

Appropriate Beamwidth



Ratios of peak Doppler velocity differences associated with simulated tornadoes (a–h) and of peak rotational velocity signatures associated with simulated mesocyclones (i–p) relative to the simulated broadside values as a function of range and off–broadside azimuth angle for four broadside beamwidths (BW_o). Contour lines are at ratio intervals of 0.05. Curved dotted line indicates range (R) at which beamwidth is equal to the core diameter (CD) of the vortex specified by R = (57.296° CD / BW_o) cos θ.

- The **figure at the left** shows how normalized peak Doppler velocity differences (tornadoes) and peak rotational velocities (mesocyclone) decrease away from the broadside azimuth perpendicular to the antenna face (vertical 1.0 dashed line) as a function of range and beamwidth
- Except close to the radar, the velocity differences for the two tornadoes degrade about the same, independent of range or beamwidth because the tornadoes are smaller than the beamwidths
- There is less degradation of peak mesocyclone rotational velocities because vortices are larger than the smaller beamwidths at most ranges
- The **figure at the right** shows how the Doppler velocity signatures become weaker than the true (simulated) vortex values as a function of range and beamwidth
- Broadside beamwidths of 1.0° and 1.5° result in weaker rotational velocities (shaded bands) than those detected by the super–resolution WSR–88D (dashed curves), whereas beamwidths of 0.5° and 0.75° result in the same or stronger rotational velocities
- Since the shaded band for a broadside beamwidth of 0.75° (increasing to 1.06° across the face of the antenna) is coincident with and on the stronger side of dashed super–resolution WSR–88D curve, we deduce that a phased array broadside beamwidth of about 0.75° will be needed to provide at least the same tornado and mesocyclone detection capability as the current WSR–88D



Ratios of the apparent peak rotational velocity to the true peak rotational velocity for Tornadoes 1 and 2 and Mesocyclones 1 and 2 as a function of range and four broadside beamwidths (BW_o). The shaded band represents the spread of ratios between the azimuth angle at BW_o and the transitional azimuth angle of ±45°. The dashed curve represents the WSR–88D super–resolution effective beamwidth of 1.0°.

The Bottom Line

- If operational weather radars are upgraded with phased array antennas that have flat faces (as opposed to cylindrical antennas, for example), then—based on this study—there should be four faces and they should have broadside beamwidths of about 0.75° in order to maintain the same detection capability of small–scale severe weather events available with the current National Weather Service's WSR–88D radars
- Much more research and development work needs to be done, such as dual polarization, a dramatic decrease in the cost of the antenna elements, and making sure that the radar system also meets the needs of the aviation community
- Therefore, it is likely that phased array antennas would not become operational until the 2030 time frame

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