NCAR

Informational Briefing:

Spectrum Width Estimator Problems and their Impact on the NEXRAD Turbulence Detection Algorithm (NTDA)

Greg Meymaris and John K. Williams, NCAR

NEXRAD Technical Advisory Committee Meeting

Norman, OK

March 28, 2007

National Center for Atmospheric Research

Outline

- NTDA implementation update
- Spectrum width impact on NTDA
  - Spectrum width estimator problems make it difficult to discriminate null and light from moderate or greater turbulence
- Simulation results
  - The legacy R0/R1 pulse-pair estimator
  - A poly pulse-pair "hybrid" method
- Case-study results
- Summary and request for TAC endorsement

NTDA implementation update

- NTDA version 1 has been delivered and successfully integrated into the WSR-88D software baseline for ORPG Build 10.
- NCAR/RAL's experience with the ORPG technology transfer process has been very positive.
- Currently working through OSIP for approval of NTDA data collection and dissemination.
- Plan to develop NTDA-2 for ORPG Build 12
  - Will provide improved accuracy and greater coverage.
  - Will supply EDR even in low-dBZ conditions below 10 kft.

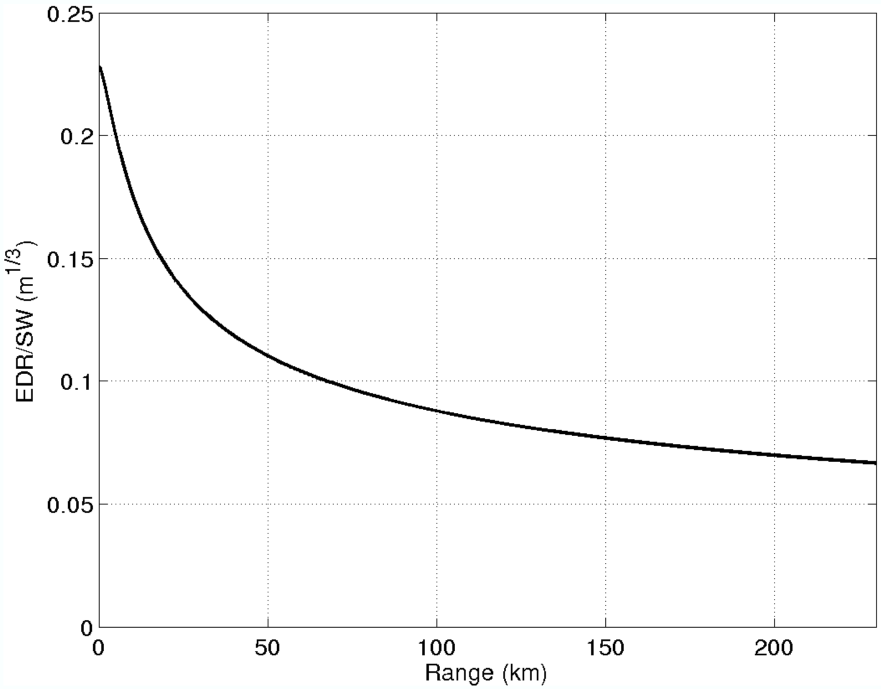
NTDA evaluation update

- NTDA presentation at TAC telecon on November 1 showed disappointing evaluation results. Causes:
  – Imperfect aircraft/radar collocation
  – Spectrum width estimator inaccuracy
  – QC did not account for differences between VCPs
- Short-term solution
  – Modified NTDA QC to treat each VCP individually, with interest maps based on worst-case SW simulation performance statistics for that VCP.
- Long-term solution may require ORDA implementation of an improved SW estimator.

NTDA-1: Spectrum width method

$$\varepsilon^{1/3}(r) = \left\langle \mathrm{SW}^2 \right\rangle^{1/2} f(r)$$

- $\varepsilon^{1/3}$: EDR estimate (turbulence)
- SW^2: measured spectrum widths
- $\langle \cdot \rangle$: local conf-wtd mean
- $f(r)$: theoretical "scaling" factor for range *r*



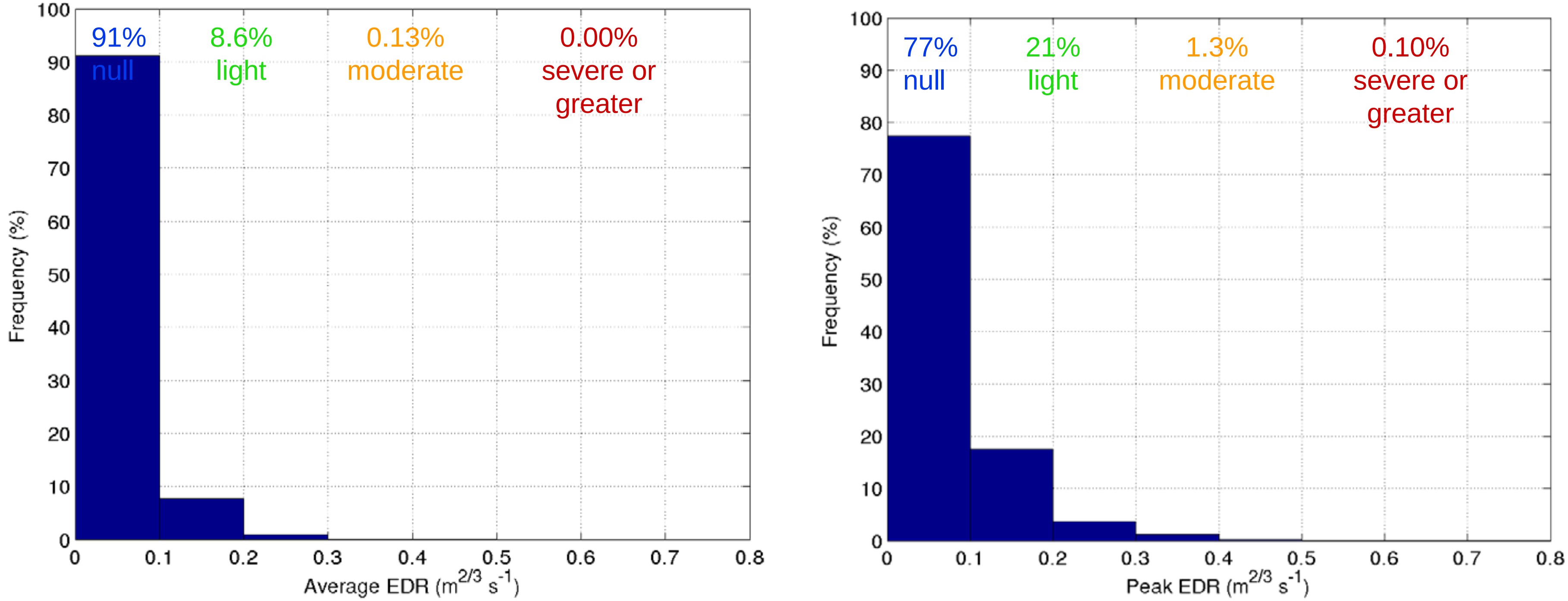
NTDA SW to EDR "scaling" function *f*(*r*)
(dependent on beam volume and windowing)

EDR and turbulence severity

EDR $(m^{2/3}\ s^{-1})$	SW (5 km) $(m\ s^{-1})$	SW (150 km) $(m\ s^{-1})$	Severity
0.0 – 0.1	0.0 – 0.4	0.0 – 1.2	Null
0.1 – 0.3	0.4 – 1.3	1.2 – 3.9	Light
0.3 – 0.5	1.3 – 2.2	3.9 – 6.6	Moderate
0.5 – 0.7	2.2 – 3.1	6.6 – 9.3	Severe
> *0.7*	> 3.1	> 9.3	Extreme

Accurate estimation of small spectrum widths is essential for distinguishing null from light or moderate turbulence. This is not addressed by the current SW specification.

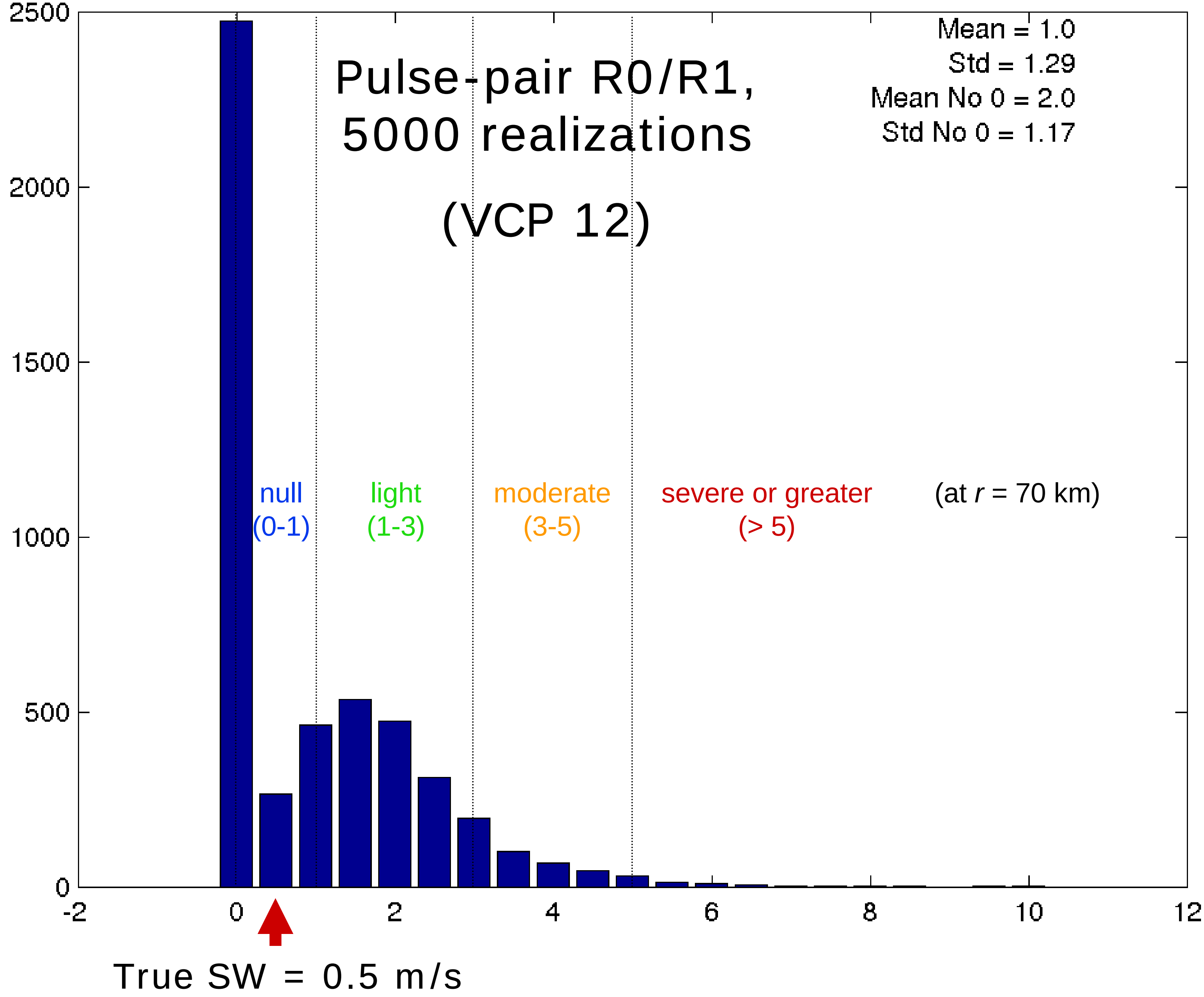
Distribution of aircraft EDRs



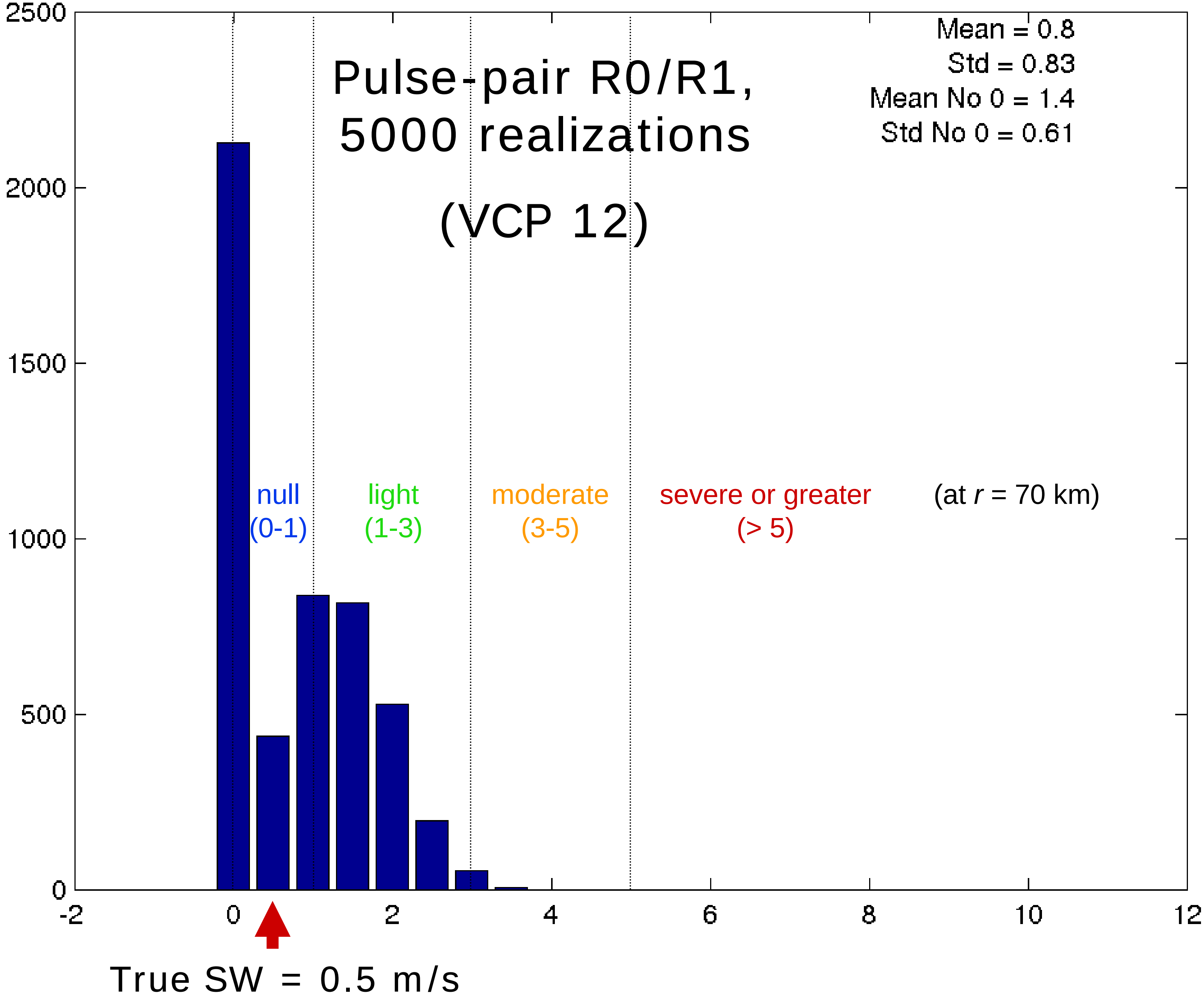
United Airlines *average* and *peak* EDR over 1-minute flight segments above 20 kft associated with SNR > 10 dB (within 5 km horizontally and 500 m vertically).

Even very rare SW overestimates when turbulence is null or light may cause false alarms to exceed correct detections.

Simulation results: N = 40 pulses, T_s = 988 μs, SNR = 10 dB and PR = 50 dB



Simulation results: N = 40 pulses, T_s = 988 μs, SNR = 30 dB and PR = 50 dB



NEXRAD Technical Requirement for SW

- **Spectrum width computation**:
  autocorrelation, pulse-pair (R0/R1 or R1/R2 for SZ-2)
- **Spectrum width estimate standard deviation (from 1996):**
  "For a true spectrum width of 4 m s^{-1} the standard deviation in the estimate of the spectrum width shall be less than or equal to 1.0 m s^{-1} including quantization errors, for S/N greater than 10 dB. Precision: 0.50 m s^{-1}.

  Note 2: Spectrum widths of 1 to at least 10 m s^{-1} shall be calculated…. Significant biases introduced by the computational technique shall be minimized.

  Note 4: Precision is defined as the quantization, the smallest resolvable increment."
- **Number of pulses averaged**: 29 to 280
- **Deficiencies**:
  – Doesn't limit relative error for lower SWs
  – Doesn't address estimator bias for lower SWs (bias cannot be removed by averaging)
  – Doesn't address saturation

AWRP

NCAR

Implications

- NTDA now uses VCP-dependent interest maps to remove SW data in conditions where simulations show it to be seriously compromised, but
- Better SWs could improve NTDA accuracy, reduce false alarms, and extend NTDA coverage into low-SNR regions at the edges of storms where aircraft commonly fly.
- The TAC could endorse an update to the spectrum width TR along with the research and development needed to meet it.

Spectrum Width Estimators for the NEXRAD ORDA

NCAR

R0/R1 Pulse-Pair Estimator

- R0/R1 (used on NEXRAD, both on Legacy and ORDA):

$$\frac{\sqrt{2}v_a}{\pi}\left|\log_{10}\left(\frac{R_0}{|R_1|}\right)\right|^{1/2}$$

$$R_0 = P_T - P_N$$

P_T – total power
P_N – noise power

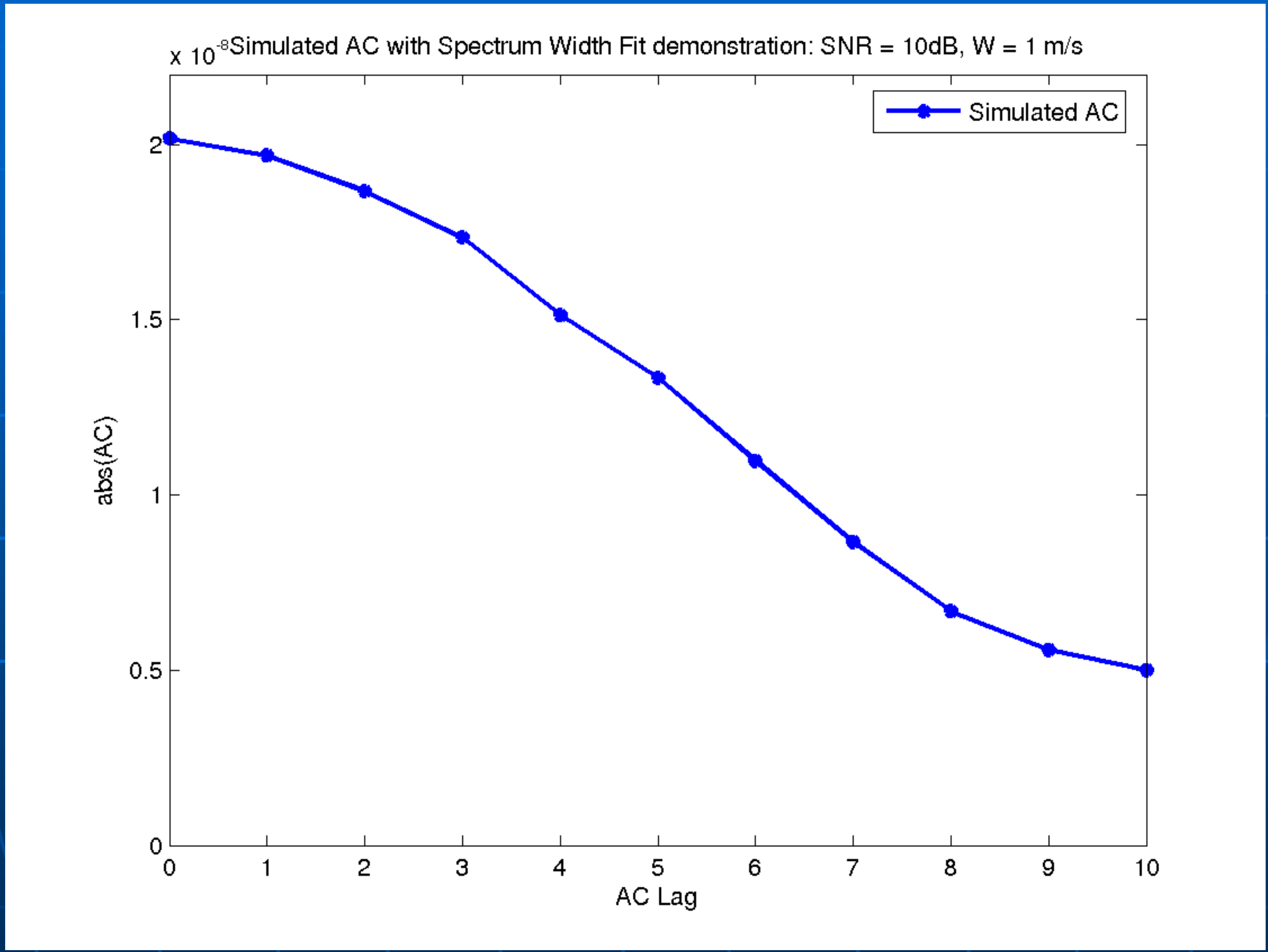
Good:

- Simple and fast
- Generally good results
- Saturation at large fraction of Nyquist velocity
- Saturates “gracefully”

Bad:

- Assumes exactly 1 Gaussian shaped signal
- Sensitive to estimate of Noise Power P_N (leads to bad performance for low SNR or small widths)
- Sometimes R0<R1

Pulse-Pair R0/R1: Simulated AC, SNR 10 dB, W=1 m/s

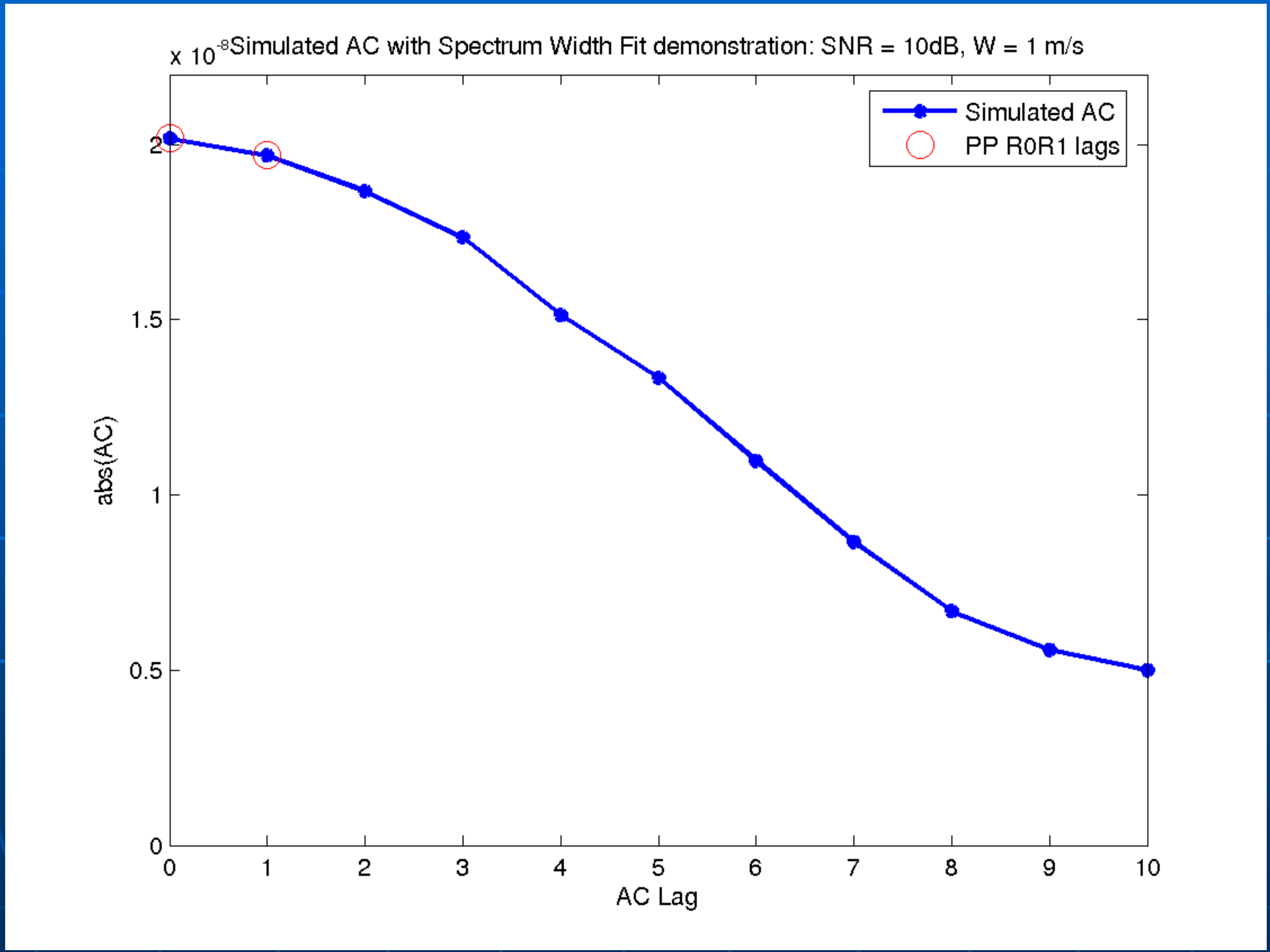


Autocorrelation Magnitude

Autocorrelation Lag

Pulse-Pair R0/R1: Simulated AC, SNR 10 dB, W=1 m/s

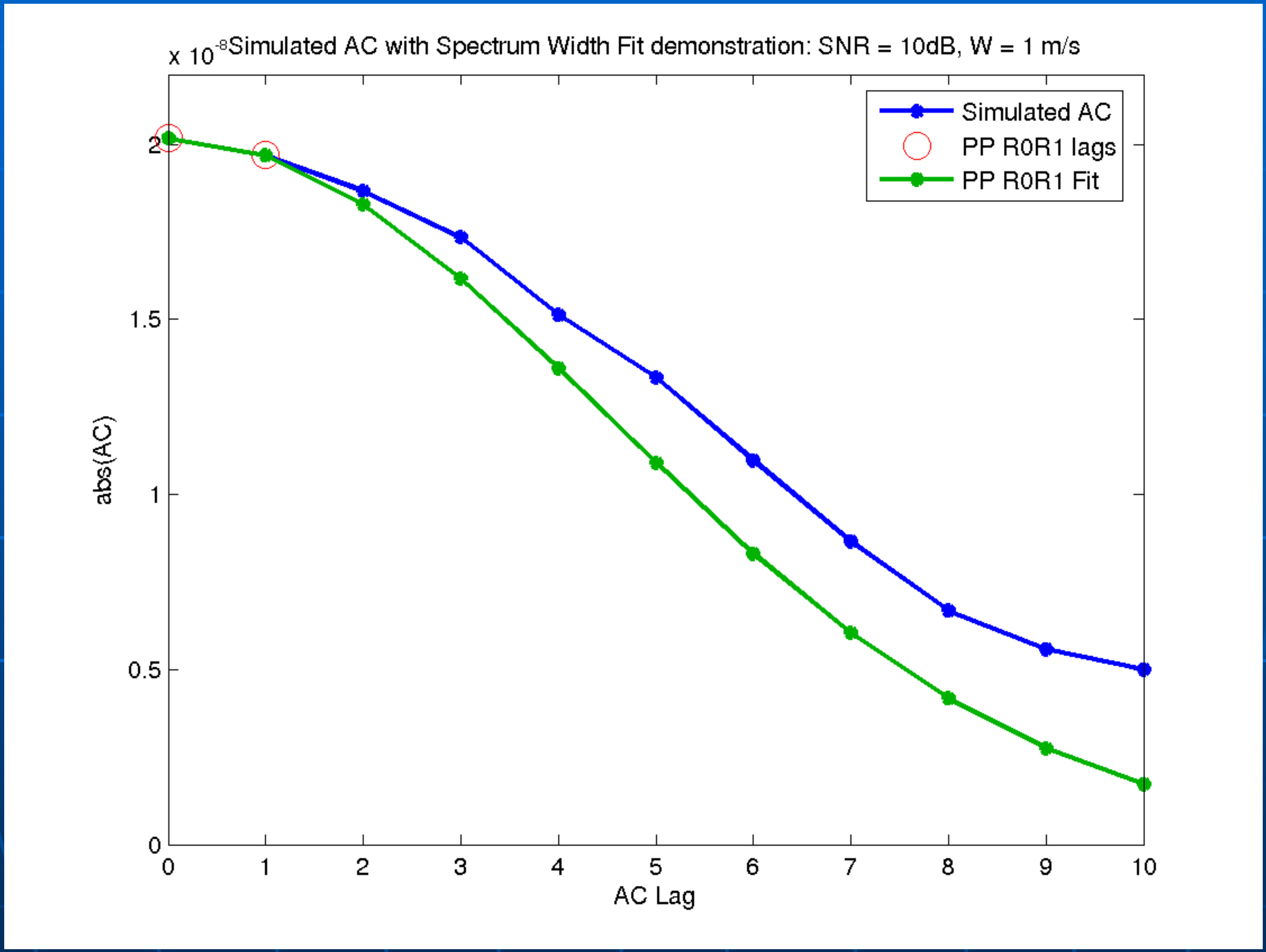
Autocorrelation Magnitude



Autocorrelation Lag

Pulse-Pair R0/R1: Simulated AC, SNR 10 dB, W=1 m/s

Autocorrelation Magnitude



Autocorrelation Lag

NCAR

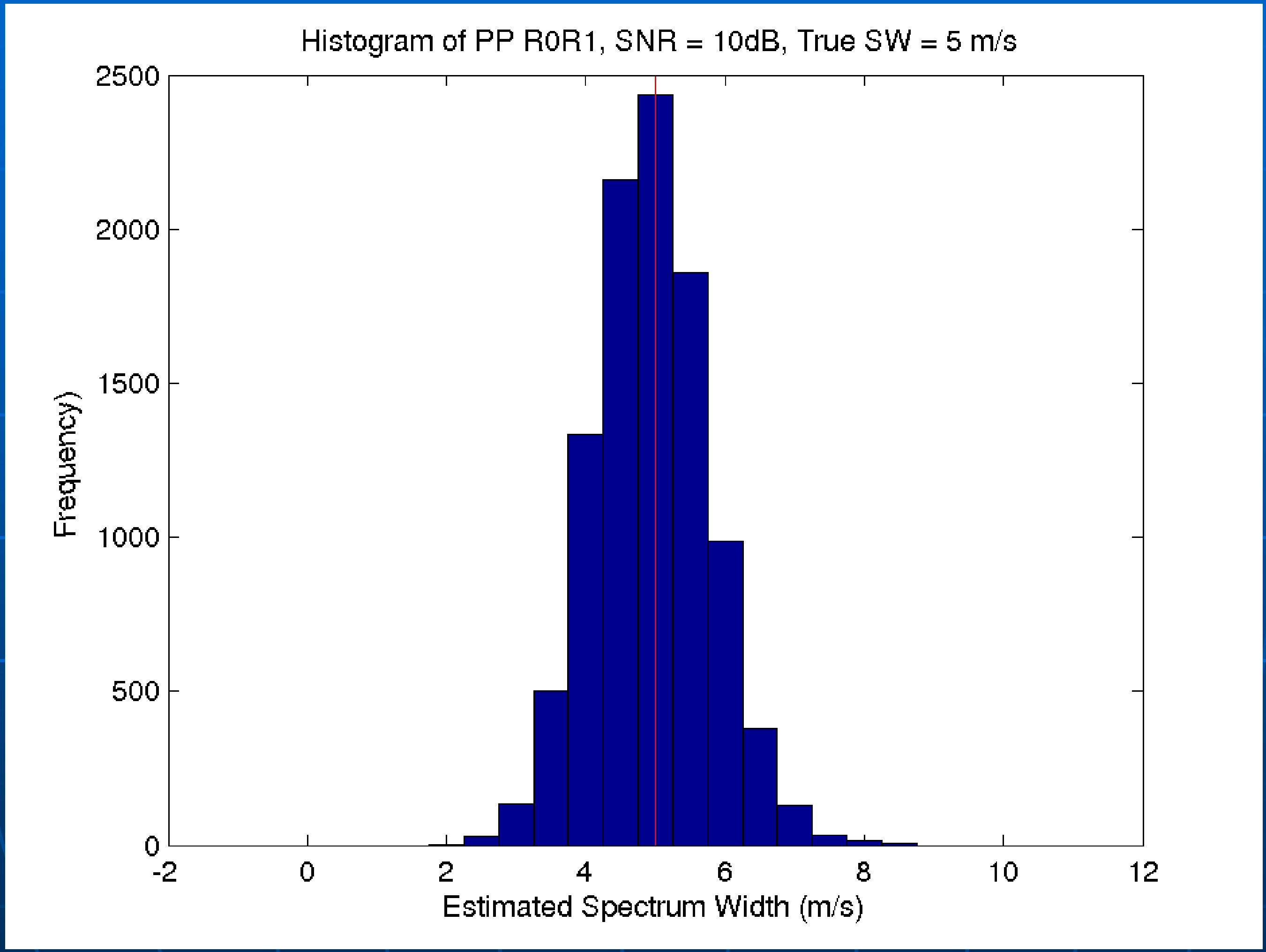
Evaluation Methodology

- Simulation Studies
  - Used I&Q simulator as detailed by R. Frehlich and M. J. Yadlowsky*
  - Varied SNR's and input ("true") spectrum widths
  - Used elevation #1 of VCP 12 with PRI #5, short (988 μs, N=40)
  - Computed estimator bias and standard deviation using 10000 time-series per scenario

* Frehlich, R. and M. J. Yadlowsky, 1994: Performance of mean-frequency estimators for doppler radar and lidar. *Journal of Atmospheric and Oceanic Technology*, 11, 1217-1230; corrigenda, 12, 445-446.

PP R0/R1 Histograms: SNR = 10dB, W = 5 m/s

Frequency



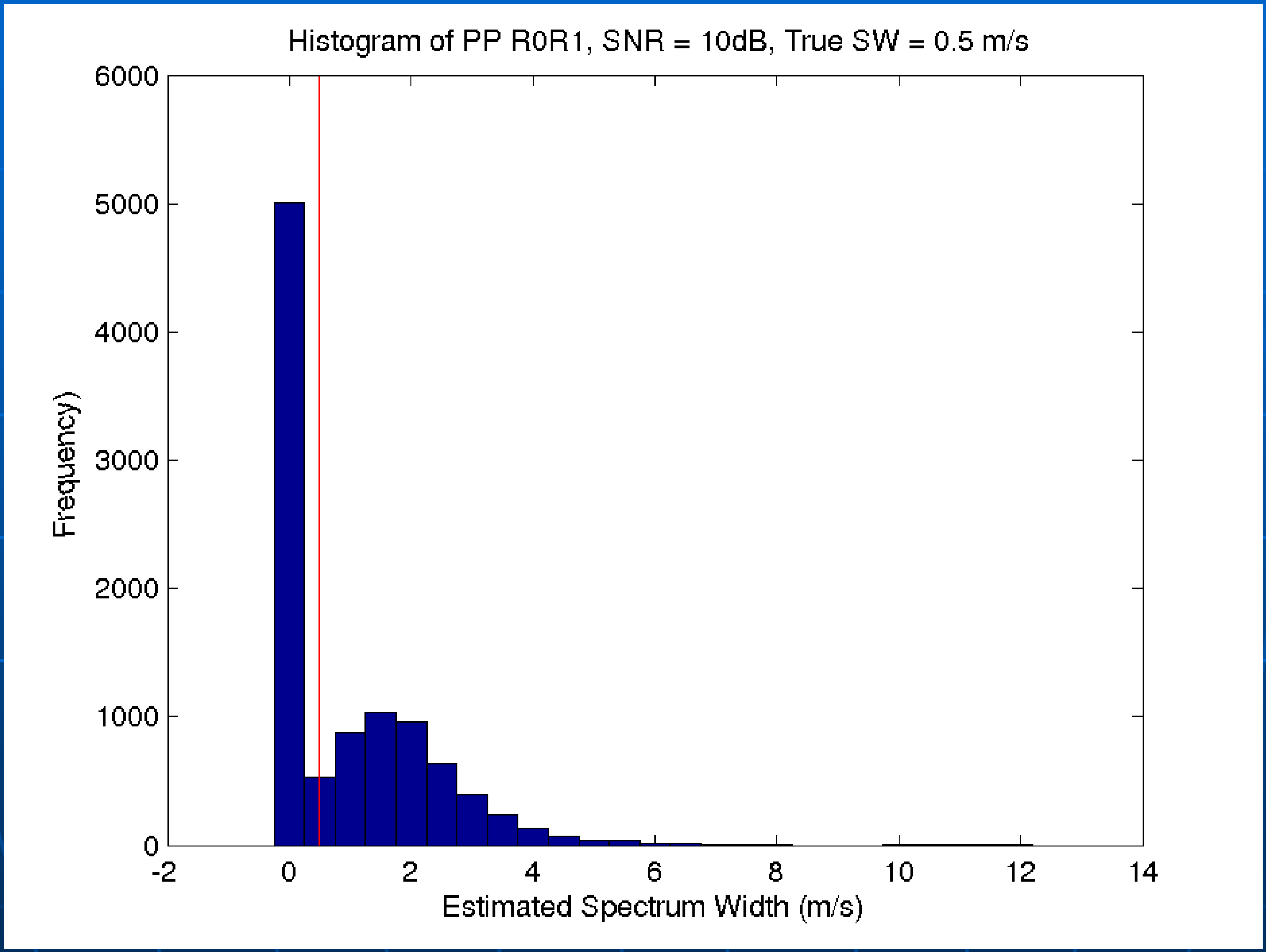
Red line indicates true W

Estimated Spectrum Width (m/s)

NCAR

PP R0/R1 Histograms: SNR = 10dB, W = 0.5 m/s

Frequency

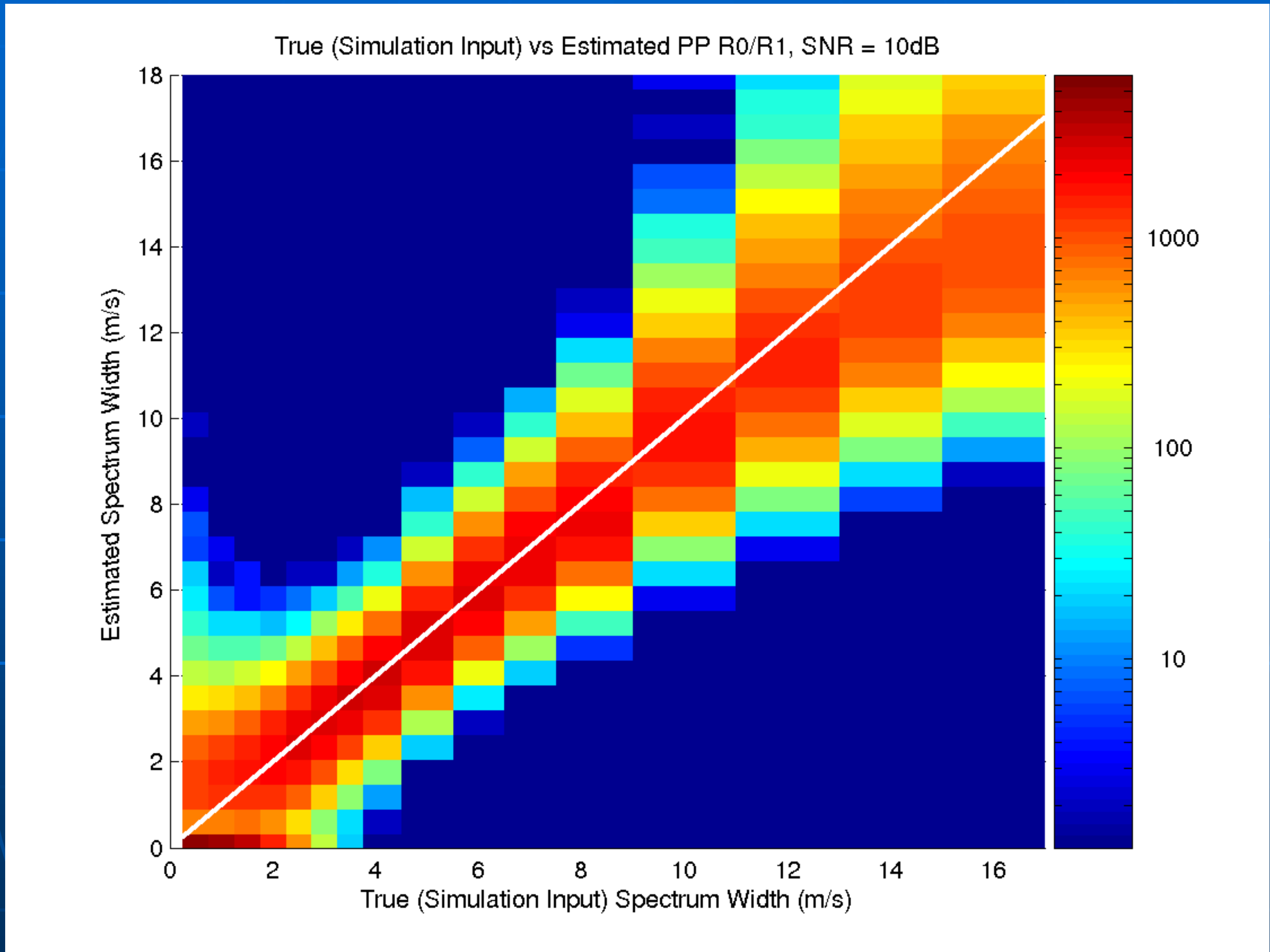


Red line indicates true W

Estimated Spectrum Width (m/s)

# PP R0/R1 2D Histograms – True vs. Estimated:
SNR = 10dB

Estimated Spectrum Width



Frequency (log scale)

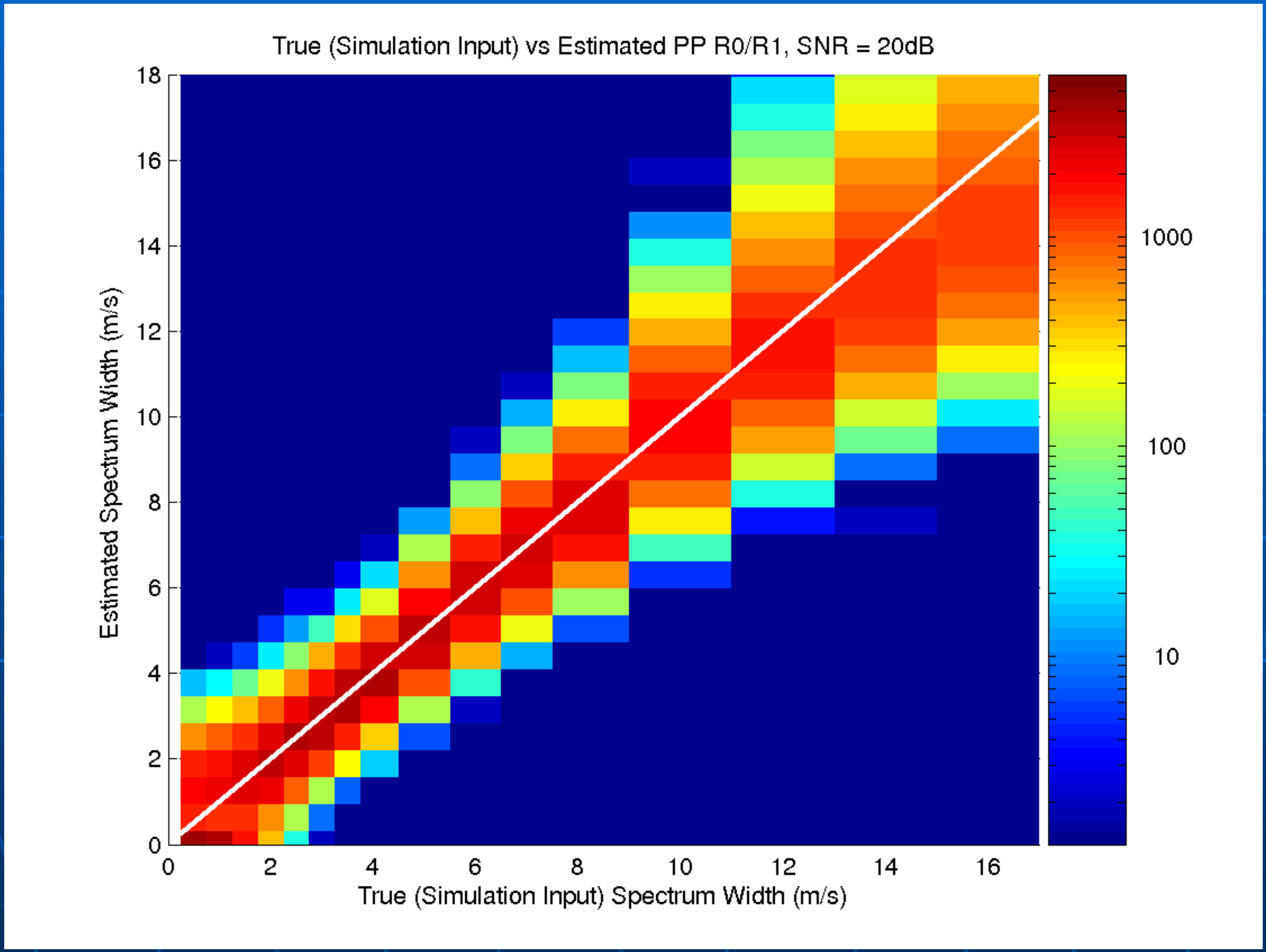
True (Input) Spectrum Width (m/s)

NCAR

PP R0/R1 2D Histograms – True vs. Estimated:

SNR = 20dB

Estimated Spectrum Width



Frequency (log scale)

True (Input) Spectrum Width (m/s)

NCAR

R1/R2 Pulse-Pair Estimator

- R1/R2 (will be used in ORDA, in SZ-2):

$$\frac{2v_a}{\pi\sqrt{6}}\left|\log_{10}\left(\left|\frac{R_1}{R_2}\right|\right)\right|^{1/2}$$

Good:

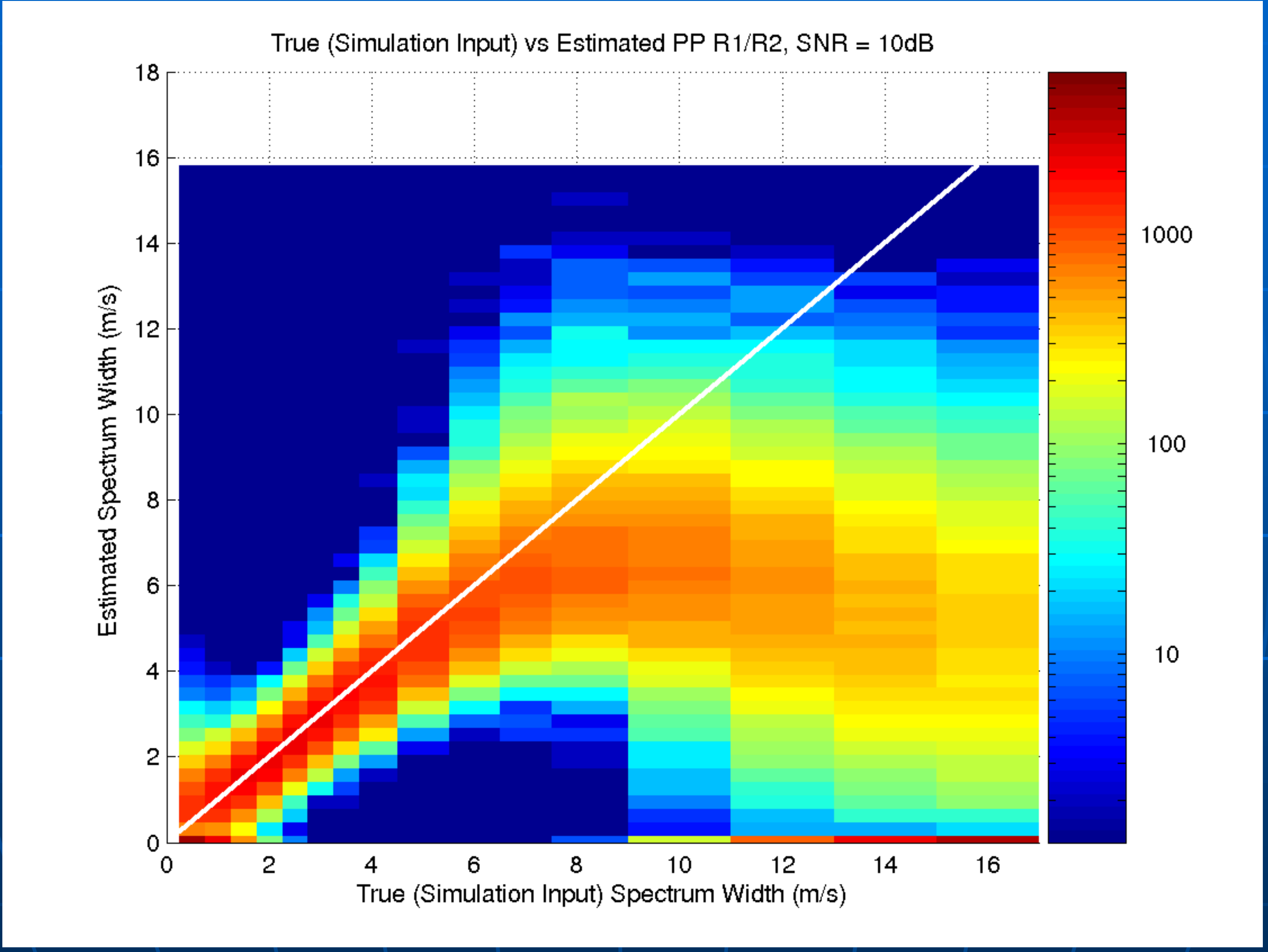
- Simple and fast
- Generally good results
- Insensitive to estimate of noise power P_N

Bad:

- Assumes exactly 1 Gaussian shaped signal
- Saturates for spectrum widths above ~1/3 Nyquist
- Saturation failure mode extremely poor

PP R1/R2 2D Histograms – True vs. Estimated:

SNR = 10dB



Estimated Spectrum Width

Frequency (log scale)

True (Input) Spectrum Width (m/s)

R0/R1/R2 Least Squares Estimator

- Poly-Pulse Pair method using R0, R1, and R2
- Proposed to be used as part of hybrid estimator.

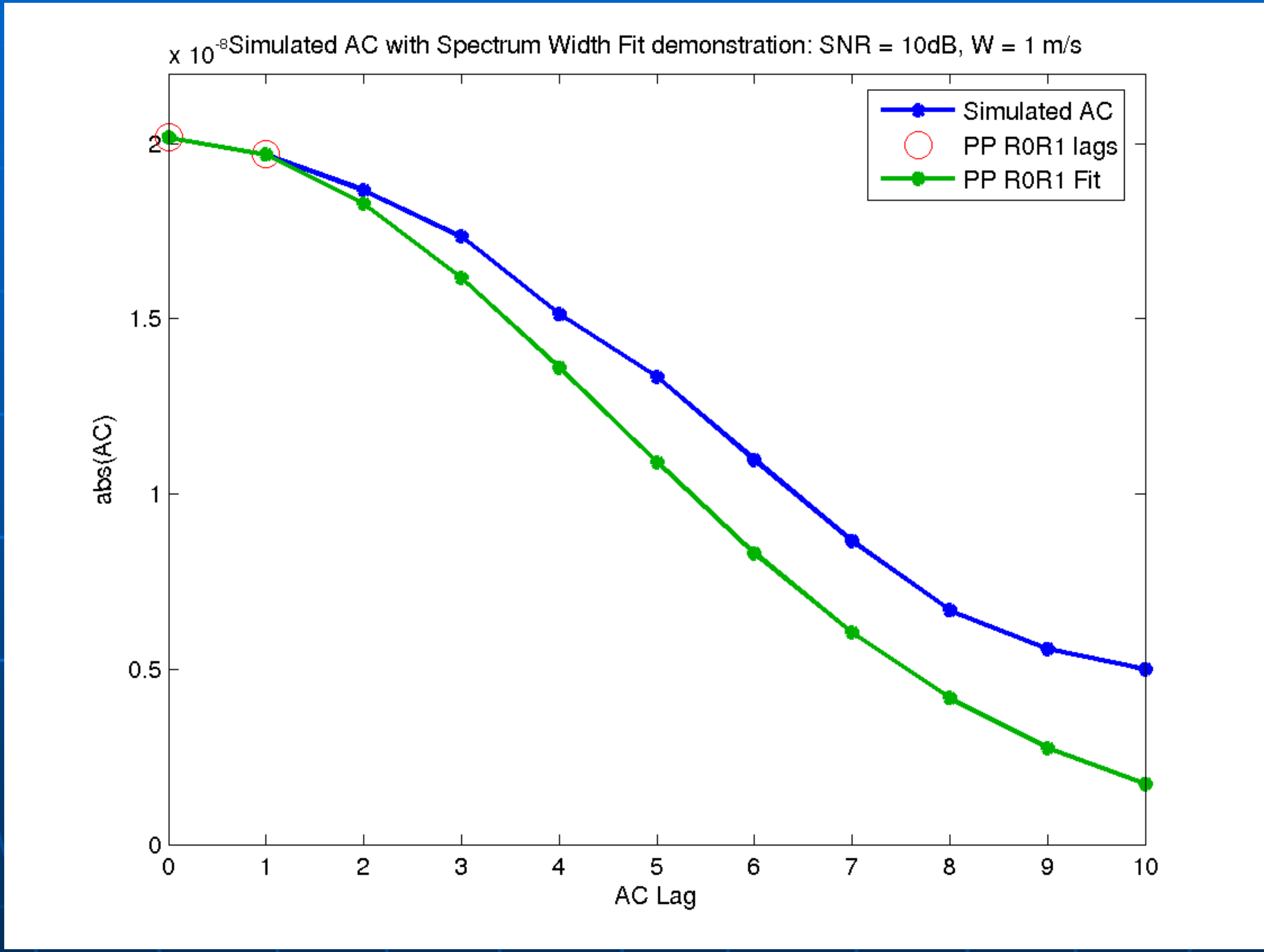
<u>Good:</u>

- Simple and fast
- Generally good results
- Less sensitive to estimate of noise power P_N
- Saturates more gracefully than R1/R2

<u>Bad:</u>

- Assumes exactly 1 Gaussian shaped signal
- Saturates for spectrum widths above ~1/3 Nyquist

Pulse Pair LS 2: Simulated AC, SNR 10 dB, W=1 m/s

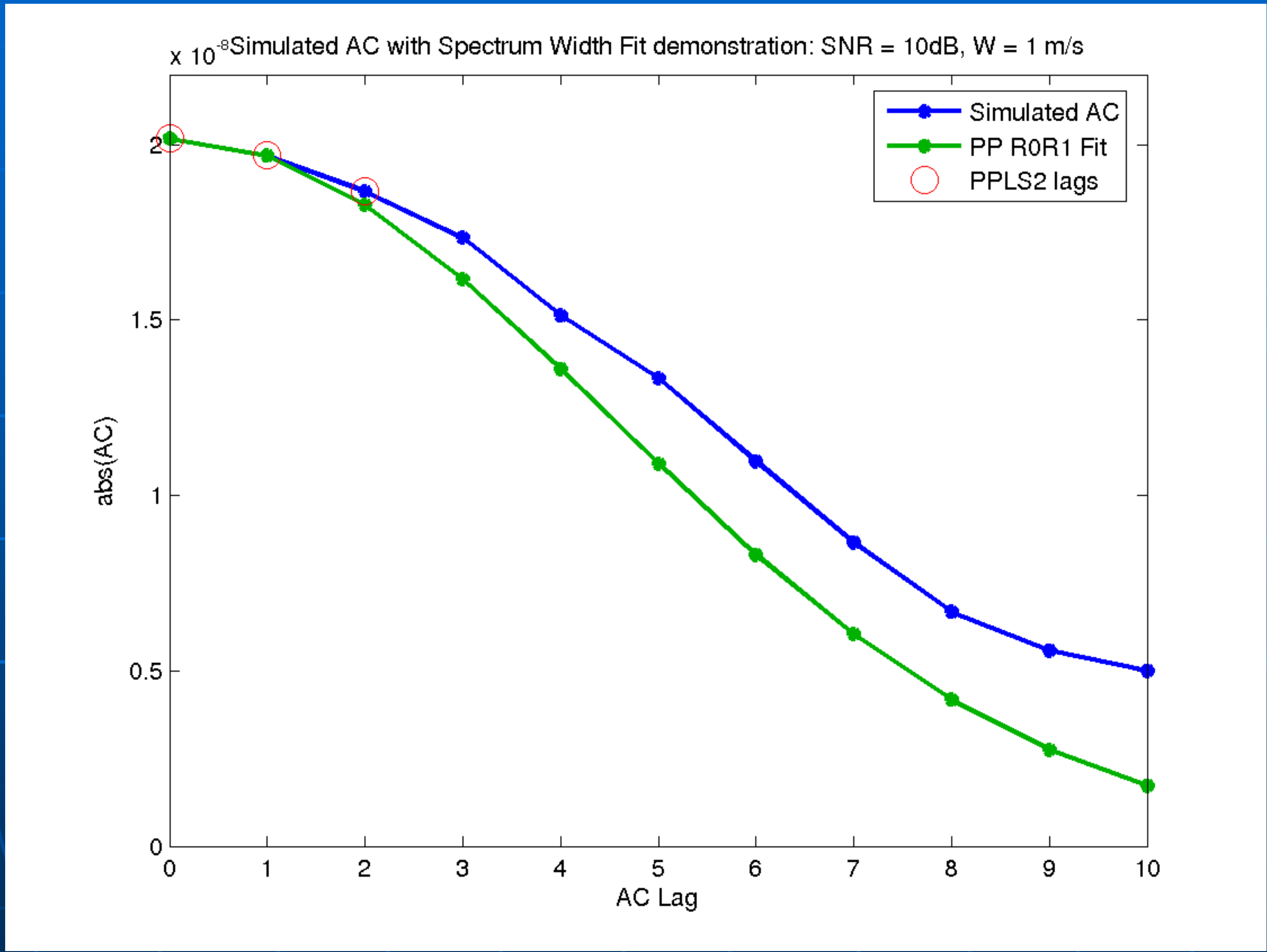


Autocorrelation Magnitude

Autocorrelation Lag

NCAR

Pulse-Pair LS 2: Simulated AC, SNR 10 dB, W=1 m/s

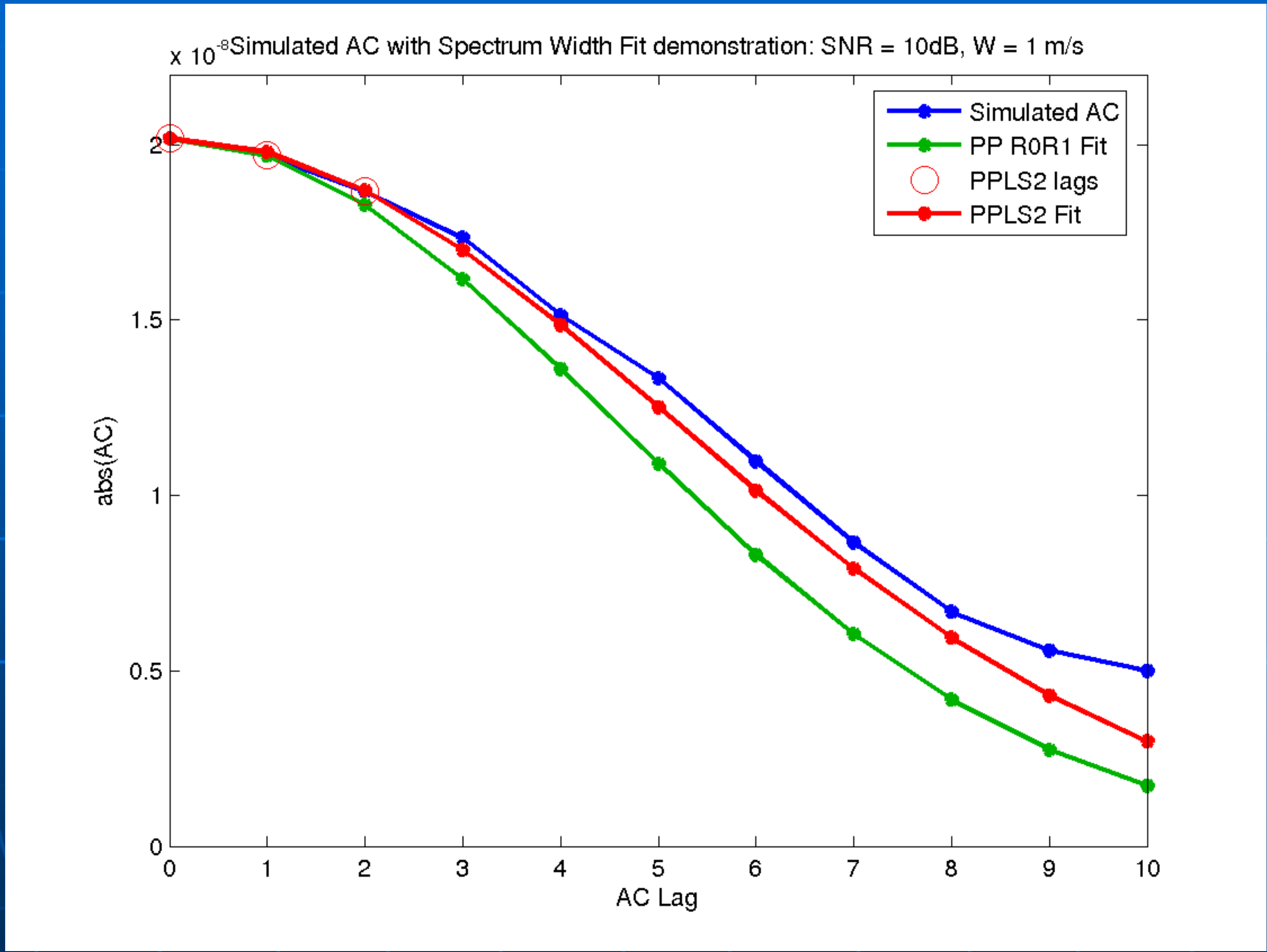


Autocorrelation Magnitude

Autocorrelation Lag

NCAR

Pulse-Pair LS 2: Simulated AC, SNR 10 dB, W=1 m/s



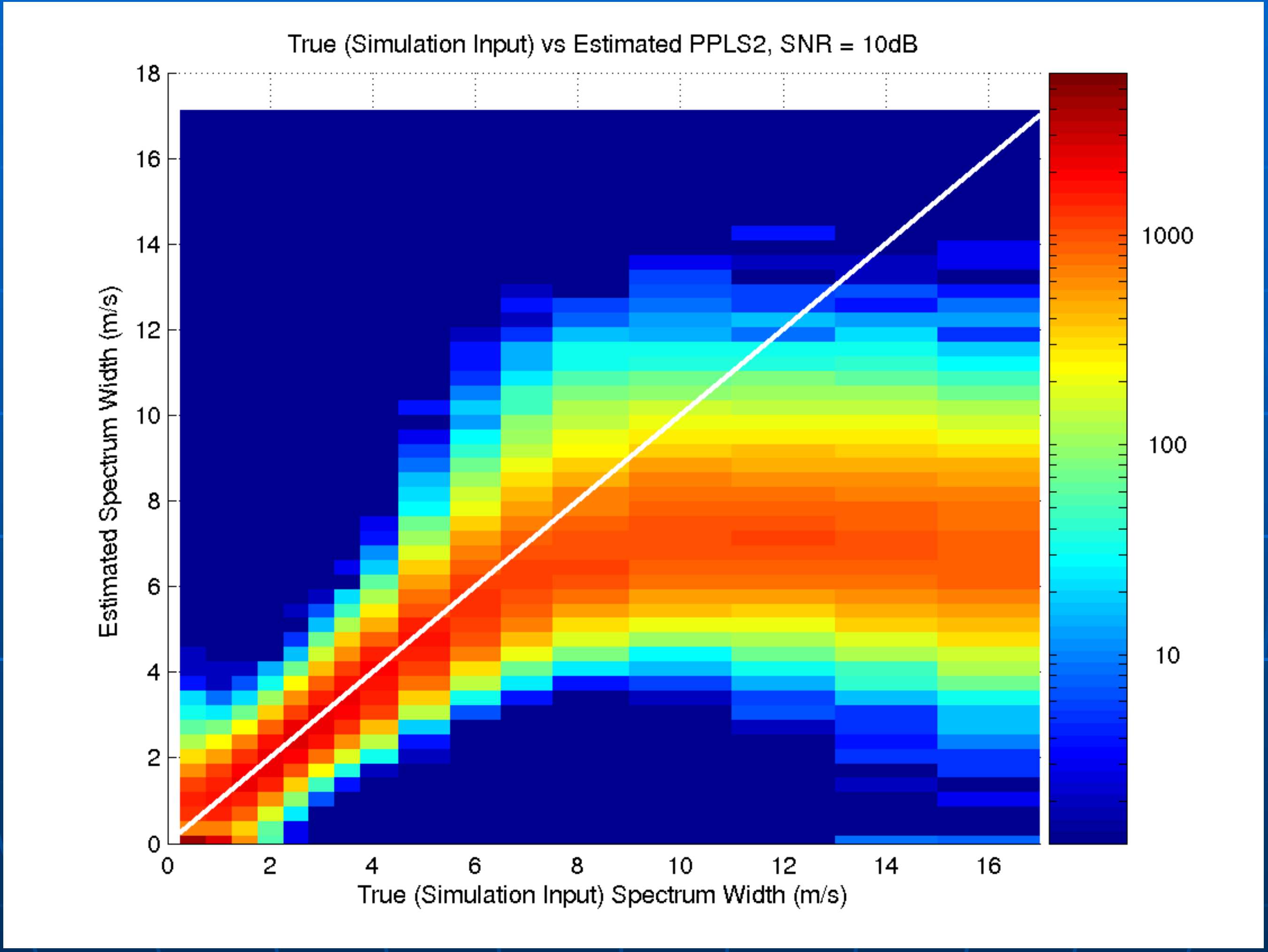
Autocorrelation Magnitude

Autocorrelation Lag

NCAR

PPLS2 2D Histograms – True vs. Estimated:

SNR = 10dB



Estimated Spectrum Width

Frequency (log scale)

True (Input) Spectrum Width (m/s)

NCAR

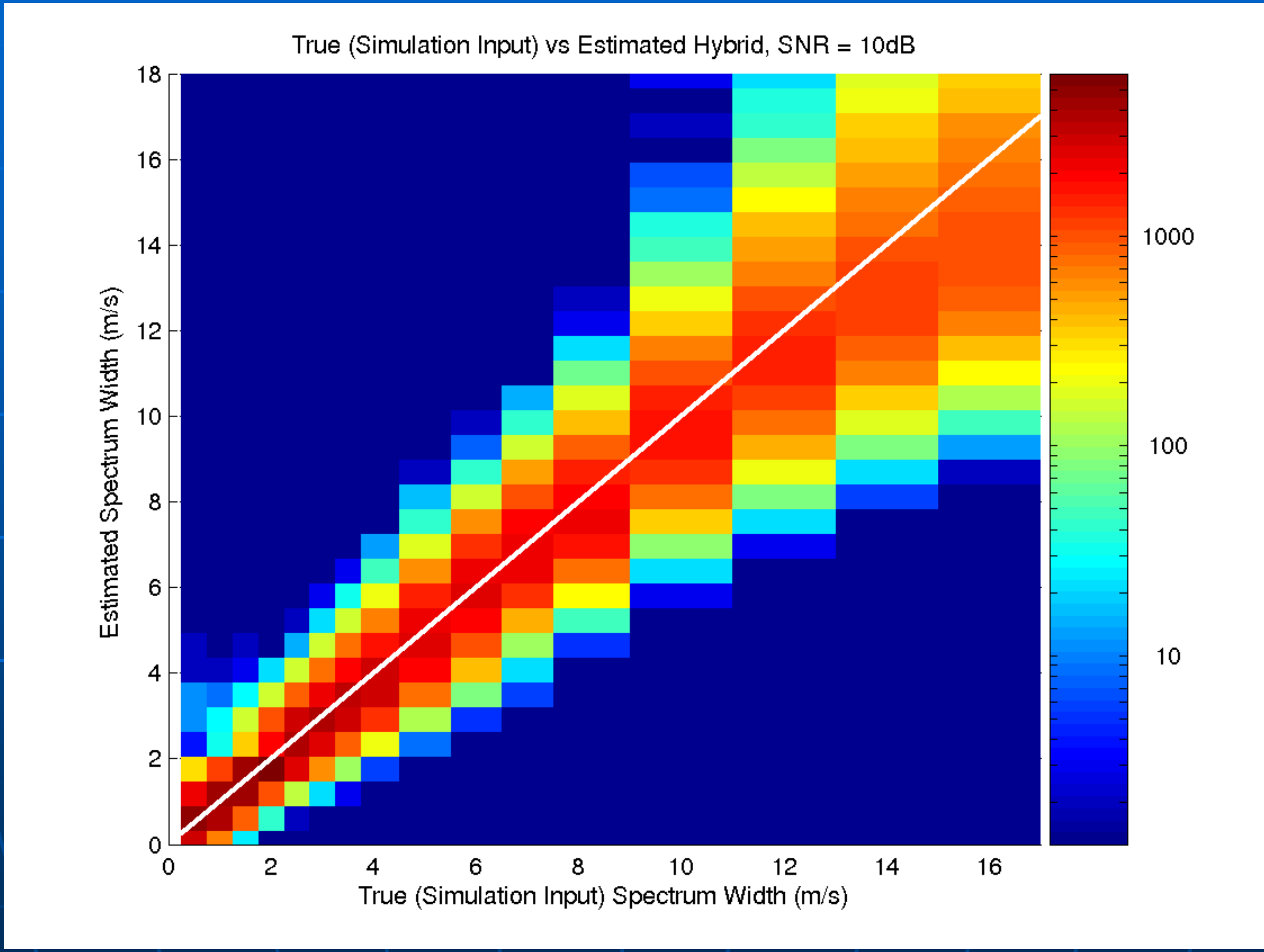
Hybrid Spectrum Width Estimator

- Compute pulse-pair spectrum width estimators (R0/R1, R1/R3, PPLS 2)
- Decide whether the (normalized) spectrum width is “large”, “medium”, or “small”
- Use best estimator for that size spectrum width

Hybrid 2D Histograms – True vs. Estimated:

SNR = 10dB

Estimated Spectrum Width



Frequency (log scale)

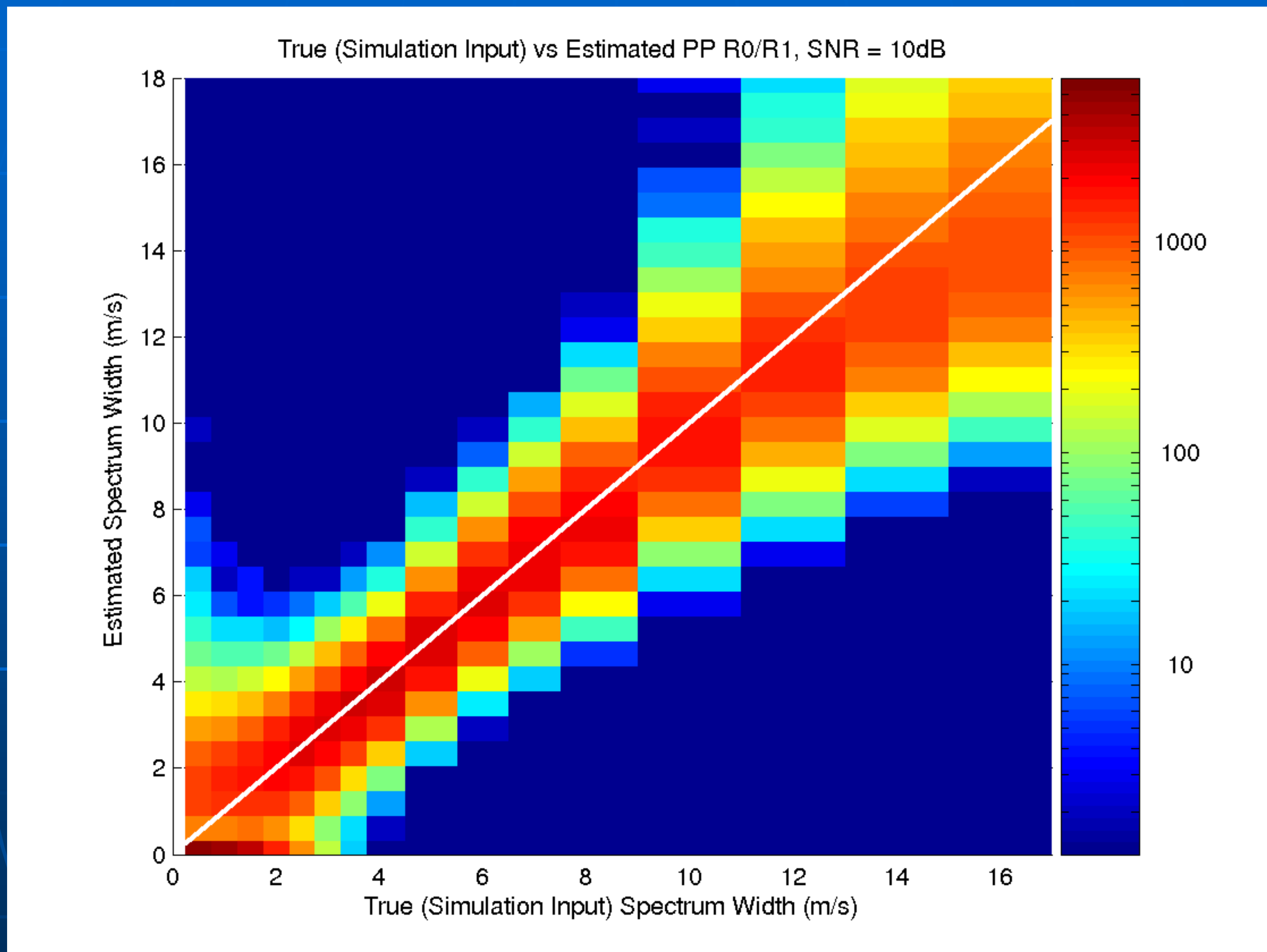
True (Input) Spectrum Width (m/s)

NCAR

PP R0/R1 2D Histograms – True vs. Estimated:

SNR = 10dB

Estimated Spectrum Width



Frequency (log scale)

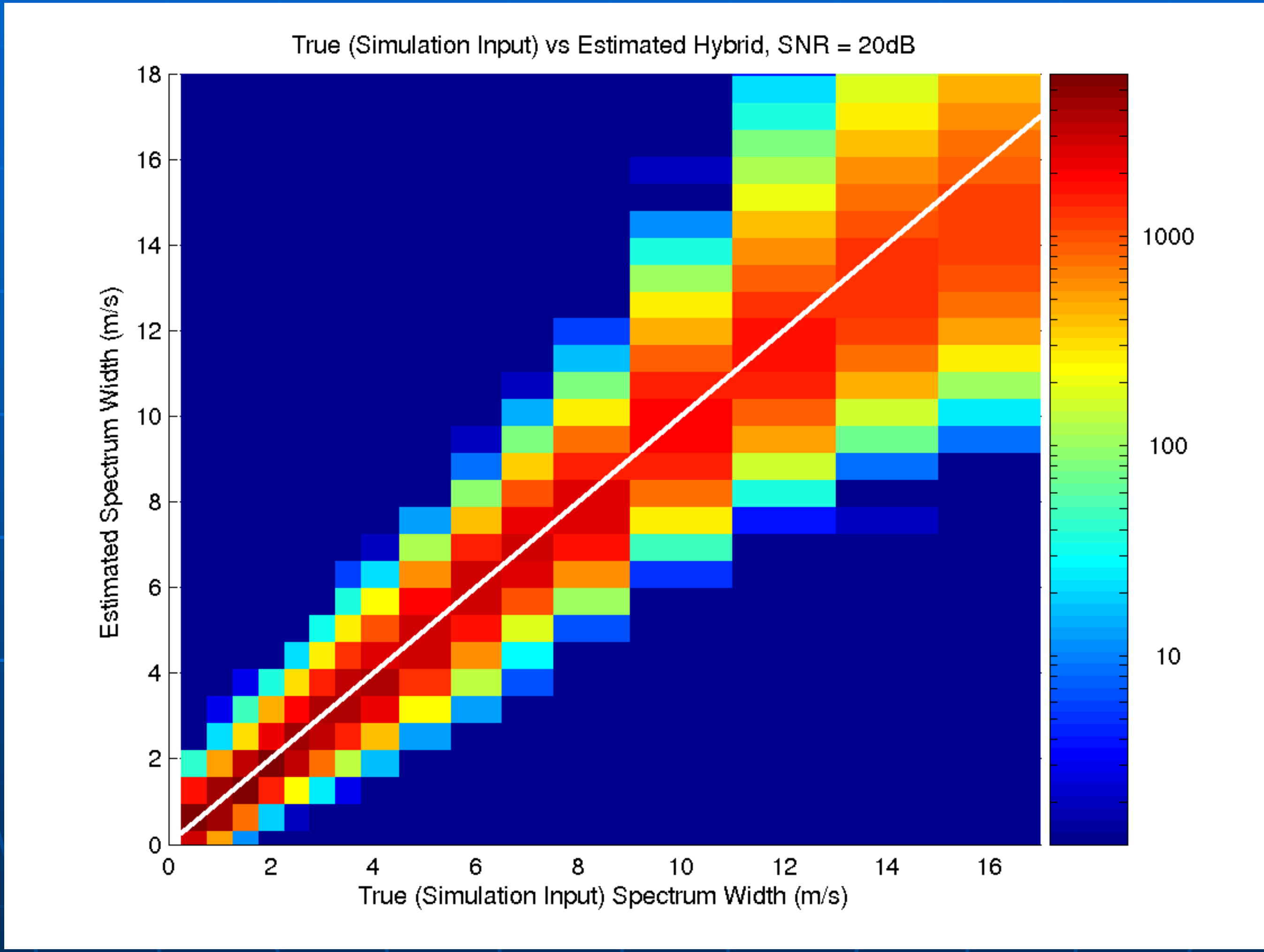
True (Input) Spectrum Width (m/s)

NCAR

Hybrid 2D Histograms – True vs. Estimated:

SNR = 20dB

Estimated Spectrum Width



Frequency (log scale)

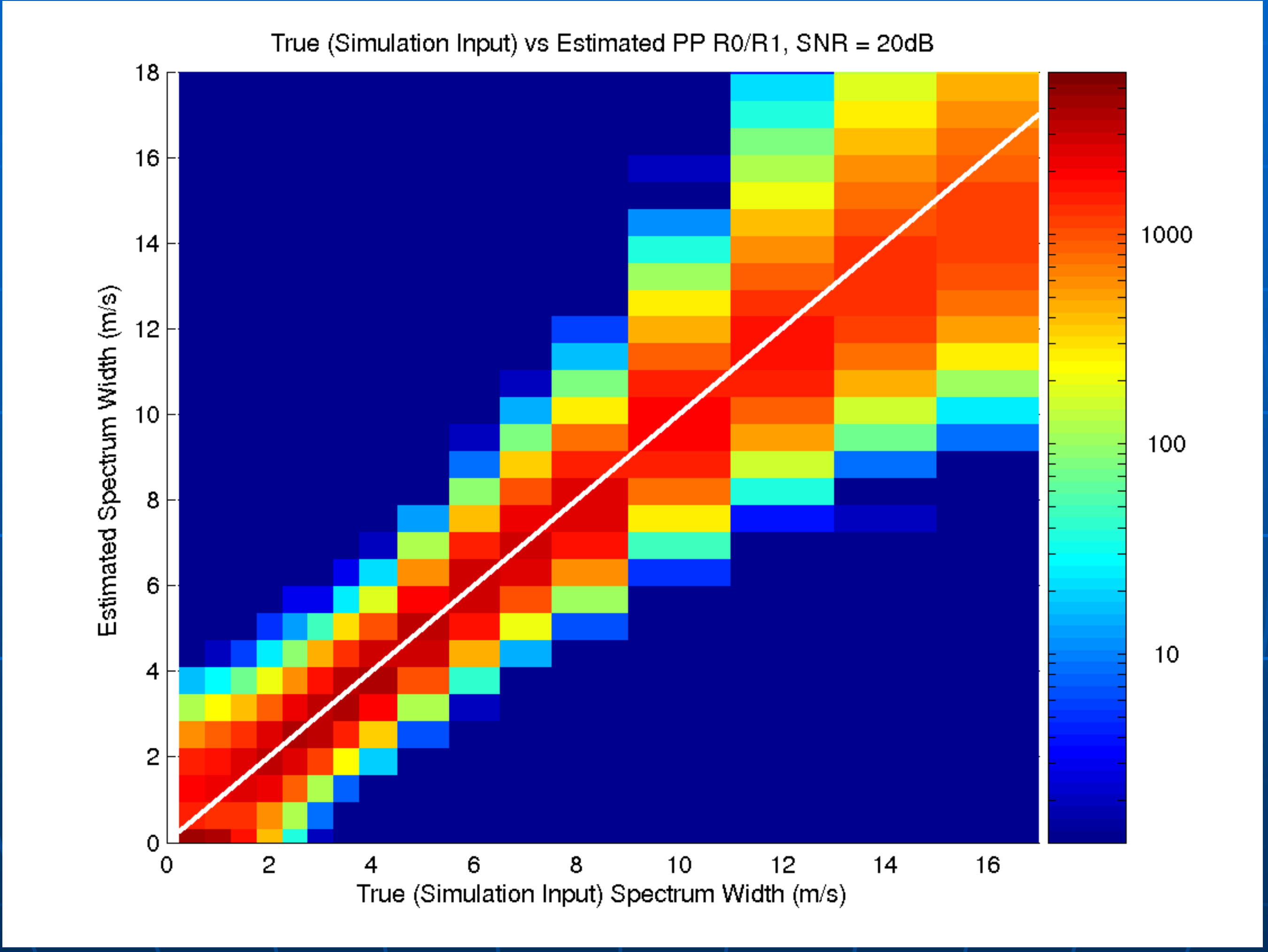
True (Input) Spectrum Width (m/s)

NCAR

PP R0/R1 2D Histograms – True vs. Estimated:

SNR = 20dB

Estimated Spectrum Width



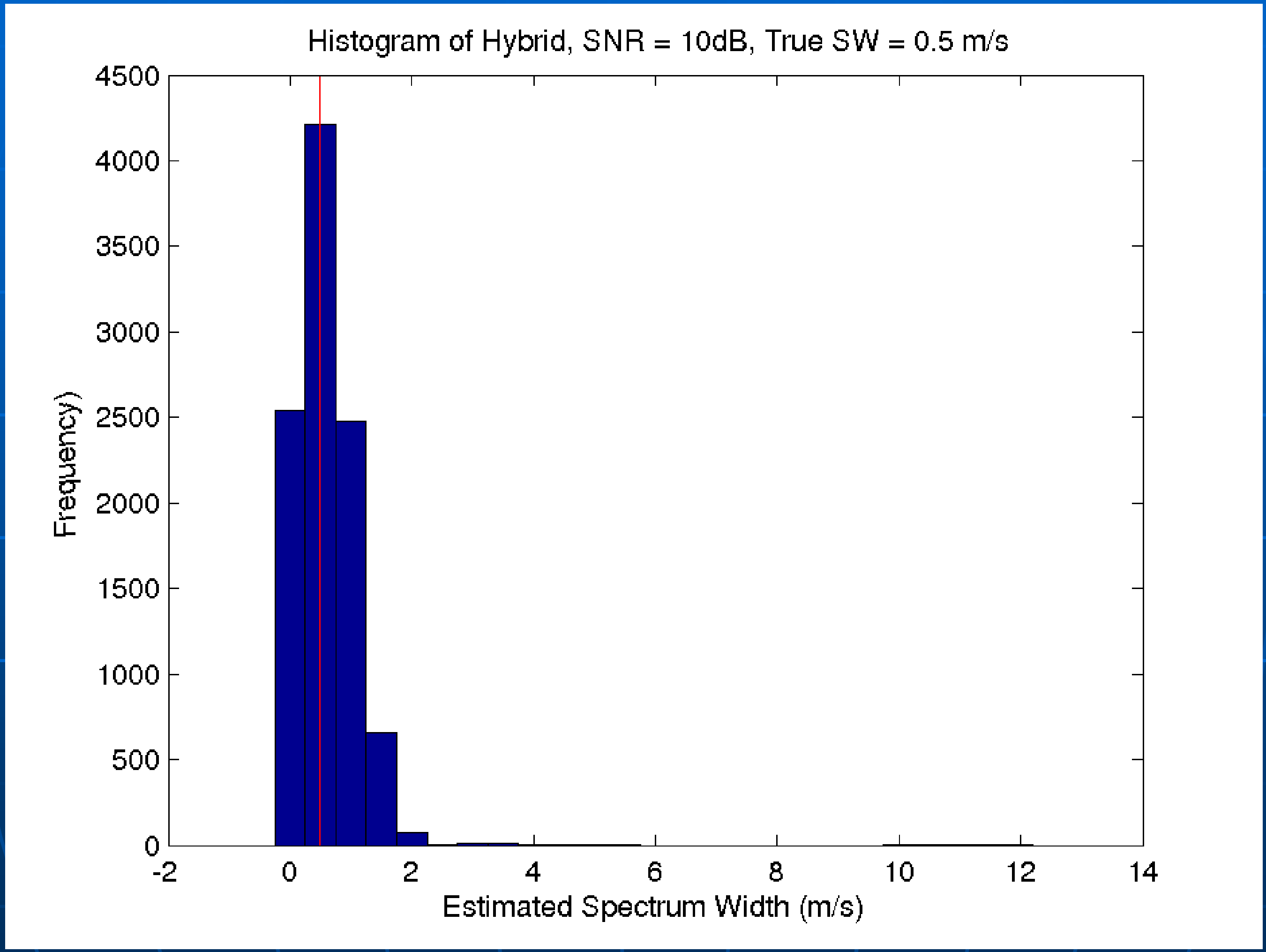
Frequency (log scale)

True (Input) Spectrum Width (m/s)

NCAR

Hybrid Histograms: SNR = 10dB, W = 0.5 m/s

Frequency

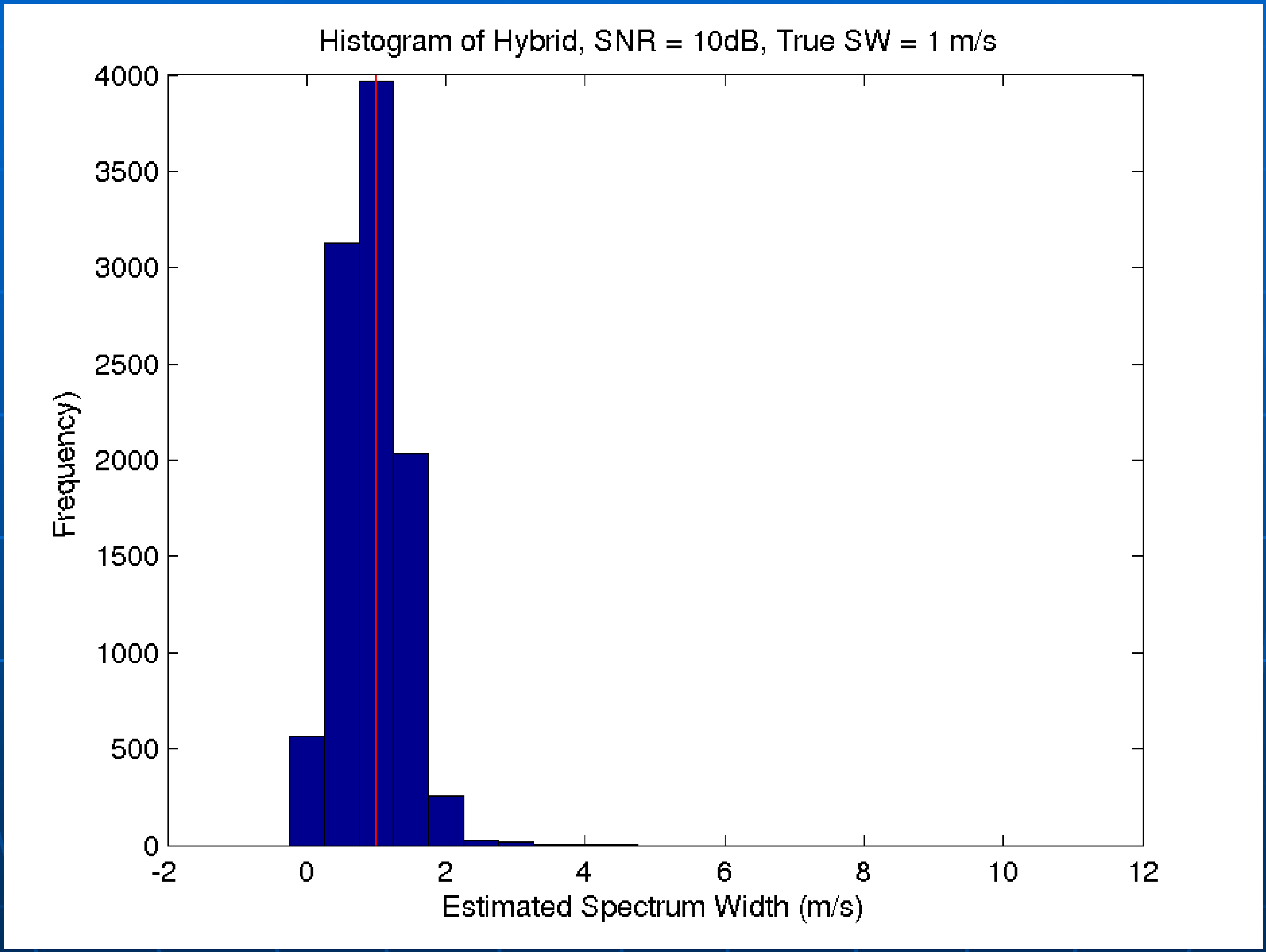


Red line indicates true W

Estimated Spectrum Width (m/s)

Hybrid Histograms: SNR = 10dB, W = 1 m/s

Frequency



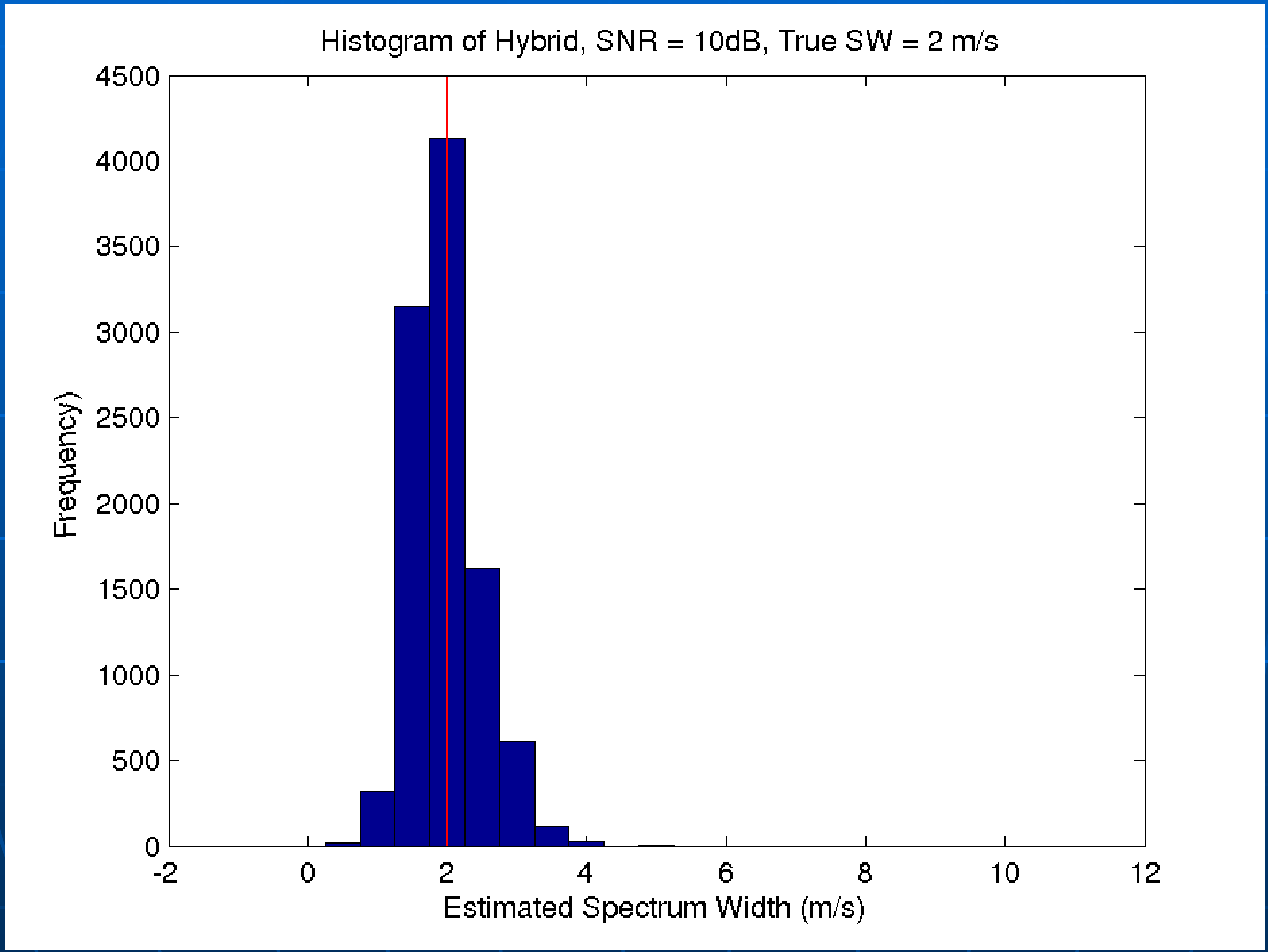
Red line indicates true W

Estimated Spectrum Width (m/s)

NCAR

Hybrid Histograms: SNR = 10dB, W = 2 m/s

Frequency



Red line indicates true W

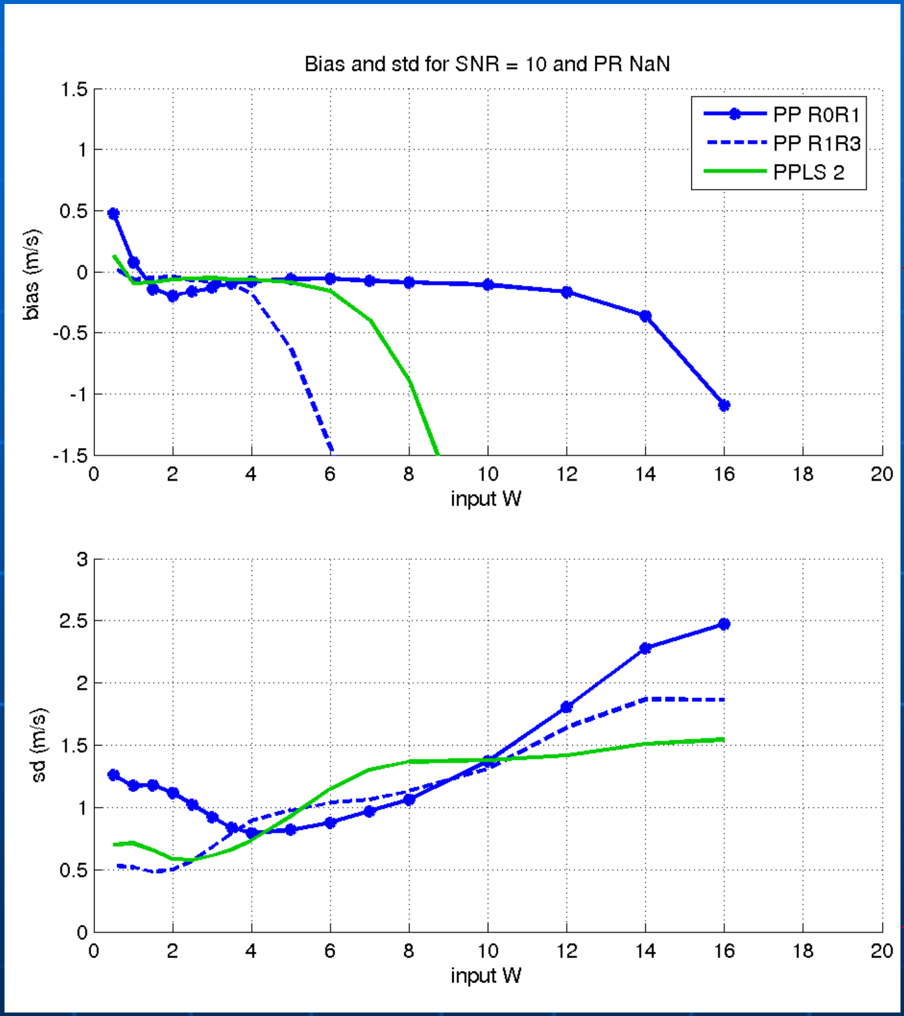
Estimated Spectrum Width (m/s)

NCAR

Bias and STD plots: SNR = 10 dB

Bias (m/s)

Std (m/s)



Vertical Ticks 0.5 m/s

Optimal

Horizontal Ticks 2 m/s

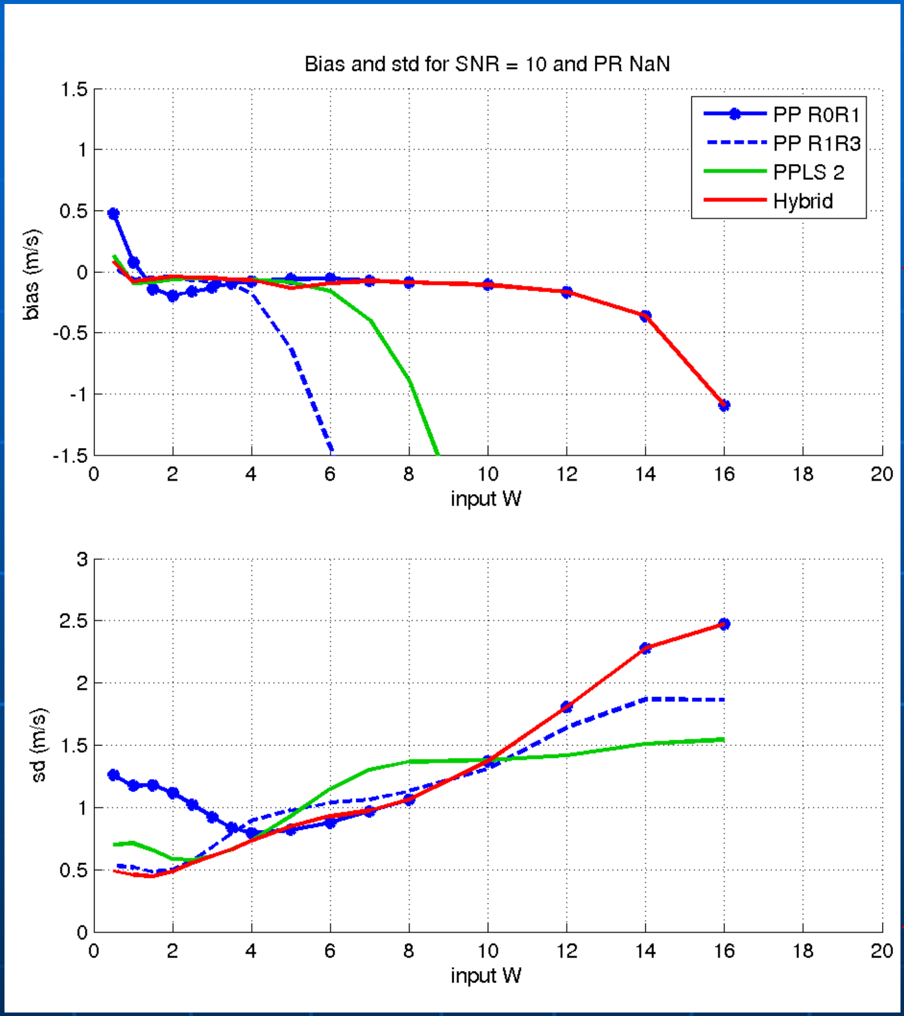
Vertical Ticks 0.5 m/s

Optimal

Input W (m/s)

NCAR

Bias and STD plots: SNR = 10 dB



Bias (m/s)

Std (m/s)

Vertical Ticks 0.5 m/s

Optimal

Horizontal Ticks 2 m/s

Vertical Ticks 0.5 m/s

Optimal

Input W (m/s)

NCAR

Bias and STD plots: SNR = 20 dB

Vertical Ticks 0.5 m/s

Bias (m/s)

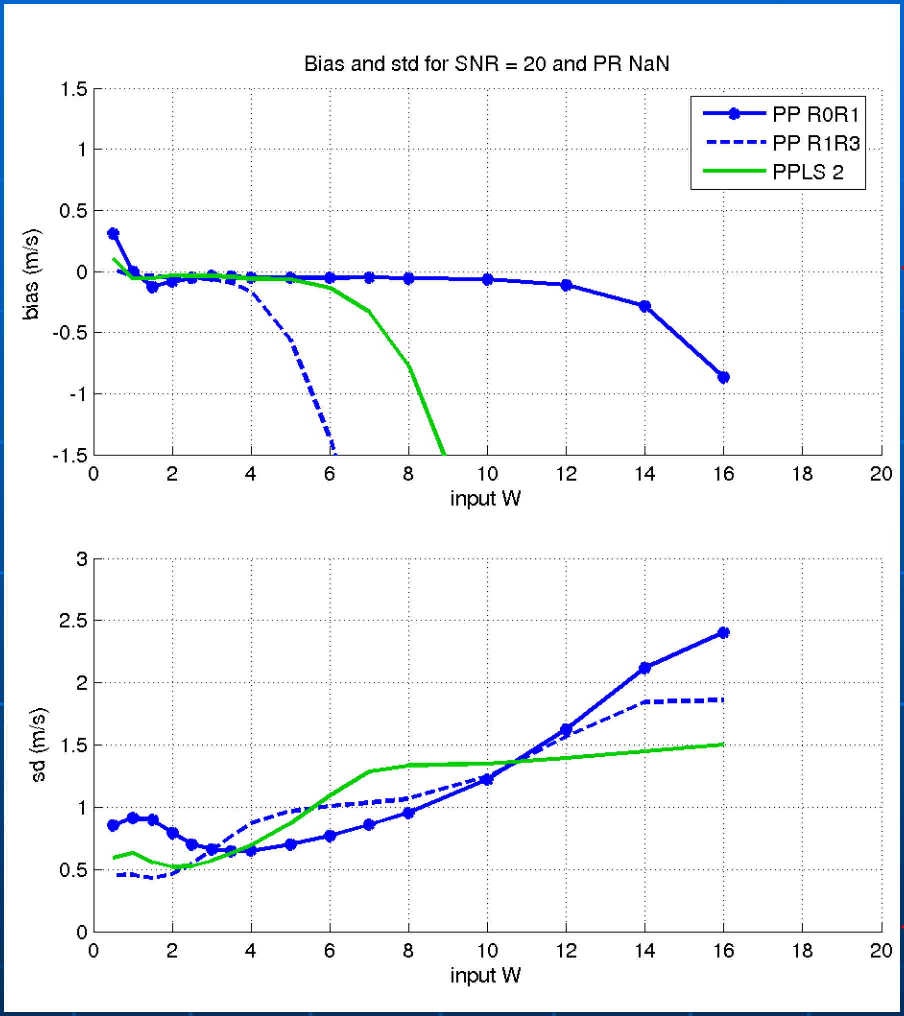
Optimal

Horizontal Ticks 2 m/s

Std (m/s)

Vertical Ticks 0.5 m/s

Optimal



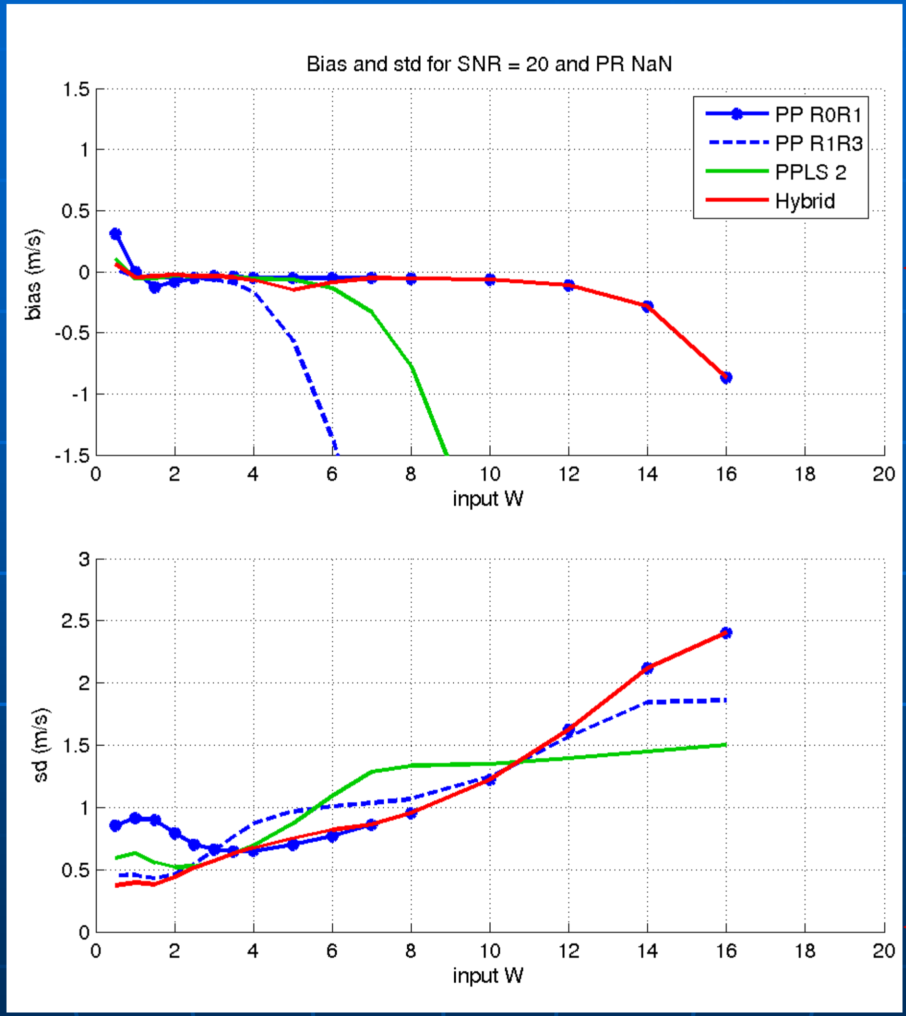
Input W (m/s)

NCAR

Bias and STD plots: SNR = 20 dB

Bias (m/s)

Std (m/s)



Vertical Ticks 0.5 m/s

Optimal

Horizontal Ticks 2 m/s

Vertical Ticks 0.5 m/s

Optimal

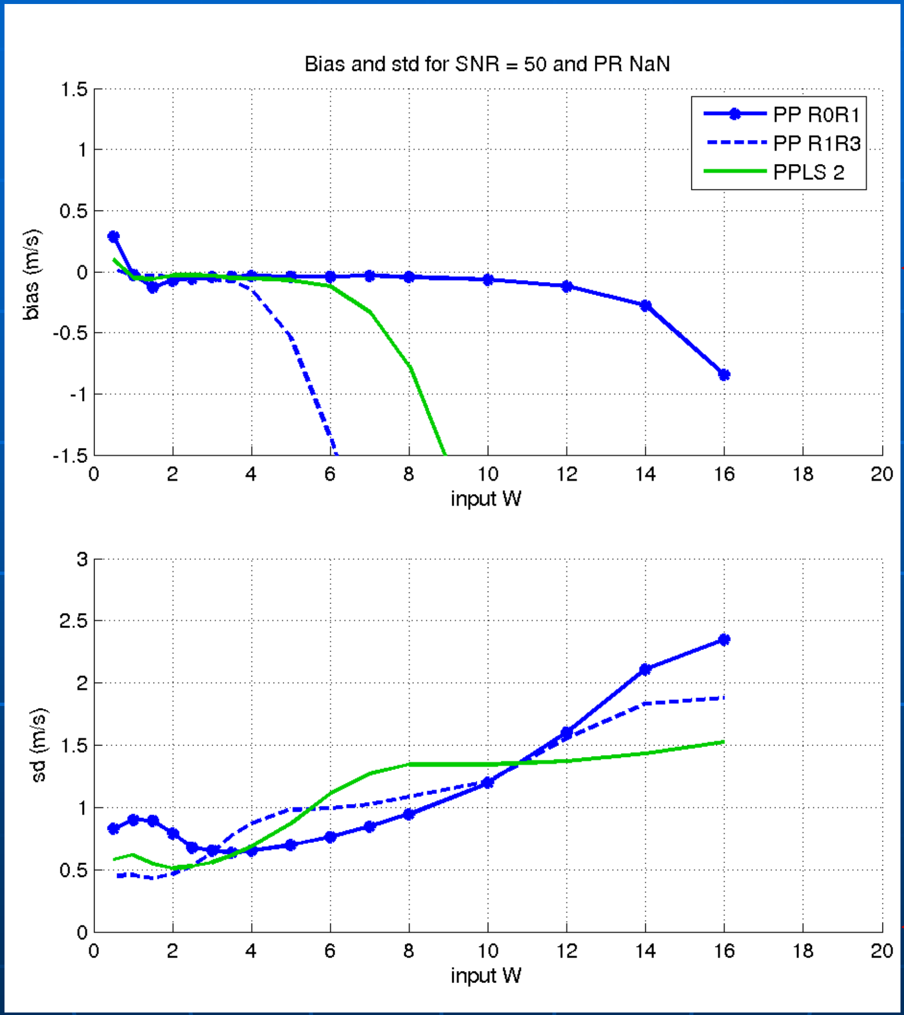
Input W (m/s)

NCAR

Bias and STD plots: SNR = 50 dB

Bias (m/s)

Std (m/s)



Vertical Ticks 0.5 m/s

Optimal

Horizontal Ticks 2 m/s

Vertical Ticks 0.5 m/s

Optimal

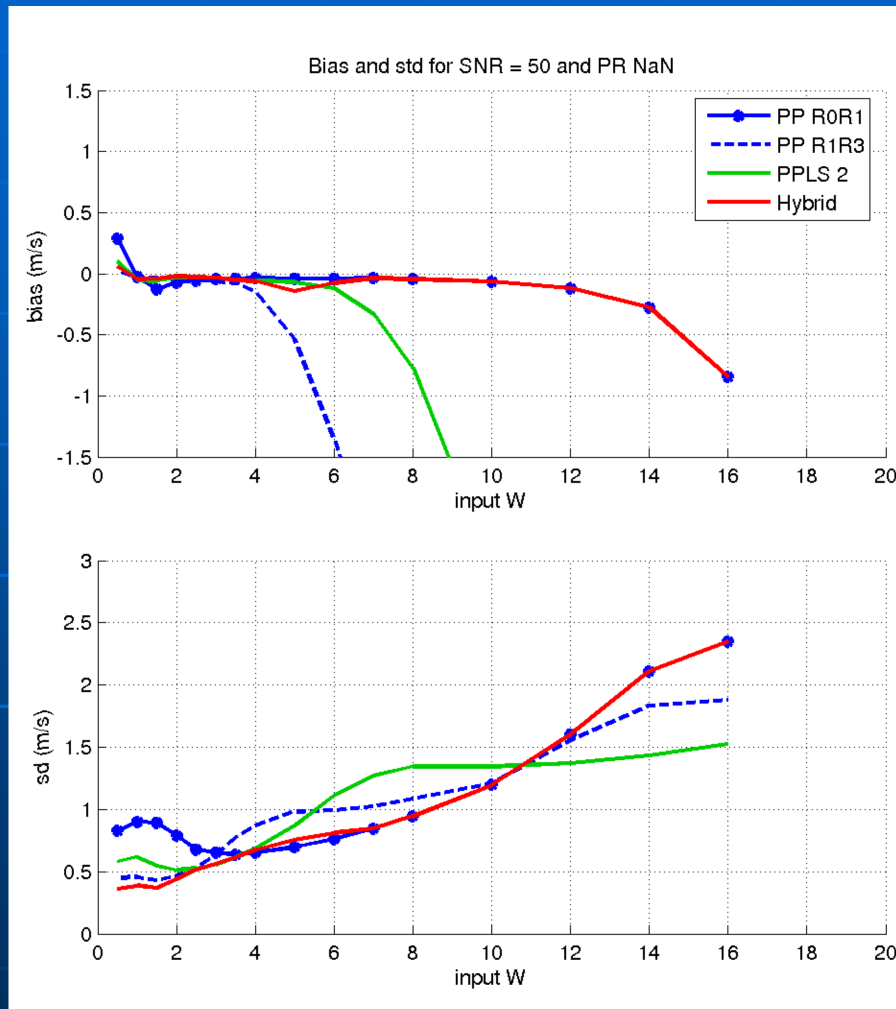
Input W (m/s)

NCAR

Bias and STD plots: SNR = 50 dB

Bias (m/s)

Std (m/s)



Vertical Ticks 0.5 m/s

Optimal

Horizontal Ticks 2 m/s

Vertical Ticks 0.5 m/s

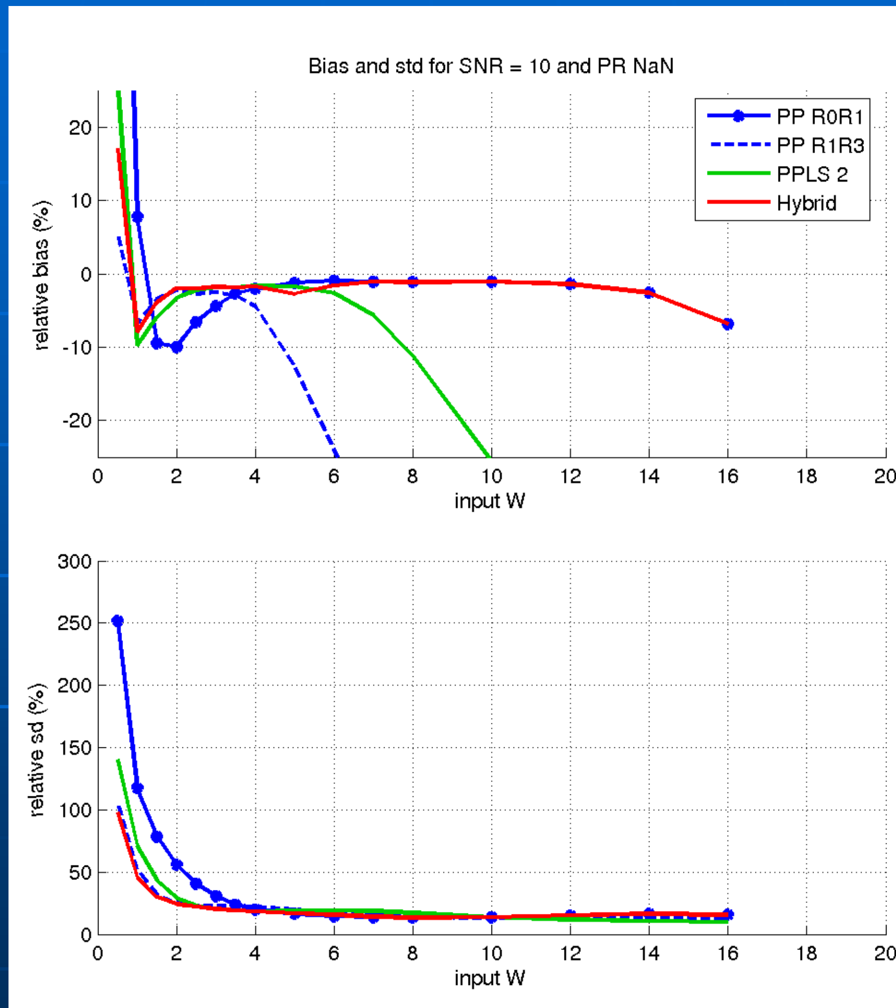
Optimal

Input W (m/s)

Relative Bias and STD plots: SNR = 10 dB

Relative Bias (%)

Relative Std (%)



Vertical Ticks 10 %

Optimal

Horizontal Ticks 2 m/s

Vertical Ticks 50 %

Optimal

Input W (m/s)

NCAR

Summary and Conclusion

- Pulse Pair R0/R1 performs poorly for low SNRs and/or small spectrum widths. Pulse Pair R1/R2 performs poorly for large spectrum widths and very narrow spectrum widths.
- Results show the hybrid estimator outperforms standard pulse-pair estimators for VCP 12, PRI 5.
- Computational complexity at run-time is minimal.
- Recommendation: Improve NEXRAD SW's by using a poly-pulse pair hybrid estimator!
- More work is required to evaluate this approach on a full range of operational scenarios. However, we chose one of the more difficult VCP's for testing.

Case Study

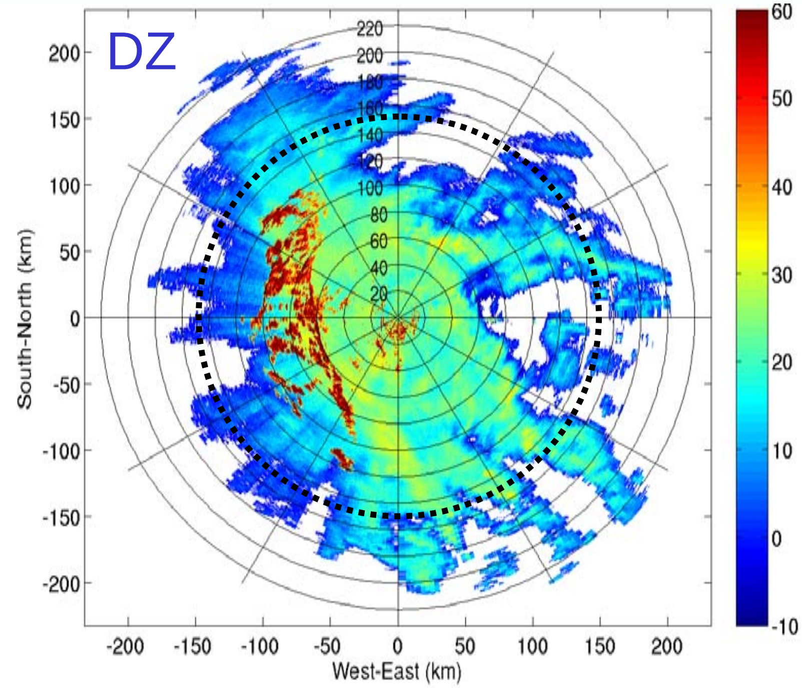
KFTG (Denver), 10/26/2006

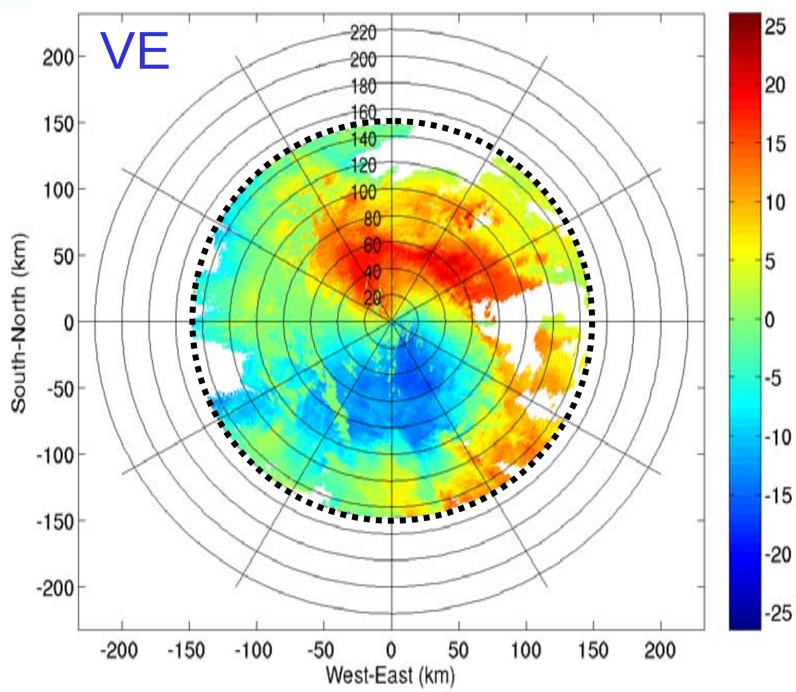
Stratiform snow case.

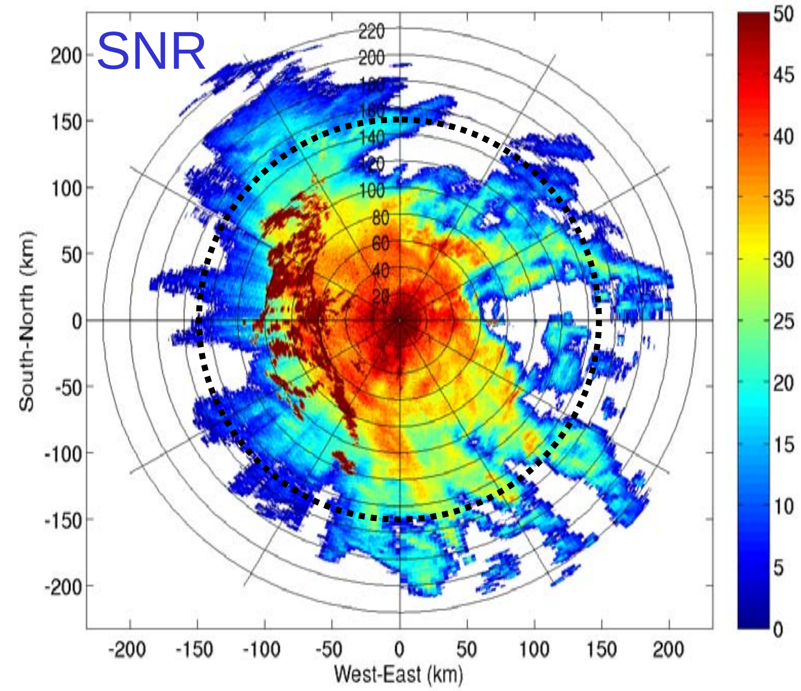
VCP 21, PRI #5

(N = 88 pulses, T_s = 988 μs)

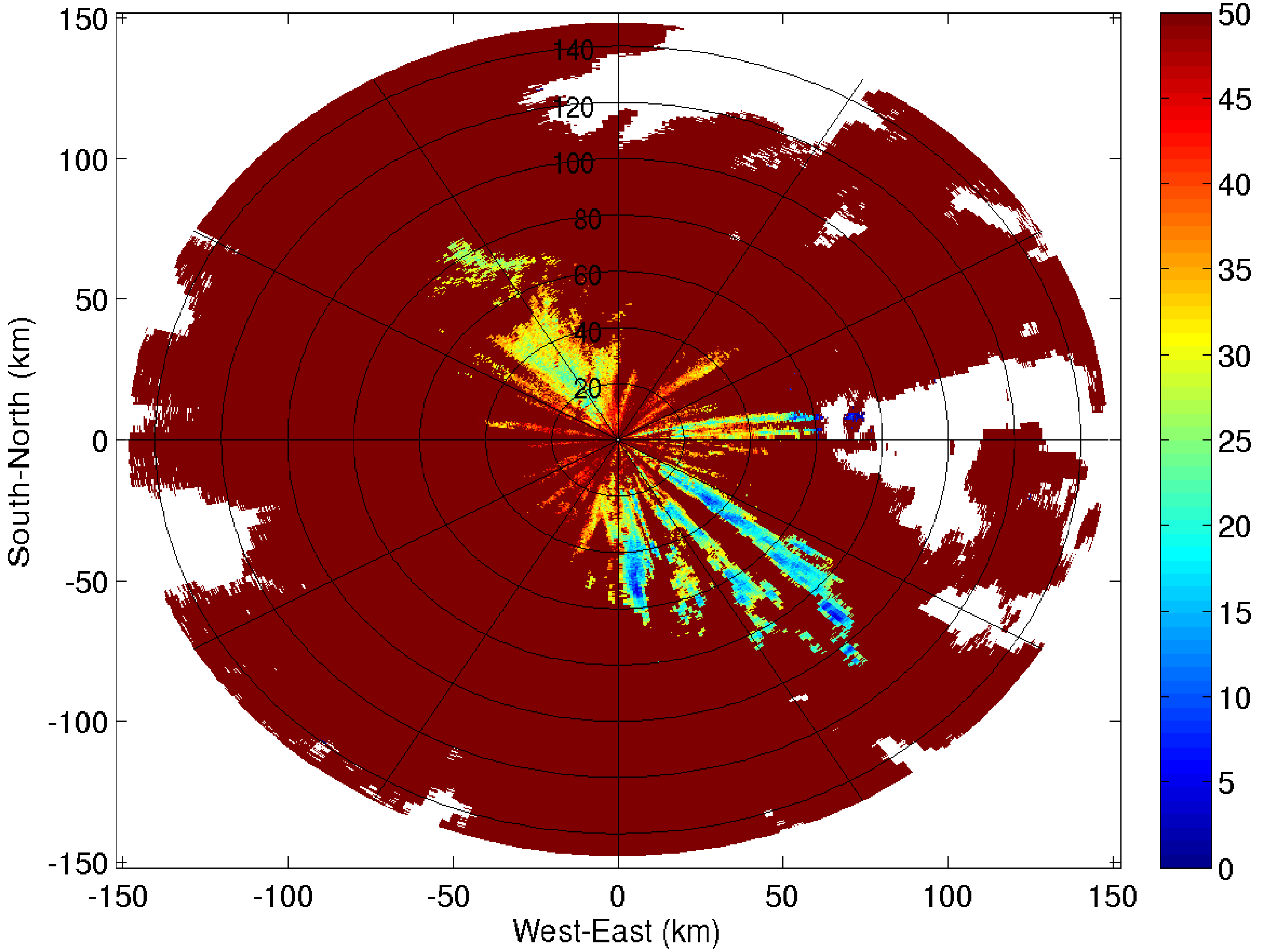
Clutter filtering off.



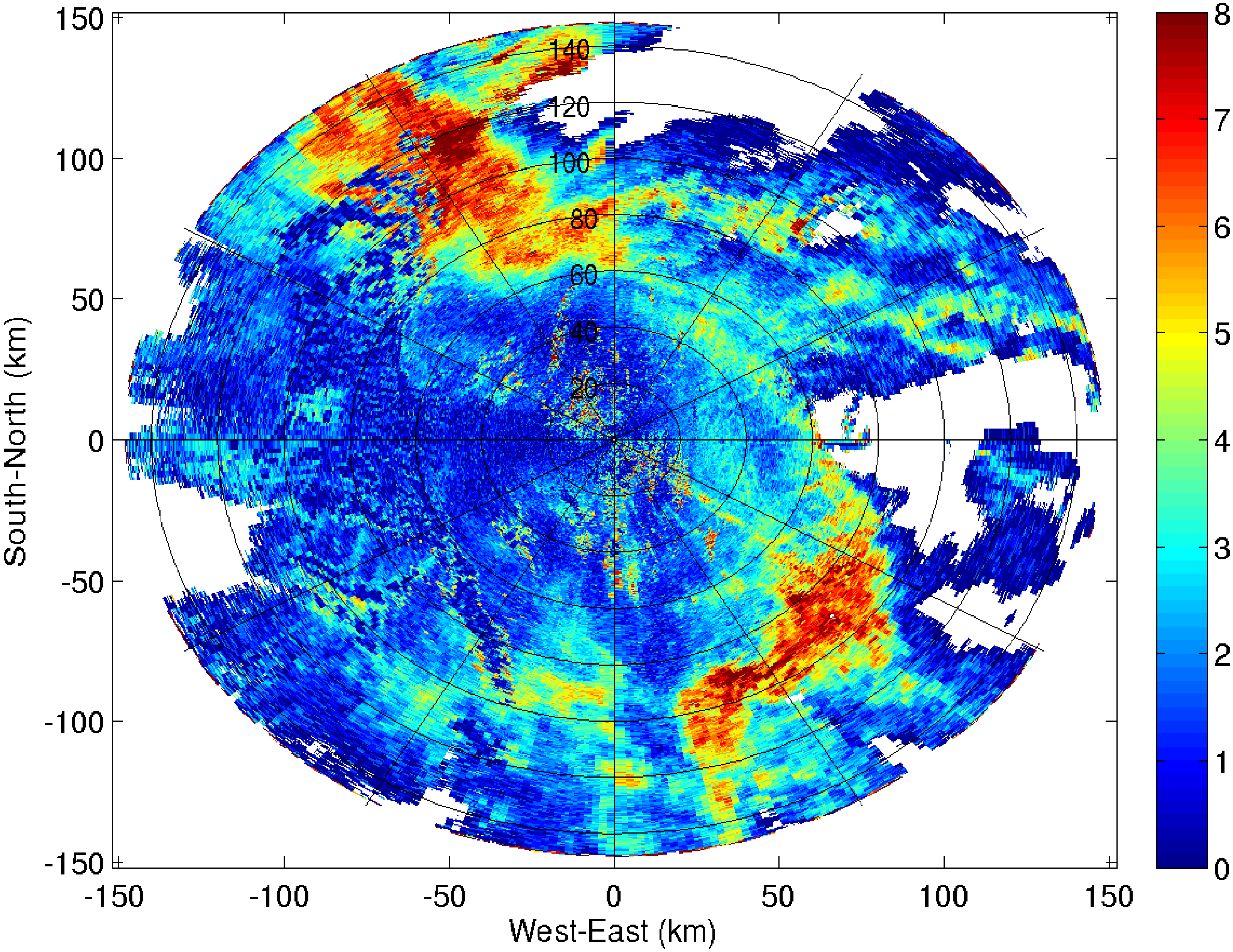




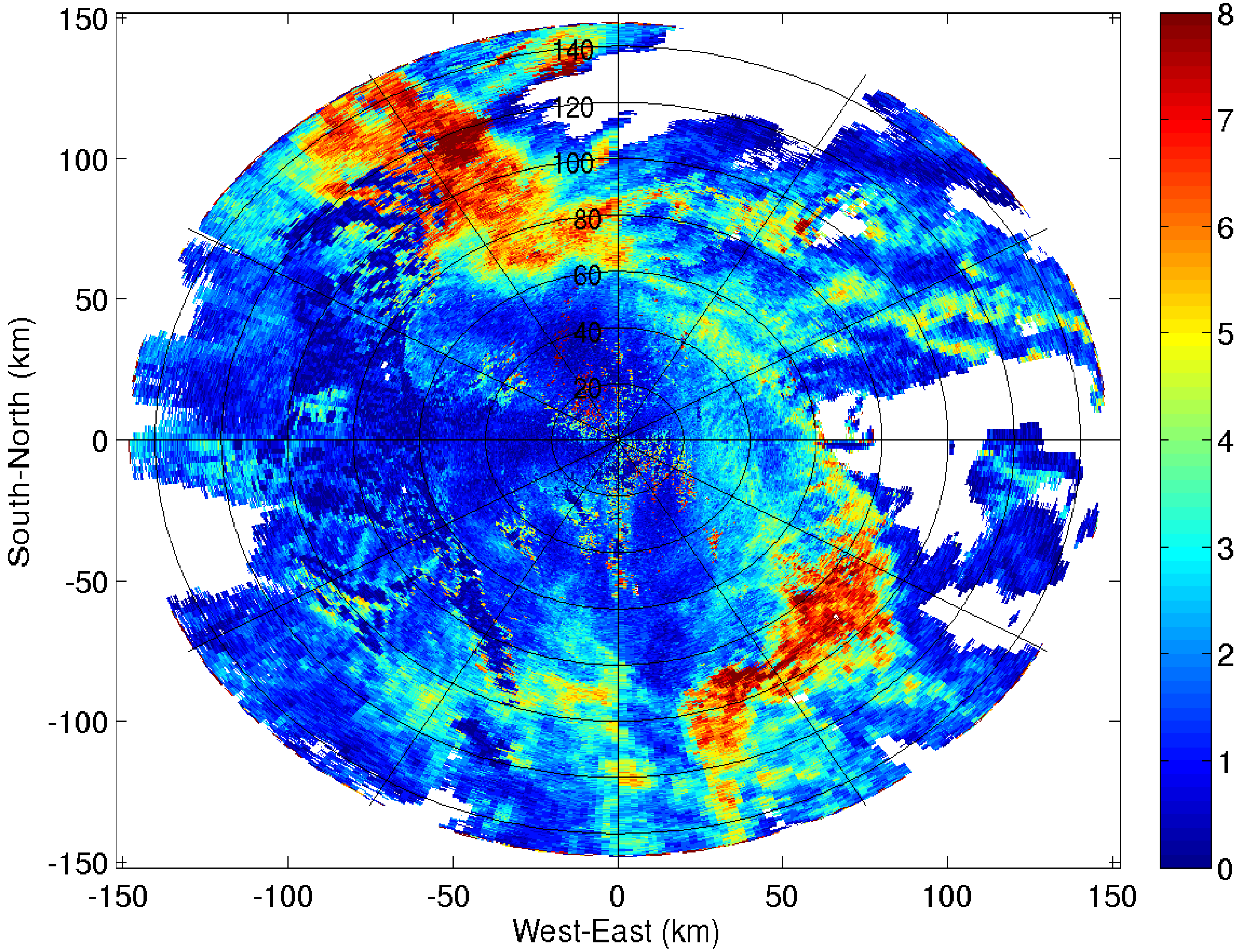
Overlaid power ratio, PR (dB)



SW from VCP 21 legacy R0/R1 (m s-1)

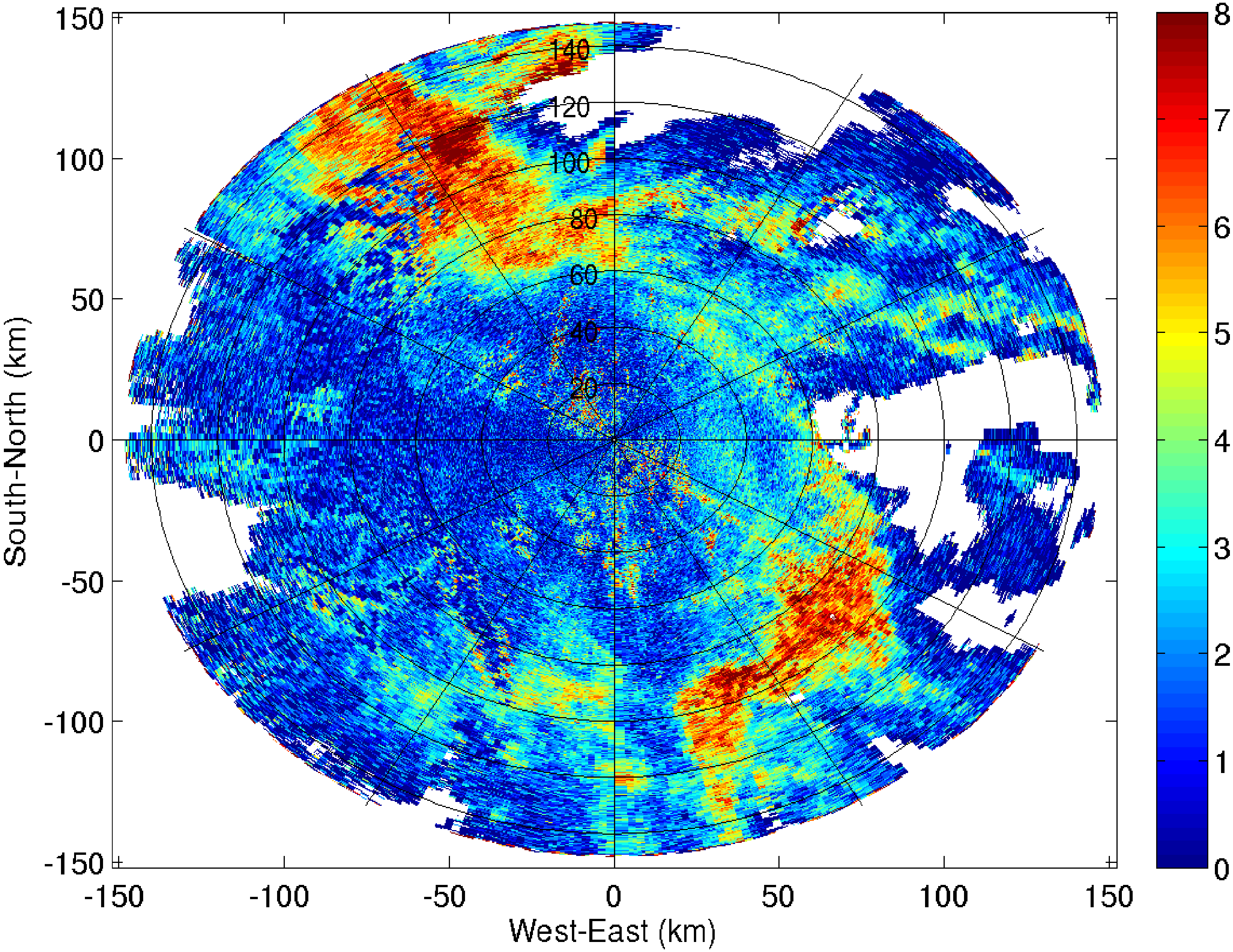


SW from VCP 21 poly pulse hybrid (m s^{-1})

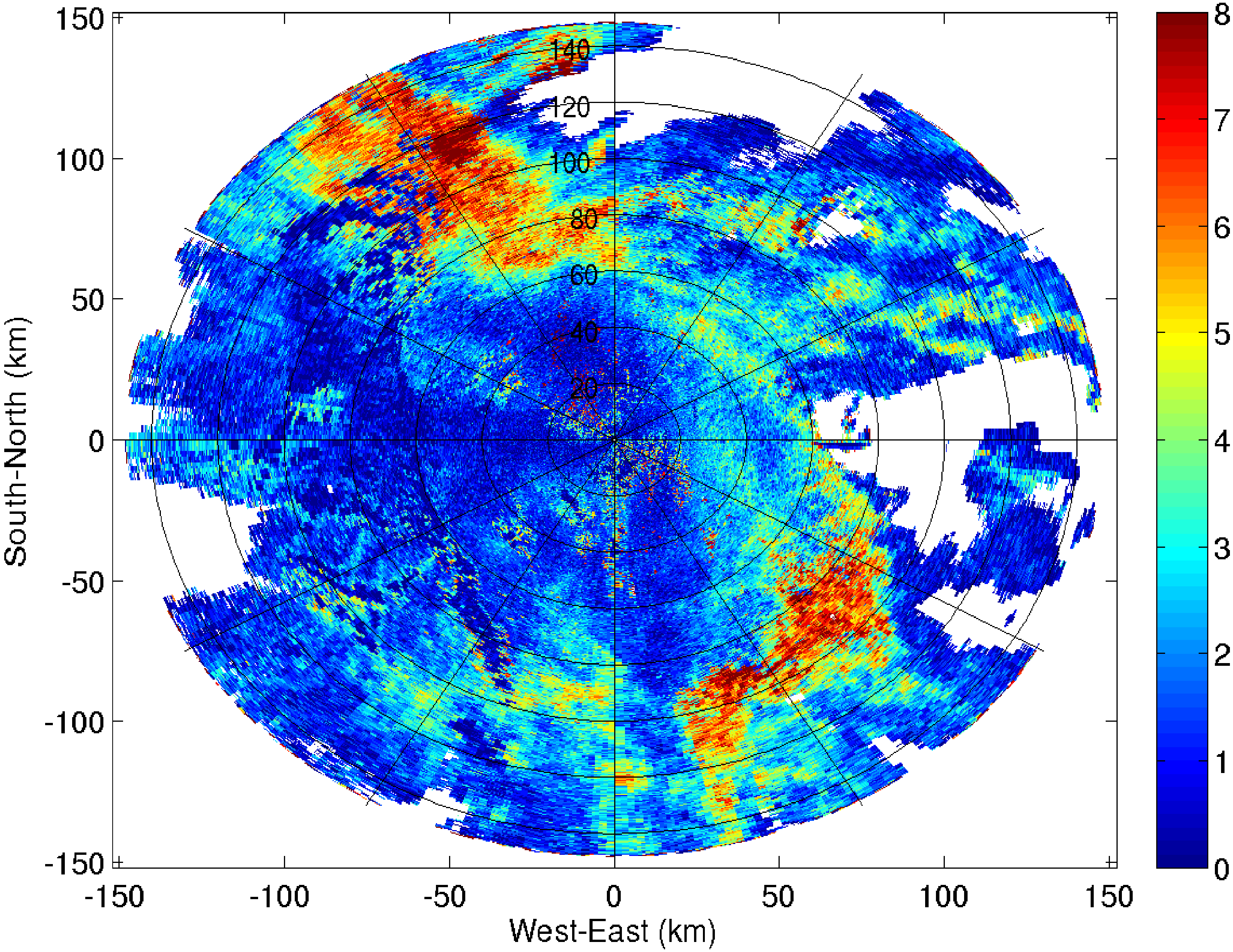


SW from VCP 12 legacy R0/R1 (m s^{-1})

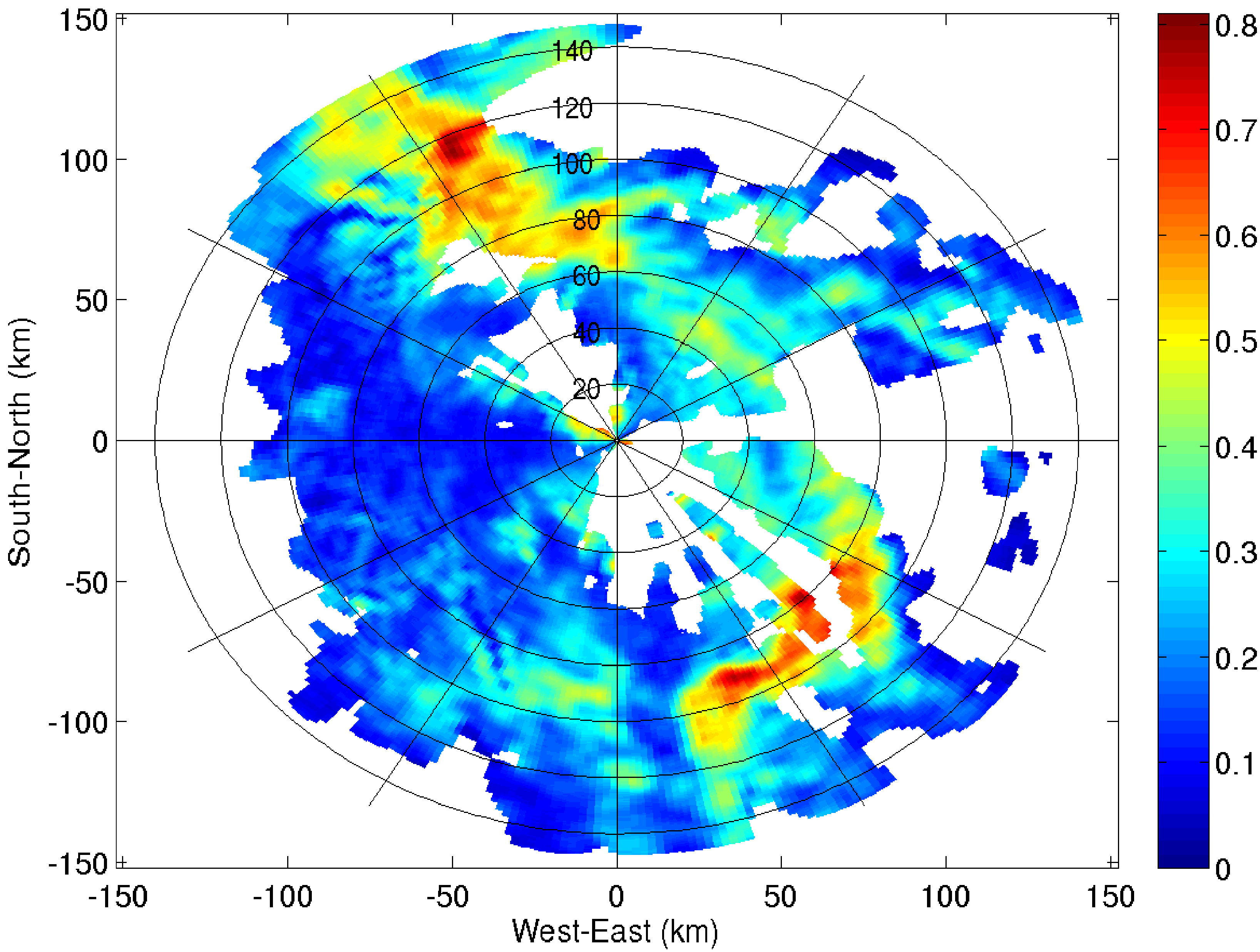
(*VCP 12 emulated by processing middle 40 pulses per radial*)



SW from VCP 12 poly pulse hybrid (m s^{-1})

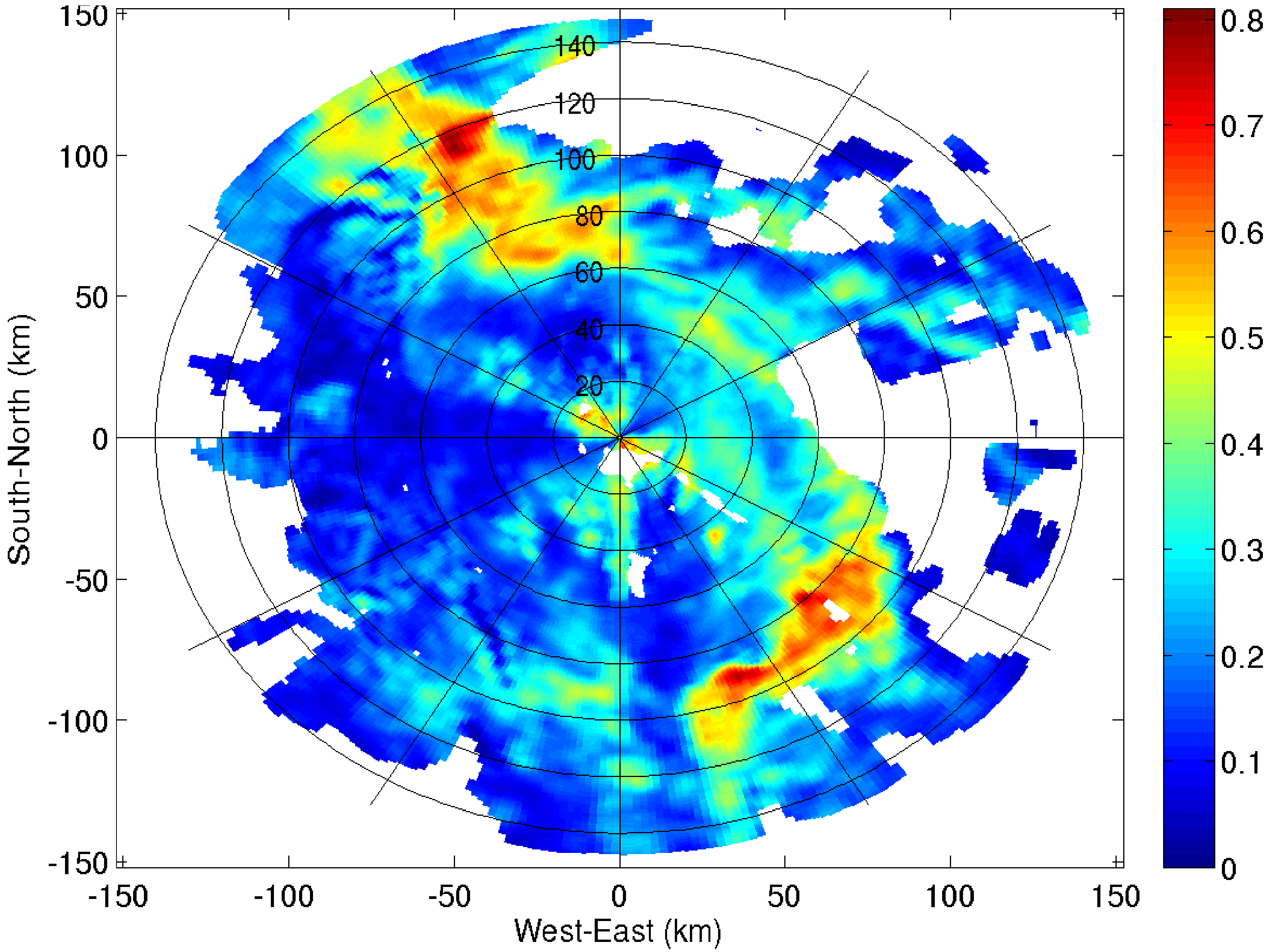


NTDA EDR from VCP 21 legacy R0/R1 ($m^{2/3}$ s^{-1})

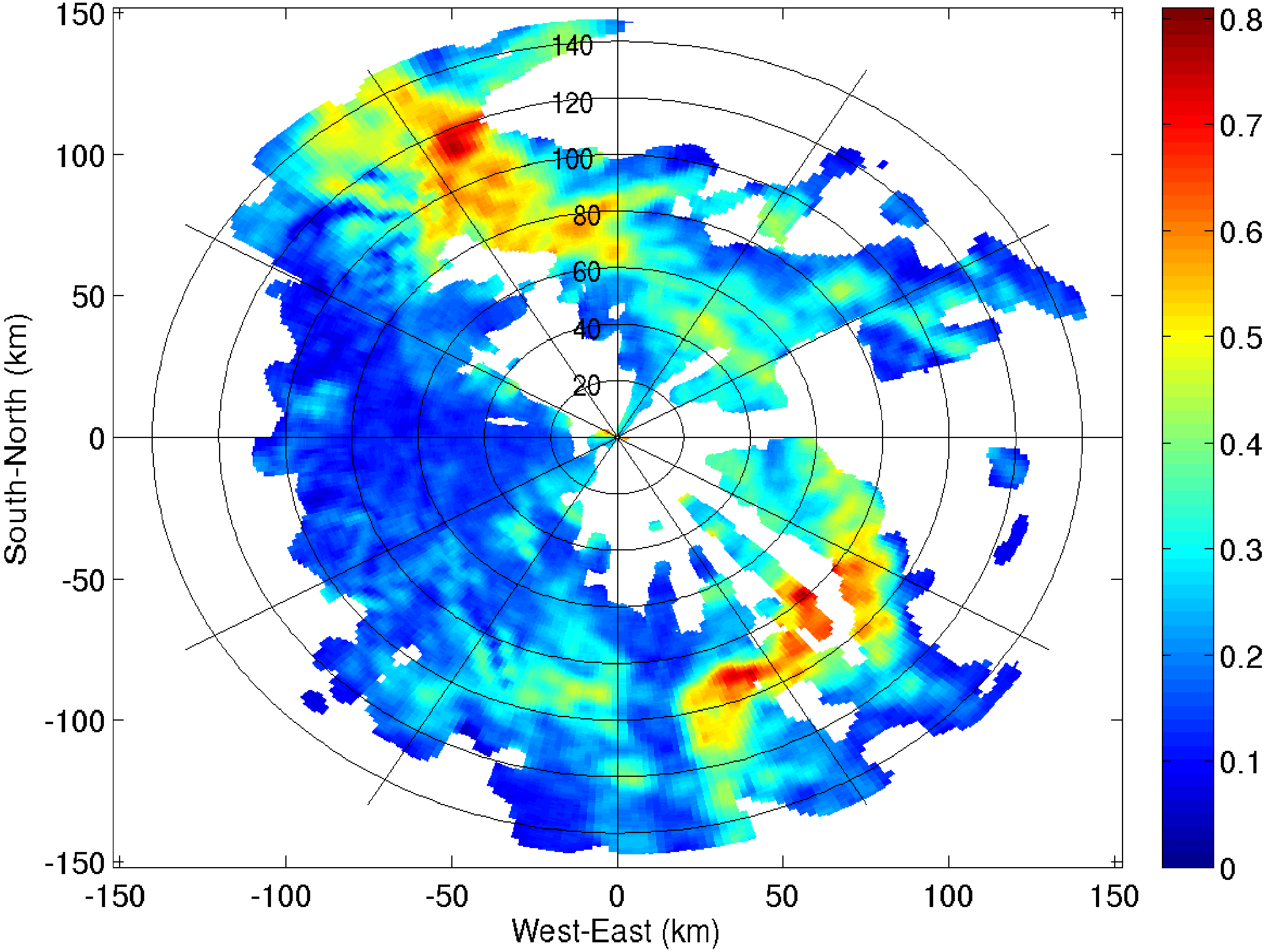


NTDA EDR from VCP 21 poly pulse hybrid ($m^{2/3}$ s^{-1})

relaxed QC increased coverage by 18%

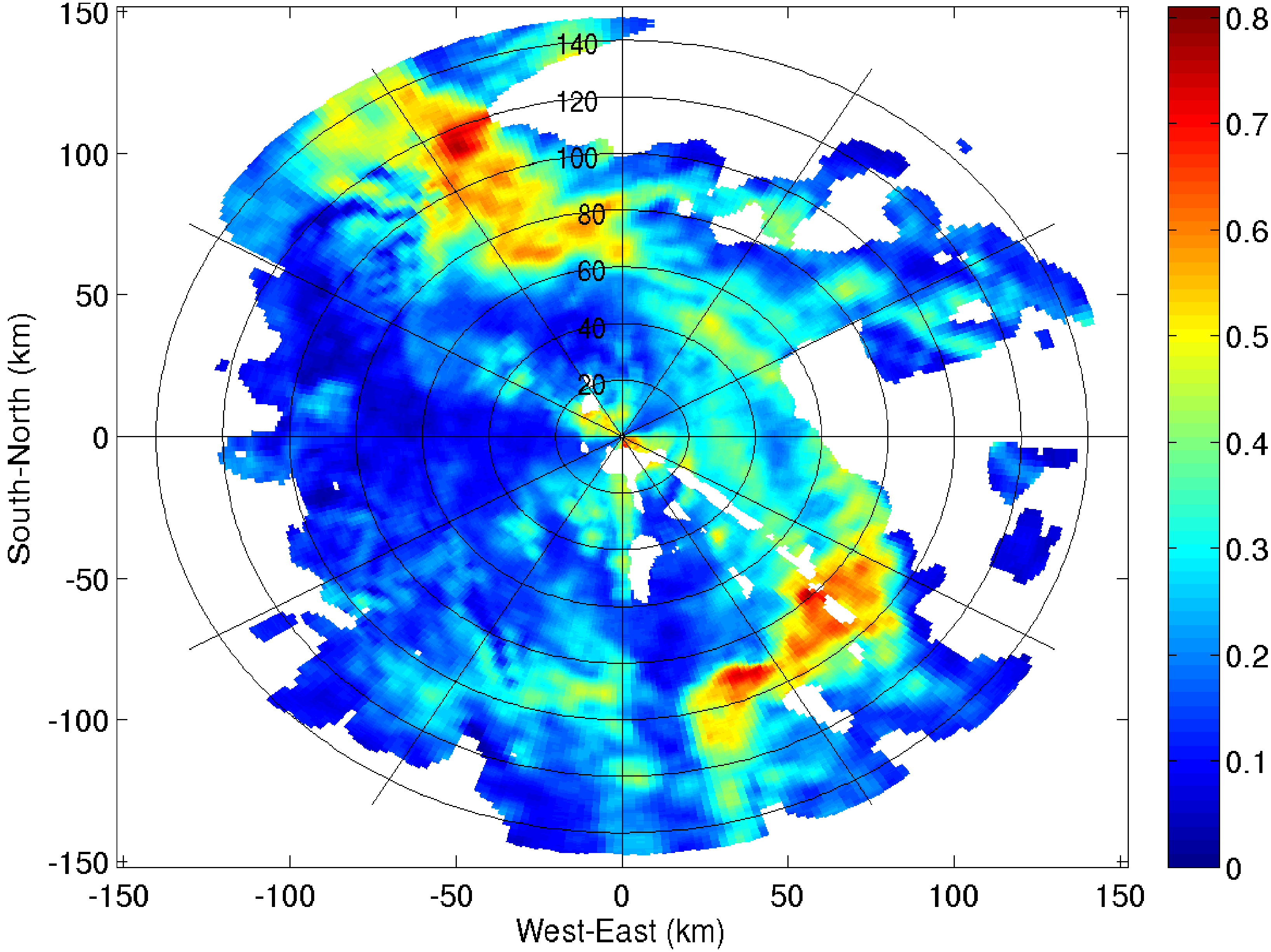


NTDA EDR from VCP 12 legacy R0/R1 ($m^{2/3}\ s^{-1}$)



NTDA EDR from VCP 12 poly pulse hybrid ($m^{2/3}$ s^{-1})

relaxed QC increased coverage by 23%



Case study summary

- Legacy spectrum width is very sensitive to overlaid echoes (NTDA QC uses VCP 21 threshold of ~40 dB PR, VCP 12 threshold of ~50 dB PR)
- The poly pulse hybrid spectrum width estimator
  - appears to show improved accuracy for low SWs
  - is much less sensitive than R0/R1 to overlaid echoes
  - is less sensitive to the number of pulses (this could aid QC in “mixed method” VCPs like 211, 212, 221)
  - is expected to be less sensitive to errors in noise estimation, which may be enhanced in thunderstorms.
- The hybrid method allowed relaxation of the NTDA’s SNR threshold by 5 dB and PR threshold by 20 dB, leading to about 20% increased coverage.

Relevant TAC Technical Needs

- **TN-31: Evolution of WSR-88D hardware and software to implement advances in technology and science**
  (Priority # 1, March 1999 ranking)

  Description: Ensure the continued capability of the WSR-88D system to implement desired mission support improvements, by employing an ongoing program to plan and execute WSR-88D upgrades.

- **TN-32: System Performance**
  (Priority # 2, March 1999 ranking)

  Description: System Performance includes assessing and improving (1) the performance of system hardware; (2) *the quality of base data*; and (3) the *performance of the algorithms*.

- **TN-17: Turbulence Analysis Techniques**
  (Priority # 9, March 1999 ranking)

  Description: Develop an algorithm that will locate and quantify turbulence that is hazardous to aircraft.

Possible alternative NEXRAD TR

- **Spectrum width computation**:
  autocorrelation, poly pulse-pair, spectral technique, or hybrid
- **Spectrum width estimate standard deviation:**

  "For a true spectrum width between 2 m s^{-1} and 12 m s^{-1}, the relative standard deviation in the estimate of the spectrum width shall be less than or equal to 25% and relative bias shall be less than or equal to 10% for SNR > 10 dB and overlaid PR > 20 dB. For a true spectrum width less than 2 m s^{-1}, the standard deviation shall be less than 0.5 m s^{-1} and the bias shall be less than 0.2 m s^{-1}. These values include quantization errors. Spectrum width shall be reported with a precision of 0.1 m s^{-1}."
- **Number of pulses averaged**: 29 to 280
- ***Notes**: These performance targets are equivalent to the current specification at 4 m s^{-1}; they appear to be achieved by the hybrid SW estimator method on simulated data. If windowing is used, oversampling may be required at fast scan rates.*

SW-related challenges for NTDA

- SNR and PowerRatio calculated from DZ are not always accurate
  - DZ may be adjusted by clutter filtering causing PowerRatio to be in error. This compromises QC effectiveness, particularly in the region following the unambiguous range.
  - In multi-method VCPs, the unambiguous range for each SW estimate may not be known.
  - Direct access to SNR and PR associated with each SW measurement would be helpful.

SW-related challenges for NTDA (2)

- Calculating SW-to-EDR factors and performing optimal QC require knowing *N* and the windowing method used for each SW estimate.
  - These can be estimated from VCP, PRF, and elevation number via VCP description tables, but this is awkward.
  - SZ-2 may use long pulse data for some estimates, and it is difficult to accurately determine when this happens.
  - Direct access to this information would be helpful.
- Saturation of the R1/R2 pulse-pair SW estimator used in SZ-2 could yield pseudo-random SWs that would lead to missed detections.
- Staggered PRT SWs could also exhibit low saturation levels.

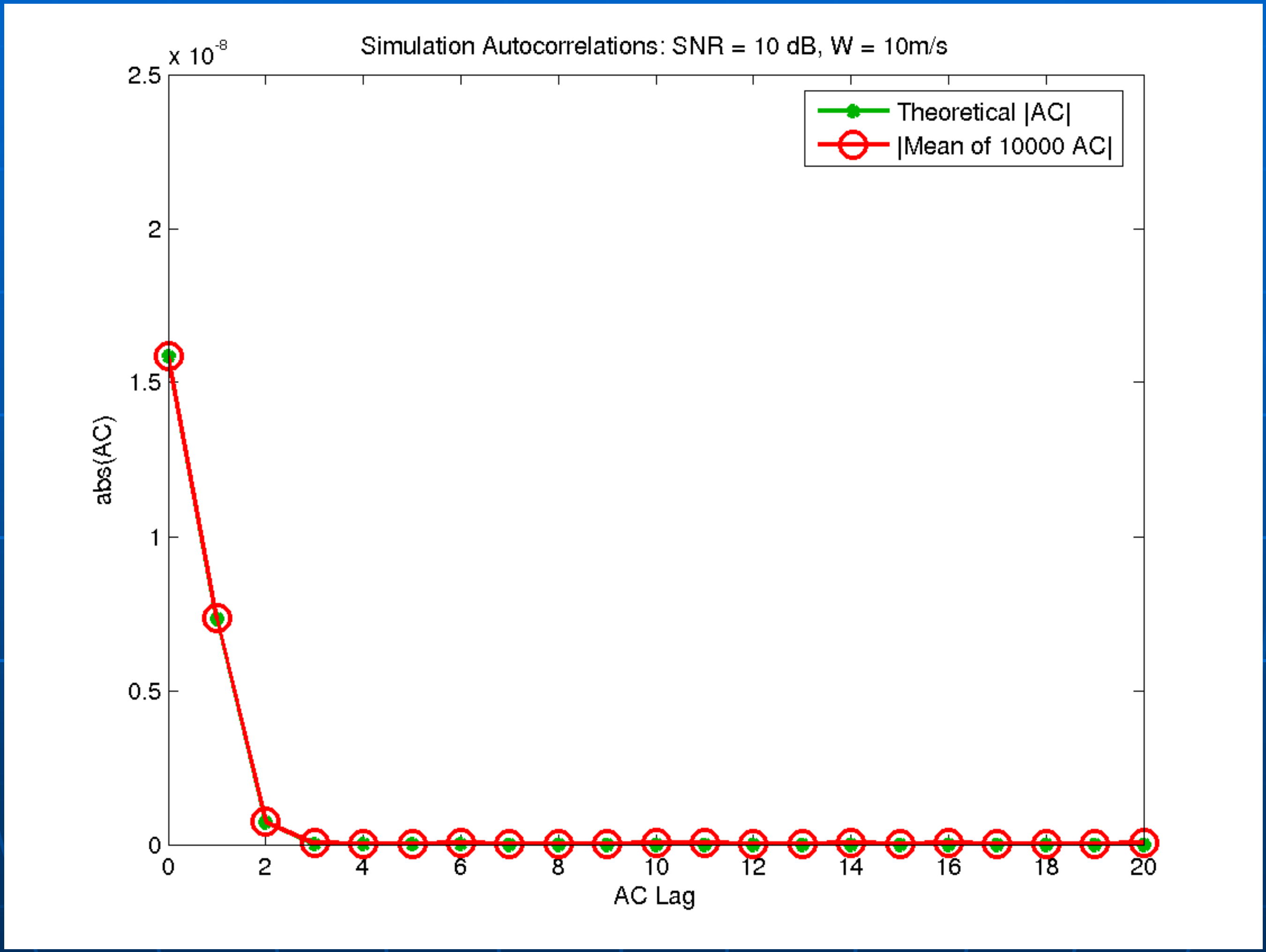
Future NTDA plans

- FAA AWRP funding for FY07 includes
  - continued support for ORPG Build 10 integration testing
  - operational 3-D mosaic development
  - a summer operational demonstration
  - evaluations and modifications to adapt to ORDA changes
  - beginning research and development of NTDA-2
- NCAR’s FAA AWRP manager indicates that NEXRAD SW estimator upgrade is an “operational systems issue” unlikely to be approved for FY08 AWRP funding.
- TAC endorsement and outside-AWRP funding are essential for improving NEXRAD SW quality.

Extras

Simulation Verification: SNR = 10 dB, W = 10 m/s

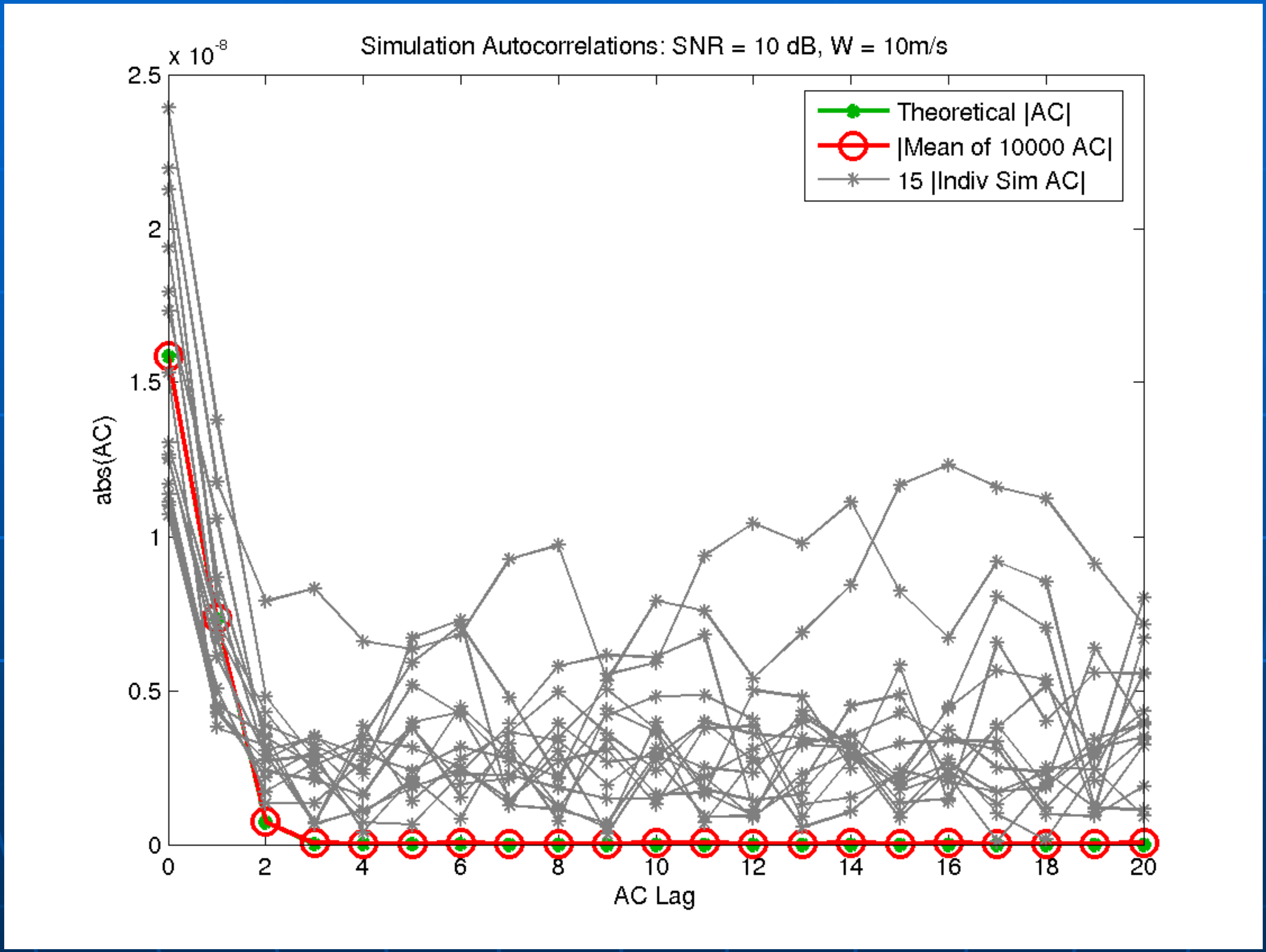
Autocorrelation Magnitude



Autocorrelation Lag

NCAR

Simulation Verification: SNR = 10 dB, W = 10 m/s



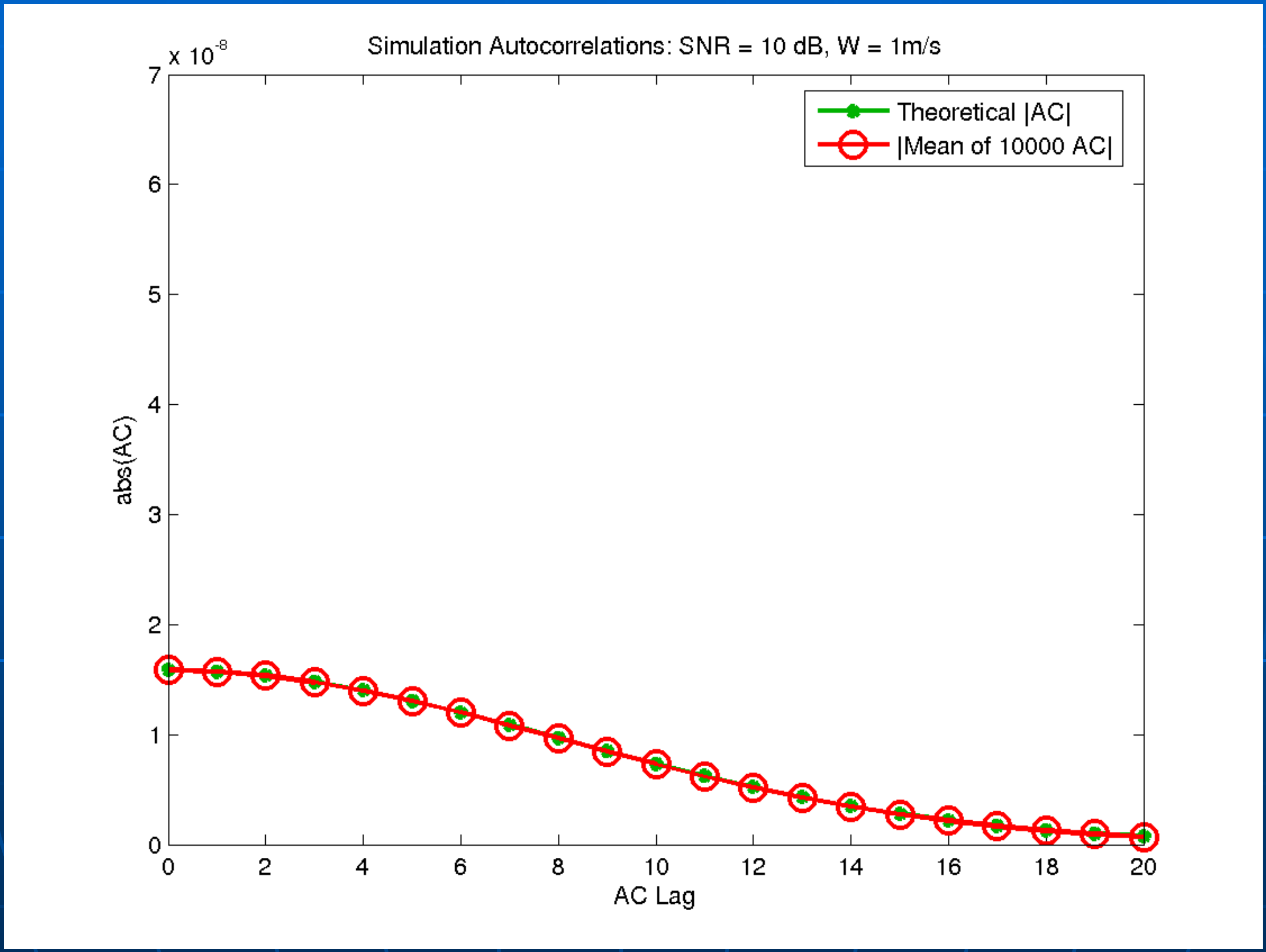
Autocorrelation Magnitude

Autocorrelation Lag

NCAR

Simulation Verification: SNR = 10 dB, W = 1 m/s

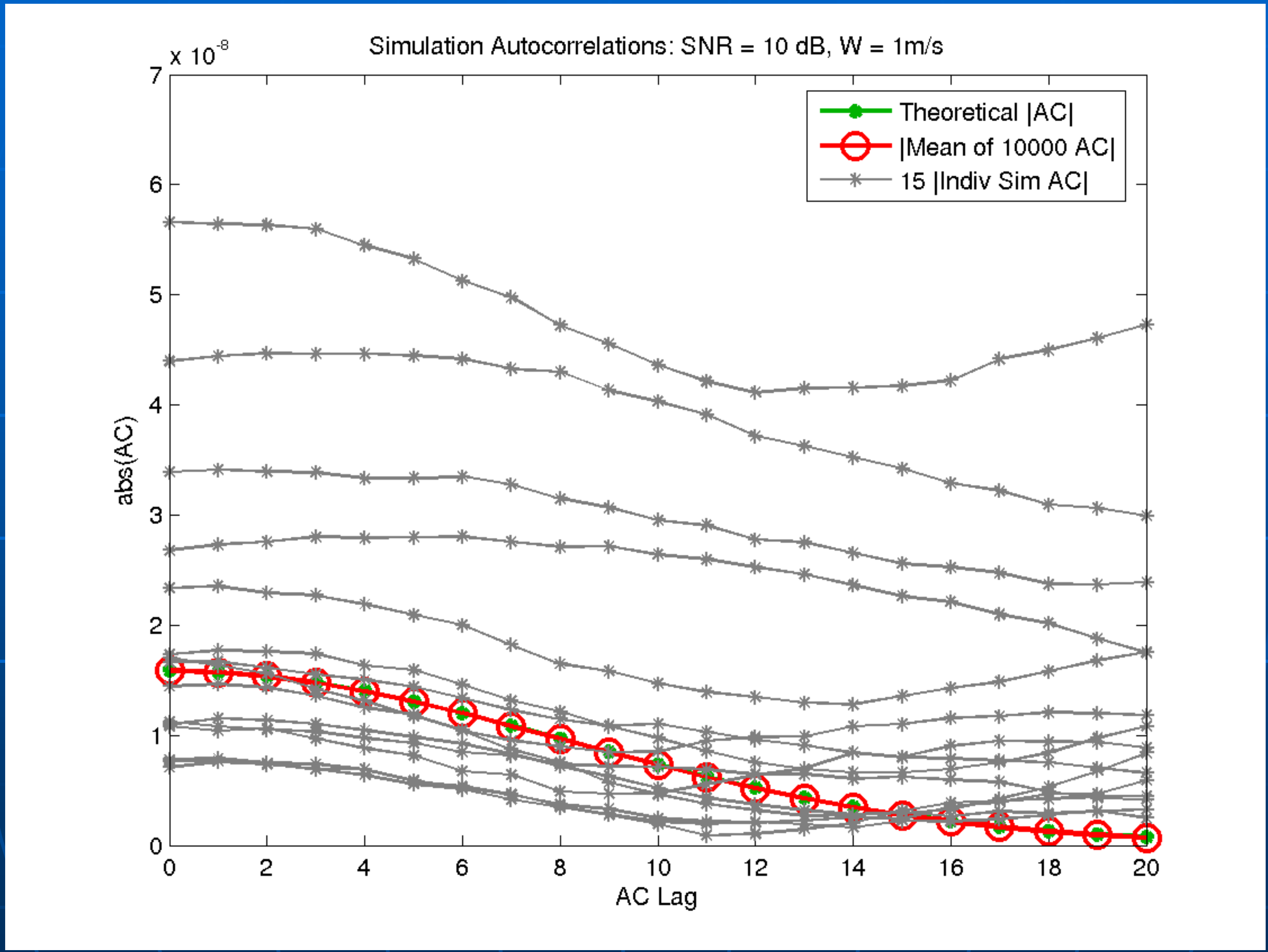
Autocorrelation Magnitude



Autocorrelation Lag

NCAR

Simulation Verification: SNR = 10 dB, W = 1 m/s

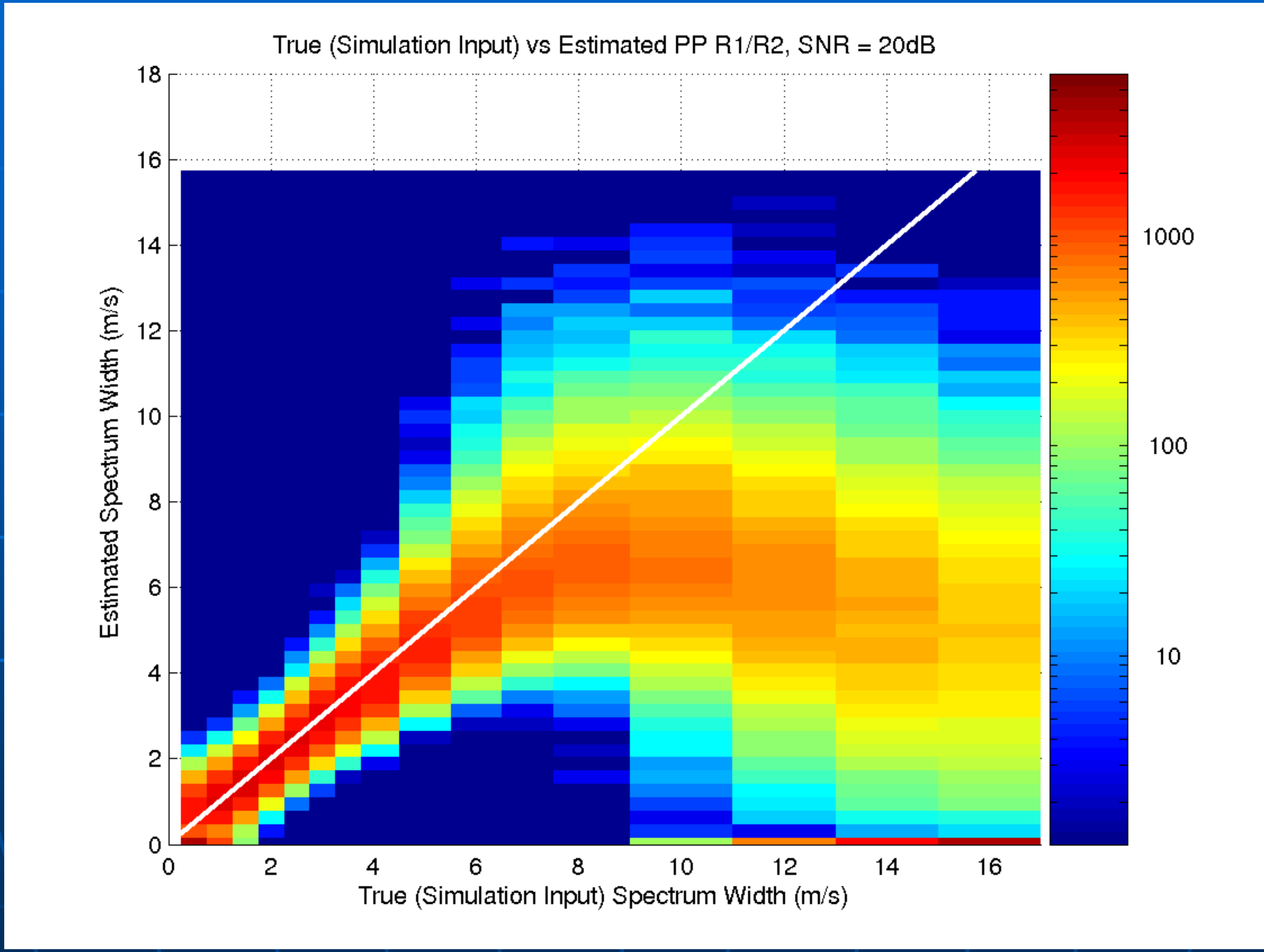


Autocorrelation Magnitude

Autocorrelation Lag

PP R1/R2 2D Histograms – True vs. Estimated:

SNR = 20dB



Estimated Spectrum Width

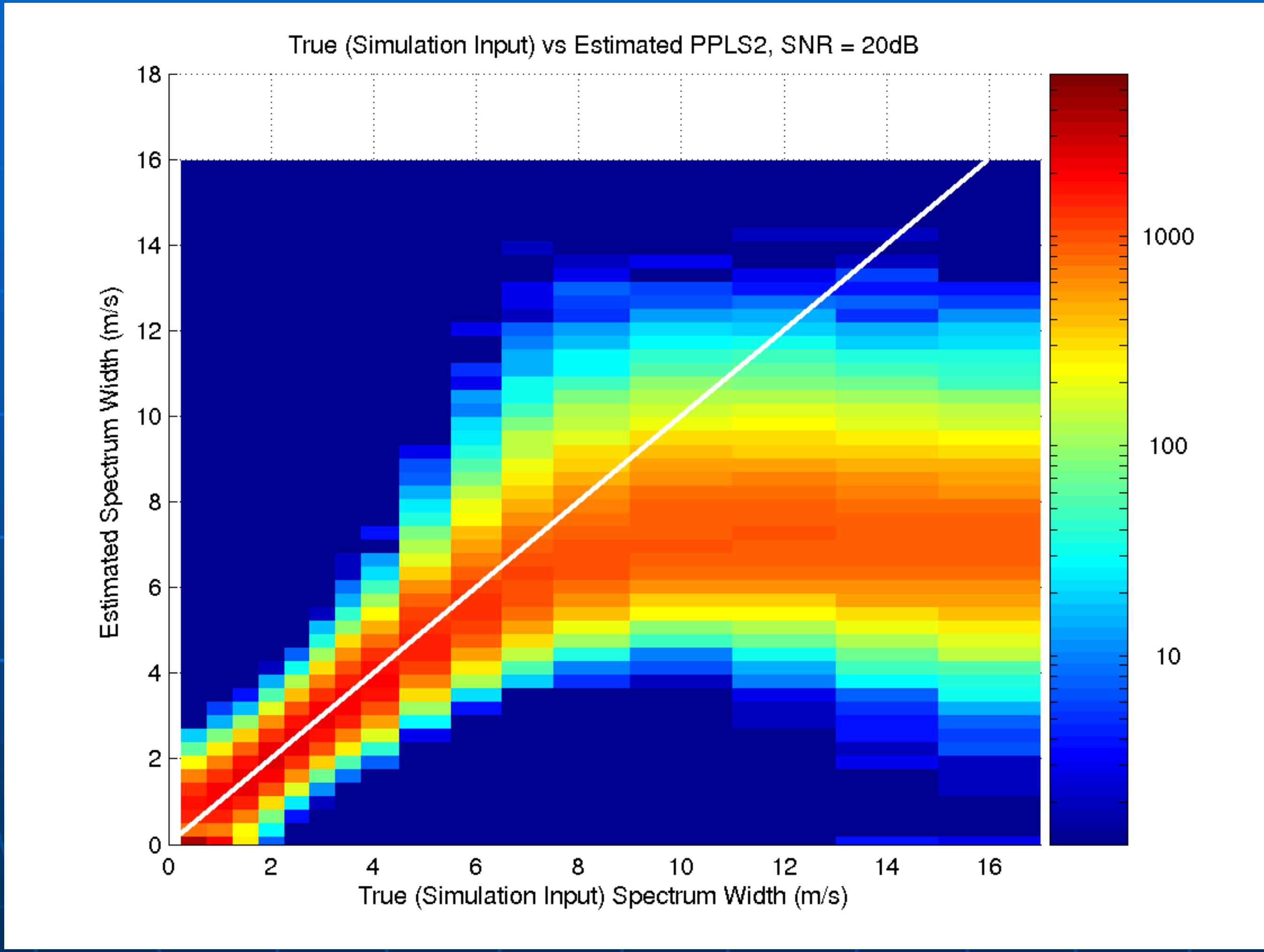
Frequency (log scale)

True (Input) Spectrum Width (m/s)

NCAR

PPLS2 2D Histograms – True vs. Estimated:

SNR = 20dB



Estimated Spectrum Width

Frequency (log scale)

True (Input) Spectrum Width (m/s)

NCAR

Bias and STD as a function of *N*