NEXRAD Technical Advisory Committee Meeting
March 21, 2006

Super Resolution

Technical Briefing

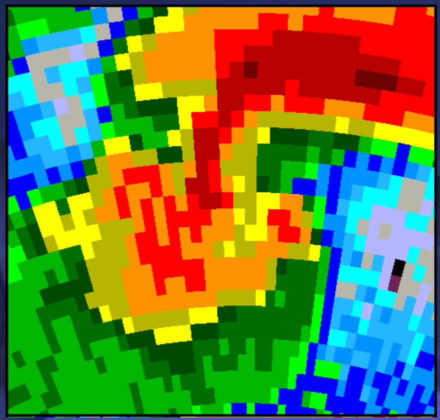
Sebastián Torres[1,2], Chris Curtis[1,2], Rodger Brown[2], Eddie Forren[1,2], and Michael Jain[2]

[1]Cooperative Institute for Mesoscale Meteorological Studies
[2]National Severe Storms Laboratory

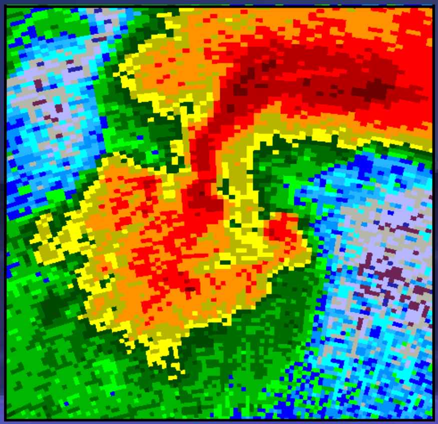
What is Super Resolution?

- Legacy spatial sampling (Legacy Resolution)
  - Reflectivity: 1-km by 1-deg grid
  - Doppler: 250-m by 1-deg grid
- Super Resolution spatial sampling
  - 250-m by 0.5-deg grid
  - Super Resolution is initially proposed for the **lower antenna elevation angles** (first few tilts of existing VCPs) and for **visualization** as an additional base data product

Legacy Resolution



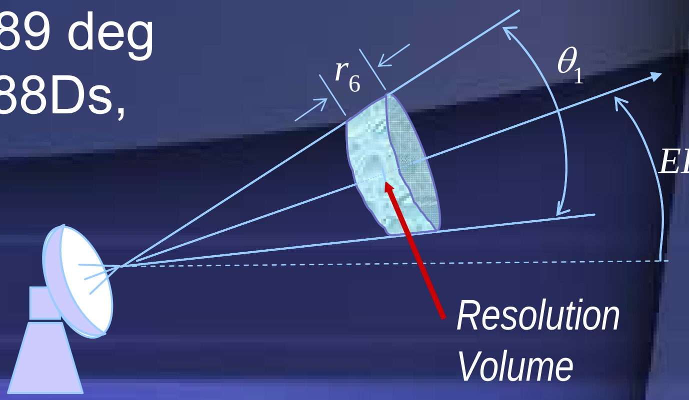
Super Resolution



Tornado outbreak in Oklahoma City
10 May 2003
(Curtis, Forren, and Torres 2003)

The Resolution of Super Resolution

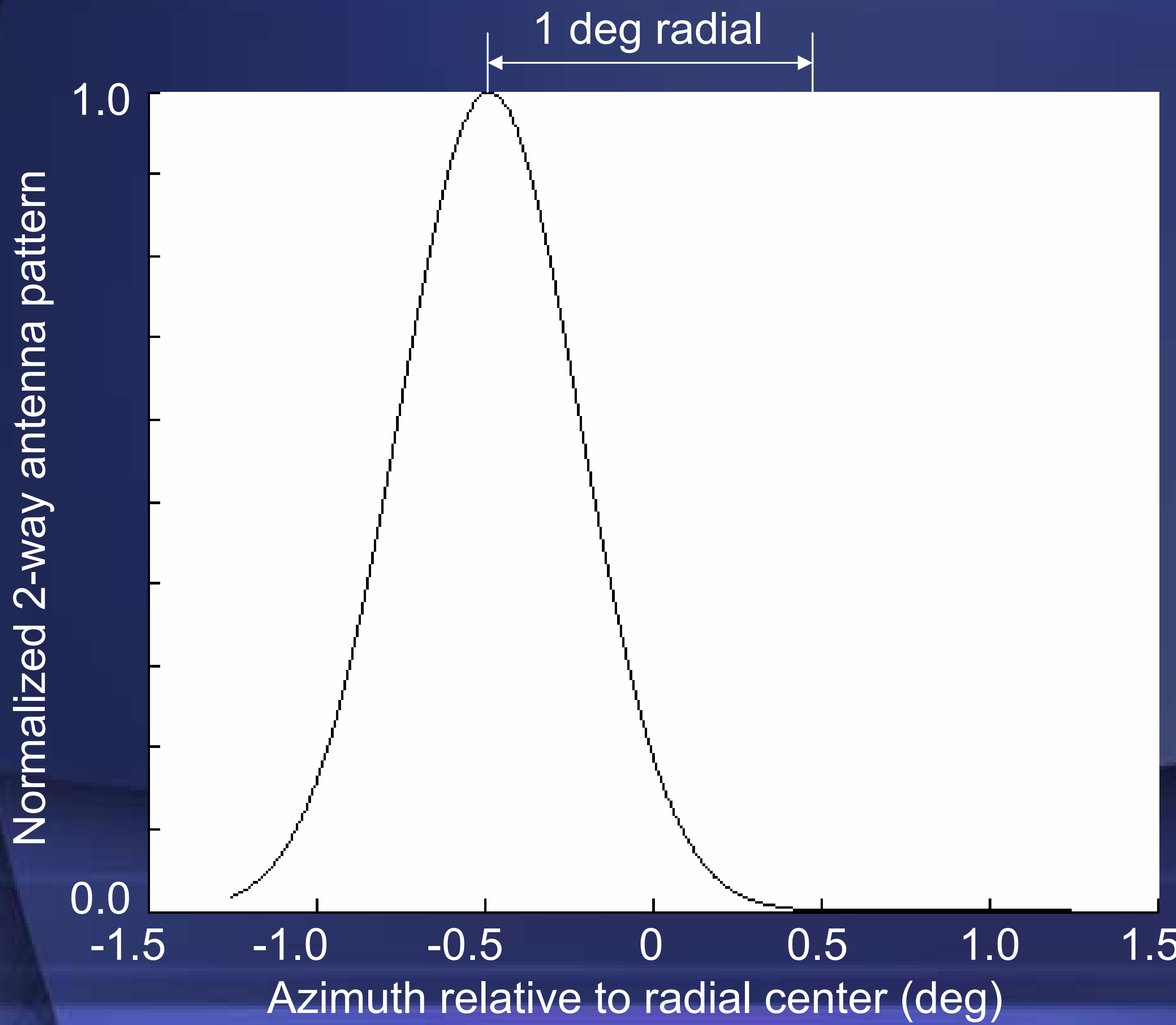
- Range resolution with short pulse and matched filter is 250 m
  - Legacy range averaging for reflectivity must be removed
- Azimuthal resolution cannot be smaller than the resolution of the antenna beam pattern without advanced signal processing techniques
  - Two-way 6-dB beamwidth is 0.89 deg (average for operational WSR-88Ds, Brown et al. 2002)
  - Azimuthal resolution is dictated by the **effective antenna pattern**



Effective Antenna Pattern

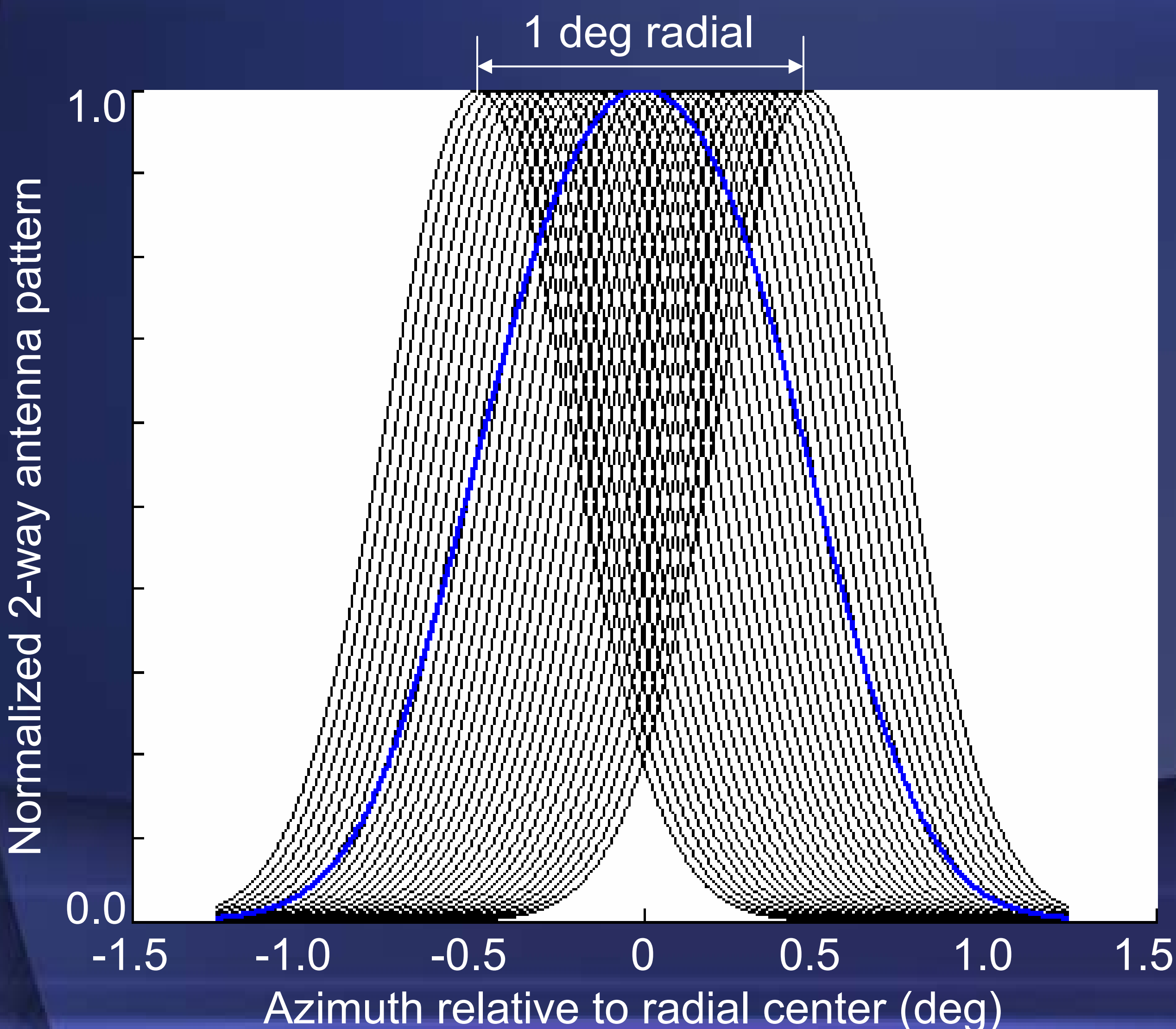
- The effective antenna pattern of a scanning antenna depends on
  - Antenna beam pattern
  - Antenna motion
  - Number of samples used for integration (*M*)
  - Data windowing
    - Weights applied to *M* samples of the time-series data
- The **effective antenna pattern** describes how hydrometeor contributions to the moment estimates are weighted based on their azimuth relative to the center of the beam

Effective Antenna Pattern



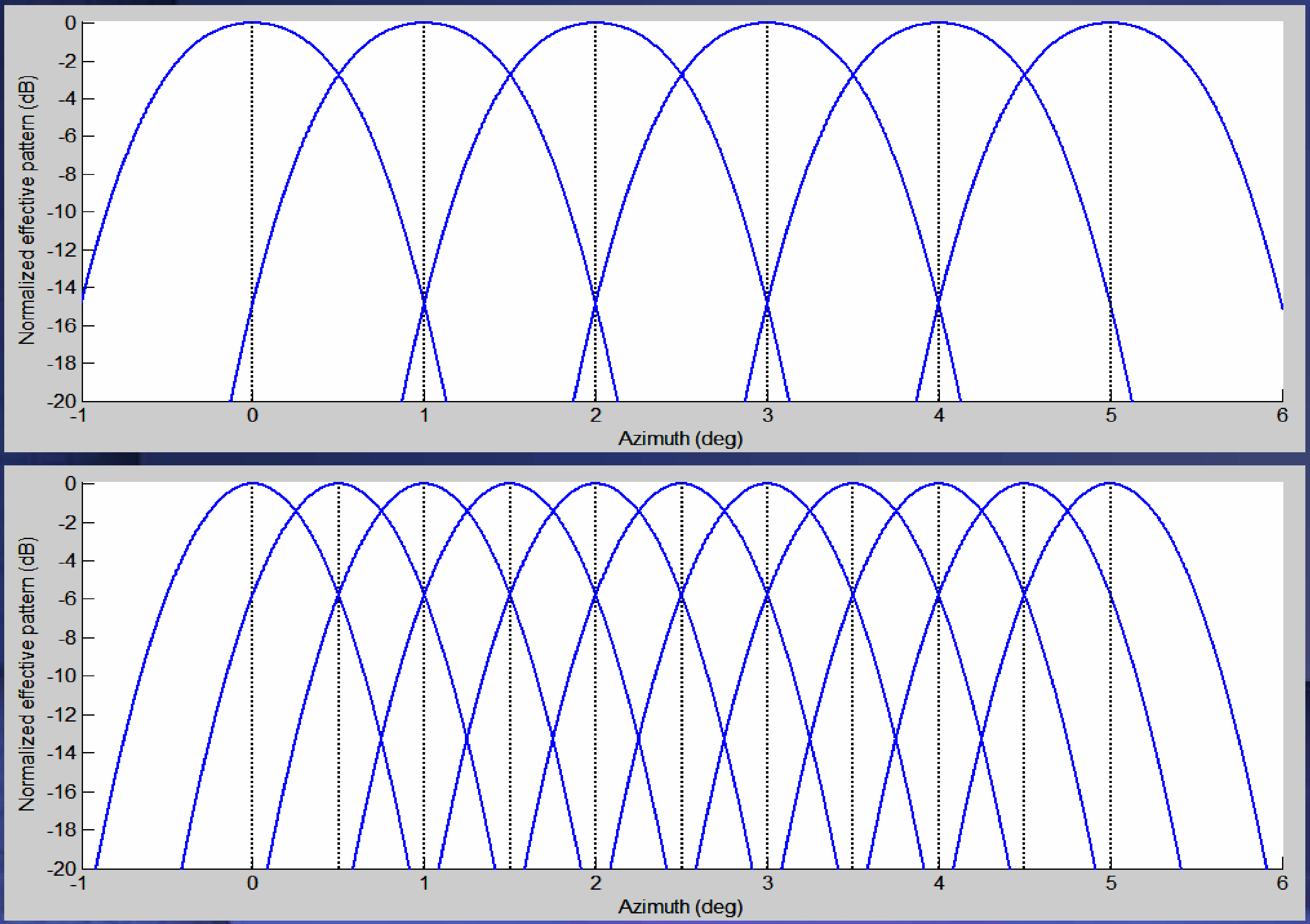
θ_1 = 0.89 deg
M = 32
Von Hann
(*a.k.a. Hanning*)
window

Effective Antenna Pattern



θ_1 = 0.89 deg
M = 32
Variable window

Azimuthal Sampling



Legacy Resolution

Super Resolution

Rectangular window

How do we implement Super Resolution?

- Design goals & constraints
  - Produce **stronger signatures** of mesocyclones and tornadoes
  - Assure **compatibility** with current and future (planned*) signal processing techniques
  - Adhere to **CPU load** and bandwidth limitations
  - Meet NEXRAD **requirements** for errors of estimates
    - Provide acceptable base data to ORPG algorithms

What can we change?

Parameters under control

Antenna rot. rate (α)
Pulse repetition time ($\mathbf{T_s}$)
Azimuthal sampling (Δ**AZ**)
Range sampling (Δ**r**)
# of samples per radial (**M**)
Data window

Determined by VCP definition

Producing Stronger Signatures

- Benefits from Super Resolution data are realized through (Brown et al. 2002)
  - Finer range sampling
  - Finer azimuthal sampling
  - Narrower effective antenna pattern (smaller effective beamwidth)
    - Reduce azimuthal extent of radial
      - Collect fewer samples per radial
      - Reduce antenna rotation rate
        - » Unacceptable operationally if resulting in *significantly* increased VCP times
    - Apply a data window

What can we change?

Parameters under control

- Antenna rot. rate (α)
- Pulse repetition time (T_s)
- Azimuthal sampling (Δ**AZ**)
- Range sampling (Δ**r**)
- # of samples per radial (**M**)
- Data window

Determined by VCP definition

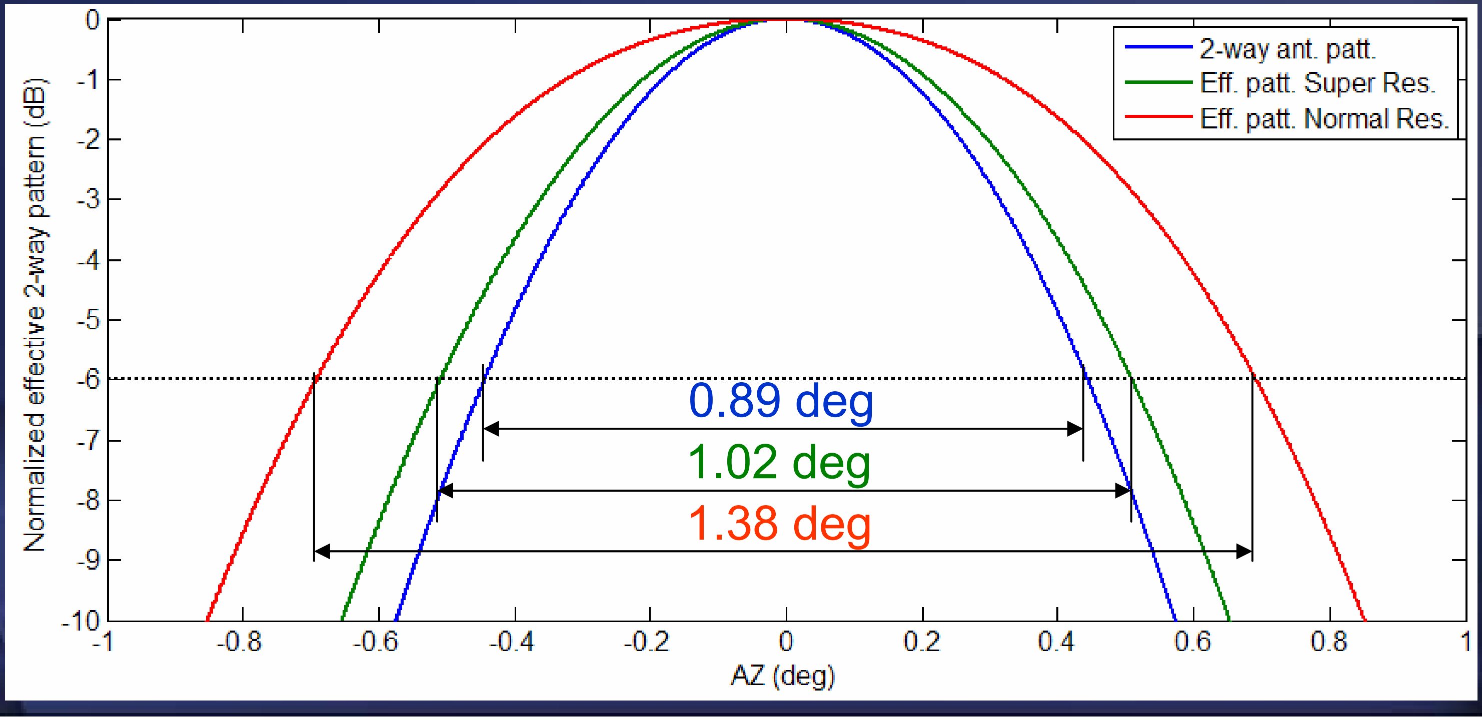
Super Resolution

$\Delta AZ = 0.5$ deg

$\Delta r = 250$ m

Producing Stronger Signatures (cont'd)

- Goal for azimuthal resolution
  - Same as would be obtained with **conventional*** super resolution (splitting legacy 1-deg radials into two halves)



Assuring Compatibility with ORDA

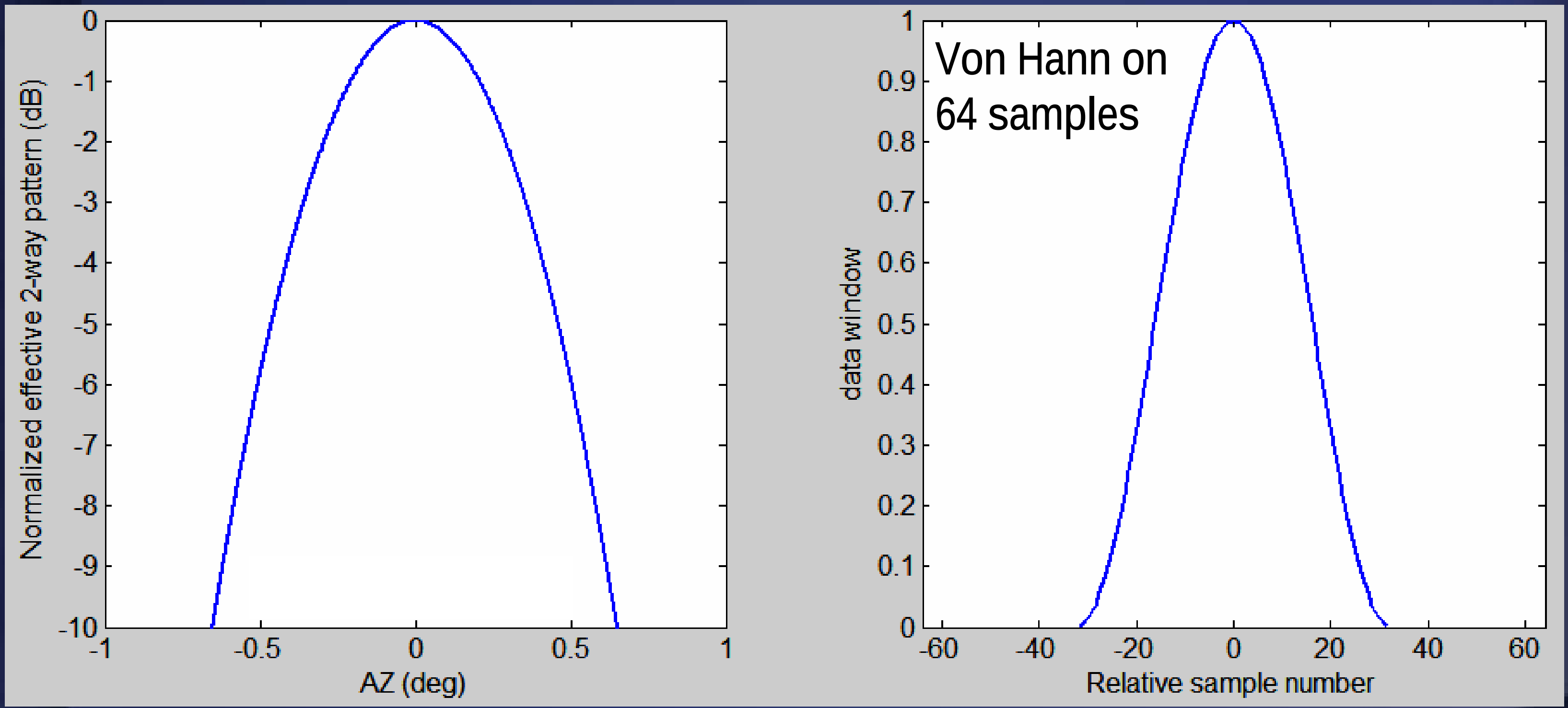
- Need to maintain (or increase) number of samples per radial
  - Keep current performance of GMAP
    - *M* ≥16 is recommended for GMAP
  - Compatibility with SZ-2 algorithm
- The only viable alternative is to apply a data window
  - GMAP and SZ-2 already require data windowing
- No compatibility issues with dual polarization

What can we change?

Parameters under control

Antenna rot. rate (α) ☑
Pulse repetition time ($\mathbf{T_s}$) ☑
Azimuthal sampling (Δ**AZ**) ☑
Range sampling (Δ**r**) ☑
# of samples per radial (**M**) → Maintain or Increase
Data window

Applying a Data Window



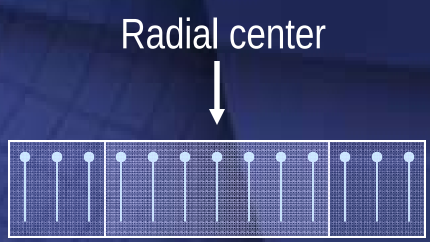
- The same effective beamwidth can be obtained with different combinations of samples per radial and data window

Adhering to System Limitations

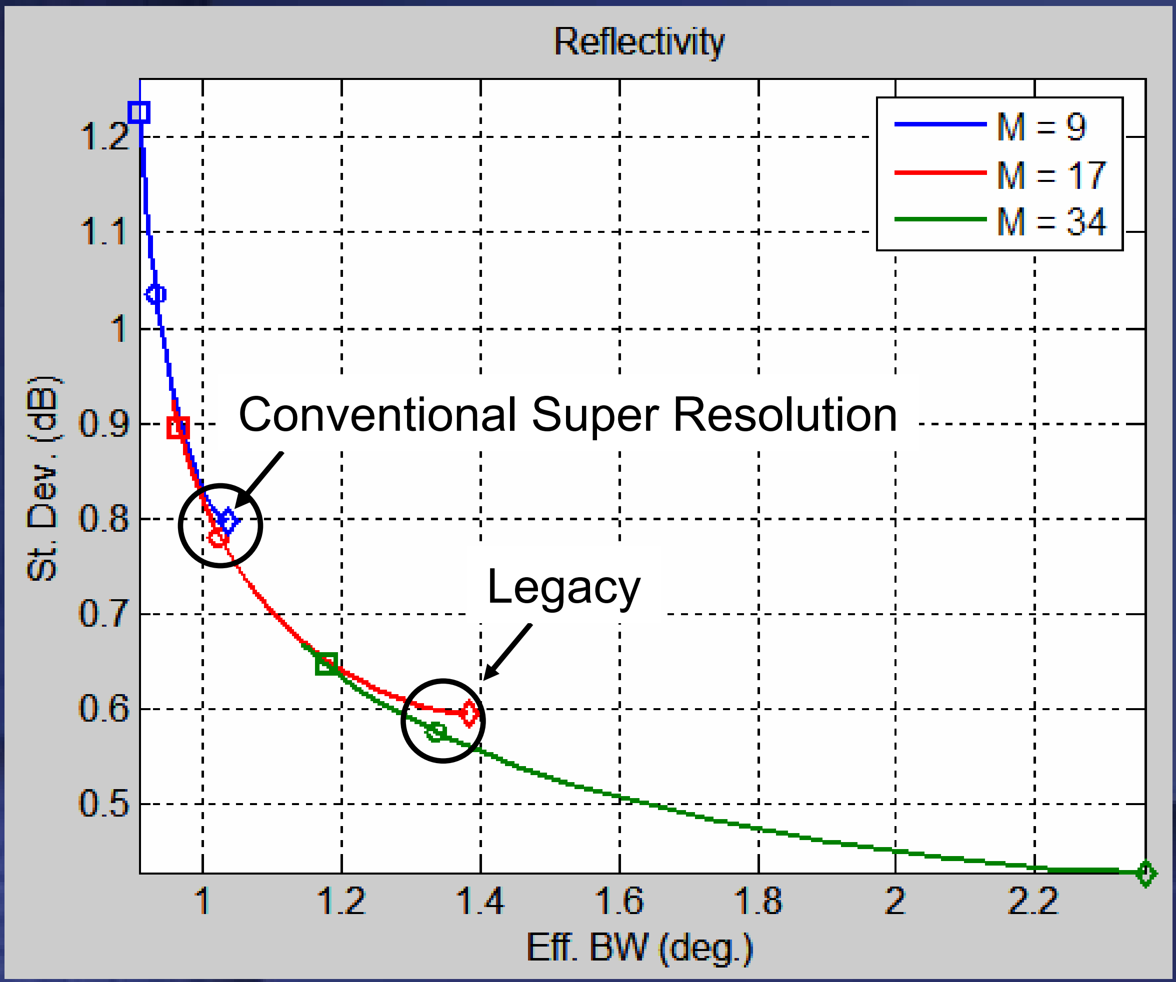
- Increasing the number of samples increases the computational complexity
  - For ORDA FFT mode, doubling the number of samples in the radial **more than doubles** the number of computations
  - To conserve processing capability, use the fewest number of samples
    - This becomes an important consideration when adding future enhancements/capabilities
  - Maintain the current number of samples per radial
    - How about increasing the number of samples to reduce the errors of estimates?

Meeting Error Requirements

- Errors of estimates are inversely proportional to the effective beamwidth
  - Any combination of number of samples per radial and window having the **same effective beamwidth** will result in the **same level of errors**!
  - Trade off: azimuthal resolution vs. errors of estimates
    - For a given azimuthal resolution and antenna rotation rate, increasing the number of samples in the radial does not lead to reduced errors of estimates



Errors of Estimates with Super Resolution



- VCP 11, 1st tilt
  - PRI #1
  - 17 pulses in 1 deg
  - ORDA FFT Mode
  - Range averaging
- Data windows
  - ♦: rectangular
  - ●: von Hann
  - ■: Blackman
- Parameters
  - SNR = 10 dB
  - σ_v = 4 m/s

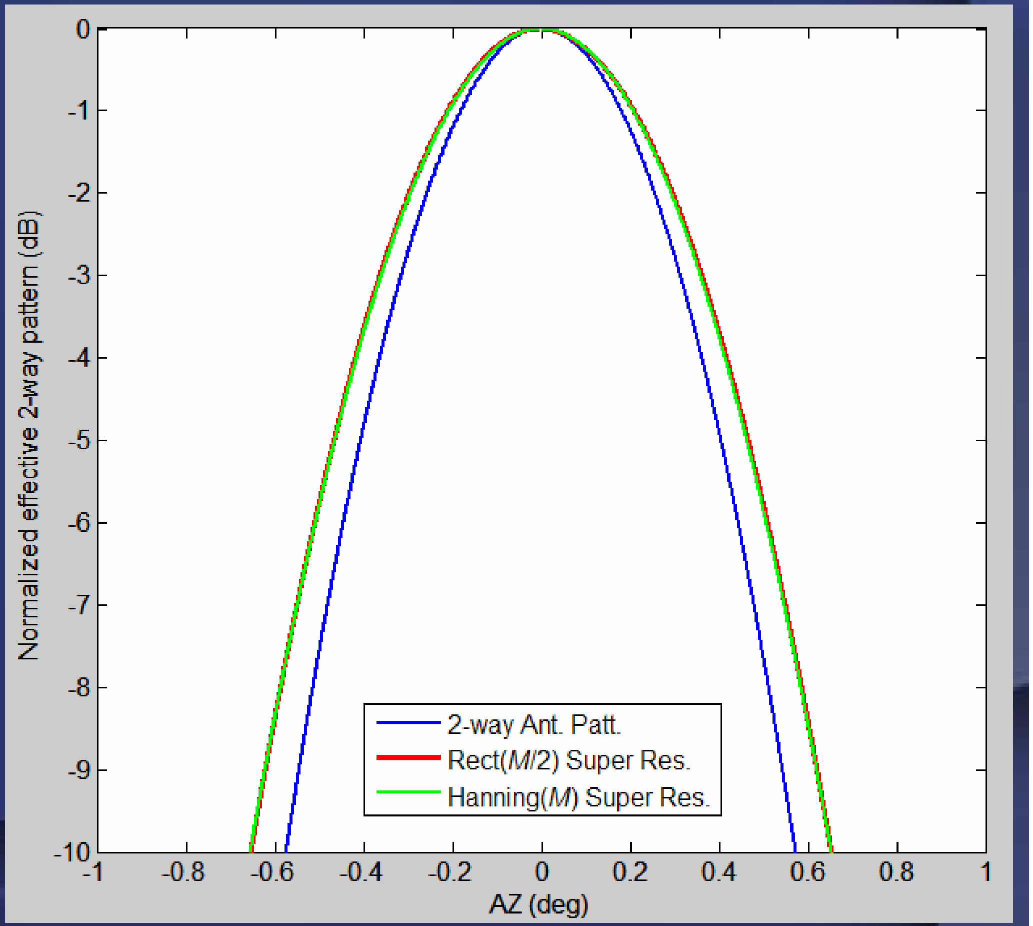
What can we change?

<u>Parameters under control</u>

Antenna rot. rate (α) ☑
Pulse repetition time ($\mathbf{T_s}$) ☑
Azimuthal sampling (Δ**AZ**) ☑
Range sampling (Δ**r**) ☑
# of samples per radial (**M**) ☑ → Maintain
Data window

Choosing a Data Window

- For the same antenna rotation rate, a **von Hann** window on *M* samples is equivalent to a **rectangular** window on *M*/2 samples (**conventional Super Resolution**)



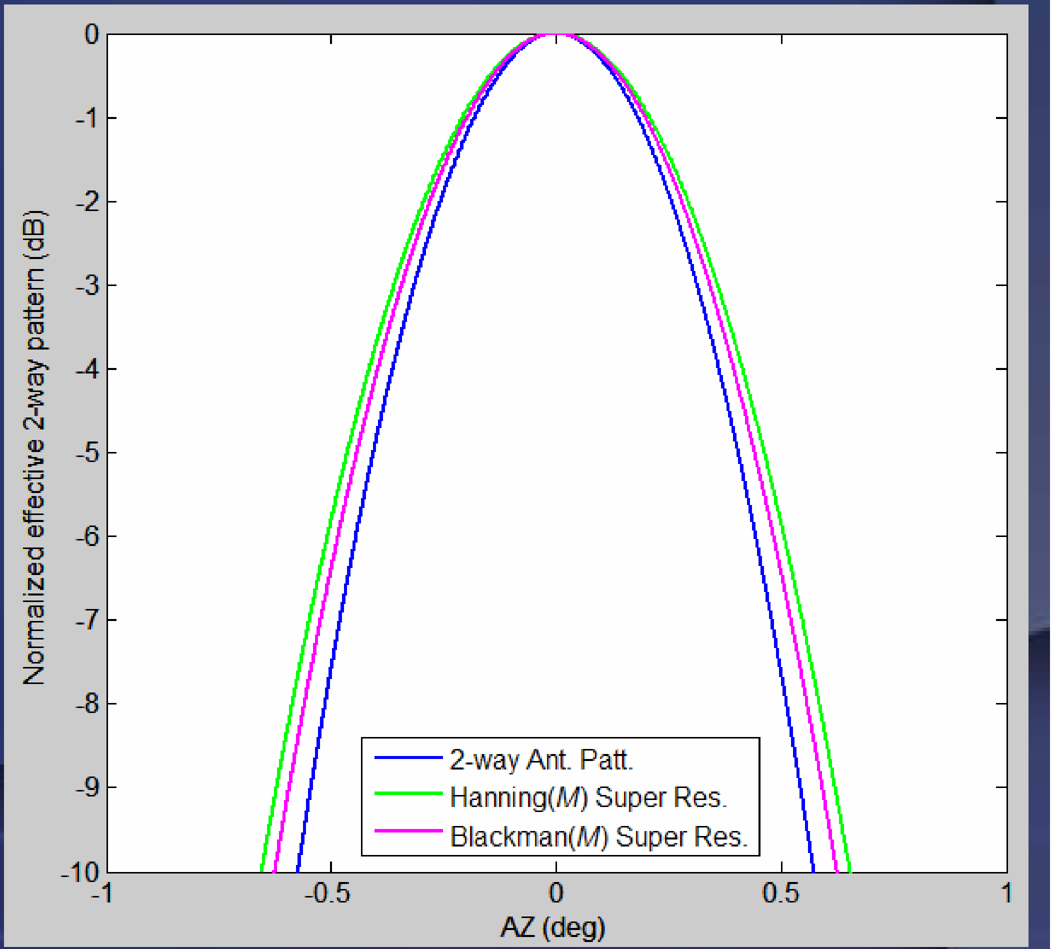
What can we change?

Parameters under control

- Antenna rot. rate (α) ☑
- Pulse repetition time ($\mathbf{T}_s$) ☑
- Azimuthal sampling (Δ**AZ**) ☑
- Range sampling (Δ**r**) ☑
- # of samples per radial (**M**) ☑
- Data window ☑ → von Hann window

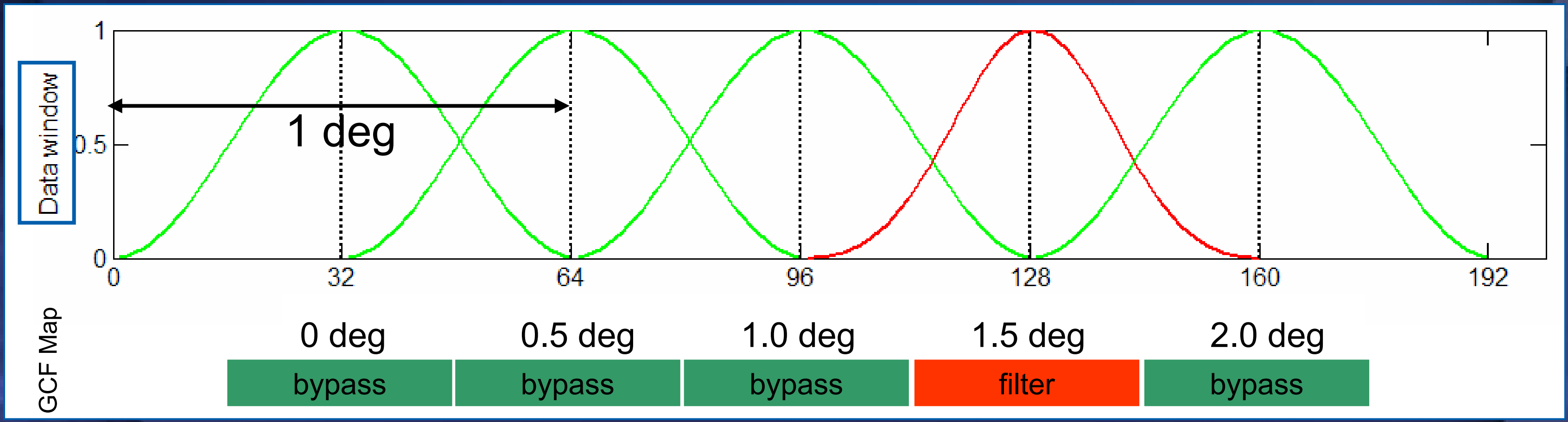
Choosing a Data Window

- For compatibility with GMAP, a Blackman window is required
- A **Blackman** window results in **better azimuthal resolution** (narrower effective beamwidth)
  - This is not necessarily better: **larger errors** of estimates



Super Resolution Recommendation

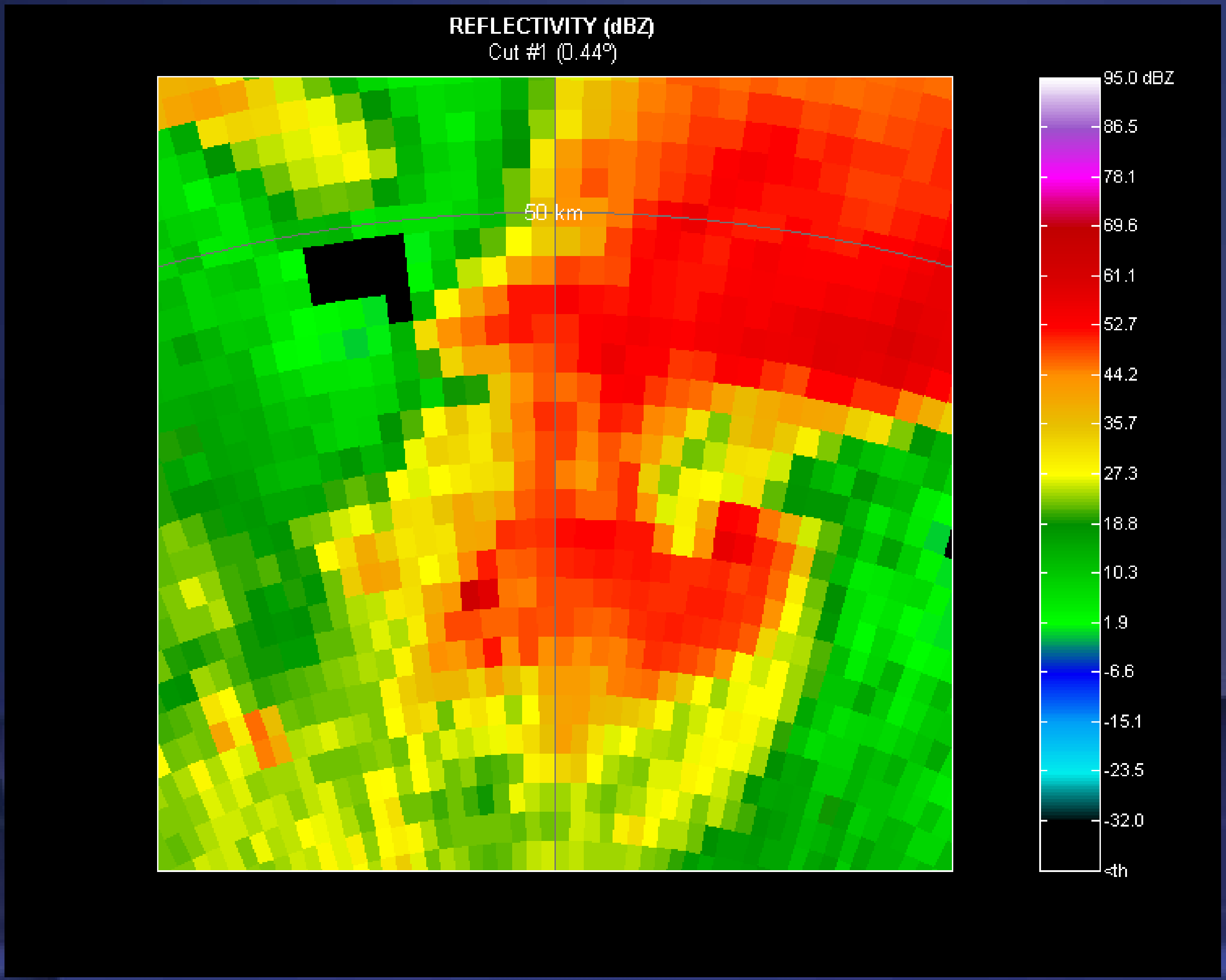
- **Overlapping** 1-deg radials with data **windowing** sampled every 0.5 deg and **no range averaging**
  - For *each* range gate, weight *M* time-series data samples with
    - von Hann window if clutter filtering is not needed
    - Blackman window if clutter filtering is needed



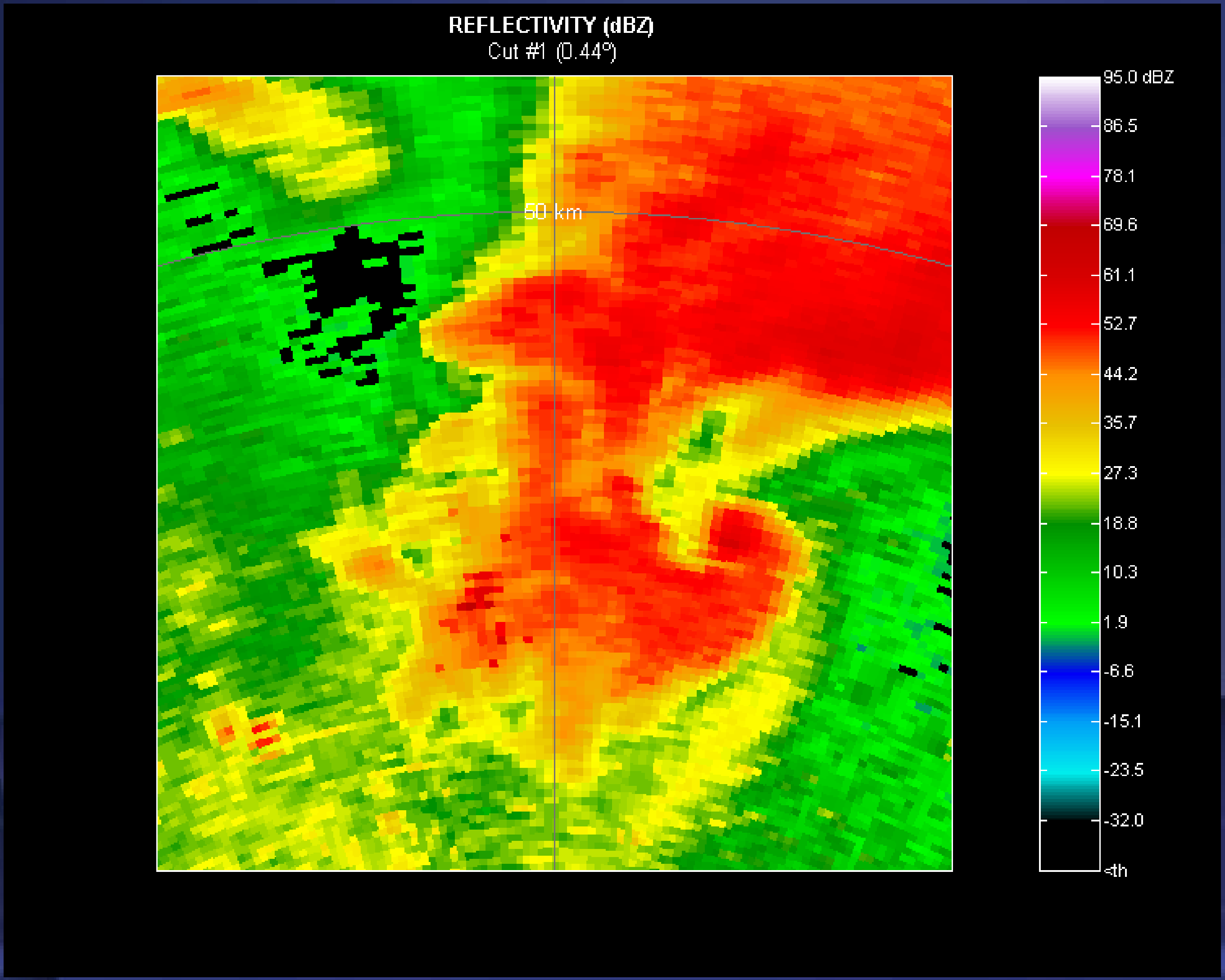
Data Examples

- Data collected with KOUN radar in Norman, OK
  - Experimental VCP
    - Cut #1: 0.5 deg, PRI #2, M = 48
    - Cut #2: 0.5 deg, PRI #8, M = 64
- F3 tornado in Edmond, OK
  - May 10, 2003 03:42 UTC

Legacy Resolution

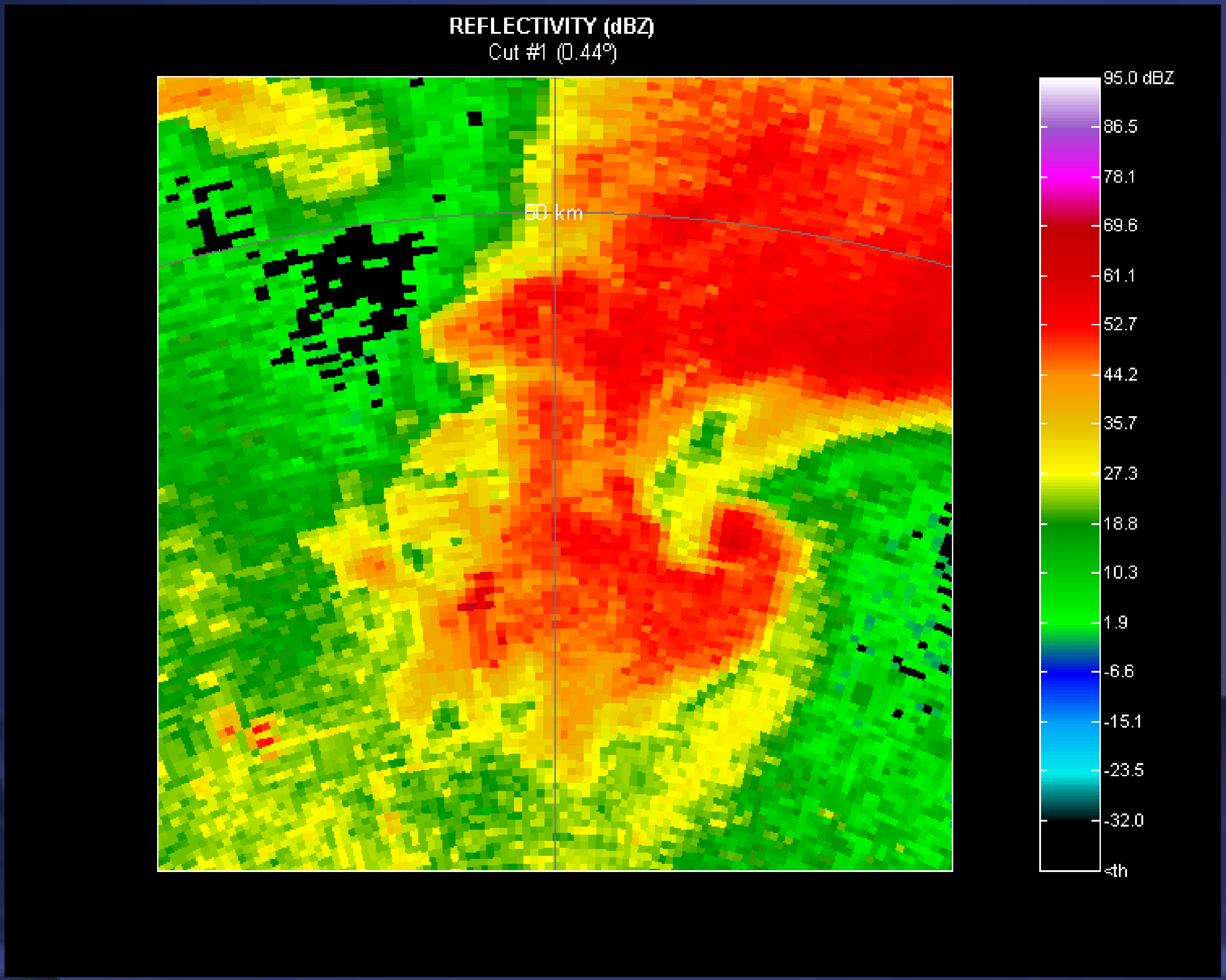


Super Resolution
Rectangular window

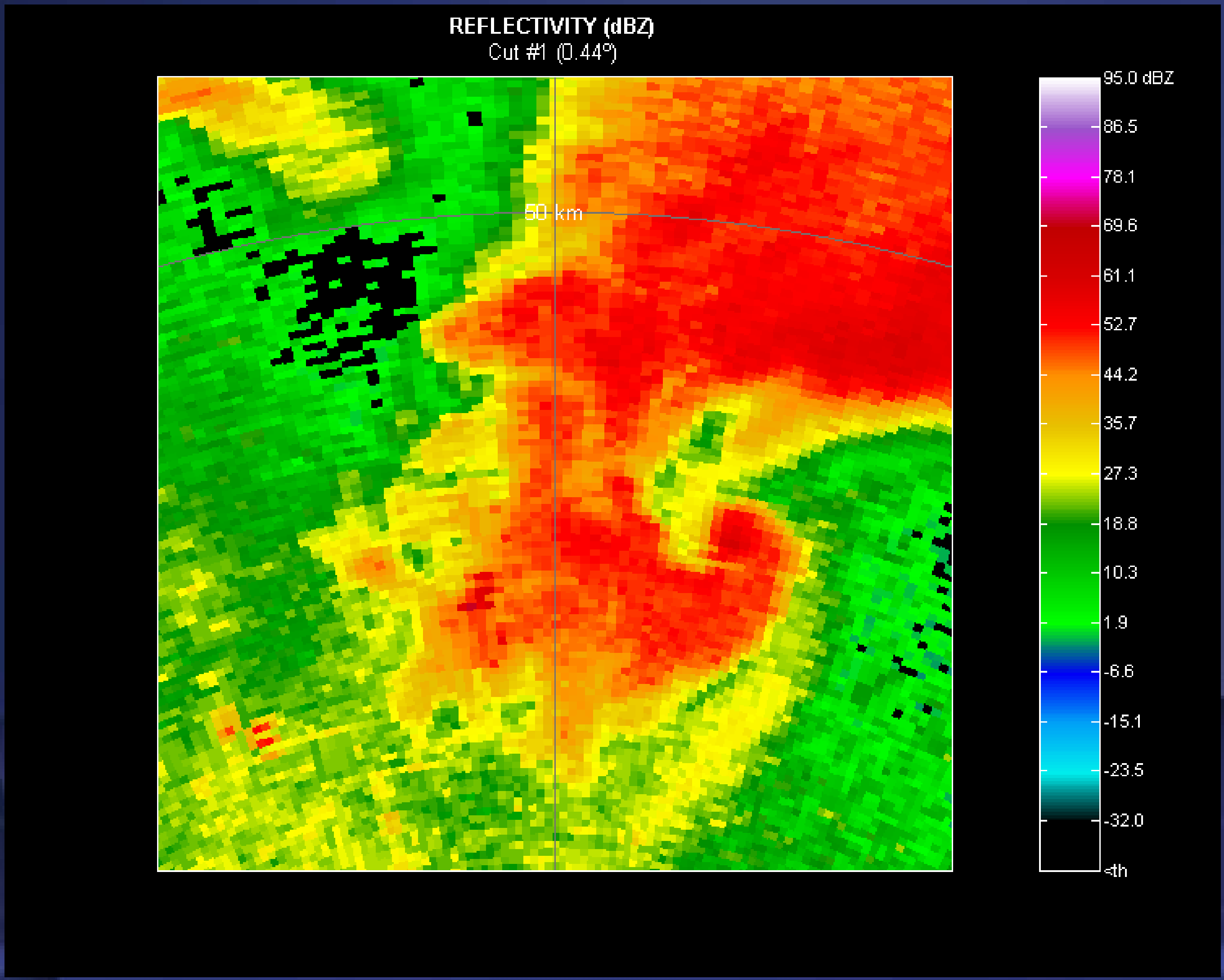


Super Resolution

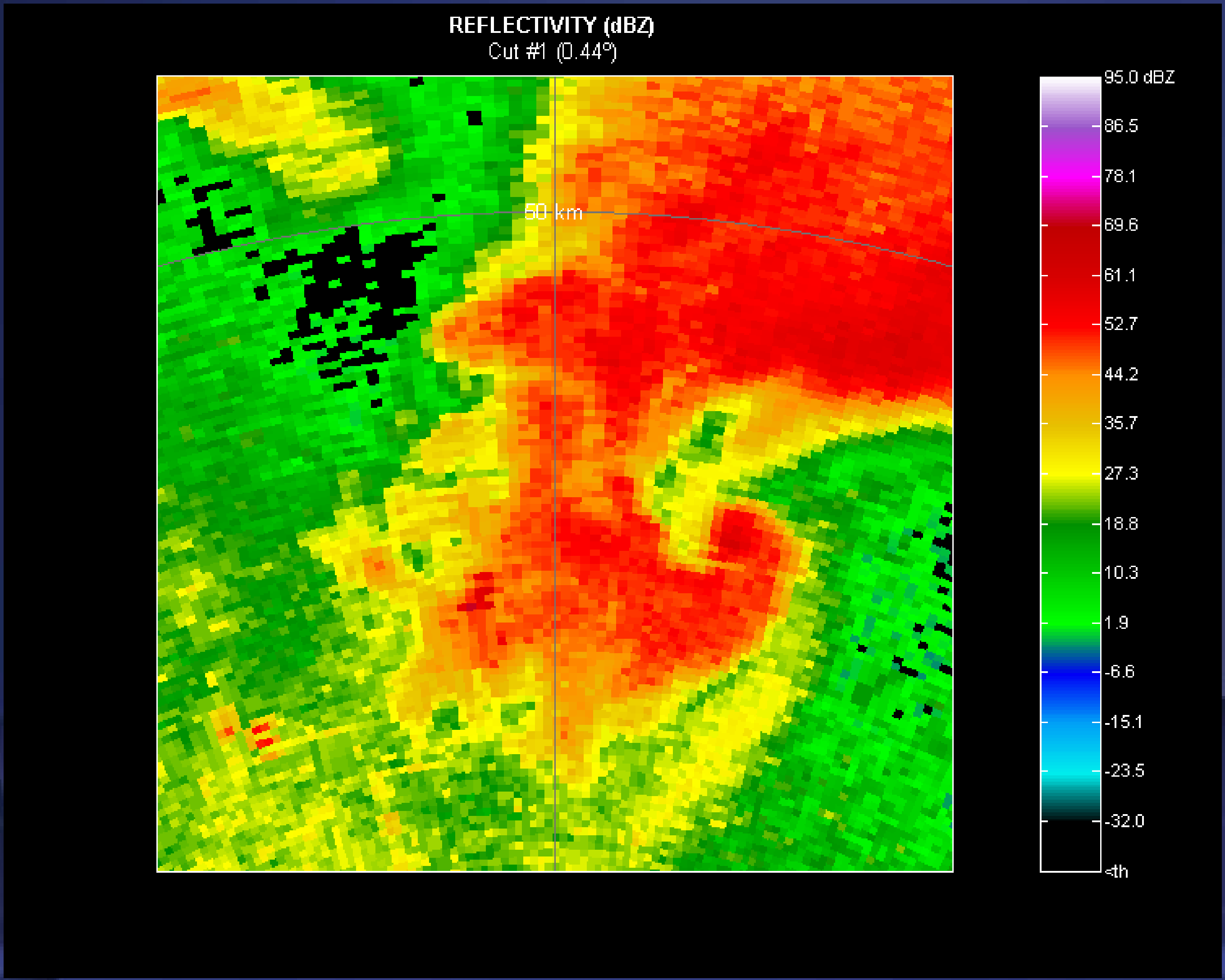
Conventional



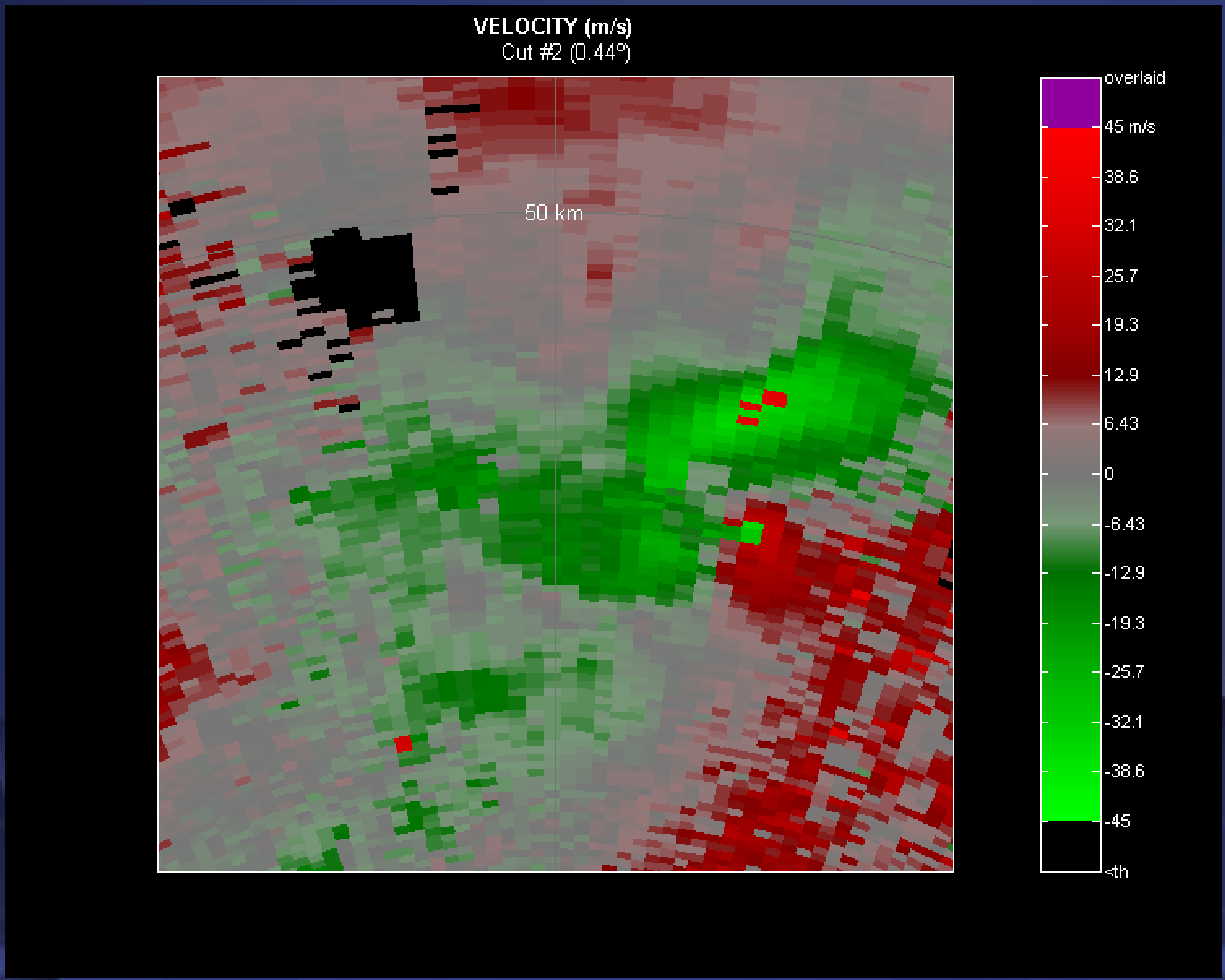
Super Resolution
von Hann window



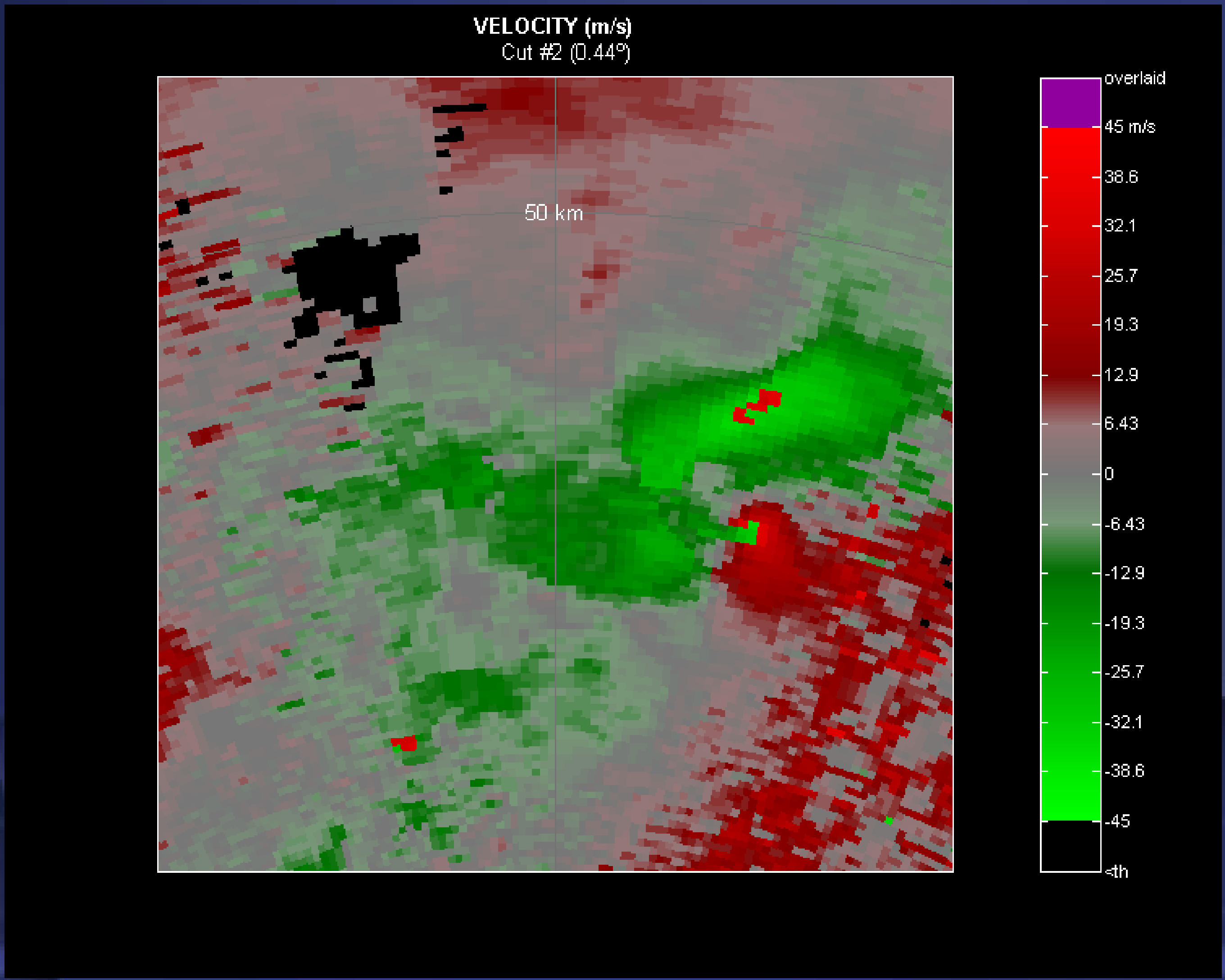
Super Resolution
Blackman window



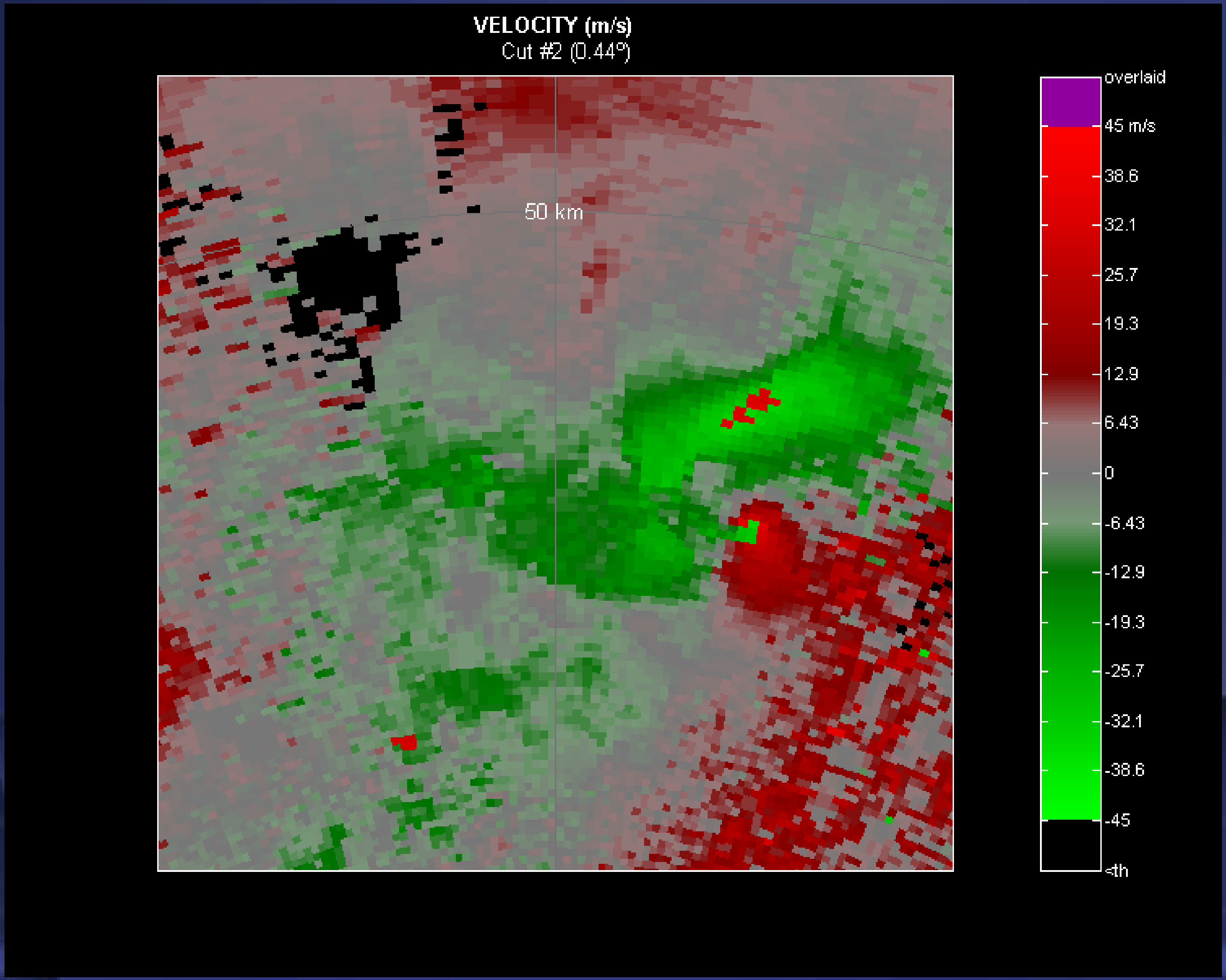
Legacy Resolution



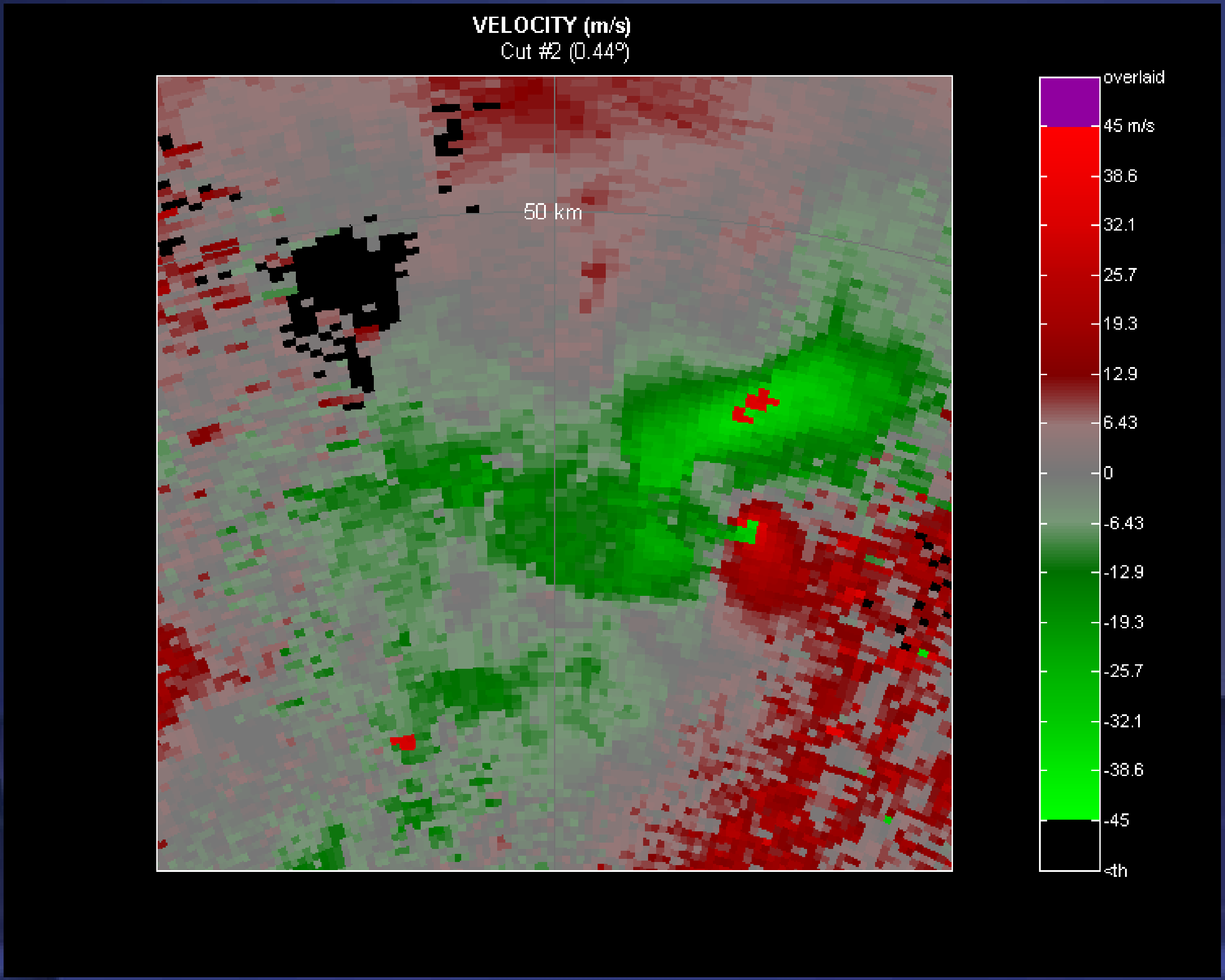
Super Resolution
Rectangular window



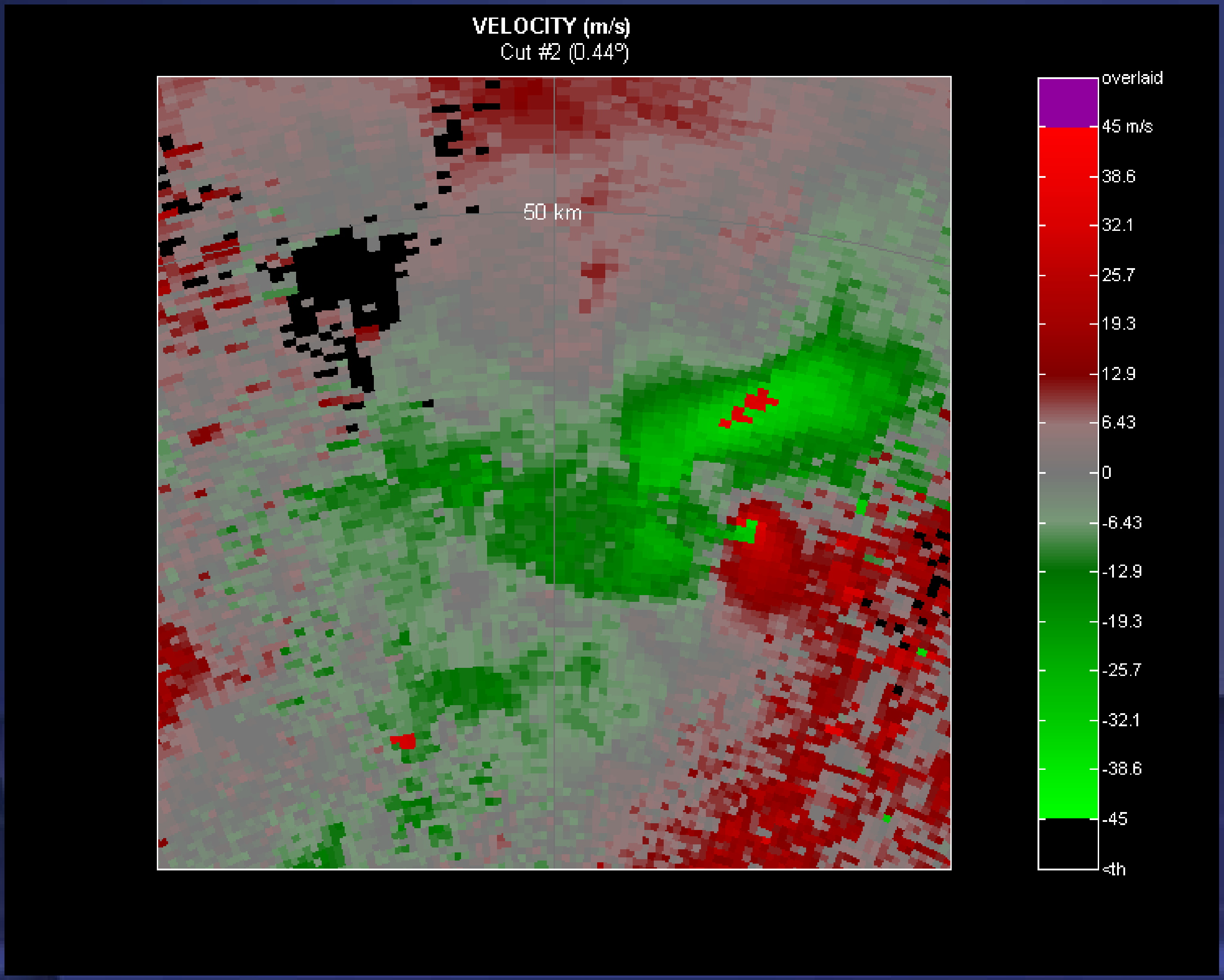
Super Resolution
Conventional



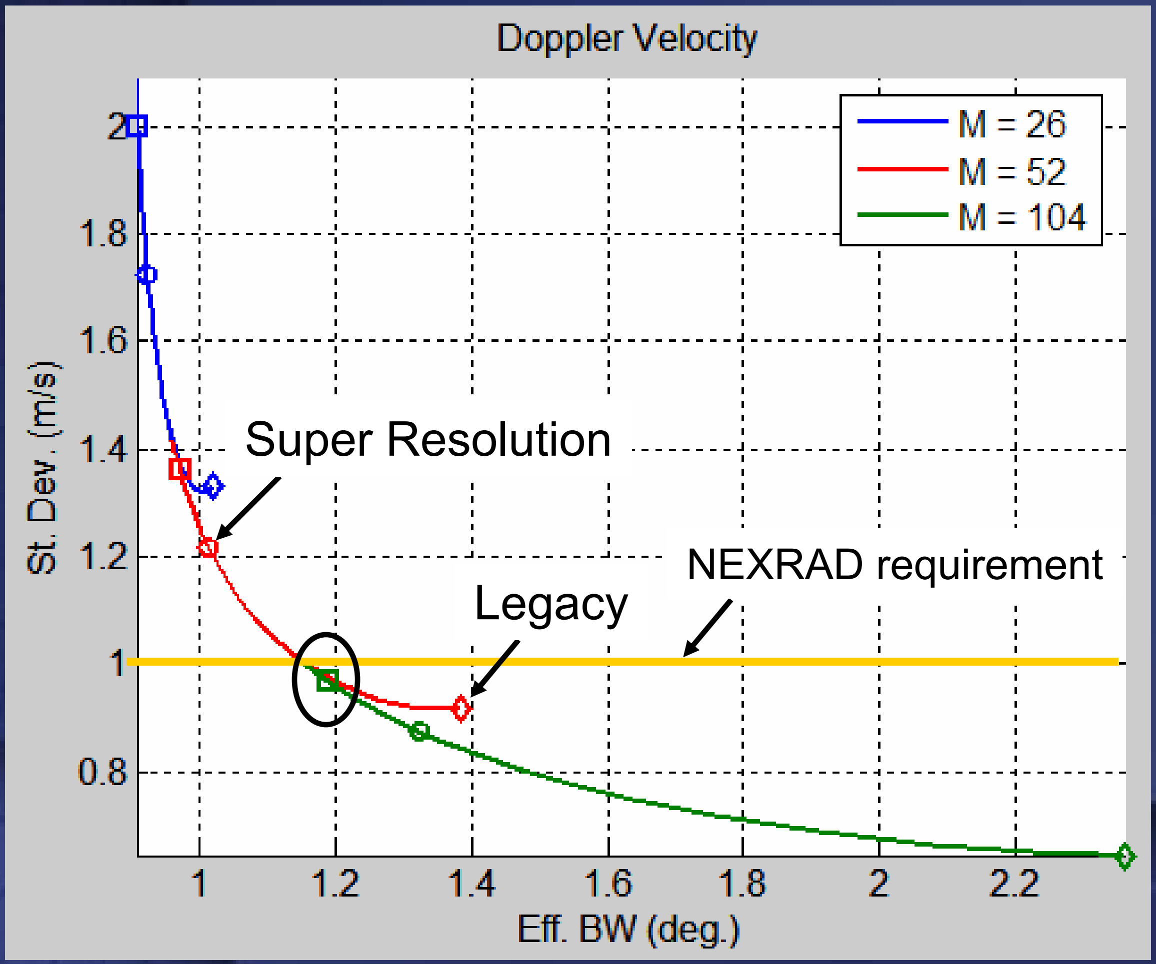
Super Resolution
von Hann window



Super Resolution
Blackman window



Errors of Estimates with Super Resolution



- VCP 11, 2nd tilt
  - PRI #5
  - 52 pulses in 1 deg
  - ORDA FFT Mode
- Data windows
  - ♦: rectangular
  - ●: von Hann
  - ■: Blackman
- Parameters
  - SNR = 8 dB
  - σ_v = 4 m/s

Meeting Error Requirements

- Produce dual streams
  - Use super resolution stream for visualization, use legacy resolution stream for algorithms
  - Increased throughput
  - Increased computational complexity
- Implement azimuthal recombination on the ORPG
  - Only quantized and censored base data available on the ORPG
- Reduce antenna rotation rate
  - Increased VCP time
- Accept higher errors of estimates
  - Errors do not meet NEXRAD requirements
  - Unknown impact to algorithms
    - Plan to evaluate after ORDA is installed on KOUN
- 0.5 deg sampling with a rectangular window
  - Increased effective beamwidth
  - Do not fully realize the benefits of super resolution
- Acquire range oversampled signals and process with a pseudowhitening transformation
  - Increased computational complexity
  - Slightly reduced range resolution

Errors of Estimates with Super Resolution for VCP-11

Cut	Param.	Legacy errors	von Hann Super Resolution errors	Additional time to meet legacy performance	Additional time to meet NEXRAD requirements
1	*Z*	0.59 dB	0.79 dB	18.84 s	0 s
2	*v*	0.96 m/s	1.35 m/s	11.96 s	10.10 s
3	*Z*	0.61 dB	0.81 dB	17.66 s	0 s
4	*v*	0.96 m/s	1.35 m/s	11.96 s	10.10 s
			Additional VCP time	**60.42 s**	**20.20 s**

For *Z*, SNR = 10 dB, σ_v = 4 m/s, 1-km range resolution
For *v*, SNR = 8dB, σ_v = 4 m/s, 250-m range resolution

ORDA Super Resolution

- Configure RVP-8 to use overlapping 1-deg radials sampled every 0.5 deg
  - Processing as usual
- Configure RVP-8 to apply clutter-filter-dependent data window
- Bypass legacy range averaging of reflectivity estimates (VCPC)
- Send 0.5-deg radials with 250-m range resolution data to ORPG
  - Changes to RDA-RPG ICD, new VCP definitions (?)
  - Compress base data
    - Throughput is 8 times higher for Surveillance cuts* and 2 times higher for Doppler cuts
    - Throughput is 9 times higher for Surveillance cuts* and 3 times higher for Doppler cuts **with dual streams**

ORPG Super Resolution

- Receive Super Resolution data
  - Decompress base data
- Generate legacy resolution base data products for algorithms
  - Take every other radial and perform recombination
    - In range for reflectivity
    - In azimuth for all moments **with azimuthal recombination**
  - Take legacy resolution stream **with dual streams**
- Generate Super Resolution base data products for display
  - Will eventually need to modify selected ORPG algorithms to fully benefit from Super Resolution data

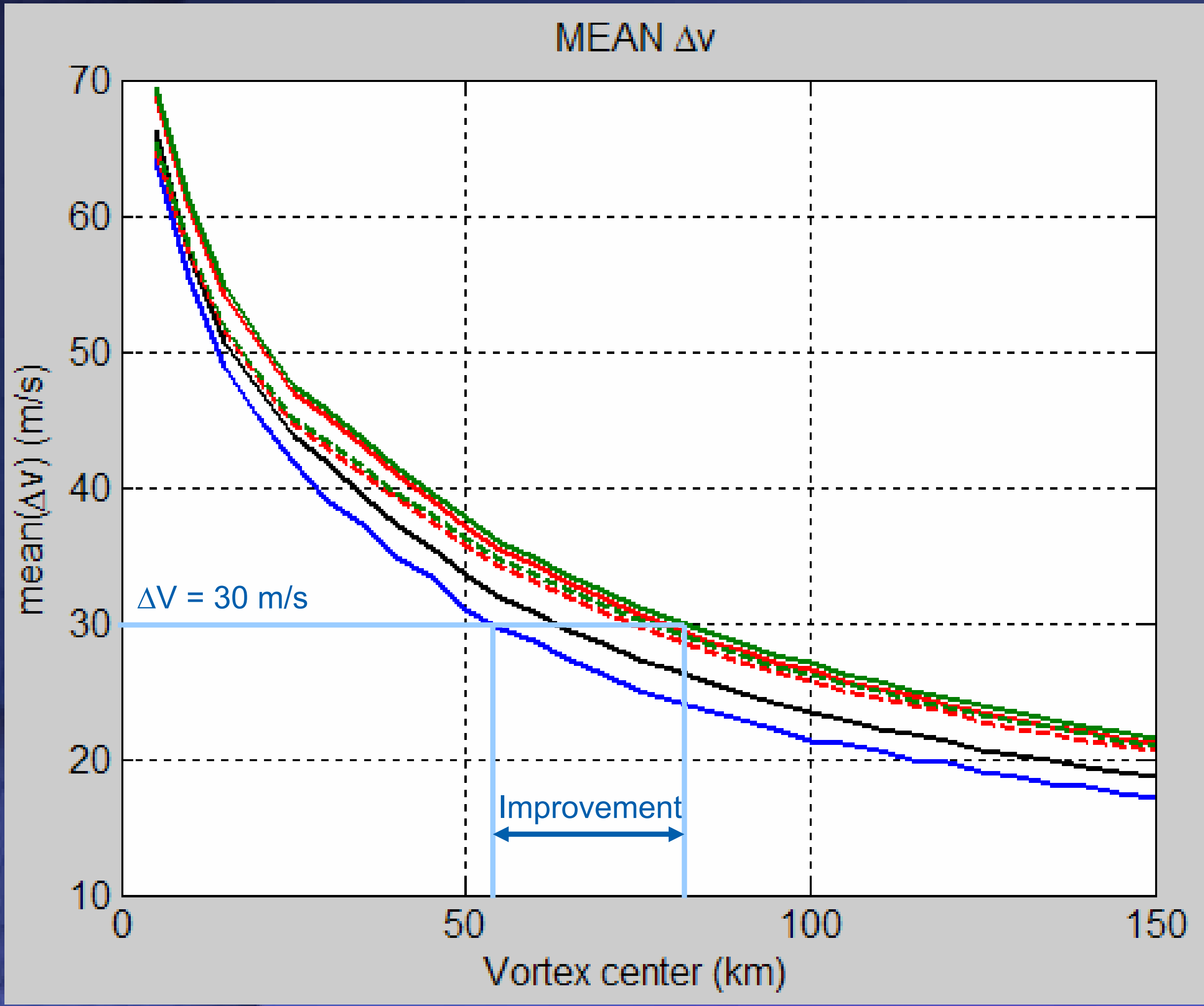
Implementation Issues

- ORDA CPU load (**key factor** in implementation decision)
  - Super Resolution at least doubles CPU load
  - Super Resolution **with dual streams** triples CPU load
  - Super Resolution **with range oversampling** increases CPU load by about 10 times
    - Range oversampling techniques increase the number of computations by a factor of *L* (oversampling factor)
      - Recommend using *L* ~ 5
  - Unknowns*
    - Baseline ORDA CPU load
    - ORDA CPU load with SZ-2
    - ORDA CPU load with Dual Polarization
  - ORDA currently being installed on KOUN
- Availability of clutter maps on a 250-m by 0.5-deg grid

Tornado Vortex Simulation

- Tornadic time-series data simulation
  - Rankine vortex model for velocity
  - Uniform reflectivity
  - Can control vortex size, strength, and location
- Moved tornado vortex in steps of 5 km up to 150 km
  - For each location, simulated tornado vortex at 100 random positions in the resolution volume
- Processed data using different schemes, number of samples, and data windows
- Computed Doppler velocity shear in azimuth (ΔV) as a measure of tornado signature strength

Tornado Detection using Super Resolution Data



- Core diameter = 200 m
- Max. tangential vel. = 50 m/s
- *M* = 64

- Legacy resolution
- Rectangular 0.5 deg sampling
- von Hann Super Resolution
- Blackman Super Resolution
- Range overs. and pseudowhitening

Conclusions

- Super Resolution data produces enhanced mesocyclone and tornado signatures
  - Potential to detect weaker and/or more distant tornadoes
- Compatibility of ORDA with Super Resolution
  - OK in theory and simulations
  - Can ORDA handle additional CPU load?
- Compatibility of ORPG with Super Resolution
  - OK in theory and simulations
  - What is the preferred way to handle base data with larger errors?

Summary

Implementation Options / Risk	Perform Range Oversampling w/ Pseudowhitening	Azimuthal Recombination	Dual Streams	0.5 deg Sampling	Slow Antenna Rotation	Allow Higher Errors of Estimates
Build 10 Schedule	Medium-High	Medium	Medium-High	Low	Low	Low
Relative CPU Loading	High	Medium	Medium	Low	Low	Low
Relative Bandwidth Loading	Low	Low	Medium	Low	Low	Low
Data Quality of Super Res Data	Low	Medium	Medium	Medium-High	None	Medium
Data Quality of Legacy Res Data	Low	Low	None	None	None	Medium-High
Operational	Low	None	None	None	High	None
Long Term Goals	Low	Medium	Medium	Medium-High	Medium-High	Medium-High

Recommendations

- To meet long-term technical goals, implement **recommended Super Resolution with range oversampling and pseudowhitening**
  - **Direct approach**
    - Higher risk
  - **Staged approach #1** (short time between stages)
    1. 0.5 deg sampling with rectangular window
    2. Recommended super resolution with range oversampling and pseudowhitening
  - **Staged approach #2** (long time between stages)
    1. Recommended super resolution with azimuthal recombination or dual streams
    2. Range oversampling and pseudowhitening